Construction requirements of the Water Supply of Constantinople and Anastasian Wall

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I hereby declare that this thesis, including the data presented (save where properly acknowledged), is my own work.

Abstract

With the end of Western Roman rule and the emergence of new polities in the medieval world, it has been assumed that the technology of mortar reverted to a weak and friable building material. However, this period brought about the implementation of large-scale construction projects that still remain as a testament to their high quality construction techniques and materials. In order to meet the needs of its growing populace, the infrastructure of the new capital city of Constantinople was bolstered by these projects, many rivaling the scale and intricacy of Imperial Rome. A prime example of this is the extensive channel networks of the fourth and fifth centuries, built in the hinterland of Constantinople to supply fresh water from springs hundreds of kilometres away. In addition, the sixth century Long Wall of Thrace was built from the Black Sea to the Sea of Marmara as a first line of defense against increased aggression.

This project examines the tradition of monumental construction in the Late Antique and early Byzantine world through laboratory analysis of mortars and valuations of the structural makeup of the Water Supply of Constantinople and Anastasian Wall. By investigating the material technology, scale, and labour requirements of these systems, a better understanding can be gained of two of the largest building project of the early medieval period.

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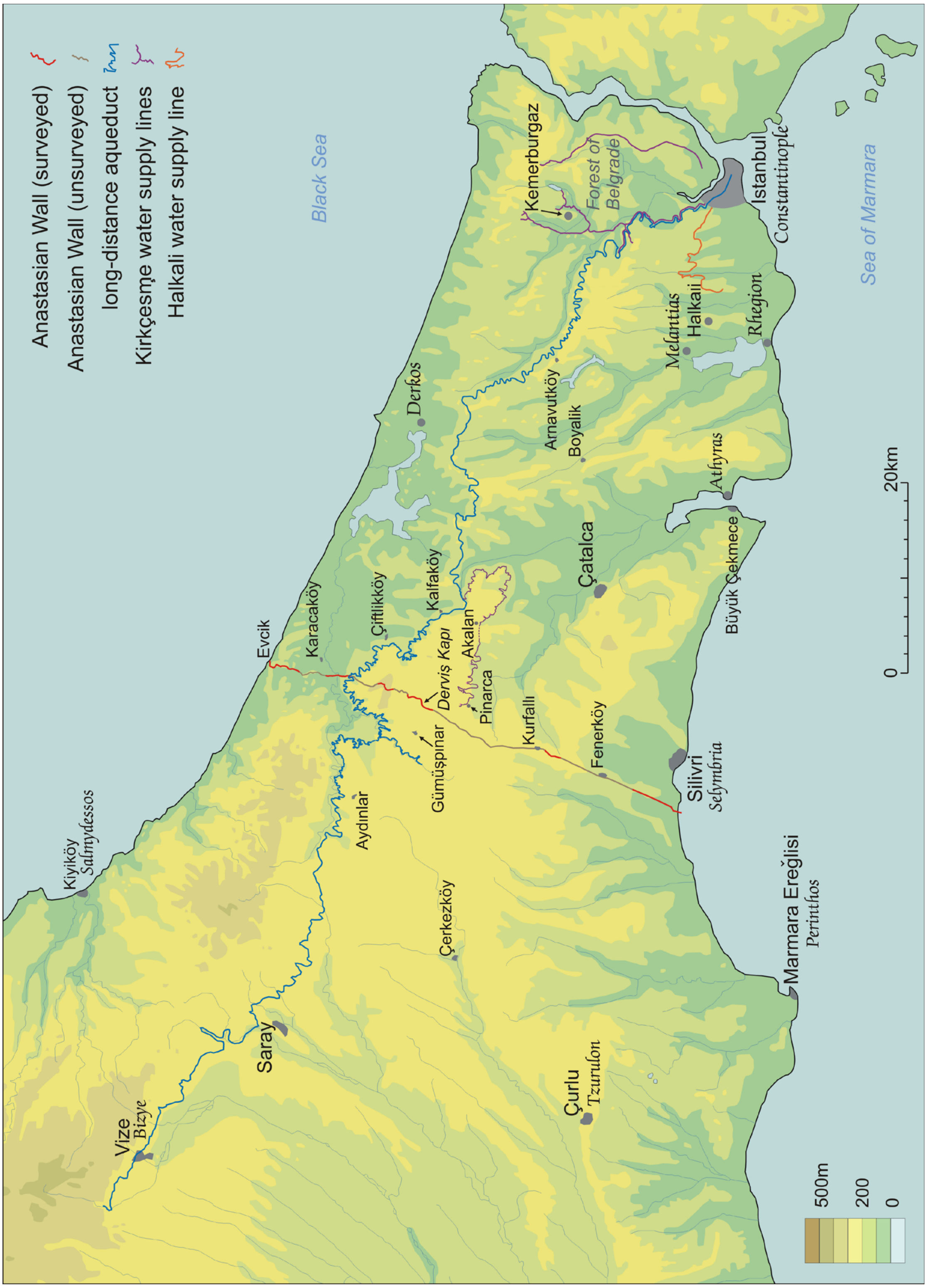
Chapter 1 - INTRODUCTION

But now we must proceed, as I have said, to the subject of the buildings of this Emperor, so that it may not come to pass in the future that those who see them refuse, by reason of their great number and magnitude, to believe that they are in truth the works of one man. For already many works of men of former times which are not vouched for by a written record have aroused incredulity because of their surpassing merit. And with good reason the buildings in Byzantium, beyond all the rest, will serve as a foundation for my narrative. For "o'er a work's beginnings," as the old saying has it, "we needs must set a front that shines afar."

Procopius, *Buildings*, 1.1.17-19

The Water Supply of Constantinople and the Anastasian Wall are principal examples of monumental construction in the Late Antique world. The water supply system, specifically the long-distance fourth and fifth-century phases, extended over a great distance to deliver much needed clean water to the city of Constantinople. The Anastasian Wall (also known as the Long Wall of Thrace) of the sixth-century stretches from the Black Sea to the Sea of Marmara, bisecting fourth and fifth-century channels of the water supply system and affectively restricting access to Constantinople by land. Through the research undertaken by the Anastasian Wall Project, led by Professor James Crow, the historical and structural framework of these systems has been covered quite thoroughly. This project aims to expand on this research by investigating material technology and the structural requirements for the construction of these large systems.



Map 1.1 - Line of the Water Supply of Constantinople and Anastasian Wall in Thrace (Crow, Bardill, and Bayliss: 2008: 11).

Initially, the objective of this project was to perform scientific tests on mortars from Constantinople, Thessaloniki and Ravenna to identify the influence of geography and local geology on mortar production techniques and quality. However, following the collection and initial programme of mortar sample testing from the Water Supply of Constantinople and Anastasian Wall, it was apparent that this analysis could be used in conjunction with an evaluation of their scale to provide a clearer understanding of the construction requirements of these vital infrastructural systems. As will be shown in this thesis, these structures were two of the largest building projects in late antiquity (Crow, Bardill, and Bayliss, 2008; Crow, 2007) and no work has been done to determine their material requirements. More importantly, nothing had been done to determine the labour requirements of any large-scale structure of the Late Roman and Early Byzantine world.

The use of the sciences has proven to be extremely beneficial in gaining a better understanding of the past. Sometimes, however, the full historical implications of the resulting scientific data may not make it into the general archaeological, classical, and architectural discussion. Specifically, this project aims to address the role that mortar plays in the continued preservation of these systems, how the mortars were made, where the raw materials components were sourced, and where the production sites were located. By applying scientific methods such as petrography, scanning electron microscopy, and x-ray diffraction, to the mortar material used in the Water Supply of Constantinople and Anastasian Wall, this project aims to build an understanding of their material technologies.

In addition, this project will continue to investigate large-scale construction in Late Antiquity by evaluating the scale of these structures. To achieve this, many resources and methods will be implemented such as local topographical data of the Thracian Peninsula, structural measurements taken by the Anastasian Wall Project, image analysis of architectural elements, and the development of formulas to calculate the volume of water supply and long wall. This volumetric data can be used to dissect these systems into their individual material building blocks.

Estimating the individual construction materials necessary for the water supply and long wall is the first step to understanding the building process. Working backwards from the point of material application to the sourcing of raw materials will be used to retrace the numerous required production processes. This ultimately leads to the final goal of this project. Calculating the individual construction materials, secondary raw materials, fuel resources and hypothetical locations of production and construction, man-power will be estimated for every available step of the construction process necessary to erect the Water Supply of Constantinople and Anastasian Wall.

While this project intends to be as comprehensive as possible, there are limitations that were impossible to overcome without further time and research. Understanding the labour and material requirements is only the first step to a much larger study of the implications of building the Water Supply of Constantinople and Anastasian Wall. This thesis will conclude by discussing the results of these findings as well as the possibilities of future expansion of this research.

Chapter 2 - AN INTRODUCTION TO THE WATER SUPPLY OF CONSTANTINOPLE AND THE ANASTASIAN WALL

‘Your city, you say to me, is a little one, or rather no city at all, but only a village, arid, without beauty, and with only a few inhabitants.’ But, my good friend, this is my misfortune, rather than my fault; if indeed it be misfortune; and if it is against my will, I am to be pitied for my bad luck, if I may put it so; but if it be willingly, I am a philosopher. Which of these is a crime? ... But we, you go on, have walls and theatres and racecourses and palaces, and beautiful great Porticoes, and that marvellous work the underground and overhead river, and the splendid and admired column, and the crowded marketplace and restless people, and a famous senate of highborn men.

Gregory of Nazianus, *Orations* 33, *Against the Arians* 6

After the defeat of Licinius in 324, Constantine was now the sole ruler of a reunified Roman empire. In the time Constantine spent in Thrace during the war against the Goths, as well as Licinius, Constantine realised the strategic and defensive benefits of the peninsular city Byzantium (Gregory, 2005: 50; see also papers in Grig and Kelly, 2012). When the decision was eventually made to move the administrative capital of Roman Empire to the small city of Byzantium much work had to be done in order for it to be worthy of the name ‘New Rome’. The fourth, fifth, and sixth centuries saw many large construction projects within the city intended to lift the status and glory of Constantinople. However, with a growing population and increasing threats from its neighbours, the history of the infrastructural growth of Constantinople extended far beyond the confines of the capital city.

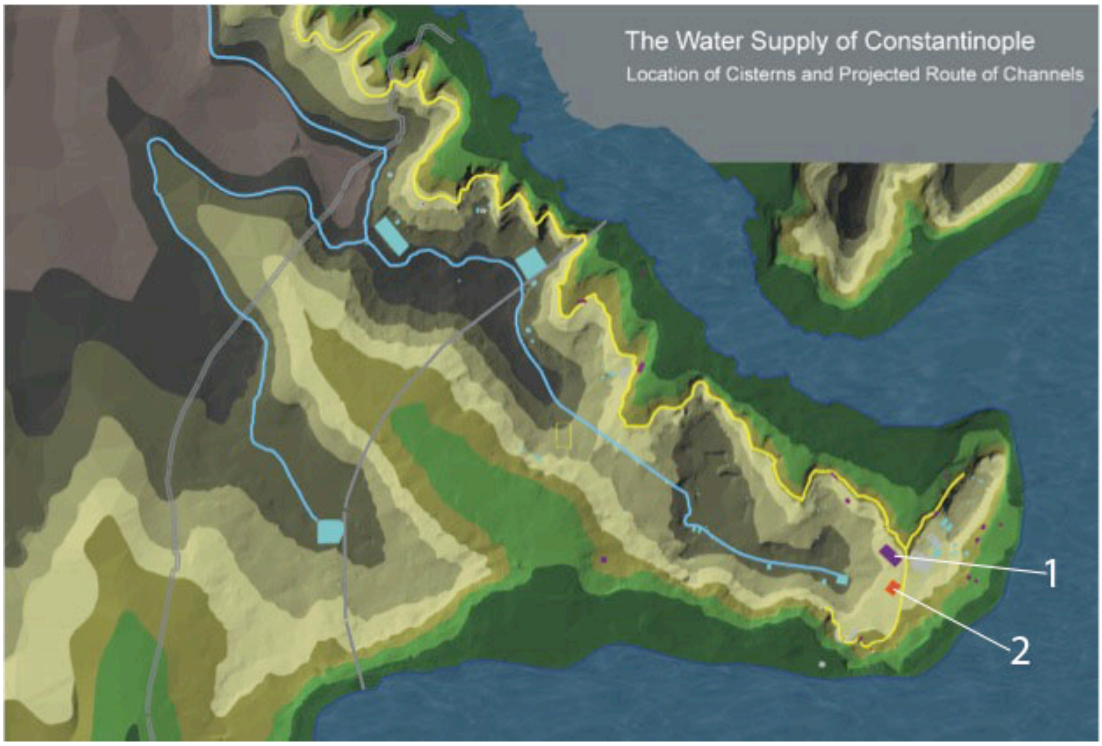
Two of the largest construction projects of Late Antiquity, while benefiting the city of Constantinople, were primarily built well outside the city walls. The Water Supply of Constantinople extended far into Thrace— almost 120 km to modern Vize— upon completion of its fifth-century phase. This system of channels, tunnels, and aqueduct bridges brought much needed water to the many baths and cisterns of the city (Crow, Bardill, and Bayliss, 2008). As a first line of defence, the sixth-century Long Wall of Thrace, also known as the Anastasian Wall, was built from the Sea of Marmara to the Black Sea. At a distance close to 65 km from the city (Crow and Ricci, 1997: 235), this fortified system of towers, forts and curtain walls restricted access to Constantinople and small settlements outside of the protection of the Theodosian Land Walls. Through evidence from archaeological fieldwork and historical sources, this chapter aims to contextualise the work carried out in this project by briefly outlining the history, previous research of these systems, as well as architectural and building material evidence. This will serve as the foundation for determining the true significance of material technology and the workforce required to construct these systems, which will be investigated in later chapters.

2.1 - The Water Supply of Constantinople

In his important study of the Water Supply of Constantinople, Mango (1995: 9) suggests that water consumption in the Roman city was more an attribute of culture than a physical need. Nevertheless, peoples of the past and present have gone to great lengths to ensure sustainable quantities of water, this certainly being the case with late antique Constantinopolitans (Crow 2007). The aim of this historical background is to review the evidence of the long distance supply lines that were built from the water sources to the city walls. Not surprisingly, most of the written evidence focuses on the work within Constantinople. However, recent archaeological research of these systems has significantly increased our knowledge of this system from water source to destination within the city.

2.1.1 - Second Century Water Management

Water had been flowing into Byzantium through an aqueduct system prior to Constantine's decision to turn the city into 'New Rome'. The location of the city was poorly situated for natural fresh water sources such as wells, springs and streams (Mango, 1995: 9) creating a need for water transport from the hinterland. According to Pliny the Younger (*Letters* 10.37-38) Hadrian provided an aqueduct for Nicaea in 123. It was likely that he did the same for Byzantium on his trip to Bithynia and Thrace (Crow, Bardill, and Bayliss, 2008: 13; Mango, 1995: 10).



Map 2.1 - Projected paths of major water supply lines within the city of Constantinople (after Crow, 2007: 254). Blue line = Valens, yellow line = Hadrian, 1 = Basilica Cistern, 2 = Baths of Zeuxippos).

By the later fourth century two separate aqueduct channels would have flowed into Constantinople at different elevations. According to a recent detailed study by Crow, Bardill, and Bayliss (2008: 13), the lower elevation line (30 m above sea level and lower), which followed the northern slope of the ridge running to the Bosporus, is the Hadrianic system (yellow line on Map 2.1) since its location between the First and

Second Hills would have supplied the earlier city of Byzantium. While the exact line of the channel outside the city is unknown, the source (or sources) is most likely springs in the Forest of Belgrade (see Map 1.1). Based on the research of Professor Çeçen (1996) the line of this system has been mapped by Crow, Bardill, and Bayliss (2008: Chapter 3) and a calculated length of almost 47 km. Unfortunately, nothing can be said with certainty about the Hadrianic system's structure due to the lack of physical and textual evidence.

2.1.2 – The Long-Distance Water Supply through the Fifth Century

The city was growing in population and prosperity after its dedication in 330 and the quantity of water provided by the aqueduct of Hadrian proved insufficient (Mango, 1995: 12; Crow, Bardill, and Bayliss, 2008: 9). To remedy this problem, a long-distance water supply was most likely initiated by Constantius II in the mid-fourth century and inaugurated by Valens in 373 (Crow, 2007: 270; Crow and Ricci, 1997: 232).

It has been postulated that the higher line inside the city (see blue line on Map 2.1), which includes the 971-m long Aqueduct of Valens (called Bozdoğan Kemeri in Turkish), was originally Hadrianic (Mango, 2004: 20; Andrèossy, 1828: 432-433) or rebuilt over the site of a Hadrianic line (Çeçen, 1996: 51-52). Crow, Bardill, and Bayliss (2008: 13-14) indicated that the elevation of the Aqueduct of Valens would have to abruptly drop 10 m to supply the majority of the lower city such as the Baths of Zeuxippos and the Imperial Palace. With the acropolis being the single structure of the pre-Constantinian city at the height of the Aqueduct of Valens, it is more likely that the higher line is associated with the buildings that populated these hills in the fourth century and later (Crow, Bardill, and Bayliss, 2008: 14).

Fortunately, there is much more surviving evidence for the fourth and fifth-century water supply lines since the vast majority was built far beyond the fast expanding modern Istanbul. Mango (1995: 9) aptly stated, "The dependence of Constantinople on its European hinterland is nowhere more clearly illustrated than in the domain of water supply." The evidence for this statement comes from years of surveys of the Thracian landscape. First, Çeçen (1996) began surveying the system in 1991 by recording bridges and channels on the ground and then surveying by helicopter as the forest became denser. Crow, Bardill, and Bayliss (2008: 5) indicate that, while not fully integrating this work into the broader historical context, Çeçen was the first to shed light on the monumentality of the late-antique water supply system by providing the first comprehensive maps and measurements.

Over three-quarters of a century before the work of Çeçen, Oreshkov (1915), a Bulgarian officer base in Çiftlikköy, spent some time (maybe during truce between December 1912 and February 1913) studying the Anastasian Wall as well as some of the major aqueduct bridges of the water supply (Crow, Bardill, and Bayliss, 2008: 3-4). However, the first person to consider the archaeology of the channels as well as aqueduct bridges was Dirimtekin (1968). While he did not fully address the relationship between the narrow and broad channels, his study showed the complex nature and monumentality the system (Crow, Bardill, and Bayliss, 2008). Unfortunately, these earlier studies have rarely made it into discussions of Roman aqueducts. Crow, Bardill, and Bayliss (2008: 4) explain that, "there remains a reluctance to develop a fully integrated understanding of infrastructures and their significance for classical and late antique urban history." The opportunity was taken by the Anastasian Wall Project to introduce the water supply into the historical, classical, and archaeological community when their first permit was granted in 1994.

Under the direction of Professor James Crow the Anastasian Wall Project team used remote sensing, field survey, and GIS to fully document the Water Supply of Constantinople (Crow, Bardill, and Bayliss, 2008: 5-6; Bayliss and Crow, 2000: 25). This work uncovered an even larger and much more complex system than had been discussed by Çeçen (1996) providing even clearer evidence of its importance within the framework of Roman and Late Roman infrastructural construction. Crow, Bardill and Bayliss (2008: 1) state, "The surviving remains and history of the Byzantine water supply of Constantinople represent one of the most extraordinary legacies from the ancient world." They calculated the total distance of the supply line in the fifth century to be 336 km to Vize and a distance of 215 km in the fourth century line from Danamandıra. Total length of three channels of the aqueduct system, including the Hadrianic system was calculated at 592 km. This more than doubles Çeçen's (1996) estimate of 242 km. Crow, Bardill and Bayliss continue by stating, "This was a Roman achievement even if it exceeded anything constructed in old Rome of the western empire and until recently it has not been presented in most studies on ancient aqueducts."

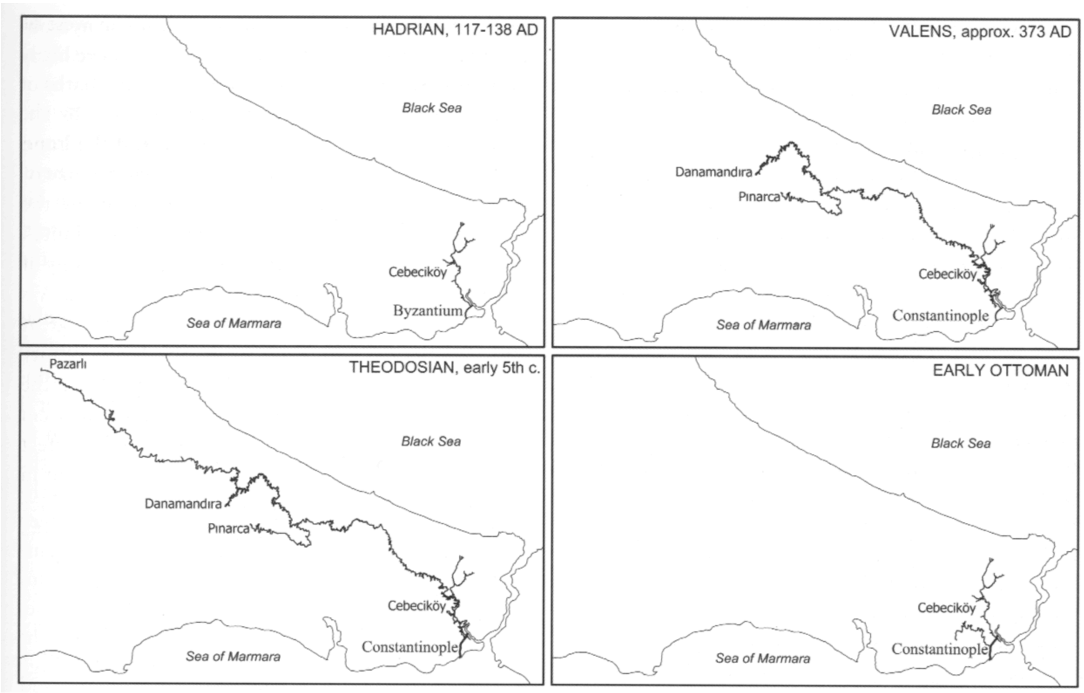


Figure 2.1 – Chronological development of the Water Supply of Constantinople (Crow, Bardill, and Bayliss, 2008: 11).

The fourth-century phase of the Water Supply of Constantinople sourced water from two major spring sources. The first was from springs around Danamandıra and the second was the supplementary channel closer to Constantinople near the modern village of Pınarca, both being narrow channels averaging 0.7 m wide (upper-right panel of Figure 2.1). The addition of the fifth century saw the extension of the water supply to Vize (Pazarlı Spring). At this source, the channel was narrow, like the fourth century channel. As this line approached the precursory fourth-century lines, the channel became much wider, averaging 1.5 m. It continued running mostly parallel (although at a higher elevation) until the two channels merged somewhere near Kalfaköy. Over the section where the channels of the two phases ran parallel, many new monumental bridges, such as Kurşunlugerme and Büyükgerme were built to accommodate the terrain.

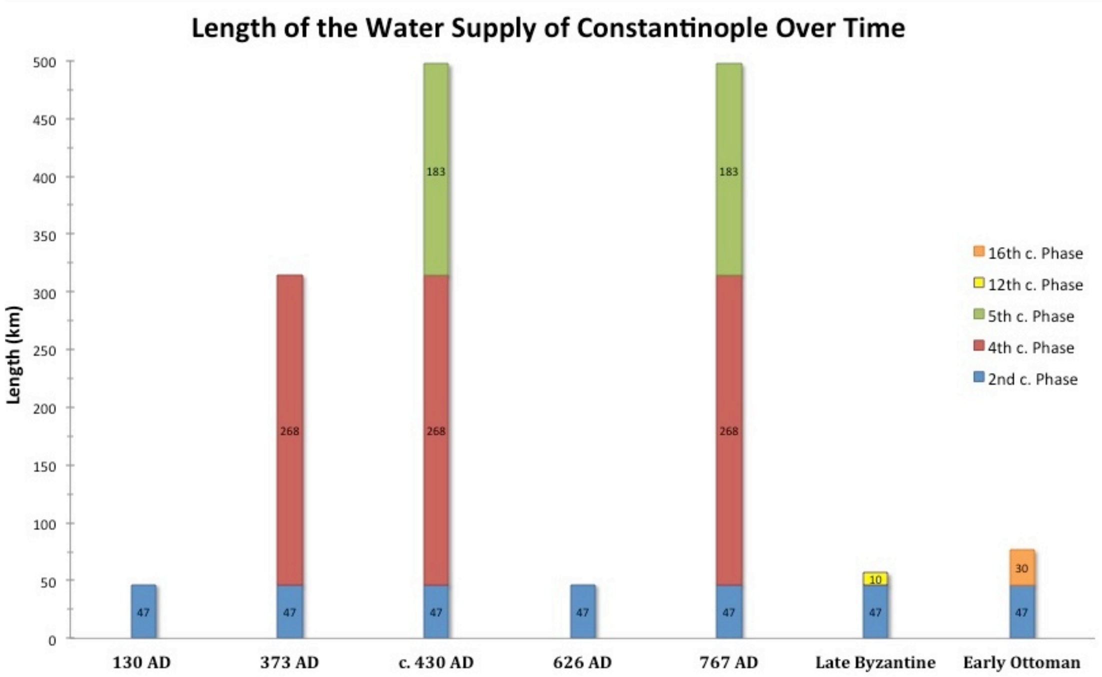


Figure 2.2- Length of the Water Supply of Constantinople outside the city walls over operating status of each phase. See Chapter 7 for a more detailed discussion of the distance measurements and Chapter Five for the methods employed.

As Figure 2.1 and Figure 2.2 indicate, the full extent of the water supply varied considerably over time. However, other than a period of disruption lasting 150 years during the early seventh century, the full extent of the system flowed until the late 12th century. This period of disruption should not be understated, as it would have limited the water supply to the lower parts of the city. The fear of insufficient water flow to the city seems to be a common theme in the histories of Constantinople and the maintenance required for such a long an intricate system eventually proved too much to keep it running (Crow, 2012: 52-53). It should be noted that the distances used in Figure 2.2 are based on the reanalysis of the channel lengths covered in Chapter 7. Similarly, a greater discussion of narrow and wide channels also takes place in Chapter 7. Also see Chapter 3 of Crow, Bardill, and Bayliss, 2008 for a comprehensive analysis of the surviving evidence of the channels and bridges of the water supply.

2.1.3 - Architecture of the Long Distance Water Supply

In the hinterland of Constantinople, the long distance water supply of the 4th and 5th centuries is made up of two primary structural elements: bridges and channels. The majority of the channel systems are built in the 'cut and cover' method whereby a vaulted masonry structure is built in a ditch and covered over (Figure 2.3) with inspection shafts for maintenance access. The course of the channel also runs through rock-cut tunnels in a few instances (Crow, Bardill, and Bayliss, 2008: 46, 108) and on few occasions over earthen embankments (Crow and Maktav, 2009).

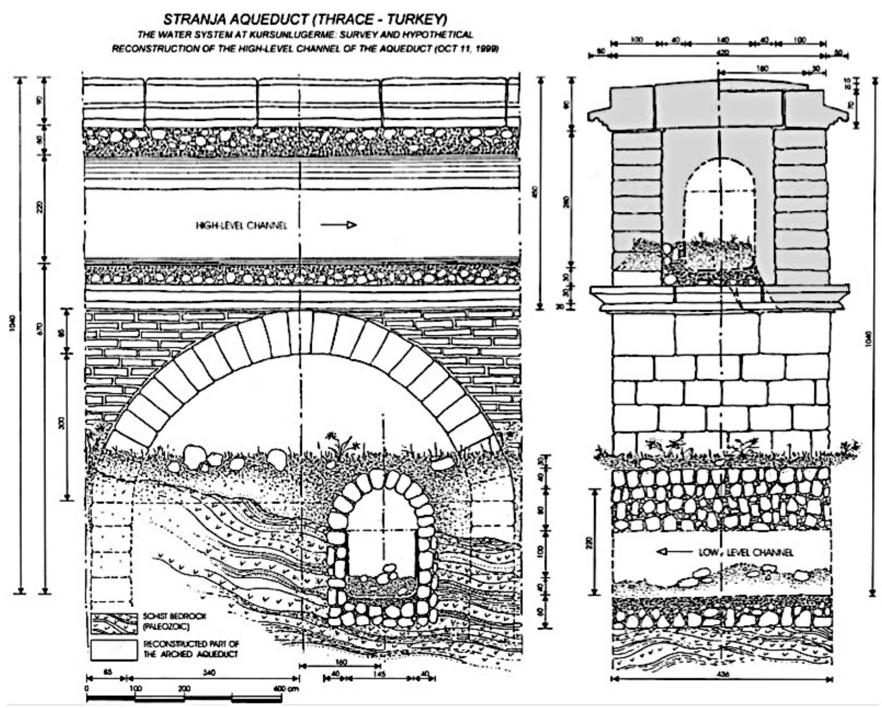


Figure 2.3 - Kurşunlugerme aqueduct; north-south section showing low-level channel passing beneath arch of later high-level aqueduct (after Bono, Crow, and Bayliss, 2001: 1329).

As mentioned above, the water supply was made up of narrow and wide channels. The walls and channel floors of both are made of small squared blocks or rubble set in hard pink mortar. These walls and flooring of the wide channel average 1.5 m thick while the narrow channel average 0.65 m. The vaulting of the wide channel is typically a shallow curve, also made of squared blocks or rubble. The narrow channel has a greater variety of vaulting such as steep or shallow segmental arches or pedimented vaults, all of which are built with rubble stone. The difference in vault construction has not been linked to specific building phases (Crow, Bardill, and Bayliss, 2008: 107). The type of stone used in the construction is associated with locally available resources such as limestone and schist (Bono, Crow, and Bayliss, 2001; Crow, Bardill, and Bayliss, 2008).

The other primary structural element of the water supply is aqueduct bridges. In the 4th- and 5th-century phases, aqueduct bridges were constructed with a mortared rubble core faced with stone blocks. In the 4th century, bridges were typically face with rough rusticated limestone blocks and timber cribwork was used to strengthen the core (Crow, Bardill, and Bayliss, 2008: 103). On the whole, bridges of the 5th-century phase were longer and wider (see discussion in section 7.1 of Chapter 7). In the largest of these, which Crow, Bardill, and Bayliss (2008) coin as 'monumental bridges', they are faced with large metamorphosed limestone blocks fastened by iron clamps set in lead. These blocks are commonly quarry-dressed with drafted margins and typically contain a mason's mark (Figure 2.4). The longest and widest of these bridges, Kurşunlugerme, is buttressed.

Figure 2.4 - Crystalline limestone block from Kurşunlugerme with drafted margins and mason's mark.

In the construction of aqueduct bridges, rubble stone used in the core of the structures seems to be made of the same (or similar) stone materials to the facing stones (Figure 2.4). The best evidence for this comes from 5^{th}-century monumental bridges like Kurşunlugerme and Kumarlıdere where, most likely due to seismic events, the facing stones have sheered off to reveal the mortar rubble core (Figure 2.5). This has revealed almost entire portions of the outermost core consisting of pink mortar surrounding rough stone.

Figure 2.5- Exposed mortar rubble core from Kumarlıdere (K31).

2.2 - The Anastasian Wall

Like most major cities in Late Antiquity, Constantinople relied heavily on its fortifications. The importance of Constantinople, through imperial building and patronage, led to its rapid growth (Crow and Ricci, 1997: 235). While the city held a naturally defensive position surrounded by water on three sides, additional protective barriers were built, rebuilt, and expanded to ensure Constantinople's protection.

2.2.1 – Fortification of Constantinople prior to the Long Wall of Thrace

While a network of ancient walls had outlined the city of Byzantium, Constantine knew its defensive benefits from his time there at war with the Goths (Gregory, 2005: 50). According to later traditions (see vol. 2 of Gibbon, 1821: 285; Turnbull and Dennis, 2004: 5) in 328, Constantine walked the future bounds of the city, effectively drawing the line of the wall from the Sea of Marmara to the Golden Horn. Despite the success of the Constantinian walls at deterring the Goths in 379, this proved restrictive for the quickly expanding city (Turnbull and Dennis, 2004: 5).

In 423, the Theodosian walls were completed around 2.5 km west of the walls of Constantine (Turnbull and Dennis, 2004: 7; Crow, 2007a; Ward-Perkins, 2012: 62-64). Despite being heavily rebuilt after its destruction from an earthquake, which occurred only 20 years after it was finished, the fortifications of the city repelled countless attacks for over a millennia.

2.2.2 – Defence under Anastasius

Fortification was of great importance to Emperor Anastasius. Justinian's defensive projects usually get the greatest discussion in modern studies and historical texts. However, Crow (1995) and Haarer (2006) argue that many of these were refortifications or additions to fortifications already built or started under Anastasius. Brick stamps from the southern section of the wall indicate an Anastasian date of construction rather than an earlier date (Bardill, 2004: 124).

The Anastasian Wall, also known as 'the Long Wall of Thrace', was one of the most impressive Roman barrier walls in Europe and one of the most striking achievements of the reign of Anastasius (Crow, 1995; Napoli, 1997: 280-296; Crow, 2007). Procopius of Gaza (21; Chauvot, 1986) a contemporary of Anastasius, praised the wall, saying:

> *What was the grandest and passes all imagination was to raise a high and powerful wall crossing all of Thrace. It passes from sea to sea, barring the route*

of barbarians, an obstacle to enemy aggression. The wall of Themistocles in Athens was smaller by report.

It has been argued that the Wall was first constructed under Theodosius II and only rebuilt by Anastasius (Whitby, 1985). However, Haarar (2006, 107-108; also see the forthcoming study on the Thracian Long Wall by Crow et al.) indicates that this confusion likely comes from the mention of a long wall in the 5th-century text of Herodotus, misinterpreted as the Anastasian wall, and most likely referencing the Chersonese Wall. 6th-century writers such as Procopius of Caesarea, Procopius of Gaza, and Evagrius all indicate the Long Wall of Thrace was a project of Anastasius (Haarar, 2006: 107).

The Anastasian Wall stretches from the Sea of Marmara to the Black Sea, covering a variety of different terrains. The southern section of the wall starting just west of Silivri, which only survives as broken construction materials and low mounds, runs across open agricultural fields. Further to the north, sections of the curtain wall, towers, and forts are well preserved to a height up to 4 m (Crow, forthcoming). The length of the wall has been estimated to be approximately 56 km long by William and Friell (1999) and 50 km by McAdams, Kocaman, and Kara (2010) but through systematic surveys of the wall, a figure of 46 km (Crow, forthcoming) is probably more reliable. No matter the discrepancy in length, William and Friell (1999:113) aptly state that the Anastasian Wall was a major investment in construction and military presence. Interesting, despite this investment and the multiple instances of being repaired or rebuilt, the wall fell into disrepair and disuse around a century after its construction, likely before the Avar siege of Constantinople in 626 (Crow, forthcoming).

2.2.3 – Architecture of the Anastasian Wall

The Anastasian Wall is made up of a single line of curtain walls, towers, and forts as well as a parallel earthen ditch (Figure 2.6). Based on the surviving evidence, towers varied in shape from rectangular and pentagonal, as well as the occasional larger hexagonal tower. Forts were of regular plan and built on the inside of the wall

(Crow, forthcoming; Crow and Ricci, 1997: 247). The long wall had forts (two planned and six identified by the Anastasian Wall Project) spaced roughly 3.5 km apart, and an estimated 340 towers occurring every 80-120 m (Crow, forthcoming).

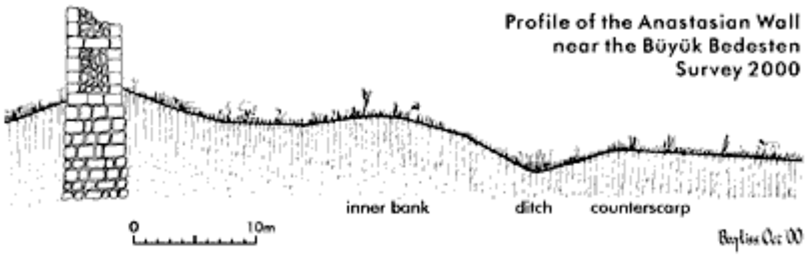


Figure 2.6 – Cross section of the Anastasian Wall near the Büyük Bedesten (after Richard Bayliss, 2000).

The surviving curtain wall, forts and towers are constructed in a similar fashion to the bridges of the water supply with a compacted mortar and rubble core faced with blockwork (Figure 2.6 – Cross section of the Anastasian Wall near the Büyük Bedesten (after Richard Bayliss, 2000).Figure 2.6). Debris found in the southern section of the wall near Silivri indicates that there may have been alternating brick courses in the south where the wall no longer survives. However, excavations carried out just north of Silivri in 2000 and 2002 by the Istanbul Archaeological Museum found no evidence of the use of structural brick. They did revealed the foundation of the curtain wall made of large mortared rubble between 2.5 and 3 m deep, similar to what was revealed by treasure hunters and identified by the Anastasian Wall Project at Derviş Kapı (Crow et al., forthcoming).

As mentioned above, towers were built in a variety of shapes but forts seem to be designed using the same plan. For more information on the dimensions of these structural features, see sections 5.7.5 - Anastasian Wall Structural Volume and Surface Area Calculations and 7.1.2 – Total Volumetric Estimates.

Figure 2.7 - Well preserved portion of curtain wall along the road leading to Evcik. Notice the alternating courses of large crystalline limestone blockwork and rough quarried stone facing.

There are two types of facing stone used in both the Anastasian Wall. From the well-preserved section of curtain wall south of Evcik (Figure 2.7) and also from elsewhere along the length of the Anastasian Wall as far south as Kurfallı, it is clear that similar crystalline limestone blockwork to the monumental aqueduct bridges of the 5th-century water supply was employed. In the middle section of the Anastasian Wall, there is evidence of a variety of stone sources, including schist and coarse sandstone. Soft white limestone is also seen in the middle section of the wall.

Little more than general macroscopic observations of the mortars, such as colour and brick aggregate size, have been offered from the studies of the Water Supply of Constantinople and Anastasian Wall. Similarly, since there is no evidence of the use of brick masonry (whole bricks) for the fourth and fifth-century phases of the water supply and very little known of the role it played in the southern sector of the long wall (See Bardill, 2004 for a discussion of associated brickstamps found near Silivri), little discussion of its role in mortars takes place in previous research on these structures. However, through sample collection and laboratory analysis, this project intends to develop a better understanding of this copiously applied material in Chapter 6. Similarly, little is known about the exact sources of stone used these structures. It is clear that all types fit it with the local bedrock geology (addressed in later chapters), but no evidence of large quarrying sites has been identified. While this project does not aim to identify these stone resources, future research is planned in order to obtain a more detailed picture of this important element of construction.

Chapter 3 - HISTORIC MORTARS: ARCHAEOLOGICAL, ARCHITECTURAL, AND HISTORICAL OBSERVATIONS

The ancients by means of writing established the wise and useful practice of handing down to posterity their sentiments on different subjects, so that not only those might not be lost, but that by their works continually increasing, a gradual advancement might be made to the highest point of learning. Our obligations to them therefore are great and many, from their not having sullenly kept their knowledge to themselves, but on the contrary, having recorded their opinions on every subject.

Marcus Vitruvius Pollio, *de Architectura*, VII 1

What are the qualities that made lime-based mortar an almost universally applied building material for structures in the Roman, Late Roman and Byzantine Periods? This is a complex question with an equally complex answer. Many scholars (see Chapter 4) have dedicated much time studying the many aspects of historic mortars. In regards to this project, this chapter will focus on some general principles relating to mortar production and application, in hopes of determining the requirements for large-scale projects in the Late Roman world.

The intention of this chapter is to address the archaeological and classical scholarship relating to mortars and similar materials of the Classical and Byzantine world. The first section deals with the technological advancements of lime-based mortar from its humble beginnings to ingenious observational science that led to revolutions in large-scale construction. Here, modern scholarship will be paired with classical written sources to chronicle the nature of this technology from the both the modern and historical perspective.

By including research on mortar technology, architectural application and construction requirements over a large geographical and chronological scale, this chapter aims to build a solid foundation for the analytical observations on the

Anastasian Wall and Water Supply of Constantinople. However, this chapter does not stand as the only investigative techniques for the study of construction materials. In Chapter 4, the discussion of mortar technology will continue by examining the scientific and experimental research of composite construction materials and their attributes in structural forms. As this chapter provides the historical background for the development and exploitation of these materials, Chapter 4 will discuss the laboratory techniques that have been used to answer some lingering questions about historical construction projects.

3.1 – Composite Material Technology

As far back as the third century B.C., Roman civil engineering and architects commonly used lime-based mortars for a range of purposes. A Roman politician and writer named Marcus Porcius Cato (234-149 B.C.) outlined what could be the first written recipe and description of early mortar application in his book *On Agriculture*. Cato (18.6-8) makes mention of stone, lime, sand, water, straw, and earth as the constituents of mortar at this time:

> *The owner will furnish the timber and necessary material for this and deliver it on the ground, and also 1 saw and 1 plumb-line (but the contractor will fell, hew, square, and finish the timber), stone, lime, sand, water, straw, and earth for making mortar…. Construct the enclosure walls of mortar, rough stone, and rubble (the owner furnishing all the material) five feet high, 1½ feet think, with a one-foot coping, 14 feet long, and let out the plastering…. The owner shall build the foundation 1½ feet think, and will furnish one modius of lime and two modii of sand for each linear foot.* (Hooper and Ash, 1999: 29)

One of the primary aims of this study is to gain an understanding of the binding materials used in the long-distances phases of the Water Supply of Constantinople and Anastasian Wall in Thrace. To achieve this, we must look at the fundamentals of historical mortars such as the historical understanding of this technology through written evidence, the basic properties of its chemical metamorphosis, and its application.

A question that must be addressed regarding construction techniques of the Late Roman and Byzantine empires is how much things have actually changed from Antiquity. The regular reference to the importance of Roman hydraulic concrete technology by many scholars as well as the scholars commonly dismissing detailed discussions of hydraulic mortars without volcanic additives necessitates a discussion on development. Unfortunately, late-antique sources rarely reference materials outside of the unreliable *On Building* by Procopius.

3.1.1 – Lime Production

The Greeks used lime for wall plastering, to line cisterns, and by the third-century BC, Greek engineer Philo of Byzantium recommended its use in fortifications in his work *Mechanical Syntax*.(Adam, 2005: 65, 337). Adam (2005: 65) stated that it was the Romans who revolutionized the use of lime (*calx* in Latin) mortars, replacing things like dried clay and gypsum to form “a permanent ‘glue’.” It is clear that lime-based mortar was seen as a vital resource for the Romans because from the first century A.D. onwards, builders used it in the majority of construction and restoration projects (Delatte, 2001: 109). Since building projects were becoming more grandiose during this time, it was the perfect material to meet their increasing demands.

What made lime-based mortars better than dried clay or gypsum? Delatte (2001: 110-111), Winter (1979: 139), and MacLaren and White (2003) outlined the chemistry of producing lime from limestone, where kiln temperatures reaching 1000° C for up to 7 days (Ousterhout, 2008: 133; DeLaine, 1997: 13) drives off bonded carbon dioxide:

$$CaCO_3\ (s) \rightarrow CaO\ (s) + CO_2\ (g)$$

The friable product CaO is calcium oxide; also know as quicklime, burnt lime, or caustic lime. Once water is added to the calcium oxide, it will violently react (slake) and disintegrate into a powder. As the quicklime combines with water to form putty, it can swell up to four times the original volume (Lancaster, 2005: 53):

$$(CaO\ (s) + H2O\ (l) \rightarrow Ca(OH)_2\ (s)$$

The resulting slaked lime product, $Ca(OH)_2$ is a paste substance known as calcium hydroxide (Winter, 1979: 139). As this paste is stirred, it slowly forms calcium carbonate:

$$Ca(OH)_2\ (s) + CO_2\ (g) \rightarrow CaCO_3\ (s) + H_2O\ (l)$$

This forms by the leaching of water diluting the calcium hydroxide, which is then replaced by atmospheric carbon dioxide.

The chemical reaction that occurs during the burning process is important for a technical description of the chemical metamorphosis but the production process is essential to understanding the human interaction. Adam (2005) states that Roman kilns would range from 2 to 7 meters in height and were typically built into the sides of hills. This would not only help to build and load a kiln but would aid significantly in insulation, retaining heat and maintaining the required temperatures for a significantly greater period of time (Dix, 1979: 262). Correspondingly, the walls of the cavity of the kiln would be lined with fireproof stones coated by clay mixed with broken pot sherds to protect the kiln from external moisture and retain heat (Adam, 2005: 67). According to Ousterhout (2008: 133), although no lime kilns have been excavated in the territory of the Byzantine Empire, two have been studied. One dates to the late eleventh century from Kiev and the other to the early twelfth century from Suzdal. Both had internal diameter of 3 meters. There is no evidence associated with lime production found around Constantinople but, as the next section discusses, the projects undertaken in the late antique city would require an industry equivalent to Rome at the height of the empire.

Lancaster (2005), in her book *Concrete vaulted construction in Rome*, describes the logistics of producing lime. She states that limestone was typically fired beside the quarries to ensure that similar stone was being fired in the same batch. This was done because different stone requires varying firing times and temperatures, meaning uniform stone would produce uniform lime (Lancaster, 2005: 53). Vitruvius (*On Architecture*, 2.6.2) was also clear about the selection of limestone explaining, "The lime from close-grained, harder stone will be most useful in structural forms, while that made from porous stone will be best in plaster."

However, according to Ousterhout (2008: 133) this attention to detail did not continue into the medieval period. He identified that early mortars from Kievan Rus' (around the 11th century) indiscriminately used different qualities of lime, even in the same wall. Lancaster (2005: 54) offers an explanation for this based on findings at Ostia and Rome, stating that the use of spolia from the fourth century onwards meant that a variety of stone types were fired together in the same kiln. Because of the differing firing temperatures between types of calcareous stones, this would have caused uneven firing, resulting in poor quality quicklime.

The result of fired limestone is an unstable substance also known as 'caustic lime'. It is so reactive that, if left to sit, a chemical process can cause the quicklime to become inert. According to Lancaster (2005: 54), this is called 'air slaking' which occurs when quicklime pulls water and carbon dioxide from the air, causing a weak chemical reaction that keeps the quicklime from reacting further when slaked.

Once limestone is burnt and the resulting quicklime is slaked, a further process will not only keep the lime from setting but will increase the strength of the chemi
Pliny (*Natural History*, Book 36, 175-177) indicated that the proper treatment of slaked lime was also important in quality control. He states:

> *The slurry* [a lime paste] *also becomes better the older it is; in the laws concerned with the old buildings there is even a regulation preventing a contractor from using a slurry less than three years old. As a result, no cracks disfigure the plaster of those buildings.*

Once lime has been produced, it can be used for a number of purposes. This is the fundamental ingredient of mortars but, as will be discussed later in this chapter, other ingredients owe to the success of large-scale construction in the antiquity and beyond.

3.1.2 – Pozzolana

Unlike other additives to lime-based mortar such as sand and pebbles, both natural and artificial materials can provide the crucial element to large-scale construction in the Roman and Byzantine periods. Curtis (1913: 197) presents an early view of the difference between sand and these other chemically reactive materials, stating, "Sands vary greatly in composition and size of particles, but consist mainly of fragments of quartz crystal. The fragments are so hard that the particles do not wear down to form a muddy paste, which would then be more susceptible to chemical reaction.".

The first type of mortar additive with an additional chemically-reactive element was called *pulvis puteolanus* by the Romans, roughly translating to 'earthy material from Puteoli' (Oleson et al., 2004: 199). The modern word pozzolana (used from here forward as any material added to mortar that causes an additional chemical reaction with lime) is derived from the same town north of Naples, now called Pozzuoli (Delatte, 2001: 109). Volcanic ash or pumice contains 27.8 to 32.6% silica (silicon dioxide or SiO_2) that, when crushed and powdered, contains the ability to chemically bond with lime (Winter, 1979: 140). These unconsolidated volcanic substances also contain large amounts of alumina (aluminium oxide or Al_2O_3), that also act as a reactive agent which increases the ability for lime to absorb dissolved carbon dioxide in an aquatic environment (Hale et al., 2003: 135). Mortar of this natural pozzolana gains increasing strength over time because of its rich aluminate phases that allow for controlled moisture absorption (MacLaren and White, 2003: 623).

Somewhere between 50 and 26 B.C. the architect and military engineer Marcus Vitruvius Pollo wrote his famous work *On Architecture*. Comprised of ten books, it contains some of the most important information on Roman architecture and engineering. Here, Vitruvius gives the earliest known discussion of volcanic pozzolana that makes makes so powerful it can withstand the tests of the environment and time:

> *There is also a kind of powder which, by nature, produces wonderful results. It is found in the neighbourhood of Baiae and in the lands of the municipalities round Mt. Vesuvius. This being mixed with lime and rubble, not only furnishes strength to other buildings, but also, when piers are built in the sea, they set under water.* (Granger, 2002: 101)

Pliny the Elder (23 to 79 A.D.) may be describing this same phenomenon in his work, *Natural History,* when he states:

> *But other creations belong to the Earth itself. For who could marvel enough that on the hills of Puteoli exists a dust—so named because it is the most insignificant part of the Earth—that, soon as it comes into contact with the waves of the sea and is submerged, becomes a single stone mass, impregnable to the waves and every day stronger, especially if mixed with stones quarried at Cumae.* (Humphrey et al., 2003: 244-245)

The second pozzolanic additive to mortar was crushed pottery because it had similar chemical properties to that of volcanic materials. Vitruvius explains, "Furthermore, if anyone adds a third part of crushed and sifted burnt brick into the river or marine sand [and lime], he will make the composition of the materials better to use" (Humphrey et al., 2003). Pliny, following Vitruvius, says, "If a third part of crushed potsherds also is added, the substance will be better."

Hale et al. (2003: 135) states that crushed pottery additives were weaker due to the silicates and aluminates being less porous, thus less chemically reactive than volcanic pozzolana. According to Lancaster (2005: 58) the pozzolanic nature of crushed brick and other ceramics increases with higher firing temperature (However, this will be contested in the next chapter, specifically in section 4.1.1).

Lancaster (2005: 58) continues the discussion of ceramic pozzolanic materials by describing that, like volcanic materials, fired clays are rich in soluble silica, the key component to the pozzolanic reactions. However, she continues by stating that terracotta has a slower chemical reaction than volcanic pozzolana because it has less porosity, resulting in less surface area for reaction to occur. These claims about the microscopic nature of ceramic pozzolana will be discussed in the next chapter where scientific studies of materials, such as pozzolana, will be reviewed.

3.1.3 – Brick Production

While there is no evidence for the use of brick masonry in the original construction phases of the Water Supply of Constantinople or Anastasian Wall, brick was still used in abundance as pozzolana in mortar. It is highly unlikely that brick would have been produced with the intention of being used in mortar. Rather, this material could easily be the by-product (wasters) of the production of structural bricks, making the production process an important addition to the conversation of mortar technology.

Adam (2005) gives a comprehensive explanation of brick production in the Roman era. He states that, like pottery, temper was required to reduce the shrinking and warping during the firing process. Ousterhout (2008: 129-30) reaffirms Adam's statement by indicating that, unlike mud bricks which would have been mixed with straw, fired brick would have required the addition of sand to temper the clay and prevent cracking. The structure of a typical Roman (Adam, 2005: 63) or Byzantine (Ousterhout, 2008: 130) brick kiln had a bottom section called the combustion chamber, separating the space above containing bricks, called the charge chamber or pot.

According to Adam (2005: 63) modern kilns in Kairouan (Tunisia) with charge chamber 3 m in diameter and 4 m tall takes around 3 hours to fire using brushwood and dried grass in hot dry weather. These reach temperatures up to 800°C near shelf and 450° by the top vent. The upper layer of bricks is usually thrown away because it isn't suitable for construction. Ousterhout (2008: 129) states that 800 to 950°C were optimum firing temperatures of brick and required 12 hours of firing and a week to cool down. The difference in firing time between Adam and Ousterhout is most likely related to the size of the kiln. Ousterhout (2008: 130) refers to two 12th-century kilns from Smolensk studied by Rapport. They measured 4.2m and were estimated to produce between 4,000 and 5,000 bricks. This would equate to roughly 50,000 over the 8 to 10 firings over a year period (Ousterhout, 2008: 130).

In regards to Constantinople, Ousterhout (2008: 128) claimes that bricks must have been produced locally. No evidence of production sites have been found but they were most likely located outside the walls of the city because of space needed and smoke pollution produced (Bardill, 2004; Also see *Codex Theodosianus* 9.17.4 for regulations regarding lime burning). The need was significant for bricks in the Late Antique and Byzantine world, and no place was this more true than Constantinople (see section 3.2 of this chapter). For example, Ousterhout (2008: 130-131) estimates that a moderately large church such as the Protoka in Smolensk would require a little less than 1 million bricks. However, approximately 1.2 million would need to be fired due to improper fire or breaking (Ousterhout, 2008: 131). This means that firing brick only yielded an 83% success rate. This

3.1.4 – Stone Selection and Quarrying

Ward-Perkins addressed stone in Late Antiquity in The Great Palace of the Byzantine Emperors (1958). He claimed that the use cut stone was not as prevalent from the fourth to sixth centuries while it was quite often used in conjunction with brick masonry. Ward-Perkins (1958: 75) references the Aqueduct of Valens and the sea-walls as the very rare exceptions. He states, "Cut stone was an expensive material, to be used when needed, but to be used sparingly."

Fant (2008: 133) made similar remarks for marble production, stating, "Thus the marble trade of the fourth century was already foreshadowing that of the medieval period, when most quarries had become inaccessible and crumbling Roman structures became the chief source of supply." He (Fant, 2008: 133) continued by stating that Diocletian's price edict most likely only covered reused stone since most of the quarries were under state control.

Ousterhout (2008: 136) offered an opposing view stating, “Because of the continued importance of Constantinople as a center, a great variety of imported stones appear in its buildings as well.” He goes on to outline the local stones that were also used in construction of Constantinopolitan buildings. Tertiary limestone and sometimes sandstone for general construction were quarried locally around modern Bakirkoy (about 2 km outside west of the southern terminus of the Theodosian Land Walls). The colour varies from cream to silvery grey. 100 km^2 west and northwest of the city (between Bakirkoy and Safrakoy) mactra limestone belonging to the upper Miocene period was used throughout the Byzantine period. Stratiform deposits 25 to 50cm thick were best for building and were usually found at a depth of 6 to 7 m (Ousterhout, 2008: 136).

3.2 – Composite Materials in Monumental Constantinople

Discussions of construction using mortar in Constantinople are essential in the understanding of building projects of the Water Supply of Constantinople and Anastasian Wall. While there are numerous references to the colour and application of mortars around Constantinople (Cutler, 1966; Krautheimer, 1967; Ersen, 1999; Özkan-Aygün, 2006; Çakmak, 2009; Ćurčić, 2010), this section will just focus on the most comprehensive studies of Hagia Sophia, the Great Palace, and the Land Walls.

3.2.1 - Hagia Sophia

Hagia Sophia may be one of the most well recognized monuments of the Byzantine world because of its impressive scale. However, more impressive is the fact that such a massive structure has stood for almost 1500 years with the majority of the structural elements being from original 6th century construction. The construction of Hagia Sophia started in 532, immediately after the destruction of the original church during the Nike Riots. It was dedicated in 536 under the reign of Justinian the Great and completed in 537.

The foundations of the church are well placed in terms of the surrounding geology. It rests upon natural rock, which is Folded Devonian schist at the crest of the Devonian anticline. Because this rock is a compressed and old formation, it was good for a structure on the scale of Hagia Sophia (Emerson and Van Nice, 1943: 411). However, due to an earthquake and the original dome being very shallow, only twenty years after it was built the dome fell. Studies done on the church as it stands today have been carried out to determine the effects of such seismic episodes. It was found that the behaviour of the structure is directly related to the "mechanical and chemical properties of the mortar and bricks used in its masonry" (Moropoulou et al., 2002: 543).

The main piers are the key supports for the dome and were made of stone while the majority of the rest of the church is built of brick and mortar (Mainstone, 1997: 69). Like many structures before and after, the bricks were laid in overlapping courses between thick beds of mortar. In the case of Hagia Sophia, the mortar joints are usually thicker than the bricks themselves by a ratio of 1:1.5 (Ward-Perkins, 1958: 71) to 1:1.66 including vertical joints (Emerson and Van Nice, 1943: 418). The brick shape is roughly square and measures 40 to 50 millimetres wide whereas the horizontal mortar joints are typically 50 to 60 millimetres (Mainstone, 1997: 70). While the mortar beds vary in thickness, they always seem to maintain this standard of being thicker than the brick, making this an intentional construction technique. According to Mark and Çakmak (1992: 11-12), the practice of using thick mortar joints is first observed in 3rd century, citing portions of the Niceae Walls. There is no consensus on this matter but could be linked to the availability of materials and economic advantages (Mark and Çakmak, 1992: 12) or to the decrease in the thickness of brick while mortar joints remained the same (Ward-Perkins, 1958: 76). It is also possible that this practice is related to structural performance, both during the construction process and in seismic events (see discussion of scientific studies section 4.1.3 of the next chapter).

Unlike many structures of Constantinople and beyond, Hagia Sophia has a unique construction style for its size and date. The archetypal technique usually consisted of walls that had alternating courses of banded brick and mortared rubble faced with dressed stone (Krautheimer, 1986: 79, 80). However, the wall elements of Hagia

Sophia are entirely brick and mortar construction, even stretching throughout the core (Emerson and Van Nice, 1943: 415). J.B Ward-Perkins (1958: 71) attributes this to heavy thrusts that would be applied throughout the structure due to its monumental scale. Krautheimer (1986: 156) states that the use of solid brick and mortar masonry makes "a nearly homogeneous resilient mass". While he says this is not as 'resilient' or 'homogenous' as Roman concrete construction, Mark and Çakmak (1992) claim that solid brick and mortar masonry is very reminiscent of its behaviour.

Mainstone (1997: 70) states that the structural mortar used in Hagia Sophia was not unique to 6th century construction in Constantinople. It is comprised of sand, slaked lime, marble dust, a sizeable proportion of crushed brick, and the occasional addition of pebbles (Mainstone, 1997: 70; Emerson and Van Nice, 1943: 418; see further discussion the next chapter by Moropoulou et al., 2002). Special attention should be paid to the crushed brick element of the mortar, which can range in size from 10 millimetres to a finely pulverised dust (Mainstone, 1997: 70). While the larger brick fragments only serve as aggregate, this brick dust is the key element to making this mortar remarkable because, as mentioned earlier, it acts as a pozzolanic additive. The article *Haghia Sophia, Istanbul: Preliminary Report of a Recent Examination of the Structure* by William Emerson and Robert L. van Nice (1943: 418) states that the proportion of slaked lime to crushed brick was one to one. Unfortunately, upon further research no other information regarding the process of analysis or further findings could be found.

Emerson and Van Nice (1943: 418) indicated that in a study carried out by Professor Frederick K. Morris from the Massachusetts Institute of Technology, it was found that grains of granite were found in samples of mortar. These granite grains most likely got incorporated into the mixture with the addition of sea sand. On closer inspection, it was concluded that this came from exposed granite on the Black Sea coast as far north and west of Istanbul as Dobruja. This indicates quite clearly that river sand was at least used in a portion of mortar of Hagia Sophia. Emerson and Van Nice (1943: 418) continue by suggesting that the use of sea sand along with proportion of brick to lime reflect the writings of Vitruvius and one his recipes. However, the addition of brick is not reliant on the use of sea sand in late antiquity. This is an instance where an overreliance on ancient texts can be misleading.

Not surprisingly, Hagia Sophia is mentioned in a number of historical sources. While most of these texts do not focus on its construction or building materials, there are a few instances where they briefly address these issues. Procopius, celebrating the achievements of Emperor Justinian in the mid-6th century *On Building* (1.1.53), briefly mentions construction of the four main piers of Hagia Sophia:

> *These were held together neither by lime (titanos), which they call "asbestus", nor by asphalt, the material which was the pride of Semiramis in Babylon, nor by any other such thing, but by lead (molibdos) poured into the interstices (telma), which flowed about everywhere in the spaces between the stones and hardened in the joints (harmonia), binding them to each other.*

While lead was not used as a masonry material as Procopius suggests, Mainstone (1997: 187) references sheets of lead at the springing of arches used to equalize the pressure. More closely paralleling this architectural evidence of these piers, Paul the Silentiary's poem, read at Hagia Sophia's rededication in 562 to commemorate the completion of the second dome, states:

> *In the joints they have put sheets of soft lead, lest the stones, as they lie on one another, and heavy weight bears upon heavy weight, should have their backs broken; with the lead between, the stone foundation is pressed softly and is gently burdened.* (Lines 476-480)

The section of the poem by Paul the Silentiary also references the mortar used in the construction of Hagia Sophia, stating, ‘in their midst the workman has mixed and poured the dust of fireburnt stone, binding them together with the builder’s art (Lines 455-457). It is unclear whether ‘fireburnt stone’ is referring to lime or brick but based on the methods of production of both materials, it could be that he is referring to both. The unknown author of the 8th- or 9th-century *Narratio de S. Sophia*, also references mortar, saying it was not made with water but with broth of barley and bark of elm.

3.2.2 - The Great Palace of Constantinople

Ward-Perkins (1958: 53-104) dedicates a large chapter on construction in *The Great Palace of the Byzantine Emperors 2nd Report*. The chapter entitled, "Notes on the Structure and Building Methods of Early Byzantine Architecture" is one of the most comprehensive examinations construction through material evidence of structures around Constantinople.

In regards to the Great Palace, he discussed the type of facing stones, mortar, brick, and construction methods. He stated that dressed stones are local grey limestone, which Van Millingen (2010: 44) claimed were quarried from the neighbourhood of Makrikeui. However, much of this stone was reused from destroyed buildings (Ward-Perkins, 1958: 56).

In addition, he offers one of the most detailed descriptions of the mortars used in the palace (see Table 3.1). The Palace substructure mortar is "pinkish or greyish white", and in almost all cases contains a high percentage of crushed brick, often in quite large nodules, together with small pebbles and other impurities that got into the mixture with the sand. Carelessly shaped bricks typical of Early Byzantine construction are set in thick mortar joints that make up over half of the masonry mass. Ward-Perkins (1958: 57) clarifies his choice of nomenclature by stating:

> *The term 'mortared rubble' is here used in preference to 'concrete' or opus caementicium since, despite a superficial resemblance to the concrete of Roman Italy (to which the term opus caementicium is usually applied), it lacks many of the essential properties of that unique building material.*

Table 3.1 - Description of mortars used in the Great Palace (Ward-Perkins, 1958: 54-57).

Location	Description
Early pier (Ib, of the phase preceding the 'greenstone' piers) incorporated in south-west pier of chamber D.	Average, 38 cm. square by 4cm.; 5 courses to 44cm. Very white mortar with little or no crushed brick.
Upper (original) arch between the two 'greenstone' piers IIb and IIc in Chamber D.	Average, 36 cm. square by 4 cm. Mortar contains rather less crushed brick than the next example
Lower (added) arch between the same two 'greenstone' piers piers in Chamber D.	Average, 34 cm. square by 4 cm. Crushed brick in mortar.
Walls of antechamber substructures (Chambers A-D, Apsed Hall period).	Average, 33-34 cm. square by 4-4.5 cm.; 5 courses to 46-47 cm. Mortar greyish white, containing much crushed brick, some of it in quite large lumps.
Substructures on axis of apsed hall, earlier phase.	33-35 cm. square by 3.5-5 cm. (a very irregular batch); 5 courses to 47 cm. Mortar containing large lumps of brick.
Substructures on axis of Apsed Hall, later phase.	Indistinguishable from the preceding example.
Vaulted chambers added against the outer face of the south-west wall of the Apsed Hall; Later than Apsed Hall.	Average, 34 cm. square by 4 cm.; 5 courses to 46-47 cm.

Ward Perkins (1958: 57) goes even further by addressing the quality of the mortars. In exceptional cases he claimed they can be very hard but is typically friable and easily broken up. He states that the mortar "lacks the tensile strength and consistency of Roman concrete, and was rarely used as a material in its own right in cases where heavy loads or stresses were involved." Mortar and rubble was used as 'filling' above vaulting in the antechamber and south-west outer wall of the Apsed Hall. He claimed that mortar was “used as an inert, space-filling mass; it is the bricks that do the work.”

3.2.3 - Walls Of Constantinople

No other fortification of a Late Roman or Byzantine city can compare to the Theodosian land walls of Constantinople in terms of scale and intricacy. Of course, this can be attributed to the significance of the city and empire it was built to protect. These fortification walls, as we know them today, were built under the rule of Theodosius II (Ahunbay and Ahunbay, 2000: 227) with the main wall being completed in 413, taking less than a year to finish (Krautheimer, 1986: 73) Unlike other city walls of the time that consisted of a single wall, the land walls of Constantinople were made up of a large inner wall, a formidable outer wall, and a moat. The inner wall was over 12 metres high with over 96 towers reaching a height of more than 18 metres and spaced out every 50 to 55 metres (Ahunbay and Ahunbay, 2000: 229). The outer walls averaged 8m high and also had towers that were elevated to10.6 metres. The moat was the first line of defence, spanning a width of 18.5 metres and 6 metres deep. The wall of the moat closest to the city extended another 2 metres above the ground between it and the outer wall. (Turnbull and Dennis, 2004: 9)

This fortification was said to impenetrable due to the care put into its design and construction, not to mention the might of the building materials employed within (Ahunbay and Ahunbay, 2000: 227). By looking at the remaining structure of the wall, three main types of materials are easily identifiable: dressed stone, baked brick, and mortar. The careful selection of such materials is a hallmark of roman engineering that is sure to have continued for such building projects. The sections of the walls that are built using stone are typically tertiary limestone collected from a quarry located three miles west of the Golden Gate (Turnbull and Dennis, 2004: 9). In some cases such as the southern section of the wall, the stone was cream-coloured sandstone from a quarry located just outside the city at the south end of the wall

(Ahunbay and Ahunbay, 2000: 229)**.** While no remains of major brick production areas have been found around the city, it is assumed they were also produced locally (Turnbull and Dennis, 2004: 9).

According to Krautheimer (1986: 73) alternating courses of brick and blockwork facing had been a typical construction technique along the west coast of Asia Minor, later being adopted in Constantinople. This makes the construction of the Theodosian Wall typical of this architectural tradition of the eastern empire since it consisted of bands of brickwork stretching throughout the thickness of the wall with alternating bands of mortared rubble faced with dressed stone (Ward-Perkins: 1958: 66). Brick bands ranged from 38 to 40 centimetres and were made up of five brick courses. Alternating bands of stone-faced mortared rubble were typically between seven and eleven courses high (Ahunbay and Ahunbay, 2000: 229). The foundations of each portion of the inner wall, outer wall, moat walls and towers were all of carefully stacked limestone blocks (Ward-Perkins, 1958: 66).

The mortar used in the original 6th century structure of the walls is also typical. It consists of lime, sand and crushed brick aggregate, and a fine brick dust (Ahunbay and Ahunbay, 2000: 229; Ersen, 1999: 107), making the appearance pink in colour. Other than the pointing used in the joints of the portions of the wall immediately visible from major thoroughfares such as the Golden Gate, which consisted of a very hard dark pink mortar with a higher ratio of brick dust to lime (Ahunbay and Ahunbay, 2000: 229, Ward-Perkins, 1958: 66), the mortar was quite uniform in appearance between the mortared rubble core and brick joints. J.B. Ward-Perkins (1958:66) states that the likely case for the pointing in these areas refers only to its aesthetic quality of contrasting the deep pink mortar with the cream coloured stone blocks because as mentioned earlier, the application of pointing adds no structural properties. Later repairs and additions are marked by a different type of mortar that usually consisted of large brick aggregate with little to no brick powder (Ersen, 1999: 107). This mainly white mortar would not have the same structural and hydraulic properties as the original mortar and usually resulted in a material that was quite friable.

3.3 – Remarks on Construction Materials in Constantinople

One of the interesting aspects of construction in Constantinople is the heavy reliance on brick masonry construction. This chapter has outlined three of the largest construction projects of the city— Theodosian Walls, Hagia Sophia, and the Great Palace— each utilising brick masonry construction. It should be noted that this is not limited to these structures. Alternating stone block facing and brick courses are found at church structures such as the Paracclesion of the Pammakaristos, the refectory of the Monastery of Manuel, and Bogdan Serai (Church of St. John in Petra) (Van Millingen, 1912: 28) as well as the 4th-century hippodrome (Krautheimer, 1965: 73).

As was discussed in sections 2.1.3 and 2.2.3 of the previous chapter, there is no evidence of the use of brick masonry in the construction of the Water Supply of Constantinople or Anastasian Wall. Despite the use of brick masonry in both open and closed cisterns and reservoirs within the city (Crow, 2008: 129-138), evidence from the Aqueduct of Valens only shows brick used in later repairs to narrow the arches (Crow, 2008: 121). Just like the 4th- and 5th-century bridges of the water supply and the curtain wall, towers, and forts of the long wall, construction of the Aqueduct of Valens consists of mortared rubble faced with dressed stone blocks (Ward-Perkins, 1958:65). When considering the Anastasian Wall, this type of construction is actually more reminiscent of the early 5th-century walls of Corinth than the large city walls of Constantinople, Thessaloniki, and Nikopolis (Gregory, 1979: 271-272).

of the water supply and long wall is The two systems at the centre of this study rely almost completely on stone and mortar. It can be argued that the mortars from these two systems are common when compared to the other structures within Constantinople. The architectural discussion of structures within Constantinople show that crushed brick was a common and important ingredient in ubiquitously applied mortar. However, there are questions left unanswered about crushed brick's role in the success of late antique architecture. Much of this is due to the lack of information regarding materials in late antique writing and the overreliance of modern scholars on Roman texts such as Vitruvius and Pliny (see evidence from section 3.1).

The next chapter will review scientific studies of mortars containing ceramic additives aiming to explain why this particular technology was chosen. This will be used as jumping board for a scientific examination of mortars from the Water Supply of Constantinople and Anastasian Wall (Chapter 6), arguably the most important material for the success of these largest construction projects undertaken in the ancient world.

Chapter 4 – PREVIOUS SCIENTIFIC MATERIAL STUDIES

I, therefore, O Cæsar, do not publish this work, merely prefixing my name to a treatise which of right belongs to others, nor think of acquiring reputation by finding fault with the works of any one. On the contrary, I own myself under the highest obligations to all those authors, who by their great ingenuity have at various times on different subjects, furnished us with copious materials; from which, as from a fountain, converting them to our own use, we are enabled to write more fully and expediently, and, trusting to whom we are prepared to strike out something new.

Vitruvius, *On Architectura*, 1.0.10

The previous chapter introduced some construction methods and materials, specifically relating to mortar production technology and application. These historical, architectural, and archaeological observations are fundamental to the understanding of Roman and Late Roman construction techniques but many unanswered questions still remain. What are the mortars' exact recipes? Where did the source material for the mortar originate? What happens during the hardening process to create such a durable material? What were the necessary conditions at each stage of manufacture to produce a suitable mortar? Are there any variations in recipe relating to the functional purpose of the mortar? What is the micro-structural relationship between mortar and other adjoining materials? These questions, while seemingly simple, cannot be answered using macroscopic observation alone. Many details can be inferred about things like the relationship between aggregate and the lime binder. Similarly, comparisons can be made between the state of preservation of a monument and the methods and materials used to construct it. However, the exact details of these relationships can only truly be speculation without more intensive scientific studies.

The use of science can lead to the answers of these important questions with surprising accuracy. This chapter reviews a selection of the important scientific studies that have been carried out to explore the intricacies of mortar and other associated materials.

There seem to be three types of discussion of historical composite construction materials such as lime-based mortars. The first are the architectural and archaeological studies of construction materials centred on the macroscopic nature of these materials in relationship to the structural requirements (see Chapter 3). The second is the physico-mechanical, mineralogical, and chemical studies carried out through scientific analysis in the laboratory. The third discussion of mortar comes from a single study using experimental archaeology. This chapter will discuss these scientific studies, outlining their approaches, methods and results and will finish by discussing the involvement of experimental archaeology by the ROMACONS Project. Most importantly, this chapter aims to show how laboratory analysis has been used to answer important questions regarding our understanding of the both the technology, production and application of historic construction materials.

4.1 - Laboratory Analyses of Historic Mortars

The development of numerous scientific methods and their application in the field of archaeology has revolutionized our ability to understand the past. This is particularly true in the cases of studies relating to building materials technology. While information of historical importance obtained through scientific material studies does not always make it into archaeological, historical, or classical sources, the intent of these studies is to investigate new techniques that can play an instrumental role in our knowledge of monuments of the past.

The point of this section is not to explain the science behind laboratory methods used in mortar studies. In fact, much of these techniques are explained in regards to their importance to modern cement and concrete properties. The primary focus of this section is to indicate how these methods and resulting data have been used to further our understanding of historical characteristics of material production technology. For discussions on the science and development of many of the scientific techniques, see

Moropoulou, Bakolas and Bisbikou, 1995, Middendorf et al., 2005, Konsta-Gdoutos, 2006, John, Poole & Sims, 1998, Goins, 1997, Elsen, 2006, Janssens and Van Grieken, 2005, Moropoulou and Polikreti, 2010.

Since the studies presented in this chapter are rich in information, the reviews will be structured in format to ensure that the most pertinent data is included. A discussion of these studies will be included at the end of each section. In the majority of cases, the scientific techniques employed in these studies have been referred to by their shortened form in this chapter. The full name of these techniques and their acronyms are as follows:

AAS – Atomic Absorption Spectroscopy
AFM – Atomic Force Microscopy
CPDT – Clamp on Point Displacement Transducer
DSC – Differential Scanning Calorimetry
EPMA – Electron Probe Microanalysis
ESEM – Environmental Scanning Electron Microscopy
EDXS – Energy Dispersive X-ray Spectroscopy
FT-IR – Fourier-Transform Infrared Spectroscopy
ICP – Inductively Coupled Plasma Atomic Emission Spectrometry
IR – Infrared absorption analysis
INAA – Instrumental Neutron Activation Analysis
LVDT – Linear Variable Displacement Transducer
MFO – Fiber Optical Microscope Observations
NAA – Neutron Activation Analysis
PCA – Principal Component Analysis
SEM – Scanning Electron Microscopy
SEM-EDS – Scanning Electron Microscopy-Energy Dispersive Spectroscopy
TEM – Transmission Electron Microscopy
TGA – Thermogravimetric Analysis
TG/DTA – Thermogravimetry/ Differential Thermal Analysis
TG/DTG – Differential Thermogravimetric analysis

XRD – X-ray Diffraction
XRD^2 – Two-dimensional X-ray Diffraction

4.1.1 - The Function of Pozzolana in Lime Mortars

As discussed in the previous chapter, pozzolana is the key to producing a strong and waterproof lime-based mortar. This section will present a selection of scientific studies that identify and investigate the qualities of volcanic and brick pozzolana.

Studies

The study of the interaction between volcanic pozzolana and lime under different environmental conditions is important for an understanding of the masonry technology of structures within Rome and parts of west Italy. A good example this type of analysis comes from the 2005 article by Sánchez-Morala, Luque, Cañaveras, Soler, Garcia-Guinea, and Aparicio. The authors first collected samples of mortar from the second century catacombs of Ss. Callistus and Domitilla located outside the ancient walls of Rome. These samples were tested using polarized light microscopy of thin sections cut to 35µm to determine mineral interaction and porosity, ESEM and EDS to obtain data on crystal shapes and morphology, mercury intrusion porosimetry to further analyze porosity, IMP and AAS to obtain chemical compositions, and XRD analysis to identify mineral interactions between the volcanic materials and lime.

To fully understand both the formation and preservation of these mortars, the microclimatic nature of the catacombs' environment was measured to determine relative humidity, CO_2 concentration, temperature, and radon isotope (^{222}Rn) concentrations. These environmental readings showed over 97% relative humidity with constant temperatures ranging between 15 and 17°C, water chemistry with pH values close to neutral, and high CO_2 concentration values of 1700 and 3500 ppm. After comparing the data obtained from sample analysis and environmental conditions, the authors were able to come to some interesting conclusions. First, the environment, specifically the high levels of CO_2, would have expedited the calcification of the lime by 500%. Second, lime lumps found within the mortar samples indicated possible dry slaking due to the low water to mortar ratios. Despite the fact that the catacombs were cut into natural volcanic beds, the third conclusion was that other, less altered volcanic material was used as a pozzolanic additive. Finally, large contents of unstable minerals in the volcanic additives were identified as the catalysts for chemical reactions around aggregate grains, forming the necessary hydrous calcium aluminosilicates.

The article "Interaction between clay and lime in 'cocciopesto' mortars: a study by 29Si MAS spectroscopy" by Zendri, Lucchini, Biscontin, Morabito (2004) discusses the crystalline formations of important minerals during brick firing processes and the subsequent chemical reactivity of these minerals when mixed in lime-based mortar. The first step of their testing was to recreate mortars using carefully manufactured bricks from pre-identified clay sources. The clay that was chosen for testing had a high percentage of phyllosilicates, which the authors state are the key ingredients referenced in other testing of cocciopesto mortars. The composition of the clay was 42.5% kaolinite, 31% cristobalite, 13.5% andesina, 10% quartz, and 2.5% montomorillonite. Firing temperatures between 500 and 900°C were stated as being the range required for the necessary transformation of phyllosilicates to their amorphous phases. Thus, samples of this clay were then fired at temperatures of 500, 550, 600, and 700°C, providing a comprehensive look at these transformations at different stages of heating. Si MAS spectroscopy was applied to the raw clay and then to each sample heated at their designated temperature. This test was also done on samples of mortar, containing a 1:1 fired ceramic to lime putty ratio, that were left to cure for 5 months in different environments. The first environment was allowed to cure in open air at 60% humidity and the second was in an N_2 atmosphere with 100% relative humidity.

The results from the unfired clay after the five-month period in open air showed very little reaction with the lime due to the crystalline formation of the phyllosilicates. At

500°C, around 40% of the crystalline form was converted to their amorphous states necessary for satisfactory hydraulic reactions. The highest amount of identifiably converted amorphous phyllosilicates came from the clay that was fired between 550-600°C, indicated by the heavy interaction with lime after the five-month curing time. In the N_2 environment the reaction of lime with the amorphous phyllosilicates was found to be more 'sluggish' after the five-month period. Yet, because the environment is devoid of CO_2 and thus, the immediate transformation from $Ca(OH)_2$ to $CaCO_3$ is inhibited, it was found that lime is forced to interact with the contents of the fired clay.

In their article "Characteristics of brick used as aggregate in historic brick-lime mortars and plasters", Böke, Akkurt, İpekoğlu, and Uğurlu (2006) discussed their findings on the relationship between firing temperature and the pozzolanic nature of crushed brick. They studied crushed brick mortars from 14th- and 15th-century Ottoman bath buildings in Edirne and Bursa using XRD, SEM-EDS, AFM, TGA and chemical analyses. They collected seven samples of brick-lime plasters, one sample of dome mortar, and three dome bricks. All of the plasters and mortars were found to be quality mortars with pozzolanic reactions due to the addition of crushed brick. However, testing of the structural brick used in the dome showed that it would not have been nearly as successful as a pozzolanic additive based on "less amount of amorphous material" (Böke et al., 2006: 1121). Their findings suggested quite clearly that bricks were specially selected for the mortars, depending on function. The authors concluded that bricks had high amounts of clay minerals and must have been fired at low temperatures to produce a quality hydraulic mortar.

The 1997 article "Study of the pozzolanicity of some bricks and clays" by Baronio and Binda focuses on the analysis of new mixes of brick and lime-based mortars used for the restoration and repair of historic building masonry. A variety of clays were fired at different temperatures and then tested to determine their pozzolanic nature using petrographic and mineralogical testing such as SEM-EDS and XRD. These were then compared to data from tests of historic brick and lime based mortars. It was found that a finely crushed powder made of pozzolanic brick created a high degree of pozzolanicity. This would not include modern bricks not only because they fired at a high temperature but also because they have low clay content. They also state that "When the basic material [of the pre-fired brick] is clay, then a thermal treatment can give pozzolonicity properties." Furthermore, depending on the type of clay being used, the temperature of firing must be chosen carefully. They concluded that other tests of historic mortars from the 5th century work at the Church of S. Lorenzo were representative of the highly pozzolanic bricks produced in their clay testing, which allowed these mortars to last for centuries.

Discussion

It is clear from these studies that a range of scientific methods can be used to identify and investigate both volcanic and ceramic pozzolanic materials. Interestingly, three out of four of these studies use a combination of SEM, EBSD, and XRD techniques to answer questions about the crystalline shape, morphology, and mineral interactions of pozzolanics with lime. These methods were used to show that low-fired and finely crushed bricks had a better pozzolanic reaction than large pieces of brick or those fired at higher temperatures. Additionally, 29Si MAS spectroscopy produced the same conclusions, but was also able to pinpoint the best firing temperature for pozzolanic reactivity for the types of clay being tested.

While these studies do not definitively answer whether brick was intentionally fired at low temperatures for use in mortar, it is very likely that under-fired wasters would have been beneficial in the use of mortars. Since the periphery of kiln load would not have reached the temperatures of the core— a significant percentage the overall yield (Ousterhout, 2008: 131)— the resulting wasters could have been used as high-quality pozzolana.

4.1.2 - Identification of Brick Provenance

A crucial aspect of any archaeological material is sourcing its origin. This provenance information can be used to identify things like the knowledge of local resources, trade networks for special goods, and the technology of manipulating raw materials. This section will review studies using scientific methods to identify the provenance of ancient and historic bricks.

Studies

The article "Bricks and Tiles of the Classis Britannica: Petrology and Origin" (Peacock, 1977) may not use the most current methods of scientific analysis but serves as a good foundation for methodical analysis in archaeological provenance studies. Using predominantly a hand lens, bricks from Dover, England and Boulogne, France with stamps attributed to the naval fleet of Roman Britain (Classis Britannica) were examined to investigate their geological origin.

The brick from Boulogne, designated Fabric 1, was described as being "hard and of a fairly uniform buff colour" using Munsell 5YR 7/6 (Peacock, 1977: 236). Scattered quartz grains and ~2mm lumps of reddish-brown limestone were also a clear feature of this brick. Fabric 2 from Dover was quite different. It was described as reddish pink in colour (Munsell 2.5YR 6/8) with "lenses and swirls of creamy white clay" (Peacock, 1977: 237). Inclusions included 1-3mm pieces of iron ore, siltstone fragments up to 10mm and small grains of quarts on the surface. Unlike Fabric 1, no quartz was observed throughout the cross-section of Fabric 2. Thin sectioned samples of each type of brick were inspected but Peacock states that this "adds little to what can be seen in the hand specimen" (1977: 238). By comparing these bricks to the local clay deposits, it was found that the raw clay of Fabric 2 most likely originated in Hastings Beds (specially Fairlight Clay beds on the coast), immediately southwest of Dover. It was possible that raw clay could have come from other locations to the north and northeast that had varying clay layers, including that of Fabric 2. However, due to the uniformity of clay materials of Fabric 2, it was considered unlikely that material was sources in mixed clay locations. Fabric 1 on the other hand could only be matched to clay deposited from Desvres, southeast of Boulogne.

By comparing these findings to archaeological evidence of brick use in both Dover and Boulogne, it was concluded that only one stamped brick from Fabric 1 was found in Dover while both fabrics were commonly used together in Boulogne. Peacock concluded that two brick production sites associated with the Classis Britannica were located on each side of the English Channel and that "British material was exported on some scale to Boulogne but movement in the other direction was probably more limited" (1977: 245).

The article titled "Provenance and Technology Investigation of Agia Sophia Bricks, Istanbul, Turkey" by Moropoulou, Çakmak, and Polikreti (2002) discussed the findings of analysis of bricks used in the construction of Hagia Sophia in Constantinople. The focus of this research was to determine firstly the origin of source clays and secondly to test whether the ninth century text, *Diegesis*, was correct in stating that special lightweight bricks were ordered from the island of Rhodes. Samples were taken of different types of brick from the dome, entrance, and hypogeum of Hagia Sophia dating to the sixth and tenth centuries. Samples were also taken from other fifth and sixth-century constructions in Istanbul such as the Theodosian city walls, the Church of Saint Irene, and the Church of Saints Sergius and Bacchus. In addition, for further comparative purposes, samples of broken brick and roof tiles were taken from the excavation site of the Great Basilica of Rhodes. Mineralogical and micromorphological tests on these bricks included NAA to determine different amounts of certain key chemical elements, SEM to distinguish different manufacturing techniques shown in the micromorphology, TG/DTA to test the course of chemical and morphological reactions that occurred during firing, porosimetry to determine pore size related to firing temperature, and fragment tests to determine tensile strengths. Using the data from these tests they then applied principal component analysis to see if there were obvious distinguishing markers between bricks from the sites in Istanbul and those taken from Rhodes. Moropoulou et al. conclude not only that the samples of brick tested from Hagia Sophia are not representative of those locally produced, but also that the clay bodies of bricks from Rhodes and Hagia Sophia are quite similar. They state, “The probability that the samples from the sixth-century dome of Agia Sophia belong to the Rhodes sample group in >90%,” and that such “results confirm the textual evidence” (Moropoulou, Çakmak, and Polikreti, 2002: 371)

The article, “Study and characterization of the ancient bricks of monastery of “San Filippo di Fragalà” in Frazzanò (Sicily)” by Cardiano et al. (2004), is a discussion of tests carried out on brick samples from a range of time periods. As the title indicates, these samples were collected throughout the site of San Filippo di Fragalà to further identify the building history and to determine the state of its conservation. Collection sites included five samples from the northeast corner of the Byzantine church, four samples from the Norman church, two from the northeast main portal (Norman), and one modern sample from 1937. Tests included ICP and INAA to recognize both major and trace elements such as CaO (ICP) and rare-earth mineral (INAA), XRD and TG/DTA for raw material and baking temperature identification, and soluble salts analysis to identify state of conservation. The authors found first and foremost that all of the raw materials used to produce the bricks came from the same geological source but excavated from different local quarries. As for the Byzantine bricks, three of the samples look to be fired at low temperatures but the authors also suggested that this could be related more to firing technique and not temperature. One of the samples was identified to contain different mineral components but the authors considered that firing temperatures resulted in the development of atypical formation. The key differences between the Norman and Byzantine sources were determined to be that Byzantine bricks were made from clays rich in calcium.

Discussion

As will be discussed in upcoming chapters, mortars from the Water Supply of Constantinople and Anastasian Wall contain a large quantity of brick aggregates (see 6.3 - Constituent Quantification). The studies discussed in this section, while looking at structural brick specimens, were able to deduce some impressive information about the sourcing of raw materials using a variety of methods. Firstly, Peacock's (1977) study was the oldest included in this chapter and only used optical analysis to determine information about provenance. He (Peacock, 1997: 246) voices his trepidation in repeating similar geological provenance studies in this area or using these particular methods because it "involved a disproportionate investment or research time and resources." Furthermore, this study does not take the morphological changes that occur during the firing process into consideration when concluding the similarities of brick and clay fabrics.

Moropoulou, Çakmak, and Polikreti (2002) and Cardiano et al. (2004) use a combination of geological data and scientific analysis, such as SEM, TG/DTA, NAA, and ICP, to investigate brick samples from historic structures to determine their raw clay sources. Probably the most significant study aiming to investigate a historical account of building technology using hard science, Moropoulou, Çakmak, and Polikreti (2002) were able to confirm that the *Diegesis* was correct in its claims that lighter bricks from Rhodes were used to construct the dome of Hagia Sophia in Constantinople. Both studies confirm that local material sourcing was extremely important in brick production but that specialty materials were also imported to meet specific building criteria.

4.1.3 - Physico-Mechanical Property Testing of Mortars

Another aspect of scientific material studies is investigating the microscopic nature of mortars and how it affects the mechanical behaviour of the structure on which it was applied. By understanding the ingredients of mortars, they can be tested *in situ* or recreated to see their benefits in building technology and preservation. This section will present the methods and findings of these studies.

Studies

The first mechanical studies of mortar and brick samples from the Great Church in Constantinople were presented in the article "Mechanical Tests of Materials from the Hagia Sophia Dome." The authors, Mark and Çakmak (1994), centred their study on a slice taken from a large sample of the dome rib collected by Van Nice in 1949 during repairs carried out on the main dome. This sample was made of mortar sandwiched between two bricks, typical of the large mortar joint and brick course construction of Hagia Sophia. Van Nice determined that this sample dated from 559-563, the period of construction of the new dome of Hagia Sophia following the first dome's collapse in 558. This sample was first tested for the adhesion between the brick and mortar using sheer strength testing (the force necessary to cause the brick and mortar to separate and slide against each other). At a load of 27.3 kg the brick broke away from the mortar with an average of 1.22 kg/cm^2 sheer stress across the sliding surface. While the breakage occurred at this point, it was not a clean break between the two materials, leaving 30% of the brick's surface intact.

The second analysis was rupture testing, performed using portions of brick and mortar that had been broken away from one another during the previous adhesion test to measure each material's tensile strength. The brick specimen, measuring 8.25 by 1.63 by 1.55 cm, underwent central loading and failed at 9.53 kg. Two mortar samples, the first measuring 7.62 by 2.34 by 2.29 cm and the second roughly the same, failed at a load of 4.72 kg and 5.71 kg respectively. Both mortar samples seemed to fracture at the locations of aggregate inclusions. The tensile stresses were then calculated for the brick at 30.1 kg/cm^2, the first mortar sample at 4.3 kg/cm^2, and the second mortar sample at 5.44 kg/cm^2. The authors acknowledge from the limited range of samples that these tests do not provide sufficient statistical data, but do indicate that they are up to three times stronger than that reported from tests done on medieval lime mortars by Masson (1935). Density tests on the brick and mortar using an electronic scale showed the samples to be relatively lightweight at 1540 kg/m^3 for the brick and 1430 kg/m^3 for the mortar.

Baronio, Binda and Lombardini (1997) carried out a study of crushed brick and lime mortar joints used in brick masonry. In their article "The role of brick pebbles and dust in conglomerates based on hydrated lime and crushed bricks," they began by looking at mortar joints from S. Vitale as well as samples taken from S. Michele in Africisco, both from Ravenna and dated to the sixth century. By performing SEM and chemical analysis on these samples to determine grain size distribution, chemical reactivity, and mortar-to-brick ratios, they were able to identify aspects of the mortar recipe. They then reproduced these mortars using brick used for restoration purposes with a binder to aggregate ratio of 1:3. Some of the samples were then tested for their flexural and compressional abilities, while others were monitored to document the chemical phases of the pozzolanic reaction between the crushed brick and lime. They concluded that despite some of the brick pieces being as large as 16mm in diameter, these still produce a pozzolanic reaction with the lime over long periods of time. They also found that because of the slow calcination time, deformation such as creep and shrinkage takes place at a high degree but then becomes more stable after 28 days. One of the main research interests of this project was to determine the intended effect of thick mortar joints in Late Roman and Byzantine construction. However, they were unable to come to any solid conclusions as to why mortar joints were as thick or thicker than the brick courses. See Binda, Mirabella Roberti and Guzzetti (1996) for a discussion on the structural behaviour of the S. Vitale and its relationship to materials.

In a follow-up study of recreated mortars based on those found at S. Vitale, Binda, Tedeschi and Baronio (1999) look at the mechanical relationship of brick and mortar joints. This is based on their previous studies on recreated fifth-century mortars modelled after those used in San Vitale (Baronio, Binda and Lombardini, 1997). This study's intent was to investigate the mechanical implication of thick mortar joints with a brick-mortar ratio of 1:1 by recreating stack bond prisms of brick consisting of four 40mm-thick bricks sandwiching three 45mm layers of mortar. They measured 290mm thick five minutes after constructed and were kept at 20° C with 65% relative humidity. The mechanical behaviour of these prisms was then studied under compression at different curing times of 28, 60, 90 and 365 days. Another interesting addition was the comparative examination of compressive forces using flatjack equipment occurring in *in-situ* masonry from the base of exterior walls of San Vitale. By attaching an array of hydraulic pistons to the joints of the wall, the stresses and strains occurring in the wall were measured on a portable computer. The recreated mortar prisms were placed in a servocontrolled hydraulic MTS press that gradually applied pressure at a rate of 1μm/s. LVDTs and CPDTs were connected to these prisms to measure their mechanical nature, similar to the equipment used to measure the walls of San Vitale. The data resulting from these two tests led the authors to finally build a conclusion on the thickness of mortar joints. They stated that the experiments showed that the allowance of large deformation that initially occurs during the hardening process allows the structure to settle while more load is applied. This is also useful for allowing for the soil foundation of a building like San Vitale to settle with this deformation, ensuring the decreasing likelihood of structural cracking. This deformation that occurred early under an increasing load retarded the failure limits from applied tensile forces. This means that the plastic nature of freshly applied mortar joints compensate for the constant loading applied, hardening at a rate that can easily adjust for high tensile forces. Binda, Tedeschi and Baronio (1999: 219) conclude by stating, "Overall the Byzantine masonry proved to be an 'intelligent' material highly suitable to react towards possible stresses occurring during the structure long lifespan."

In an article from 1998 entitled "Tests on Reproduced Byzantine Masonry", Falter and Reinhardt discuss a parallel study to that of Binda, Tedeschi and Baronio (1999). They also created mortar and brick prisms but with the intent of simulating the construction of a main column of San Vitale. While these prisms are based on the same 1:3 binder-to-brick aggregate ratio similarly kept in an environment of 20° C and 65% relative humidity, they have varied mortar joints ranging from 20mm to 60mm. Other differences between these two studies are in the methods and time period of testing. Falter and Reinhardt increased the applied load in steps, mimicking the building process, whereas Binda, Tedeschi and Baronio (1999) increased the load at a constant rate. This required different testing equipment. These tests lead the authors to the same conclusion that the relationship between bricks and thick mortar joints allow for a long-lasting and sturdy building technology (Binda, Tedeschi and Baronio, 1999).

In the article "Study of ancient mortars from Sagalassos (Turkey) in view of their conservation", Degryse, Elsen, and Waelkens (2002) discussed the study of mineralogy, petrography, and provenance of raw materials used in mortars dating from the late Hellenistic to early Byzantine periods. With a specific interest in the samples from Imperial Roman construction to those of the sixth and early seventh centuries, the authors identified three types of aggregates in the mortars using XRD, SEM, and petrography. The first of these aggregates was identified as limestone containing Mesozoic and Tertiary marine deposits, the same formations as limestone used as building stone from the city. Large lime lumps were found in these samples, leading the authors to infer that the lime had been dry slaked. The second aggregate represented in the sample was crushed ceramics, which is represented in all phases of construction but is typically only found in structures that would be associated with moisture. The third aggregate was identified as volcanic tuff or lava, which were compared and found to be very similar to volcanic deposits from the nearby region of Gölçük. Fragments of these volcanic aggregates found in the mortars typically have broken edges, indicating that these materials would be crushed or broken before being added.

The second part of this study was to reconstruct these mortars using local materials and identify their potential as restoration and conservation mortars. Unlike many other studies that reproduce historic mortars, the authors burned and slaked the lime from locally identified limestone. Then, according to the data collected from the study of the historic mortars, each of the aggregates were applied to the slaked lime in appropriate proportions by weight: lime and crushed ceramics 65%/35%, lime to volcanics 45%/55%, and lime-crushed ceramic-volcanics 40%/40%/20%. The samples were then left to carbonate for 28 days before tests began even though the process could continue for years. These mortars were then tested for their strength using Grindosonic E-modulus measurement, which compares the resonance oscillation to that of quartz crystal. A freeze-thaw test was also applied to these mortars to identify the effects that seasonal change had on mortars in Sagalassos. The authors concluded from these tests that mortars employing crushed brick did not have the strength for structural mortars and would have been used only for watertight layers. They suggest that despite the mixture of crushed ceramic-volcanics having the highest strength, the most beneficial structural mortar in terms of both strength and economic impact would be the volcanic aggregate mixture, due to its performance in both the strength and freeze-thaw tests. It was also determined that mortars using crushed brick would not be able to cope with the climatic differences of the region. It should be taken into consideration that these mortars were only tested after a 28-day period and a mixture of mortar using crushed brick pozzolana requires much more time to fully harden, as seen from Moropoulou et al. (2002)

Moropoulou, Bakolas, and Bisbikou (2000a) applied a set of testing to determine the mechanical properties of a variety of mortars from Rhodes in the article "Investigations of the technology of historic mortars". While stating that many mechanical tests have been done on a range of types of mortars, they identified that problems arise while analyzing small mortar samples. They indicated that to fully understand the mechanical behavior of these types of mortars, much larger samples are required for the classical strength tests. Because of this, many samples are broken down and analyzed, then recreated to match the original sample on a larger scale. However, as they state, "these experiments do not enable us to search out the effective relationships between composite materials properties and their mechanical performance in the historic structure." To obtain proper strength measurements, instead of using these classical strength tests, the authors applied the fragment test method. This involved placing small ("gravel size") pieces of mortar within a matrix of a much harder material such as epoxy resin or a stronger mortar and then testing for tensile strength.

Once the tests on the hydraulic and mechanical nature of each mortar sample was completed, the data sets could then be evaluated to identify any correlations. They compared the CO_2/H_2O structurally bonded water ratio to identify hydraulicity and data from the fragment test method to determine tensile strength (fmt,*k* data). From this comparison, the authors concluded that as long as the ratios of binder to aggregate are roughly the same for all samples, the relationship between the mortars' hydraulic nature is directly proportionate to their strength. They make special mention of Byzantine mortars that utilized brick because of their high levels of strength and longevity, even inferring that they could be considered early forms of reinforced concrete. They state that the feature of this type of mortar allows "the structure to absorb energy without affecting its material properties irreversibly, which is not encountered in most modern masonry or concrete structures" (Moropoulou, Bokolas, and Bisbikou, 2000: 45).

The focus of many studies on historic mortars has been on the chemically reactive nature of certain aggregate materials and lime. In the 2005 article, "The role of aggregates on the structure and properties of lime mortars", Stefanidou and Papayianni discussed the relationship between non-reactive aggregates and the mechanical characteristics of a mortar. A series of 14 different types of mortars were mixed with different sizes and proportions of aggregates. The following table indicates each type of mortar mixture:

Table 4.1 – Mortar mixtures used to test the role of aggregates in structural properties (Stefanidou and Papayiaanni, 2005)

Composition	Hydrated lime	Sand (0–2 mm)	Sand (0–4 mm)	Gravel (0–8 mm)	Pebbles (0–16 mm)	B/A	W/B
1	1	1.5	–	–	–	1:1.5	0.799
2	1	1.125	0.375	–	–	1:1.5	0.795
3	1	0.6	0.3	0.6	–	1:1.5	0.793
4	1	0.5	0.25	0.25	0.5	1:1.5	0.678
5	1	2.5	–	–	–	1:2.5	0.796
6	1	1.875	0.625	–	–	1:2.5	0.738
7	1	1	0.5	1	–	1:2.5	0.743
8	1	0.75	0.5	0.5	0.75	1:2.5	0.734
9	1	3	–	–	–	1:3	0.996
10	1	2.25	0.75	–	–	1:3	0.953
11	1	0.96	0.48	0.96	–	1:3	0.935
12	1	0.72	0.48	0.48	0.72	1:3	0.928
13	1	4	–	–	–	1:4	1.008
14	1	6	–	–	–	1:6	1.382

Dry hydrated lime was used as the binder and river sand along with coarse aggregates were of a siliceous nature. Samples were stored in an environment of 20±1°C with an 85-90% relative humidity for 90 days and after, at 20±2°C and 60-70% relative humidity. Mortar samples from each of the 14 series were tested for their strength, volume change, and permeability at 28, 90, 180, 360, and 730 days. It was found that after 90 days in high humidity the mortar showed low strength values from 0.3 to 0.7MPa but showed a marked increase when stored in the dryer environment. Microscopic observations also showed that in the early stages, cracks appeared in all samples. However, in the fine sand aggregate samples, cracks developed in the lime formations whereas cracks appeared along the aggregate in the coarse gravel and pebble mortars. The tests concluded that mortars utilizing medium grained sand (0-4mm) with the lowest ratio of aggregate to binder (1:1.5 or 1:2.5) obtained the highest strength over time at around 2.5MPa. As was expected, the samples with the largest aggregates displayed the smallest change in volume over time and showed the most need for raking to achieve a 30% increase in strength compared to those samples that were not raked. This shows that coarse aggregates show a high level of volume stability, leading the authors to determine that this type of aggregate would be beneficial for long-term strength of tall masonry structures.

Discussion

These studies show an intrinsic relationship between mortar and brick in masonry structures. While neither the Water Supply of Constantinople nor the Anastasian Wall use structural brick (see sections 2.1.3 and 2.2.3 of Chapter 2), the findings relating to mortar aggregates and their impact on structural integrity are important in explaining why many ancient structures, including the two at the centre of this study, remain in a good state of preservation.

The studies by Baronio, Binda and Lombardini (1997), Binda, Tedeschi and Baronio (1999), and Falter and Reinhardt (1999) all indicated that mortar joints in S. Vitale in Ravenna experienced a great deal of creep during the construction process. This was linked to the fact that the structure was built higher, increasing the load before the mortar was fully hardened on lower levels. While this would have been a problem for a structure like the water supply where bridges must remain level, Mark and Çakmak (1994) offer that this creep might be beneficial for quickly building large structures like Hagia Sophia without causing cracking through uneven loading (also see the review from Moropoulou et al., 2002 at the beginning of the next section).

Other studies reviewed in this section showed that aggregate size (Degryse, Elsen, and Waelkens, 2002) and pozzolana type (Stefanidou and Papayianni, 2005) has an impact on the overall structural abilities. Crushed brick was found to be better for water resistance but that not suitable for structural mortars in areas with numerous freeze/thaw cycles per year. Also, samples of mortar with large pieces of brick aggregate were found to have some pozzolanic reactivity and little volume change during the curing process but the stronger mortars were found to be those that also utilised finely crushed brick powder.

4.1.4 – Lime Testing

The production of lime is the foundation of producing a quality plaster of mortar. As briefly discussed in the previous chapter, lime has been used in number of functions for millennia but the basic methods of production are the same. This section reviews a selection of studies focused on investigating some of the finer details about the production methods of lime intended for use in mortar.

Studies

A detailed discussion of the scientific analysis of the mineralogical and chemical process in the production of lime comes from the article "The effects of limestone characteristics and calcination temperature to the reactivity of the quicklime." Moropoulou, Bakolas, and Aggelakopoulou (2001) set out to understand the relationship between types of limestone, firing temperatures, and the chemical reactivity of lime. Two different types of limestone were chosen from Crete, each being macroscopically different. The first type of limestone, called Sisel (shortened to L_S for this publication), is a light gray color with few distinguishing crystals. The second type called Latzima (L_L), is dark gray and has tiny random crystals. These two types of samples were fired at four different temperatures (900°, 1000°, 1100°, 1200°C) and tested using XRD to identify crystalline compounds, transmitted light microscopy to determine shape, texture and size of grains, calcimetry for CO_2 content, AAS to determine percentage of calcium and magnesium ions, DTA/TG to determine the amount of various compounds throughout the sample, mercury intrusion porosimetry to determine porosity and density throughout each phase, and nitrogen absorption to compare with mercury intrusion porosimetry data. The resulting data was then analysed, producing some interesting results. Quicklime from high calcium content L_S samples showed a large size of crystals in an inhomogeneous distribution, low impurities, and a less compact structure compared to L_L. They stated that these factors were directly related to L_S samples being more reactive. In reference to the firing temperature, 900°C seemed to produce the most reactive lime, causing the authors to state that, "High calcination temperatures acquired in modern limekilns are the major reason for the production of low-quality lime" (Moropoulou, Bakolas, and Aggelakopoulou, 2001: 639). They concluded by implying that the rate of increased temperature during the slaking (hydration) process is directly related to its reactivity.

One of the most important aspects of a study on historic mortars is to understand the process involved in producing high-quality lime. In the article "Aging of Lime Putty: Effects on Traditional Lime Mortar Carbonation" by Cazalla et al. (2000), a study of the treatment of slaked lime was discussed. The authors note the consensus of scholars in regards to ageing slaked lime under water, even referring to historic sources like Vitruvius and Pliny. However, they also indicate that no studies had been done to classify the length of time for aging and the role it plays in producing quality lime for mortar. A total of five samples were mixed with three different ageing times and binder/aggregate ratios. Samples A and B were aged for 14 years and had ratios of 1:3 and 1:4 respectively, samples C and D were aged for one year and had the same binder/aggregate ratios as A and B. Sample E was made with a ratio of 1:3 from a non-aged commercial lime powder that only required the addition of water (unlike the others that were ages submersed in water). Quartz sand aggregate was also carefully chosen in order to not interfere with the carbonates from the lime. Tests of these samples included XRD to identify mineral phases in the hydrated lime, EXD and SEM for pore geometry as well as mortar texture, ultrasound speed propagation to determine the carbonation evolution, and open porosity testing to determine how much of the pores could be filled with water. It was found that the rate and degree of carbonation was related to the aging time of the lime mortars, especially those with a low ratio of binder to aggregate. This is due to the crystal size reduction that occurs during the aging process (a larger total surface area) causing it to be highly reactive during carbonation. The authors concluded that for conservation purposes, lime should be aged submersed in water for a period of time greater than one year and should have a binder/aggregate ratio no larger that 1:4.

Frequently, small pieces of poorly mixed or underburned lime are observed in historic mortars. In a study of mortars from Venetian buildings dating from the fourteenth to the eighteenth centuries by Bakolas, Biscontin, Moropoulou and Zendri (1995), samples of mortar joints containing lumps of lime were investigated. The article does not provide the exact sites where these mortars were collected but indicated that the samples were good representations of the period and location. Through the use of FT-IR, TG-DTG, SEM and MFO, the authors set out to determine if these lumps of lime were an intentional addition or a result of manufacturing techniques. Macroscopic observations of these lumps were described as being white or whitish yellow with sizes varying from a few millimeters to two centimeters. They were also found to be almost entirely calcium carbonate with some samples indicating silicates using FT-IR analysis. TG-DTG was used to calculate the presence of carbon dioxide, physically bonded water and hydraulic compounds and how these figures compared to the quantities of calcium carbonate. Polished sections of mortar samples containing lime lumps were produced to use MFO. This examination was to look closer at their morphological structure and qualities such as colour, shape, and relationship to the mortar matrix. Finally, SEM and EDXS were used for microanalysis and to confirm predominant elements of the lumps. By combining these methods of research, they concluded that these lumps are made up mostly of calcium carbonate with varying amounts of aluminosilicates. Their interpretation of their findings led the authors to conclude that these lumps most likely occurred because of mortar production techniques of insufficient mixing or aging of the lime. Because of the occurrence of these lumps in a wide variety of samples and their mechanical characteristics of trading compression strength for tensile strength, the authors offer that these lump inclusions were most likely intentional.

Discussion

In this section, three studies about the role of lime and its production for mortars were reviewed. Moropoulou, Bakolas, and Aggelakopoulou's (2001) experiments of firing limestones from Crete and testing their reactivity showed that high temperatures do not always produce the best lime. Tests of lime putty by Cazalla et al. (2000) showed that the aging the slaked lime by submerging it in water for over a year significantly increased its reactivity, confirming the suggestion by Vitruvius (see the discussion in section 3.1.1 of the previous chapter). The methods used in these studies were XRD, EXD, and SEM, similar to many the studies reviewed in this chapter.

Bakolas et al. (1995) used SEM, EDXS, TG-DTG, FT-IR, and MFO to investigate Venetian mortars. These methods revealed that the numerous lumps of unslaked or insufficiently burnt lime were the product of poor mixing and/or insufficient aging of lime. Some of the mortar samples from the Water Supply of Constantinople and Anastasian Wall show frequent and well-distributed lumps of lime (see section 6.2 of Chapter 6) and, while Bakolas et al. (1995) claim that this is evidence of intentional addition of materials, it is most likely a sign of sufficient mixing of the mortar before application.

4.1.5 – Comparative Mortar Studies

The recipes of mortars vary, sometimes considerably, based on structural function. While this can sometimes be observed from simple macroscopic investigations, microscopic analysis can reveal some differences that are not only unobservable by the naked eye but are essential to the success of the structure. This section will review some studies that have used scientific testing to compare recipes of mortars from a variety of sources.

Studies

In the article, "Advanced Byzantine cement based composites resisting earthquake stresses: the crushed brick/lime mortars of Justinian's Hagia Sophia," Moropoulou, et al. (2002) discussed their analysis of mortar joints in relationship to the structural resilience of Hagia Sophia during seismic activity. This study was in response to previous studies that had shown that the structural nature of Hagia Sophia "depends very strongly on the mechanical and chemical properties of the mortar and bricks used in its masonry" (Moropoulou et al., 2002: 543). Two samples tested in this study were taken by Van Nice in 1949 from a dome rib during repair, dating to the sixth century (the same as pieces used Mark and Çakmak, 1994), while two more samples from the western point of the north main arch and one sample from the southeastern abutment were collected by the authors. Three other samples dating to the tenth century were also collected and tested. Tests included EDXS to test local chemical composition, XRD to determine the mineral components of the mortar, SEM to ascertain the composition of the brick and binding material, TEM to identify the amorphous phases, and optical microscopy to identify the mineral phases of the matrix. Their first conclusion is that the ratio between binder to aggregate is between 1:4 to 1:2 of the mortars tested. They claimed that the 1:4 ratio, resulting in a friable mortar, might be due to weathering which causes calcite to be leached out. Their studies also confirmed that a ratio of 1:3 should be selected for restoration due to the quality of the mortars tested and the uniformity of such mortars throughout the Late Roman and Byzantine world. The typical ratio of Ottoman mortars is 1:2. They continued by stating that their study showed that this ratio was no accident because the interaction of the crushed brick and lime not only produce a chemically hydraulic reactivity but also is the chief reason that the mortar achieves such impressive physico-mechanical properties. For a preliminary study of microstructure from the mortars used in Hagia Sophia see "Characterization of structural Byzantine mortars by thermogravimetric analysis" by Bakolas, Biscontin, Moropoulou, and Zendri (1998).

The article by Moropoulou, Bakolas, and Bisbikou (2000b) titled “Physico-chemical adhesion and cohesion bonds in joint mortars imparting durability to the historic structures” continues the discussion of the importance of chemically reactive additives to lime mortar mixes. This particular study involves comparative analysis of many different types of mortars ranging in date from Greek Hellenistic, Roman, Byzantine, post-Byzantine, and later. A total of 40 mortar samples were collected from fortifications, monasteries, churches and other historic buildings from Rhodes, Crete, Corfu, Mouth Athos, Constantinople, and Versaille Palace (gypsum mortar). These mortars were then tested using various methods including XRD to identify the mineral constituents of the mortar, polarized optical microscopy to determine the ratio of aggregate to binder, SEM and EDXS to examine the samples’ microstructure, TEM to identify the amorphous phases, and TG-DTG to determine crystalline transitions. This collection of mineralogical tests was applied with the goal of determining the hydraulic nature of different types of mortar recipes. The samples were broken down into five distinct mortars based on their hydraulic properties:

- Typical Lime Mortars – typically sand and lime with a ratio of 1:2 to 1:3, around 1% absorbed water.
- Crushed Brick-lime Mortars – binder to aggregate ratio of 1:2 to 1:4, 6.5% bonded water, 10-30% CO_2 absorbed.
- Hot Lime Technology Mortars – around 1:3 binder to aggregate ratio, 3-6% bonded water, 18-30% CO_2 Absorbed.
- Cementitious Mortars – around 1:3 binder to aggregate ratio, raw clays fired with lime to produce pozzolanic properties, 3-16% bonded water, 10-20% CO_2 absorbed.
- Mortars with Gypsum – dehydration of gypsum occurred at a temperature of 130-160°C, $CaCO_3$ decomposition at 750°C.

- Rubble Masonry Mortar (Roman concrete binding mortar) – different lime to aggregate ratios from bottom to top indicating different times for carbonization and drying levels, 6% bound water, 19-29% CO_2 absorbed.

For a further discussion of the results of these types of mortars and the methods employed for classification, see the authors' other Moropoulou et al. (2000a) titled "Investigation of the technology of historic mortars".

The article by Ariño and Saiz-Jimenez (1996) titled "Colonization and deterioration processes in Roman mortars by cyanobacteria, algae and lichens" offers a small section on the mineralogical testing of mortars from Baulo Claudia in Spain. These samples were taken from unidentified locations within the Forum, Temple of Isis, and Temple of Jupiter. While this article's focus is to study the effects of biological organisms on the modern structural properties, characterization of the mortar was undertaken. Using XRD analysis, they conclude that the main component of the mortars was calcite included dolomite and small amounts of quartz and also had high porosity of 25-30%. No other information regarding aggregate or pozzolana was documented, most likely due to the biological aim of this article.

"Study of ancient mortars from the Roman Villa of Pollio Felice in Sorrento (Naples)" by Benedetti et al. (2004) discusses the testing and analysis of Roman mortar from the first century A.D. villa of Pollio Felice of Sorrento on the bay of Naples. The primary goal of this testing was to identify both the structure and microstructure, as well as to test the functionality of XRD to differentiate stratified layers. A single sample, measuring 33mm x 30mm x 13mm, was taken from the northern pavilion and is comprised of four different lime mortars, forming distinctive layers. Macroscopic observations showed that the innermost layer is 6mm thick and has a dark grey binder with black and white inclusions. The next layer was 8mm thick with a light grey binder, and also contained black and white inclusions. The 13mm thick third layer had a white colour and contained fragments of clay or brick. The final layer was 2mm thick, a yellowish colour, and had fine particles of ceramics. Each layer was then mechanically separated and tested using XRD and

XRD^2 (beneficial because it does not require a flat area) to determine lime-percentage and grain-size distribution. Their findings showed that each layer was distinctive, both in lime percentage and grain size. The first later had the lowest lime percentage and highest percentage of small grains while the third layer showed the highest percentage of large grains consisting of brick. Different types of volcanic deposits (most probably from Vesuvius) were used as aggregate were found in all layers, even including the layers that utilized both small and large brick granules. The authors claimed that this is due to the shared knowledge of the benefits of volcanic pozzolana in the lime mortar. Finally, they inferred that by using XRD^2 analysis they were able to show there was no significant amount of soluble salts from the marine environment that typically cause degradation of other lime mortars. This was most likely due to the small and compact nature of the surface layer, which included fine grains of brick fragments.

The follow-up article by Cardiano et al. (2008), titled "Investigations on Ancient Mortars from the Basilian Monastery of Fragalà", changes the subject of study from brick to mortar. Samples of mortar were collected from similar locations around the site of San Filippo di Fragalà and tested using many of the same methods. The mortar samples date to three distinct periods including seven samples from the original Byzantine structures, seven from the Norman construction phases, and three from the Baroque period. Each sample was examined using thin sectioning petrography, ICP, XRD, TG/DTA, and soluble salts analysis to categorize the composition of each mortar. The findings showed that neither the Norman nor the Byzantine mortars showed much homogeneity whereas the Baroque samples were seen to be quite similar to one another. The Byzantine mortars were calculated as having a ratio of binder to aggregate of 1:1.6 to 1:1.8 with the majority of the binder being crushed brick. The authors indicated that the ICP and TGA data, used to identify CaO concentrations in the mortar, could be used to formulate the hydraulic properties of the mortar. This is in contrast to the somewhat typical method of comparing absorbed CO_2 to bonded H_2O (Moropoulou, Bakolas, and Aggelakopoulou, 2001). By applying this new concept, the authors deduced that one of the Norman samples had the lowest CaO_{ICP}/CaO_{TGA} ratio at 1.35, thus having the highest resistance to moisture. The Byzantine samples ranged from 1.01 to 1.13.

Farci, Floris, and Meloni (2005) discuss the testing of mortars intended for use in Roman water supply systems in "Water Permeability vs. Porosity in samples of Roman Mortars". Two small samples, most likely dating to the first half of the first century AD, were taken from cisterns at the site of Uthina in Northern Tunisia for investigation. The authors used XRD, SEM, and optical microscopy to identify the exact mineralogical composition. The authors remarked that macroscopically, the samples looked to be, "…composed of a lime mortar containing large amounts of pottery sherds and to have different consistency" (Farci, Floris, and Meloni, 2005: 55). Furthermore, by using optical microscopy they indicated that one mortar showed a heavily compacted ivory-coloured binder with red ceramic fragments ranging in size from >1mm to 1cm. The second mortar sample was comprised of three distinct layers with the thickest being similar to the first sample. The middle layer was 5mm and contained finely crushed pottery sherds, while the outer 1mm thick layer of mortar contained an aggregate of what the authors call 'fine pozzolanic sand'. One final 1mm layer of calcium carbonate limescale appears on the outermost edge of the second mortar sample, likely due to continuous water seepage or flow. XRD analysis revealed a majority of calcite, quartz, feldspar, gehlenite minerals in the ceramic aggregates. The authors also conclude that plagioclase, sanidine, biotite and quarts as being other pozzolanic aggregates. The final conclusion of this study regarding permeability and porosity showed that despite large pores, especially in the second sample, both mortars showed a high resistivity to water and overall permeability.

Meir, Freidin, and Gilead (2005) outlined the importance of mortar testing in the understanding both the modern preservation concerns and historical technology in the article "Analysis of Byzantine mortars from the Negev Desert, Israel, and subsequent environmental and economic implications". This is a good example of bridging the scientific material studies of late Roman/Byzantine mortars and their archaeological and architectural contexts. Ten samples from the walls and ten samples from the floor were collected for analysis from the church of St. Mary Mother of God at Nessana. This is one of four Byzantine basilicas dating to the seventh century and analysis of these samples included XRD and SEM to determine their mineral components and, in turn, give comparative data for the two sources. While XRD patterns confirmed identical peaks in calcite, quartz, and dolomite, both SEM and XRD showed a well-defined difference between the other aspects of mortar used for the flooring and walls. For instance, floor mortars showed peaks of kaolinite, feldspar, and muscovite whereas wall mortars established peaks of gypsum, clinozoisite, halite, and aragonite. The authors put forward the theory that these differences could be the result of using different material sources (i.e. different types limestone or sand) based on the purpose of the mortar. The SEM tests identified charcoal particles of burnt wood but Meir, Freiden, and Gilead stated that they are unsure why this would be included in the lime mixture, postulating that it could be an intentional additive like modern fly ash. They were also unsure of the reasons why gypsum is found mixed with lime in the wall samples but inferred that the amounts must indicate purposeful addition of gypsum. They concluded that the energy needed for production of lime mortars would have required many loads of timber fuel, making it a difficult task in the sparse and arid environment of the Negev Desert.

Silva, Wenk, and Monteiro, environmental engineers from the University of Berkley, performed analysis of mortars from two sites from Rome. In their 2005 article titled "Comparative investigation of mortars from Roman Colosseum and cistern" they discuss the findings of this analysis and how it may be useful in answering some questions about mortar technology and its influence on the historical record. By studying mortars from a second century cistern found 30km away from Rome at Albano Laziale and the world-renowned Colosseum, the variations and/or similarities of the mortars were used to shed light on the relationship between recipe and function. The first test discussed was SEM, which was used to look at surface morphology. In samples from the Colosseum, large crystals of calcite covered in small prismatic particles were identified whereas the cistern showed tiny aggregates containing silica, aluminium, and calcium. Next, XRD analysis showed only high spikes from crystalline phases of calcite while the cistern mortars produced a broad range of semi-amorphous phyllosilicates. FT-IR analysis showed both samples to have a large representation of bound water, which the authors attribute to hydraulic compounds like silicate and aluminate. The Colosseum sample showed strong silica bands in certain phases while the cistern sample was stronger, both attributed to possible gypsum inclusions. DSC, TGA, and XRD testing indicated the Colosseum mortar showed higher carbonate phases meaning the cistern mortar had inferior carbonate crystallization. These tests also provided an evaluation of each mortar's hydraulic capabilities by testing for the release of bound water during heating. Importantly, the data from these tests indicated that both samples were mostly hydraulic and did not signify quartz content. The authors were unable to identify any amorphous phyllosilicates in the mortar from the Colosseum, asserting that XRD analysis is "not very sensitive for identifying amorphous phases in crystalline material" (Silva, Wenk, and Monteiro, 2005: 40). They concluded by identifying the cistern mortar as a high quality pozzolanic mortar, whereas the mortar of the Colosseum, still containing pozzolana, was of lower hydraulic quality based on its primarily structural use.

"Ancient Analogues of Modern Cement: Calcium Hydrosilicates in Mortars and Concretes from Gallo-Roman Thermal Baths of Western France" by Rassineux, Petit, and Meunier is a 1989 article outlining the study of different types of mortars within two sites in western France. While the ultimate goal of this research was determine the effectiveness of these long-lasting mortars when used as radioactive repositories (also see Rayment and Pettifer, 1987 for similar testing of mortars from Hadrian's Wall), it offers another interesting look into the technological specifications of mortars with in the Roman Empire. The sites of interest in this study included first century AD buildings at Chassenon (Charente) and Sanxay (Vienne) where samples of structural mortar were taken from a theatre and temple, and a variety of different water proofing and masonry mortars from several thermae. These mortar samples were then tested using optical microscopy of thin sections, SEM, XRD, and EPMA to identify crystalline formation, aggregate size ratios, chemical reaction zones, and mineralogical compounds. Macroscopic observations of structural mortars were described as being white lime-based binders with varying types of sand and rock fragment aggregates, depending on locally available materials. The authors determined the percentage of aggregate to be 0-40% of the total weight, differing from most other studies that use volumetric data. XRD and EPMA tests showed the binding materials are completely calcium carbonate, indicating no use of pozzolanic additives. In the case of mortars from the baths, the authors mention the large presence of brick and tile fragments and crushed ceramics in the pink-coloured binder. Thin sectioning and SEM analysis showed what the authors called 'poor quality' brick, arguing that they were under fired. However, the chemical makeup of structural bricks and crushed aggregates in the mortar were indistinguishable, containing quartz, potassium, feldspar, amphibole, and micas. In the lime-based binder containing finely crushed brick, SEM indicated the presence of hydrated calcium aluminosilicate phases representing pozzolanic reactions (the result of the chemical reaction during the absorption of CO_2 between amorphous phyllosilicates and calcium hydroxide). This clearly indicated the intentional hydraulic nature of the mortars used as water resistant layers covering the walls and floors, and the beds of mortars with larger brick aggregate in the subfloor.

Discussion

One of the major aims of studying mortars from the Water Supply of Constantinople and Anastasian Wall is to investigate technological differences and/or similarities of recipe, manufacturing technique, and raw material selection. This section provides a look at some of the methods and resultings from studies comparing similar mortar samples. Interestingly, almost all studies reviewed in this section used XRD, SEM, and/or EDXS to identify things like mineral composition and micromorphology.

Studies like Meir, Freidin, and Gilead (2005) are successful in providing a historical context to data provided by scientific analysis of mortars. Identification of wood fuel in mortar samples from the arid Negev Desert indicates imported fuel. Similarly, the inclusion of non-native aggregate materials mixed in mortars with different structural function indicates important technological adaptations of materials. In other studies, such as Rassineux, Petit, and Meunier (1989), the aims are to investigate modern applications of ancient technologies. However, the findings of these studies also reveal similar important information. For instance, mortars from Roman baths in France were tested to determine their usefulness in radioactive repositories but revealed other historical information such as the change in brick aggregate size according to the mortar's function (Rassineux, Petit, and Meunier is a 1989).

These techniques were used to differentiate mortar makeup, identify production techniques, and explain relationships between recipe and structural function of contemporary structures (Silva, Wenk, and Monteiro, 2005; Farci, Floris, and Meloni (2005); Meir, Freidin, and Gilead (2005); Rassineux, Petit, and Meunier, 1989). Other studies offer a look at technological changes over time using the same, or similar, techniques such as comparing Byzantine and Ottoman mortars from Hagia Sophia (Moropoulou et al., 2002) or classifying mortars from a range of locations and time periods (Moropoulou, Bakolas, and Bisbikou, 2000b). This section not only shows the possibility of different scientific methods in answering comparative questions about mortars but also provides good comparative evidence for the mortars that will be tested from the water supply and long wall.

4.1.6 - Mortar Studies using Petrographic Analysis

In the studies reviewed in this chapter thus far, petrographic microscopy is most commonly used in conjunction with other scientific testing methods to analyse historic masonry materials. However, much can be gathered by emphasising the use optical microscopy. This section reviews a single study that investigates the usefulness of relying on petrographic analysis alone.

Study

In the 2008 article by Pavía and Caro titled "An investigation of Roman mortar technology through the petrographic analysis of archaeological material" a discussion the usefulness of this particular method is explored. In this study, 26 samples of mortars were taken from different structures and locations in La Rioja, Spain. The sites of these samples ranged in date from the 1st century BC to the 5th century AD and came from structures dated by recent archaeological investigation.

Samples were prepared by being impregnated with resin to keep the structural matrix intact, then sectioned and polished to a thickness of 20µm. Analysis of these thin sections was carried out using a standard petrographic microscope with natural and polarized light at magnifications of 2, 10, 20, and 40. It was evident that in almost all samples, the bond between the binder and aggregate was strong based on several mortars exemplifying the pozzolanic relationship between ceramic aggregates and lime. Almost 85% of the mortars looked unaffected by weathering and the absence of cracks in the binder indicated minimal shrinkage. This was thought to be due to low firing temperatures or shorter firing times, known as 'soft-burning', of the raw limestone. While this type of study does not give a definitive answer to firing methods, the lack of under or over-fired lime fragments in the mortars suggests that this was likely evidence of soft burning.

The absence of unslaked lime was also said to indicate long slaking times with large quantities of water, increasing the plasticity and workability of the mortar as well as improving reactivity with pozzolanic additives. Analysis showed that all mortars studied showed some form of hydraulicity, found not due to hydraulic lime, but due to the addition of pozzolanic aggregates. In many mortar samples containing brick fragments, few other aggregate additives were used. The authors assert that this intentional recipe is a vital key to the awareness the builders had of their own technology and the pozzolanic nature of the mortars. Pieces of charcoal and other burned organic material were found in a majority of the samples, leading the authors to postulate that this was most likely due to contamination of fuel materials from the burning process. The one exception to this came from samples taken from the base layer mortar of a thermal bath where large quantities of burned fuel looked to be intentionally added and spread evenly throughout the mortar.

The last portion of this article outlines the significance of this petrographic study to the understanding of Roman building techniques and technology. By comparing all of the data, the authors found no distinguishable connection between the quality of the mortar and the social importance of the sites from which they were taken. Also, no relationship could be made between the deterioration due to weathering, the age of the mortars, or the specific recipe. Some of the older mortars are in just as good condition as those mixed centuries later, while other more recent mortars have weathered the same.

Discussion

Other studies reviewed in this chapter (Peacock, 1977; Rossineux, 1989; Degryse, 2002; Farci, 2005; Sanchez, 2005) have used thin section petrography in conjunction with other scientific analysis to answer a variety of questions about historic composite materials. The article reviewed in this section, however, shows the possibilities— as well as limitation— of using petrography as the only method of mortar analysis. One of the benefits of using petrography is the ability to identify the bond between aggregate and binder such as the pozzolanic reaction zones of crushed ceramic additives. Additionally, this study's methods showed that the lime binder had minimal shrinkage, leading Pavía and Caro (2008) to conclude that a thorough slaking process was applied to the lime.

However, without combining other scientific analysis, the authors indicate that thin-section petrography can be limiting. Interestingly, this study fails to mention any sand aggregates, a common ingredient of mortars, which are observable through this method and can reveal some important information about sourcing (see section 5.4.2 of Chapter 5). Additionally, this study does not discuss the proportions of material constituents of these mortars, which is obtainable from point counting statistical analysis (see section 5.4.3 of Chapter 5). These absent methods, depending on the objectives of the project, can add significant data to historic mortar analysis.

4.2 - Experimental Archaeology: the ROMACONS Project

Experimental archaeology is becoming increasingly popular for researching the past. In many cases, there is no written documentation outlining the methods in which sites were formed, how tools were made, or how materials were collected and utilized. Because of this, archaeologists can hypothesize about ways of life centred on material remains but defining cold hard facts can be tricky, if not impossible. The practice of experimental archaeology takes the next step from scholarly conjecture to testable hypotheses, applying physical experiments to archaeological data (for more information on the theory and practice of experimental archaeology, see Coles, 1979).

Numerous experiments in archaeology have been conducted over the years. Techniques like flint knapping, metalworking, musical instrumentation, environmental variations, and structural reconstruction have all been testable aspects of experimental archaeology. While these exercises have been beneficial, it is important to remember that experimental archaeology does not intended to recreate history. Instead, it is designed to give insight into how things could have been done. Like any scientific experiment, failure is just as important as successes when trying to understand a subject. This being said, experimental archaeology should not be the pursuit of an end result by any means, but to gain an understanding about the obstacles faced by the technology available at the time.

The Roman Maritime Concrete Study, or ROMACONS is the primary experimental archaeological-based work done on the topic of Roman hydraulic concrete and its use in harbour building. The team consists of Robert Hohlfelder from the Department of History at the University of Colorado, Christopher Brandon who is an architect from London, and John Peter Oleson from the Department Of Greek and Roman Studies at the University of Victoria (B.C.). The primary goal of their studies was to answer questions as to the process of mixing and creating hydraulic concrete and the method in building the foundations of a Roman harbour.

In 2004, the ROMACONS team began the field project at Brindisi, Italy. The project goal was to create a '*pila*' or platform like those found at Roman harbour sites such as Caesarea Maritima in modern-day Israel. Preparation for this project entailed two separate preliminary research sessions in 2002 and 2003, where the members of the team collected and tested core samples taken from Roman sea structures. These samples were then used to analyse the qualities of materials used in the mixtures of Roman hydraulic concrete.

Like most scholars who study Roman mortar, cement, and concrete, the team focused their attention to Vitruvius' c. 25 B.C. *De Architectura*. Since this is a written testimonial of the ingredients and quantities needed to make hydraulic concrete, it was an obvious basis for their project. The questions outlined by Hohlfelder et al. (2005: 123) are as follows:

- How was the mortar placed in forms?
- How and where was the formwork constructed?
- Was large stone aggregate mixed with mortar before being placed in forms?
- How long did it take for the mortar to set in sea water?

Because these questions were not of the type that could be answered by conventional means, experimental archaeology was the logical approach. The plan was made to take the project to the Italian coast and only use materials and tools available to the Romans, as found in the archaeological record (Hohlfelder et al., 2005: 123). The team's *pila* was scaled down to a small portion of a true Roman *pila* because of many factors. First of all, to avoid intruding on the Italian public, a proper location had to be found which would not inhibit the flow of everyday life. The second was the financial demands associated with the rental of tools, the work area, and supplies needed for mixing and making the concrete. The last reason for the scale-down was the time associated with building a full-scale Roman *pila*. Many man-hours could be saved from the mixing and setting the concrete by reducing the overall size of the structure.

The chosen location for the experiment was a local rowing club in the Bay of Naples, Italy. This was a harbour area with little water disturbance with water up to 1.7 meters at high water (Hohlfelder et al., 2005: 124). It was a suitable location to build a small *pila* that allowed for it to stay above the water level. It was also well protected by the harbour and was not subject to normal sea conditions that the team claimed would put the project at risk.

The materials were specially selected to match the specifications of the core samples taken in the previous two years. Slaked lime putty (grasello di calce) that is widely available for mode rn construction was selected because it was the best match with the lime samples. The tuff (volcanic aggregate) and pozzolana was taken from the Bay of Naples just like Vitruvius had stated and the Roman workers used at Caesarea Maritima. The planks and beams used to make up the framework were laminated, kiln-dried reconstituted wooden material of little weight, which will be referred to below in greater detail. To correct for the contaminated mud sea floor, beach sand was brought in to seal the floor, following the advice of Vitruvius (*On Architecture* 5.12.4; Hohlfelder et al., 2005: 124).

By interpreting a description by Vitruvius on how to construct a formwork, corner posts were driven into the sea floor to support edge beams. On these edge beams, planks would be attached. But, because the wood they were using was so buoyant, the strategy was changed so that the planks were secured to the harbour floor first, and then the horizontal frames could then be fastened to them. This created a two square meter formwork shell on which a frame would be added. Unfortunately, this may have compromised some of the integrity of the project based on poor material selection and that the project was based in a calm harbour environment unlike the Romans.

The team made mortar from Vitruvius' formula, which called for two parts pozzolana and one part lime together with 15 to 20% seawater (Adam, 1999). It was mixed together in a trough using variations of Roman building tools such as shovels, rakes, and mattocks as shown by writings, depictions, and material remains from the archaeological record. The team intentionally made the mixture very thick because, when dropped into the formwork, there would be no risk of it diluting into the water. This made it easy to pour into the form using two men and specifically designed wicker baskets to lower the cement into the form (Figure 4.1).

Figure 4.1 – Basket being lowered into wooden formwork created by the ROMACONS project (after Hohlfelder et al., 2005: 126).

The first layer of cement was 0.2 m thick and rested directly on the freshly laid beach sand. The new surface was compacted down and smoothed out with rakes and mattocks and then the aggregate was placed in a new layer to cover the entire area. It took eight days to completely fill the form using this layering process (Hohlfelder et al., 2005: 126). Within a day of laying the last layer of mortar, the concrete had set well enough to walk on without sinking or shifting. Finally, a layer of smooth mortar was placed over the layer of aggregate, levelled using trowels, and paved using tuff blocks (Hohlfelder et al., 2005: 126).

The team claims that the ROMACONS project could possibly be the first time that those materials and techniques were used in the last 1600 years. Despite the many questions that arise from such a statement, the team boldly tackled the project with the resources given to them. However, some of the self-imposed stumbling blocks (due to location and material selection) may have detracted from the overall scientific experiment.

4.3 – Methods and Application

Chapter 2 served as an introduction to the history and architecture of the Water Supply of Constantinople and Anastasian Wall through a discussion of modern archaeological survey and extremely limited references in historical texts. In Chapter 3, a general discussion took place on the production techniques of composite materials such as brick and lime, as well as a brief introduction to mortar technologies. However, much of this information was based on writings from the early Roman Empire or archaeological studies from the Western Roman Empire, specifically Roman Italy. The aim of this chapter has been to show how scientific studies of composite materials can be used to answer some important historical questions about building technology and architecture. It should not be seen only as a justification for scientific analysis of mortars from the Water Supply of Constantinople and Anastasian Wall. The uniform presentation of these studies— aims, methods, findings, and conclusions— help direct the proper course of action necessary to answer the research questions of this study.

The three types of scientific techniques used most frequently in these studies seem to be SEM, EDS (or EDXS), and XRD. SEM is typically used to investigate the micromorphology of mortar and brick samples in order to understand the porosity, microcrystalline formations, and the bonds between aggregates and binding materials. The use of EDS is typically used in conjunction with SEM to identify the mineral makeup of areas of chemical reaction. XRD is, by far, the most popular method for mortar and brick analysis. This is also used to identify mineralogy but of a much wider area, helping to pinpoint changes occurring during chemical transformation. Additionally the studies reviewed in this chapter have shown that XRD analysis is beneficial for producing comparative data for various materials. All three of these scientific techniques are often used with optical mineralogy and thin sectioning but, disappointingly, there is little discussion of the usefulness of this combination.

The next chapter will discuss the methods chosen to examine mortars from the Water Supply of Constantinople and Anastasian Wall based on the research questions. Many of these reflect the aims of studies mentioned in this chapter, specifically those mentioned above. However, other methods are implemented or adapted to test the usefulness in meeting other important research aims.

Chapter 5 - MATERIALS AND METHODS: MORTAR STUDIES, SYSTEM QUANTIFICATION, AND MAN-POWER

We shall now give an account of the second and less self-sufficient method in a properly physical way, so that one whose aim is the truth might never compare its perceptions with the sureness of the first, unvarying science, for he ascribes to it the weakness and unpredictability of material qualities found in individual things, nor yet refrain from such investigation as is within the bounds of possibility, when it is so evident that most events of a general nature draw their causes from the enveloping heavens.

Ptolemy, *Tetrabiblos* (1.1.1-2)

Chapters 3 and 4 reviewed scholarship on the production and application of construction materials– specifically lime-based mortars from the Roman and Late Roman periods. While these two chapters have an intrinsic connection, the juxtaposition of material and humanities used in this project has yet to be properly discussed. Significant time was spent planning the techniques and methods so that they would be as practical as possible in answering the main research questions of this project. However, no amount of time spent planning would be as telling about the prospects and limitations of trying to answer these questions.

This project was developed around the study of collection and testing of mortar samples from the Water Supply of Constantinople and the Anastasian Wall. The technological significance of mortar in monumental structures—especially mortars containing non-volcanic pozzolanic material—in the Late Roman period seemed under appreciated in my initial research phase. While mortar analysis still plays a pivotal role in this project, many other facets relating to the monumental nature of the water supply and wall were employed in conjunction. As described in Chapter 1, it became clear very early that in a study based on construction materials, that an understanding of the mortar recipes and the technology behind them would be a pointless exercise without an appreciation of the scale and complexity of these monumental networks.

This chapter discusses the various methods used to collect data relating to the construction scale, material technology, and manpower of the Water Supply of Constantinople and the Anastasian Wall. These methods and aims include:

	MORTAR SAMPLING
Mortar sample collection	• Select sample sites representative of the scale and importance of the water supply and long wall. • Obtain mortar samples that will not compromise the structural integrity of the surviving sites while still representative of the material technology.
Low-impact sample extraction	• Using the large samples collected for this project, design new methods for extracting small mortar samples *in situ* in future projects.
	MORTAR ANALYSIS
Petrography	• Identify the types of materials used in the mortar recipes. • Identify objects that were unique between samples as well as unintended additions.
Point counting	• Quantify the materials used in the mortars in order to compare the recipes. • Use the resulting percentages to quantify the total raw materials needed in the systems' construction.
SEM/EBSD	• Investigate the size of pores and the relationship between chemically-reactive materials such as brick and lime.
XRD	• Identify the relationship between raw clay sources of brick fragments used as mortar aggregate.
	CONSTRUCTION MATERIAL QUANTIFICATION
Anastasian Wall Project survey data analysis	• Build a comprehensive list of measurements from structural features. • Estimate the total length of water supply and long wall
Design formulae to estimate quantities of construction materials needed	• Input measurements into formulae to calculate the volume and surface area of individual structural elements (i.e. – forts, aqueducts). • Break down volume and surface area estimates to calculate construction material quantities

	MAN-POWER ESTIMATES
Calculate material production requirements, material transportation, and construction	• Estimate man-power to produce and procure the quantities of construction materials required. • Build hypothetical scenarios for material transportation paths using basic geological and geographical information. • Estimate man-power for the construction process using the quantities of materials and structural measurements.

These forms of analysis and data collection were all applied to the existing knowledge of the structure in the hope of shedding light on the scale and ingenuity of these two building projects. There are no known analogous published or unpublished projects that encompass all of the aspects of interest in this study, making it a challenge to build a methodology that would address all of the necessary concerns. Many methods regarding scientific testing such as petrographic, SEM/XRD and XRD analyses of mortar or brick material have been documented in other studies (see Chapter 3). Low-impact mortar sampling, specimen preparation, structural measurement and material calculations on the other hand, had to be developed through a combination of methods.

5.1 - Site Selection and Mortar Sample Collection

The original scale of this project covered a much larger geographical area and required many more sampling locations. In retrospect, the magnitude of work required for a comparative analysis of mortars from the three main cities of the Late Roman world was far too large for a PhD project. The process of obtaining permission to collect samples from numerous sites in differing countries proved to be far too constricting on the limited timeframe and goals of the project.

My PhD supervisor, Professor James Crow, had been working for many years on the Water Supply of Constantinople and the Anastasian Wall (Crow, Bardill, Bayliss, 2008). Neither of these structures is found within the land walls of Constantinople (except for the Aqueduct of Valens and numerous cisterns) but they were both built for the welfare and protection of the city and its people. When I was told in late 2007 that authorisation had been given to collect samples of mortar from these structures, it was the 'best-case' scenario for a project such as this. While the function of the water supply and Anastasian Wall are completely different, it was an ideal comparative study in regards to their construction methods, mortar technologies and geographical relationship. Both of these structures are quite similar as they both cover a long distance and it was of interest to investigate the potential variations in mortar type, recipe and application based on these geographical and functional aspects of the water supply and long wall.

When samples were being collected in the field, the full impact of a scientific study of mortars could have on the understanding of the Water Supply of Constantinople and Anastasian Wall was not yet realised. After seeing the surviving scale of the structure from aqueduct bridges like the colossal Kurşunlugerme in 2008, it was clear that influence of this study would have a much larger impact on the archaeology and history of these two structures. It was not until preparing and producing thin sections of these mortar samples that the potential of this project was fully realised.

5.1.1 - Field Work

In the summer of 2008, I joined the Anastasian Wall Project made up of a team from Istanbul Technical University and the University of Edinburgh for a fieldwork season of sites associated with the water supply system in Turkish Thrace. There had been numerous years of work carried out before my involvement and that was the final year before the book on the aqueduct system of Constantinople (Crow, Bardill and Bayliss, 2008) would be published. The goal for this year's season was to obtain final GPS data for portions of the system that had yet to be fully surveyed and to explore possible areas of the water supply that had been identified by local residence (See Crow and Maktav, 2009). This brought the team close to many of the monumental bridges of the 5th century, along with great lengths of channels that linked these bridges.

In 2009, I was able to join the Anastasian Wall Project team for second phase of fieldwork in Thrace. This time the focus of the survey work was on the Anastasian Wall, which meant that we would be looking for new features of the wall to enhance existing data. The goals were the same as the previous year including tasks such as walking the landscape around the line of the wall to take GPS points and measurements from portions of the wall. The team started at the southern end, immediately west of Silivri, following the known line of the wall north along its full extent. In many instances the team working in very close proximity to some of the monumental bridges we had visited the year before, as a result of the intersection of the water supply and the wall. This was especially true for the second half of the trip where we worked our way north of Gümüşpınar to Karacaköy. The survey ended at Evcik, where the northern end of the long wall met the Black Sea coast.

Another goal of the 2008 and 2009 seasons, and the central aspect of this thesis, was to collect mortar samples from a selection of major fifth-century aqueduct bridges and from an assortment of sites along the length of the Anastasian Wall. These samples would eventually be processed in the laboratory to determine their mineralogical formation and recipe, as will be discussed in much greater detail later in this chapter. The objective of collecting samples from features of the water supply was to obtain samples of structural and channel mortars from key aqueduct bridges over a wide geographical extent. Similarly, the purpose of collecting from the Anastasian Wall was to identify points of interest such as towers, fortifications and preserved sections of the linking wall over a large extent of its length.

5.1.2 - Sample Collection

The first requirement for undertaking any archaeological work in Turkey, especially for collecting samples of archaeological material, was to have a representative appointed by the Turkish government present at all times. This requirement was to both protect Turkish cultural heritage and as a means to facilitate the authority to remove and be in possession of such samples. When a sampling area was identified at a site, the location was carefully documented and photographed. In every case of sample procurement from the water supply system and the Anastasian Wall, samples were taken from areas that were not in any way influencing the structural integrity of the edifice. Because these structures are not currently covered under any conservation or restoration programmes, nor listed as heritage sites, it was vital that sample collection did not interfere with their future state of preservation.

To avoid damaging the integrity of the structure, no tools were used to remove pieces of mortar from any solid structure. This meant that each sample was collected from a locale where the mortar was already exposed and mostly separated from the existing matrix of the core. Furthermore, only pieces of mortar that had no load-baring affect on any other structural members were collected. Because of pre-existing fissures, in most cases, samples could be removed effortlessly from their original location. In other cases, pieces of mortar suitable for collection had already fallen away from the structure. On these occasions, the mortar samples' original position on the structure could be identified by their proximity to the source and condition of the exposed mortar core. Pieces of mortar collected for analysis that had already become detached from the core of the structure were most likely to have been only exposed for a short period. This conclusion was made after the exposed area of the core and piece of mortar were investigated, both presenting a fresh pink colour and little to no weathering.

Before the samples could be transported out of Turkey, they had to be inspected by the staff at the Istanbul Archaeological Museum. After the inspection, permission was given in writing stating that the samples were authorised for export for scientific analysis. A member of the museum staff then placed the samples in a box, sealing it with string and secured with lead seal. This was to ensure that nothing was added or removed from the box before being taken out of the country.

Figure 5.1 - Sealed box of samples of mortar from the Anastasian wall.

5.2 – Methods of Sample Preparation for Thin Sectioning

Once the samples reached the laboratory at the University of Edinburgh, observations were made on the macroscopic nature of the samples such as colour, aggregate type and size, weight, and overall dimensions. These observations, while quite rudimentary, would prove to be useful when studied against data from other analyses. Following this initial analysis, samples were photographed and prepared for scientific analysis including thin section petrography.

Because I was initially unfamiliar with several of the fundamental aspect of producing thin sections, I reviewed several manuals and articles on petrographic studies. The guidelines presented in these manuals were typically quite general in terms of the type of material to be thin sectioned. Similarly, petrographic studies, which rarely presented methods of analysis, typically focused on uniform stone material (John, Poole, and Sims, 1998; Goins, 2004; Janssens and Van Grieken, 2005; Middendorf et al., 2005; Reedy, 2008). This meant that much of these sources did not take into account the varying rigidity of materials in composite materials like the mortars of this study. Many of these methods were tested in the laboratory but it soon became apparent that they needed to be tweaked or changed completely to be advantageous for this project.

5.2.1 - New Methodologies: Preparation Stress Data and 'Micro Sampling'

There were two additional themes to this material analysis. The first was to identify any component of sample preparation that might be of use in understanding differing characteristics of the mortars. This was in response to the numerous scientific studies of similar composite building materials that involve coring, cutting, and polishing which discuss the use of these processes but not the possible significance of such strategies. In the first stages of thin section preparation, I began to see that methods had to be modified to accommodate the differences in the mortar samples. While visually similar, their behaviour under the stresses caused by cutting, grinding and polishing, led me to believe that these steps might provide useful comparative data.

The second theme of interest in these procedures was to build a methodology based on providing low-impact techniques that could be undertaken in the field. The samples that were taken from the Anastasian Wall and the Water Supply of Constantinople were large in comparison to the sample sizes required for the tests undertaken in this project. While the collection of these samples was done with preservation as a clear prerequisite, the sites provided large samples due to their associated construction techniques. Other monuments would not necessarily provide such generous quantities of mortar with any remaining structural significance. In response, new field methods were developed and practiced in the laboratory to test the effectiveness of micro-sampling. These minimally intrusive approaches, coined 'micro sampling', were designed to be used on almost any type of structure form archaeological excavations to original structural elements of restored structures and from thick flooring surfaces to mortar joints between bricks.

5.2.2 - Coring

The average size of all of the samples from the water supply was quite large considering the necessary amount needed for analysis. The first preparative step to create thin sections would be to obtain manageable-sized samples, suitable for the equipment. It was the ideal situation to test the effectiveness of micro sampling since methods and tools could be easily modified in the laboratory environment.

This process proved to be useful beyond the necessary means of obtaining a core. Observations were made about a sample's current state of quality, its general porosity, and the samples friability. Cores provided information about large pores and fissures that occurred within the sample that were not readily identifiable on the surface.

Figure 5.2 - Core sample of channel mortar from Karatepe. The core fractured during the drilling process, revealing a pocket filled with possible decayed organic material.

Multiple cores from each sample were taken from a variety of locations to ensure a more representative source of the mortar's entire makeup could be obtained. For most samples, this meant choosing at least three locations spread out over the surface for drilling. It was not required to break up the sample to get to the core since the drill bit could take cores to a depth of 4 cm. Even for thick samples that were like that from Kurşunlugerme, it was possible to start drilling another core in the same location after the first core was removed. In the case of channel lining mortar from Karatepe, it was possible to take a total of five cores from the surface in contact with the water flow. The distance between cores were the most concentrated on this sample because of the thin nature of the sample and the depth obtainable by the coring bit. It was only necessary to take one core from the opposite side at the thickest point of the sample.

Figure 5.3 - Channel lining mortar from Karatepe with holes from coring.

The treatment of samples from the Anastasian Wall was almost identical to those from the water supply. The main exception to this was the amount of cores that were taken from each sample. The size of samples from the Anastasian Wall was, on average, much smaller due to the size of mortar joints along the wall and the mortar's friability. Differing considerably from the large aqueduct bridges, the core of the wall had quite narrow bands of mortar between the smaller stone aggregate. The typical sample would only be large enough to produce one complete core. However, one sample, obtained from Büyük Bedesten, is much larger than the others and allowed for multiple cores. To compensate for only having one core per sample, at most sites, multiple samples were obtained at the same point of the mortar joint within the core.

5.2.3 – Core Preparation, Resin Impregnation, and Slide Mounting.

Cores were cut to size using the Buehler Isomet 1000 Precision Saw and they were placed in labelled mould cups that had been swabbed with a release agent. Mould cups were placed in the Buehler Cast N' Vac Castable Vacuum System and the transparent vacuum chamber was sealed for two minutes to remove air in the samples' pores for the resin to fill. Once all of the samples had been encased in epoxy resin, they were placed in a ventilated low-temperature oven for 24 hours. Once set, a total of three slices were cut from each sample using the precision saw. One slice was chosen and glued to a glass slide.

5.2.4 - Grinding and Polishing

The last process involved in producing thin sections was done using a Buehler Beta Grinder-Polisher with an attached Buehler Vector LC Power Head. This equipment allowed for the proper production of quality thin sections meeting the thickness of between 20 and 30 μm, depending on the type of sample.

Producing adequately thin slides for analysis proved to be one of the most complicated and delicate processes of the entire project. The reasons for this difficulty could be attributed to numerous factors. The most influential of these is the relationship between hard quartz aggregate surrounded by very soft lime binder.

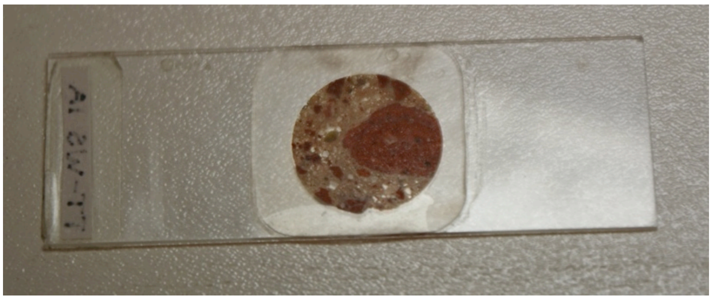


Figure 5.4 - Finished thin section of a mortar from Kurşunlugerme at a thickness of 30µm.

Once the bulk of sample had been ground away (down to around 200 µm in thickness), the abrasive paper was changed to finer grit. This step was repeated at every 30 to 50 micron interval until the sample neared the necessary thickness. At each stage a digital micrometer was used to measure the thickness to ensure that grinding was done evenly along the sample's surface. The thickness recommended by most studies and manuals on thin sectioning recommend 30 µm. However, it has also been suggested that, due to their varying composition, that mortar samples should be no more than 20 µm thick. Both thicknesses were tested under the microscope and it was found that at 30 µm was superior for performing both polarised microscopic analysis and microphotography. At 20 µm, the contrast between dark brick aggregate and light lime binder made microphotography very difficult and did not provide a noticeable difference in identifying materials using polarised light. It was decided that every sample would be ground to 30 µm for practicality and continuity.

5.3 - Microscopy, Sample Mapping, and Microphotography

Once the thin sections had been grinded to an adequate thickness, it was necessary to get familiar with each slide under the microscope. Because I had very little experience doing petrographic analysis, it was vital that I study methods dedicated to the identification of materials in thin section. It was found just as useful to use the different microscopes available in the laboratory and to see the benefits of different types of light and magnification, as this helped me become more familiar with the microscopic nature of these mortar samples.

Before image analysis could be done on these thin sections, I had to find the right microscope and camera equipment. Much of the information regarding equipment use came from the combination of microscope manuals from the manufacturers, the book *Microscope Image Processing* (Wu et al., 2008) and, most importantly, practical time using the microscopes and camera. In addition, I felt it was necessary to inspect each sample individually and develop a method for their documentation. Since this project relies heavily on comparative data, it was vital to find a way to take note of objects in the mortar with the ability to return to their exact location. This was also the first instance that microscopic identification of the mineralogy was performed. Ultimately, digital micrographs of these thin sections were required for much of this project's important analysis. Thus, each step of this section, including finding the right equipment, sample mapping, component identification, and microphotography, turned out to be as influential to this project as many of the resulting scientific studies.

5.3.1 - Microscopes

To preform petrographic analysis, it was essential to have the proper microscopic equipment. The first goal was to identify the material constituents of each mortar sample. This involved identifying the characteristics of the main materials used in the mortar recipe such as lime, brick, and sand. Similarly, it was important to identify other materials that were unintentionally added during the phases of mortar manufacture like fuel material and distinctive minerals as sand aggregate. The second goal was to quantify the types of materials making up the mortar samples. Acquiring each sample's individual recipe would be almost impossible without the use of petrography and unnecessarily difficult without the aid of microphotography. To fulfil these requirements meant that the microscopic equipment had to have both transmitted and reflected light, a separate optical tube for microphotography, a polarisation kit, and standard magnification intervals.

The first microscope used was the Olympus SZ40 Stereo Microscope. This reflected light microscope was used to study surfaces of mortar cores that had not yet been thin sectioned and to identify pieces of material in their natural state like fuel and larger stone aggregate. The Olympus SZ40 also has the ability to attach a camera, which was useful for illustrating individual components and the surface of each core. The Nikon SKE Polarising Microscope was the second microscope used for the purpose of identifying the types of minerals used in the mortar. The polarised light microscopy allowed for easy optical mineralogy but the drawback was that there was no equipment available to attach a camera to this particular microscope. However, specific elements were could be identified under normal transmitted light of the next microscope based on the initial analyses of samples using the Nikon SKE. The final microscope was an Olympus BH2 Research Microscope. This microscope was the most beneficial because of its ability to take quality photomicrographs. These images of the mortar samples in thin sections were used for all digital processing and analysis pertaining to component material quantification and aggregate measurements.

5.3.2 - Optical Mineralogy

The methods employed for optical mineralogy were quite standard. Using the Nikon SKE polarising microscope, thin section samples were analysed using and compared with other samples documented in two key publications. The first was *Atlas of rock-forming minerals in thin section* (MacKenzie and Guilford, 2007). This study not only provides the appropriate information necessary to identify types of minerals in this section but also provides colour examples of a wide range of minerals under both plain and crossed polarised light. Based on the birefringence patterns shown of minerals within the mortar samples and those depicted in the book, identification of the major and minor constituents of the mortar was made easy. Similarly, *Thin-section Petrography of Stone and Ceramic Cultural Materials* (Reedy, 2008) was helpful as a guide for looking at composite materials and identifying their mineral components. While this does not have a specific discussions on structural materials such as brick, it was particularly helpful because of its lengthy discussion of using polarised microscopy on other similar ceramic materials.

Using simple transmitted light microscopy with the Olympus BH2 was also important for the process of identifying aspects of the thin-sectioned mortar samples. The absorbance of white light through different mineral components helped contrast different elements that would be very hard to separate under reflected light microscopy. This is called bright field microscopy and is particularly helpful in differentiating the reaction zones between dark brick aggregate and lime binder. In the same way, this method is also useful for observing the crystalline formation of silica sand aggregate that is typically obscured by the surrounding binding material. Both factors contributed greatly to the quantification and material measurement through computer image analysis of the resulting photomicrographs.

5.3.3 - Sample Mapping

Because of the size of the samples were many times bigger than the area viewable under the lowest magnification through the microscope, it was imperative to have a way to document aspects of interest. This meant creating a small map (Figure 5.5) with a rough sketch of all distinguishing features of each sample so that notes could be made to identify small areas for revisiting. First, the outline of the sample's shape on the slide was drawn as a boundary. In most cases, because of the nature of many of the cores, this was a round shape. However, in instances from certain samples of the Anastasian Wall, samples were very irregular in shape.

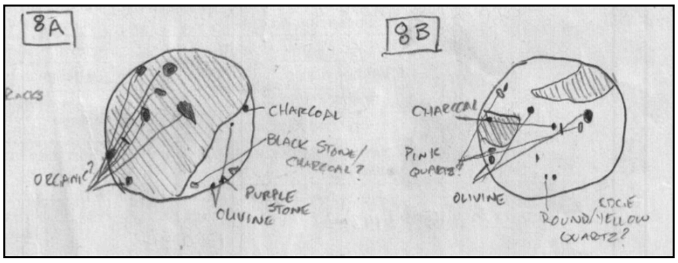


Figure 5.5 – Sample maps of thin sections TT-AW 8a and 8b.

The second step was to draw lines over the sample outlines to break it up into labelled quadrants: northeast, northwest, southeast, southwest. This was done to section the sample into more manageable working areas and for an easy way to identify locations of micrographs once they were taken. The third step was to identify and label areas of interest or unique aspects of the mortar, making sure to look for both similarities and differences between samples. Because of the random nature of the selection of cores, the exact locations of objects of interest were not important for analysis. Instead, marking them on the sample maps documented their occurrence and provided an easy method for identifying the sample area for possible future observations.

One of the most beneficial aspects of this method, other than for referencing, was having a consolidated guide to each of the samples. This offered a wealth of information that was very helpful in discussing general aspects such as brick aggregate size, possible organic matter, microfossils, and varying types of sand grains. Because this information was available for all samples, it was incredibly advantageous for comparing samples both spatially from collecting site to collecting site and for the larger geographical area between the Water Supply of Constantinople and the Anastasian Wall.

5.3.4 - Microphotography

Producing quality digital photographs of samples through a microscope was very tricky and time-consuming, yet ultimately rewarding, task. Ultimately, these micrographs would act as a means of recalling portions of the mortar samples (with the help of the sample maps) without having to go back to the microscope.

Before micrographs of the samples could be taken, it was important to get scale of the image area by obtaining measurements of each of the microscope's five different objectives. To accomplish this, a high-resolution scale with increments of 0.5mm was placed under the microscope and micrographs were taken under each objectives magnification.

It was found that a magnification of 100x was perfectly suited for identifying individual grains of most materials. Following the quadrant lines drawn on the sample maps, photographs were taken and stored in designated folders labelled by quadrant. For a typical round core sample with a diameter roughly 20mm, each quadrant would include around twelve micrographs, making an average total of 48 pictures per sample slide. Each of these micrographs measured 3mm by 2mm at a resolution of 3872 x 2592 pixels.

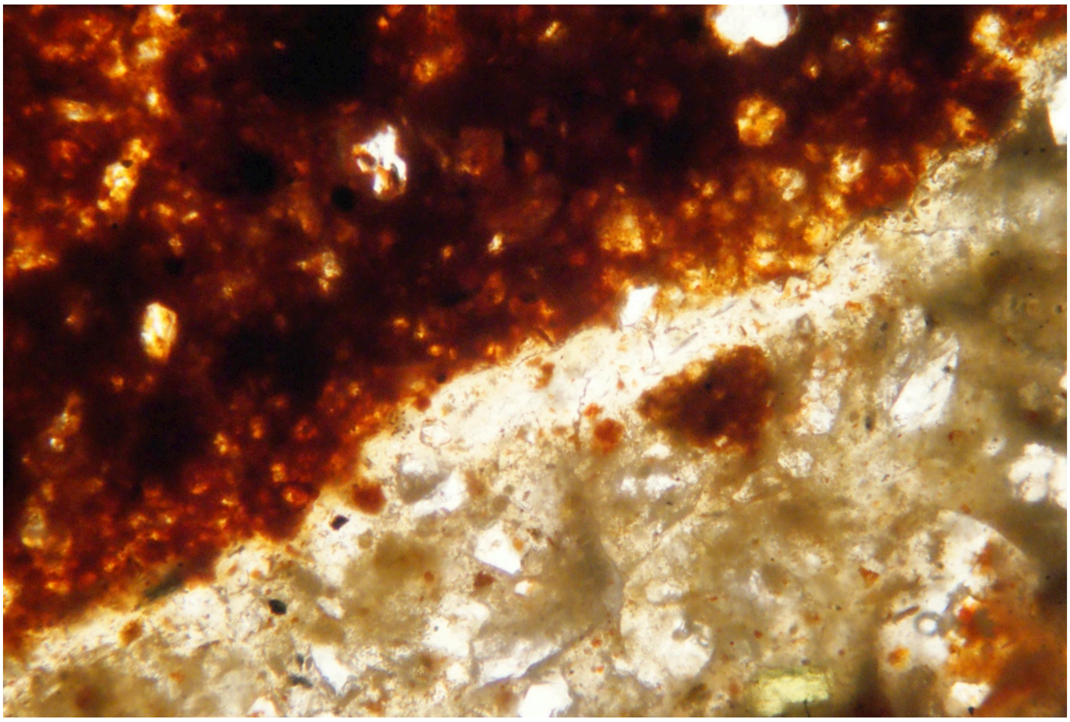


Figure 5.6 - Digital Photomicrograph of mortar under transmitted light microscopy (200x).

Objects of interest, identified while making the sample maps required higher magnifications between 200x or 400x (Figure 5.6). Increased magnification was used to pick up more detail on things like charcoal, individual grains of sand, organic material in brick, and other small atypical objects. These micrographs proved useful for detailed inspection and as a way of illustrating some of the finer features that would be impossible to see with the naked eye.

5.4 – Petrographic Image Analysis

The production and analysis of thin sections should be considered the backbone of this project. While this does not account for all of the collected scientific data presented in the next chapter, the production and investigation of mortar samples through petrographic analysis was the greatest aid in the understanding of this highly refined composite material. Even more, the investigation of these samples led to many ideas that required additional forms testing such as SEM and XRD analysis.

Image analysis of mortar samples from the water supply and long wall proved to be one of the most time consuming aspects of this project. The resulting data, however, demonstrated that this examination was the most important method for expressing the true monumental nature and material requirements of these sites. While many projects have substituted or supplemented the processes of point counting and optical granulometry for more high-tech and high-speed methods (see Chapter 4), image analysis seemed to be more flexible in both technological requirements and statistical analysis.

The process of collecting data from microscopic evaluation has been greatly enhanced by the digital age. Before, every measurement was done manually by careful study of physical photographs, producing copious amounts of data that would also have to be organised manually. With the aid of digital photography and computer software, much of the rigorous and overwhelming aspects of such a petrographic study were conveniently calculated and organised for future use. This section outlines the software, digital tools, and methods of analysis used to obtain both quantitative and qualitative from micrographs of mortar samples from the water supply and Anastasian Wall.

5.4.1 - Software and Setup

The most beneficial source for discovering ideal and affordable software came from the article *Image Analysis Protocol Instructions #1: Spatial Calibration of Images* (Reedy and Kamboj, 2004). Reedy's work on thin sections of cultural materials (Reedy, 2008) proved to be very useful for identifying aspects of these mortar samples so the advice on image analysis software provided in this article was very important.

JMicroVision software was chosen because of its ablity to provide all of the analytical tools necessary for petrographic studies. First major advantage of this programme was the ability to differentiate quantitative measurements between statistical point counting and two dimensional area selections. Both of these features used a simple material classification system that could be set up at the beginning and edited throughout the process as needed. The second advantage was its ability to consolidate and present data. Different types of analysis could be carried out but the data is managed in such a way that made it easy to compare in-programme or export to a spreadsheet. Data management turned out to be one of the most important aspects of analysing samples due to the great quantity of information produced.

The first step was to set up classes corresponding to the materials represented in the sample micrographs. These classes could be colour coded and assigned a descriptive name. These classes, used for the basis of all analytical methods, are as follows:

Table 5.1 - Point counting classes and associated colours.

Number	Material	Colour Code
1	Brick	
2	Small Aggregate (sand, etc.)	
3	Lime Binder	
4	Outside Sample Area	
5	Sand in Brick	
6	Unburned Lime/Secondary Calcite	
7	Organic Material (charcoal, etc.)	
8	Small Brick Particles*	

*Only used in Optical Granulometry

The next step for setting up the software was setting the measurement scale for the image. This was a simple process that involved drawing a horizontal line across the micrograph in the programme and inputting the actual length of the portion of sample represented. Once the micrograph was to scale, all lines, drawings and selections made on the sample became measurable.

5.4.2 - Optical Granulometry

The aim of optical granulometry is to determine the size of aggregate materials within the sample through non-destructive means. This can be done using manual microscopic observation and measurement or can be greatly aided by digital means. JMicroVision includes special drawing tools that allow the user to select multiple areas on a micrograph and then data is provided on factors such as average minimum and maximum diameter, surface area, and total number of selected objects. These factors could be individually categorised by assigning pre-identified classes or grouped together for an overall study of all selected materials.

Granulometry could be done manually by crushing and sieving the samples through varying sizes of mesh or through chemical breakdown of the calcium carbonate but these processes require the destruction of a large sample in order to obtain sufficient statistical data. The biggest problem of using this manual method is that softer aggregates, specifically brick, would be broken down with the lime binder. This would not only make quantifying the brick aggregate impossible but would cause the quartz temper in the brick to be mixed in with quartz sand aggregate from the binder, making it almost impossible to differentiate the two when measuring. Using optical inspection, especially using a computer programme provides the means to gather a vast amount of data quickly and with more accuracy.

For this study, micrographs from each core sample were selected based on the representation of particular materials. The biggest interest for these mortar samples in terms of granulometry was to identify the size and shape of three individual components of the mortars: quartz sand temper in the large brick aggregate matrix, quartz and other small aggregates within the lime binder, and brick particles mixed in the lime binder.

The first goal of this analysis was to obtain the data of quartz temper in brick and quartz used as aggregate in the lime binder. The goal of this was to compare the two types of quartz to see if there were any major distinctions in size that might indicate something about general collection locality differences. While carrying out this analysis, it was important to take note of the morphology of quartz material to identify possible weathering or heat related fracturing. This was in the hope of separating sand that was intentionally added to the mortar mixture from the quartz sand temper grains that were mixed in with the introduction of crushed brick pieces. To do this, lines were drawn around the perimeter of individual granules of quarts and labelled either ‘sand in brick’ (orange) or ‘small aggregate’ (green).

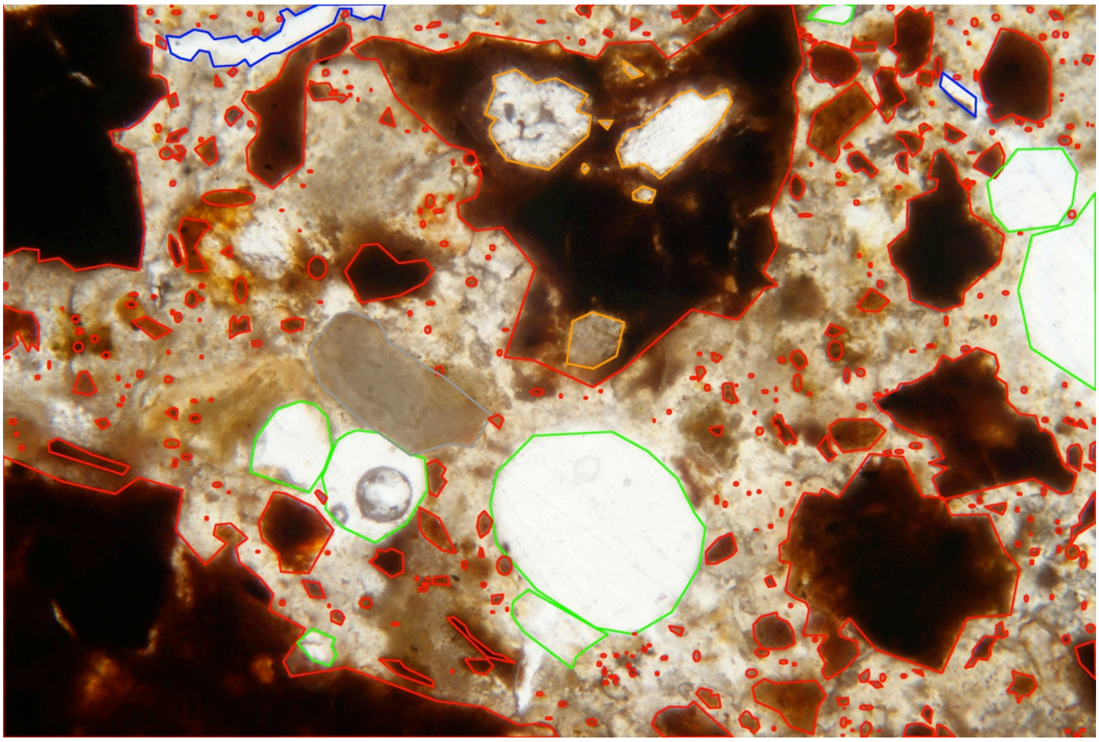


Figure 5.7 - Optical granulometry using JMicroVision.

The second goal was to separate the brick fragment sizes within a single slide into two different categories. Through simple microscopy, it was observed that a majority of samples included a wide range of sizes of brick additives. The first size group consisted of larger brick pieces, in some cases being bigger that than the slide sample area. This size group was chosen to indicate brick material that would have a smaller pozzolanic effect on the lime binder and would function primarily as an aggregate.

The second size group was made up of very small particles of brick that were mixed somewhat evenly throughout the mortar. These small particles of brick represented finely crushed brick pieces that would have highly pozzolanic interactions with the surrounding lime. To easily differentiate between the two size groups, it was typically determined that if a brick fragment still contained an attached piece of quartz temper, it belonged to the larger group. This meant that there was a very wide range in size for the large size group but only small differences for the highly pozzolanic group. In many cases, brick particles acting as highly effective pozzolana would be as small or smaller than the size of the temper found in the larger pieces, allowing for easy categorisation during this analysis.

5.4.3 - Point Counting

While limited to statistical percentages, point counting is an extremely important method for this project. Since one of the main research objectives of this project is to quantify the materials used to produce the entire late antique water supply line, determining the percentages of individual components within each mortar was essential.

Each class was assigned a keystroke at the beginning of the process of point counting. When the 'Start' button was clicked, a random point was chosen by the software on the micrograph and was highlighted by a crosshair. Each point represented a single pixel and could be zoomed in our out for further inspection. Depending on the type of material that was targeted by the software, the associated class was chosen by pushing the designated keystroke. This would automatically save this information as coloured dot and then move the crosshair to a new random location. As points were chosen, a list of the classes on the side of the screen would update the percentage of points for each class. When the point count reached 200, a button in the programme was clicked to open up a histogram of the class percentages. At the beginning of the histogram, the jumps in percentages were quite high. The goal of looking at this histogram was to ensure that enough points were taken to level out the percentages, indicated by steady nearly horizontal lines over a period of at least fifty points.

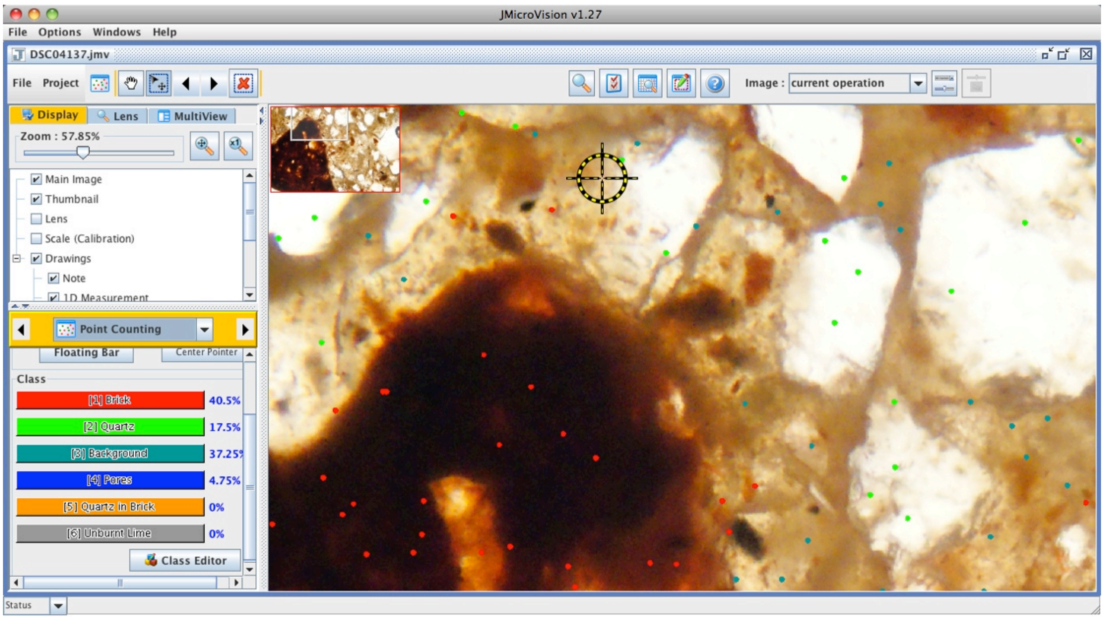


Figure 5.8 - Point counting using JMicroVision. Bottom left corner indicates the running percentage of each material group.

It was found that between 200 and 300 points per session was suitable for obtaining statistically consistent percentages for each micrograph. 200 points was a common figure for those micrographs that only represented a small number of the classes. For example, some micrographs were completely covered by large pieces of brick aggregate. Since they would only represent two classes— brick and sand temper— the histogram showed consistent percentages much earlier. However, for those micrographs that represented five or more classes, it was typical that more points would be required for statistical accuracy. While this process was quite time consuming and very monotonous, it proved to be an extremely useful technique for quantification of materials.

5.5 - SEM and EDS Analysis

Many studies based on the analysis of mortar samples use scanning electron microscopy (SEM) to gather information unobtainable by optical microscopy. As has been presented in the scientific section of Chapter 4, this has been used to identify the crystalline formation of the mortar as well as the nature and size of the mortar's pores. In addition and typically parallel to SEM analysis, energy-dispersive X-ray spectroscopy (EDS) is also a key aspect of material analysis. EDS is used to determine the chemical characterization of samples by shooting a beam of charged particles and reading the intensity of emitted X-rays, corresponding to different materials. The use of EDS is commonly found in geological studies and, in turn, for geological observations of archaeological material such as ceramic and mortar analysis.

While this project's main goal of mortar analysis does not rely on the crystallography and micromorphology but instead on quantifying the materials of the mortar samples, it was not an immediate thought that this technique was required. However, after spending some time looking at thin sections under the microscope and reading through many studies based on historic mortars, it became clear that this type analysis could be hugely beneficial for identifying subtle differences relevant to material sourcing based on crystal formation and mineralogy. Once the opportunity arose to perform this analysis, there was no doubt that there was significant benefit in having the resulting data.

5.5.1 - Equipment and Specifications

The samples were analysed in the Grant Institute's SEM lab within the School of Geosciences at the University of Edinburgh. This facility houses a Philips XL30CP electron microscope utilising an electron gun with a tungsten filament source. This has a PGT Spirit X-ray analysis system and a HKL Channel5 Electron Backscatter Diffraction (EBSD) system that produces images of specimens with a mean atomic number difference of >0.1. A connected computer with two monitors running the Windows operating system controls all of the Microscopes, X-ray, and EBSD analysis systems. This allows for real-time imaging of samples and for the export of high-resolution digital photographs.

5.5.2 - Sample Selection and Preparation

Obtaining samples for this type of analysis was one of the simplest steps of the whole project. Each mortar sample collected from the Anastasian Wall and water supply was taken out of their bags individually as was common practice. A location was chosen on each of the samples based on the represented materials and the ease at which the piece could be removed. Using a small pick and a pair of tweezers, small samples no bigger than a centimetre in diameter were removed and placed in labelled plastic bags.

Because of the time constraints and not knowing whether the resulting data would have a reasonable impact on the results of this study, it was decided to send only a few samples to the lab. These included a set of mortar samples from the three aqueduct bridges of the water supply and a set from three sites along the Anastasian Wall. The aqueduct bridges chosen were Kürsünlügerme and Büyük Germe because of their substantial size and structural core mortar collected as well as Karatepe due to the mortar samples purpose as channel lining. Samples tested from the wall came from the second-most southern sample collection site at Karanlık Ayazma Sirti, the closest sampling site to the water supply at Belgrat Tower, and at the northernmost section of the wall along at Evcik (see Chapter 6 for more information on sample locations). All samples were also chosen on the basis of achieving a wide geographical representation of collection sites and to further investigate the possible differences in mortar production techniques and recipes.

Preparing the sample required coating the samples in an ultra-thin layer of carbon, affixing them to pin grooved head sample mounts and, because of the porous nature and irregular surface of the sample, paint silver strips on both sides of each sample. This was to increase the conductivity between the sample and the sample mount for better readings during the examination process.

5.6 - XRD Analysis

A few complicated questions concerning the bricks used as pozzolanic aggregate arose from the petrographic examination of mortar samples from the water supply and long wall in Thrace. The initial problem, also a concern for much of the other construction materials, was identifying the source location of raw materials for brick used as aggregate in mortars from the water supply and wall. Other questions arose in response like did the location of the sourcing locations correspond to the kiln sites or more importantly, were these bricks intentionally produced to be aggregate in mortar?

While looking at the general qualities of the mortar under the microscope, it was evident that the larger brick aggregate pieces were not uniform. This was not only the case between sample sites but, more importantly, between pieces of brick within the same sample. These variations were not evident under normal optical microscopy for smaller, finely-crushed particles. In the larger pieces, however, the differences in colour, quantity of quartz, and quartz size were all factors that lead me to believe further scientific testing, specifically XRD analysis, could be beneficial.

5.6.1 – XRD Aims

The methods used by other scholars looking at brick and mortar materials using XRD analysis (Böke et al., 2006; Moropoulou, Çakmak and Polikreti, 2002; Cardiano et al., 2004; Baronio and Binda, 1997; Baronio, Binda and Lombardini, 1997) were repeated as closely as possible in this project. This was to ensure that the data obtained from such testing could be easily compared to the results from these studies. Specifically, the objective was to compare XRD pattern results from brick aggregates around Constantinople (see discussion of Moropoulou, Çakmak and Polikreti, 2002 in Chapter 4) with results from these samples. Furthermore, and possibly more conclusive for determining the means sourcing brick material for a pozzolanic aggregate additive, was to compare the patters from brick aggregates between the same water supply and wall mortar sample.

Another prospect of XRD analysis was to observe any suggestions of firing temperatures of this brick material. While the methods for determining this vary from between studies, the two articles (Baronio, Binda and Lombardini, 1997; Baronio and Binda, 1997) suggest that the upper limit for firing temperature can be obtained through x-ray diffraction analysis. While the details of the methods are sparsely discussed, they seem to be based on the formation of certain silica-based minerals at known temperature peeks.

5.6.2 - Sample Selection

Since the main reason for choosing to carry out XRD analysis was based on questions concerning brick aggregate, it was necessary to procure pieces from the matrix of the original mortar samples. Taking into consideration that one of the tenets of this project was to explore the effectiveness of low-impact, minimally intrusive sample collection, the process of removing material from the larger samples was carefully chosen. It was decided to remove portion of brick from as close to the surface of the sample to simulate conditions in the field, whereby pieces could be recovered from exposed sections of mortar without disrupting the integrity of the structure.

Pieces of brick on the surface of the samples were examined using a standard 10x magnifying glass prior to their removal. The intent of this investigation was to identify two visually dissimilar brick specimens from each mortar sample. While more intense magnification would be of more help, this was another instance where simple handheld equipment was used in the laboratory to test the effectiveness of a low-impact sample collection method in the field. Because of the limitation of the magnification, it was not possible to identify the configuration of the ceramic and quartz sand temper of the brick. However, it was found that the only way to see this configuration was through thin section because of the dense, opaque nature of the brick and this process would not be feasible in the field. Therefore, samples were chosen based primarily on notable differences in colour.

Brick samples were also chosen based on their size. They had to be large enough to provide a reasonable sample quantity for SEM analysis. These requirements were based on weight and since brick is reasonably light, samples had to be large enough to meet the 5 mg limit. Based on the average size of brick aggregate within these mortar samples, the largest samples from the surface were chosen. After being fully prepared, the final samples where no smaller than 3mm and no larger than a centimetre in diameter.

5.7 - Methods of Determining the Scale of the Systems

The most challenging, yet rewarding process of this project was quantifying the materials used in the Water Supply of Constantinople and Anastasian Wall. Due to the great geographical span and the varying forested terrain of Thrace, acquiring an accurate volumetric figure for these systems required an interdisciplinary approach to research and data collection The intricate nature of the entire water supply system's different construction phases complicated matters even further. In contrast, the structural requirements and function of the Anastasian Wall were comparatively rudimentary in nature. While the water supply has numerous bridges at no set intervals, many lines feeding in from different spring sources, and the complex use of narrow and wide channels, the Anastasian Wall follows a steady pattern of towers and gates with a relatively uniform height over its full extent (based on the consistent thickness of the wall- see Crow and Ricci, 1997: 252-253).

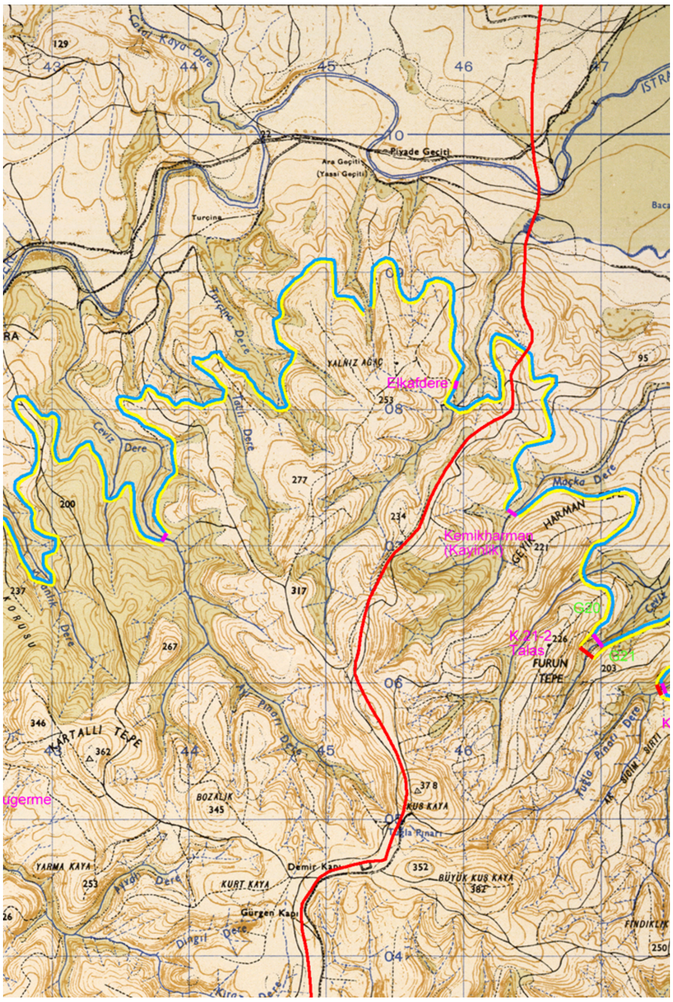
This section outlines the methods used to obtain all of the volumetric data pertaining to the construction materials of the Water Supply of Constantinople and Anastasian Wall. Including preliminary steps like data collection to the development of a range of formulas to calculate volume and surface area, this section details the process by which the quantities of construction materials were calculated. Because of their complexities, these systems were broken down into smaller components in order to calculate the overall volume of materials. These calculations are the framework on which the methods of construction material quantifications are based. While the resulting data presented in the next chapter are approximations, the methods used were designed to be as accurate as possible.

5.7.1 - Data Sources

The largest source of information on the water supply, as indicated in Chapter 2, was the book *The Water Supply of Byzantine Constantinople* by Crow, Bardill and Bayliss (2008). These works includes information gathered from years of survey work carried out under the Anastasian Wall Project and, of specific importance to this project, detailed surveys of aqueduct bridges, channels, tunnels, forts, towers, and curtain wall, as well as comprehensive discussions of building phases. Two more Anastasian Wall Project field reports](Crow, Maktav, and Turner, 2007 and Crow and Maktav, 2009) provided further information that was not to be included in the book on bridges and channels surveyed before the release of the book (Crow, Bardill, and Bayliss, 2008).

Similar data for the Anastasian Wall came from a variety of articles (Crow, 1995; Crow and Ricci, 1997; Bayliss and Crow, 2000; Crow, 2005; Crow, forthcoming) since the preeminent book (Crow et al., forthcoming) is still in preparation. These articles, coupled with unpublished survey data from the Anastasian Wall Project, yielded most of the information necessary for this project.

It was also essential to investigate resources used by the Anastasian Wall Project. Topographical maps produced by the Royal Engineers of the British Army in 1944 (Istanbul [cartographic material] : 1:25,000 Istanbul : sheet 41 / compiled and reproduced by 524 Pal. Fd. Survey Coy., R.E., Aug. 1944; hereafter referred to as 'War Office 1:25,000') were used to plan the line of the water supply and wall. These War Office 1:25,000 maps were edited by Dr. Bayliss to indicate the lines of the water supply and wall (Map 5.1), proving to be essential for estimating missing characteristics of these systems such as length, height that were unable to be surveyed. Furthermore, these maps were a crucial element for developing hypothetical construction material transport networks (see 5.10 – Man-power Estimates).



Map 5.1 – Lines of the Water Supply of Constantinople and Anastasian Wall plotted on to a War Office 1:25,000 map (produced by Richard Bayliss of the Anastasian Wall Project).

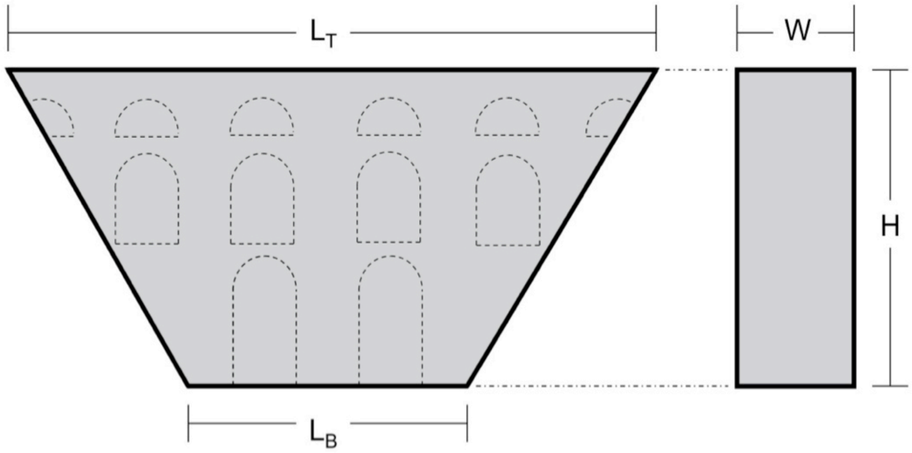
5.7.2 - Aqueduct Bridge Structural Volume and Surface Area Calculations

Even after all of necessary survey information and mapping data had been recorded, calculating the volume of the aqueduct bridges was not a simple process. Because much of the information was hypothetical based on the current state of preservation of the system and the difficulty of surveying caused by the harsh terrain of much of Thrace, it was impossible to obtain exact volumetric figures. However, the objective was to be as accurate as possible, especially since the resulting figures would be used as the foundation of the material quantification and the subsequent economic impact study of the Water Supply of Constantinople.

The first step was to create a formula that would accurately calculate the volume of each bridge based on the data fields on the spreadsheet. Throughout this project, three iterations of the formula were used for calculations. The initial formula was a very hypothetical approach to obtaining volumetric data by bypassing some fields on the spreadsheet with missing or incomplete data. This was before many of the figures, such as number and width of arches, were estimated using comparative bridge data. The purpose was to find a way of coming up with a figure that did not require any further measurements than those provided in the survey work. The formula was designed to calculate the volume of any bridge using the bridge length at the top (L_T), bridge height (H), and bridge width. However, because this was not a square structure, the calculation also required a length at the base of the bridge (L_B). The only instances where this measurement was given were in the plan drawings of five of the monumental bridges. Due to this, it was originally thought to be easier to develop a portion of the formula devoted to calculating the ratio of the number of arches at the base of the bridge (N_{AB}). This ratio was developed through the studying of typical structures at the bases of the bridges. The length of the bottom was calculated by multiplying the width of the bottom arches (W_{AB}) by the number of arches (N_{AB}) plus 1:

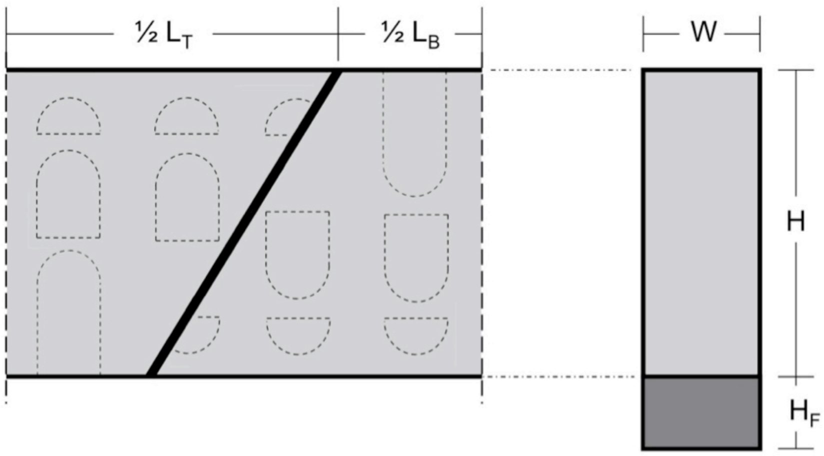
$$L_B = W_{AB} \text{ x } [2(N_{AB}) + 1)]$$

Not only was the reasoning hard to follow without an explanation, it was also clear that it was the major flaw of the volumetric formula. '2(N_{AB})' signifies the number of arches and the number of piers at the base, with +1 being the addition of the last pier at the end of the last arch. This made the assumption that the piers were all the same width as the arches and only worked for bridges that had completed data fields. If, for instance, nothing was inputted into the N_{AB} or W_{AB} fields on the spreadsheet, the resulting calculation for L_B would be zero. Similarly, this would occur when NAB was known and W_{AB} was unknown, also resulting in zero. Another major issue alluded to earlier, was that this portion of the formula assumed that all of the bridges had the same traits as many of the monumental bridges (regular intervals of piers and arches, steep slopes on both sides). Each bridge was designed differently to accommodate the terrain, making this uniformity-based formula even less accurate.



L_T	Length of bridge (top)
L_B	Length of bridge (bottom)
W	Width of bridge
H	Height of bridge

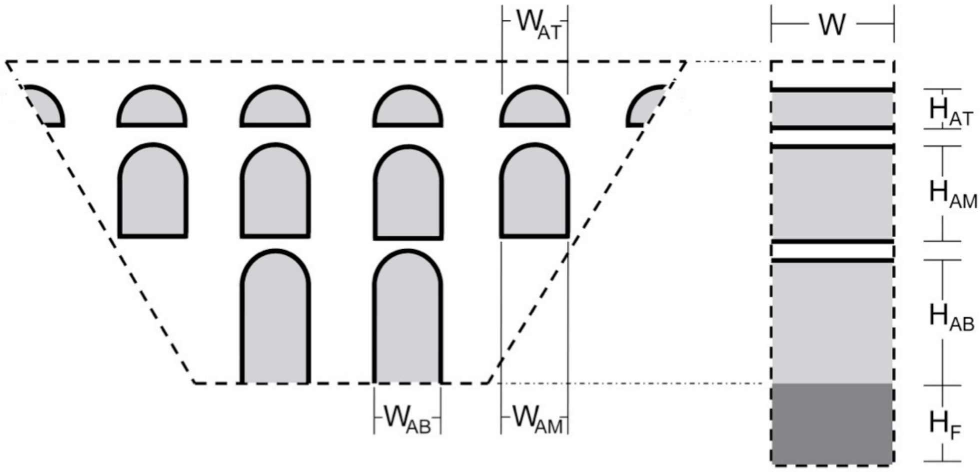
Figure 5.9 - Diagram of measurements used to calculate solid volume and surface area of an aqueduct bridge (arches calculated separately).



$$V_M = \frac{L_T + L_B}{2} \times W \times (H + H_F)$$

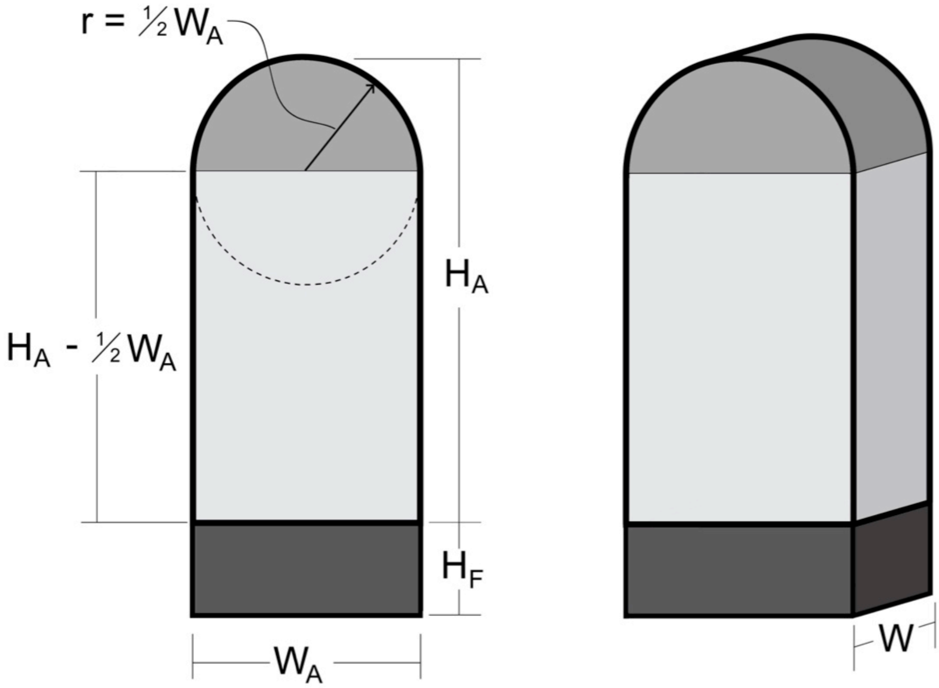
L_T	Length of bridge (top)
L_B	Length of bridge (bottom)
W	Width of bridge
H	Height of bridge
H_F	Height of foundation
V_M	Solid volume of bridge

Figure 5.10 – Formula to calculate solid volume of an aqueduct bridge (arches calculated separately).



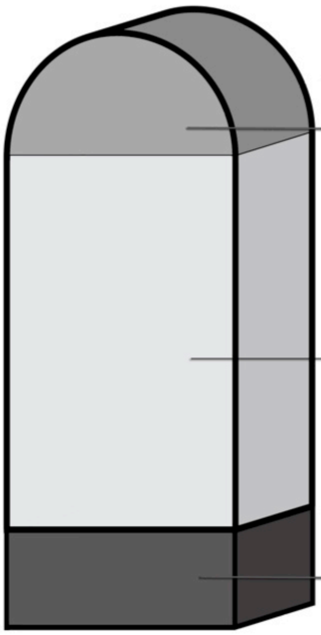
$\mathbf{W_{A(T/M/B)}}$	Width of arch (top/middle/bottom tier)
W	Width of Bridge
$\mathbf{H_{A(T/M/B)}}$	Height of arch (top/middle/bottom tier)
$\mathbf{H_F}$	Height of foundation

Figure 5.11 – General diagram of measurements used to calculate volume and surface area of arches of an aqueduct bridge.



$\mathbf{W_A}$	Width of arch
$\mathbf{H_A}$	Height of arch
$\mathbf{H_F}$	Height of foundation
r	Radius of vault
W	Width of Bridge

Figure 5.12 – Detailed diagram of measurements used to calculate volume and surface area of arches of an aqueduct bridge.



$$V_{A1} = \frac{\pi (W_A)^2}{8} \times W$$

$$V_{A2} = \left(H_A - \frac{W_A}{2}\right) \times W_A \times W$$

$$V_{ABF} = H_F \times W_A \times W$$

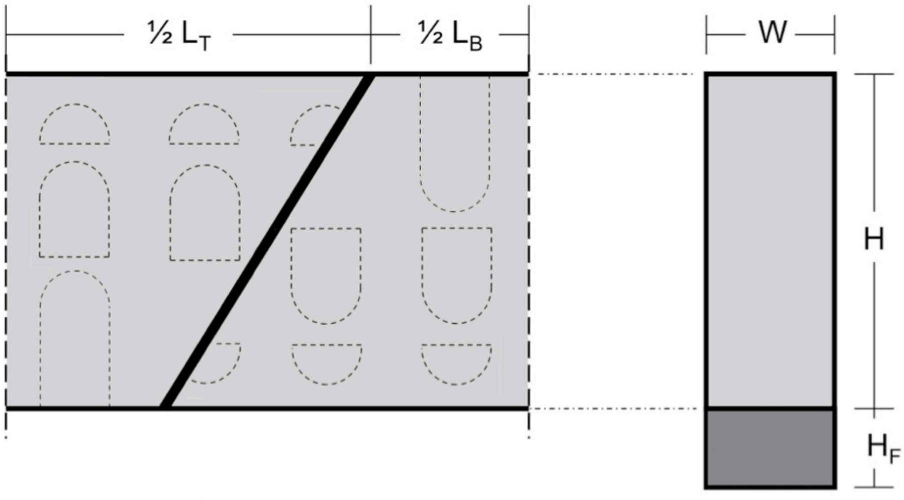
$$V_{AB\,Total} = (V_{AB1} + V_{AB2} + V_{ABF}) \times N_{AB}$$

$$V_{AM\,Total} = (V_{AM1} + V_{AM2}) \times N_{AM}$$

$$V_{AT\,Total} = (V_{AT1} + V_{AT2}) \times N_{AT}$$

$\mathbf{V_{A(B/M/T)1}}$	Volume of arch vault (bottom/middle/top tier)
$\mathbf{V_{A(B/M/T)2}}$	Volume from arch base to spring of vault (bottom/middle/top tier)
$\mathbf{V_{ABF}}$	Volume of foundation (only for the bottom tier)
$\mathbf{N_{A(B/M/T)}}$	Number of arches (bottom/middle/top tier)
$\mathbf{W_A}$	Width of arch
$\mathbf{W}$	Width of bridge
$\mathbf{H_A}$	Height of arch
$\mathbf{H_F}$	Height of foundation

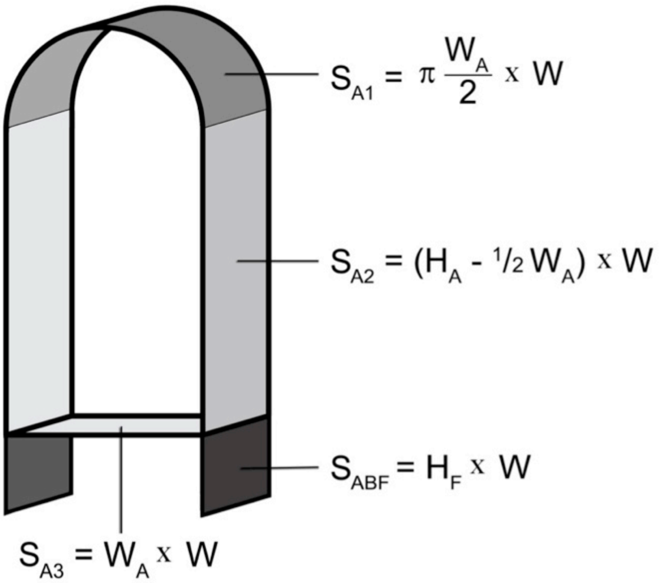
Figure 5.13 – Formulae to calculate volume of arches in an aqueduct bridge.



$$S_M = \left(2 \times \frac{L_T + L_B}{2} \times W\right) + [2 \times (H + H_F) \times W]$$

L_T	Length of bridge (top)
L_B	Length of bridge (bottom)
W	Width of bridge
H	Height of bridge
H_F	Height of foundation
S_M	Solid surface area of bridge

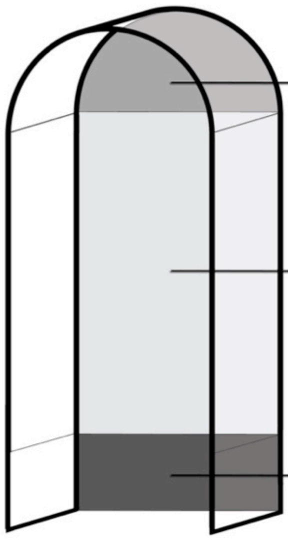
Figure 5.14 – Formula used to calculate solid surface area of an aqueduct bridge (arches calculated separately).



$$S_{AB\ Total} = [S_{AB1} + 2 \times (S_{AB2} + S_{ABF})] \times N_{AB}$$
$$S_{AM\ Total} = [S_{AM1} + (2 \times S_{AM2}) + S_{AB3}] \times N_{AM}$$
$$S_{AT\ Total} = [S_{AT1} + (2 \times S_{AT2}) + S_{AT3}] \times N_{AT}$$

$\mathbf{S_{A(B/M/T)1}}$	Surface area of arch vault (bottom/middle/top tier)
$\mathbf{S_{A(B/M/T)2}}$	Surface area from arch base to spring of vault (bottom/middle/top tier)
$\mathbf{S_{A(B/M)3}}$	Surface area of base of arch (bottom/middle tier)
$\mathbf{S_{ABF}}$	Surface area of foundation (only for the bottom tier)
$\mathbf{N_{A(B/M/T)}}$	Number of arches (bottom/middle/top tier)
$\mathbf{W_A}$	Width of arch
W	Width of bridge
$\mathbf{H_A}$	Height of arch
$\mathbf{H_F}$	Height of foundation

Figure 5.15 – Formulae to calculate internal surface area of arches of an aqueduct bridge.



$$S_{OA1} = \frac{\pi (W_A)^2}{8}$$

$$S_{OA2} = \left(H_A - \frac{W_A}{2}\right) x\ W_A$$

$$S_{OABF} = H_F\ x\ W_A$$

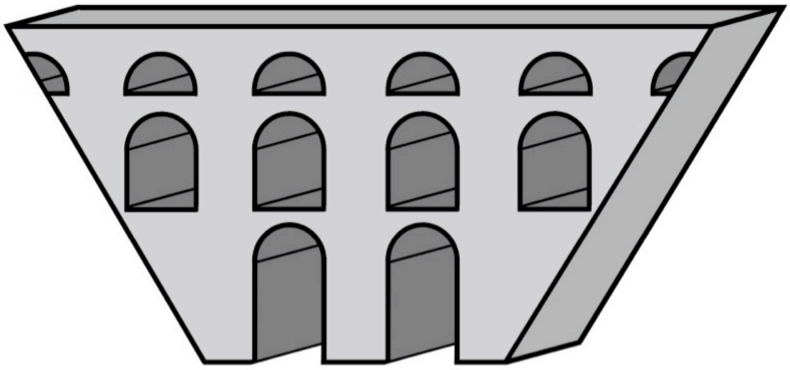
$$S_{OAB\ Total} = 2\ x\ (S_{OAB1} + S_{OAB1} + S_{OABF})\ x\ N_{AB}$$

$$S_{OAM\ Total} = 2\ x\ (S_{OAM1} + S_{OAM2})\ x\ N_{AM}$$

$$S_{OAT\ Total} = 2\ x\ (S_{OAT1} + S_{OAT2})\ x\ N_{AT}$$

$S_{OA(B/M/T)1}$	Outer surface area of arch vault (bottom/middle/top tier)
$S_{OA(B/M/T)2}$	Outer surface area from arch base to spring of vault (bottom/middle/top tier)
S_{OABF}	Outer Surface area of base of arch (bottom/middle tier)
$N_{A(B/M/T)}$	Surface area of foundation (only for the bottom tier)
W_A	Width of arch
W	Width of bridge
H_A	Height of arch
H_F	Height of foundation

Figure 5.16 – Formulae used to calculate outer surface area of arches of an aqueduct bridge.

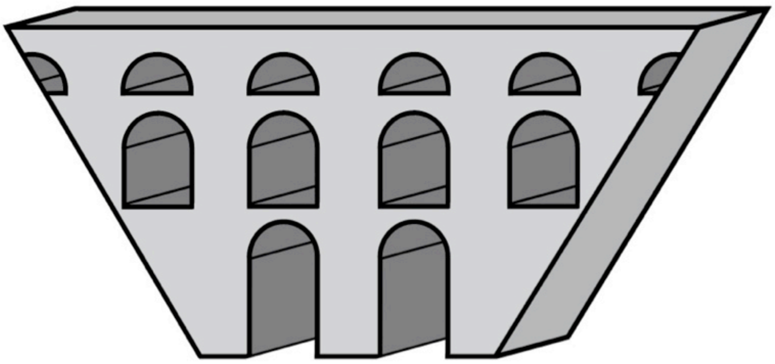


$$V_{\text{Arch } \mathit{Total}} = V_{\text{AB } \mathit{Total}} + V_{\text{AM } \mathit{Total}} + V_{\text{AT } \mathit{Total}}$$

$$\mathbf{V_{Bridge}} = V_M - V_{\text{Arch } \mathit{Total}}$$

$V_{\text{Arch Total}}$	Total volume of bridge arches
$V_{\text{A(B/M/T) Total}}$	Total volume of arch (bottom/middle/top tier)
V_M	Solid volume of bridge (no arches)
V_{Bridge}	Final volume of bridge

Figure 5.17 – Formulae to calculate the total structural volume of an aqueduct bridge.



$$S_{\text{Arch } \mathit{Total}} = S_{\text{AB } \mathit{Total}} + S_{\text{AM } \mathit{Total}} + S_{\text{AT } \mathit{Total}} - S_{\text{OAB } \mathit{Total}} - S_{\text{OAM } \mathit{Total}} - S_{\text{OAT } \mathit{Total}}$$

$$S_{\text{Bridge}} = S_M + S_{\text{Arch } \mathit{Total}}$$

$S_{\text{Arch Total}}$	Total surface area of bridge arches
$S_{\text{A(B/M/T) Total}}$	Total surface area of inner surface of arch (bottom/middle/top tier)
$S_{\text{OA(B/M/T) Total}}$	Total surface area of outer surface of arch (bottom/middle/top tiers)
S_M	Solid surface area of bridge (no arches)
S_{Bridge}	Final surface area of bridge

Figure 5.18 – Formulae to calculate the total surface area of an aqueduct bridge.

However, the final formulae used to calculate the volume of the aqueduct bridges proved to be more satisfactory (Figure 5.9-Figure 5.18). This was due in part to the collection of new measurements for L_B based on comparisons to similar bridges of known values and more importantly, the introduction of new data into the spreadsheets (see A2.1.1 in Appendix 2). In the previous two iterations of the formula, L_B was based on the ratio of pier width and number of arches. Instead of relying on this flawed ratio for such a significant figure, the length of the base was estimated for each bridge by measuring the width of the bottom of each valley using topographical maps (see section 5.7.1, page 109).

It is understood that this is not an exact figure but it takes into consideration factors that the previous formulas do not like long stretches of shallow bridges with few to no arches. The resulting changes caused by this formula had varying affects on volume calculation for each bridge but this was no surprise. Unlike changes that occurred from the second to the third formula, some bridge volumes barely changed while others increased significantly.

5.7.3 – Structural Volume of Water Supply Channel and Tunnel Structures

Easily the most complex aspects of the Water Supply of Constantinople are its numerous phases of extension, modification, and repair. GIS data collected from years of survey work and subsequent colour-coded maps outlining the channels were available for use in this endeavour. Because of the system's complexity in terms of narrow and wide channels, each significant variation had to be recorded separately in order to calculate an accurate volume. By breaking it down even further by construction phase, a more specific discussion could be made on the economic impact corresponding to time period. This was also important for a comparative discussion between the water supply and Anastasian Wall.
The interest of this part of the project was to quantify the building materials of the earlier phases, particularly from the long 5th century phase that extends as far west as Vize, thus to acquire volumetric information, it was necessary to obtain the lengths and cross-sectional areas of these different segments.

The process of figuring the length of individual channels from different building phases was relatively easy. Using computer programmes such as ArcGIS and AutoCAD, lengths could be identified over user-defined increments along the pre-existing paths drawn on the map. Instead of being able to measure the entire length of aqueduct line from Constantinople to its furthest western extent, these user-defined increments were used to obtain and separate length data by phase and channel size. However, this data did not result in the final lengths of the channels since the distance also included the bridges. Even though the length of the bridges along each section of the system only made up a small fraction of the total length, it was included in the calculation of bridge volumes as previously outlined. This meant that the length of each bridge would have to be deducted from the corresponding channel section's total length.

The next step involved in attaining an accurate figure for the total structural volume of channels was to calculating the cross-sectional area of both the narrow and wide channels. Using survey data and maps, it was evident that both the narrow and wide channels varied in size between survey sites. It was impossible to measure these small fluctuations in size over their entire length so an average area was calculated for the narrow and wide channels using all of the measurements taken at location where the channels were exposed.

Finally, once the average cross-sectional areas and lengths of each channel section had been collected, the total volume of material for each section of the system could be simply calculated.

5.7.4 – Structural Volume of Channel Lining Mortar

The channel lining mortar is one of the few constants running along the entire distance of the water supply. This thin layer of mortar, providing a watertight seal between structural elements and flowing water, would have been used to coat the entire system including aqueduct bridges, channels, tunnels. This was calculated separately because of the probable material differences between the structure mortar of the channels and aqueduct bridges. Unlike structural mortars that would require high tensile strength, channel lining mortar relied almost entirely on its water-resistant nature.

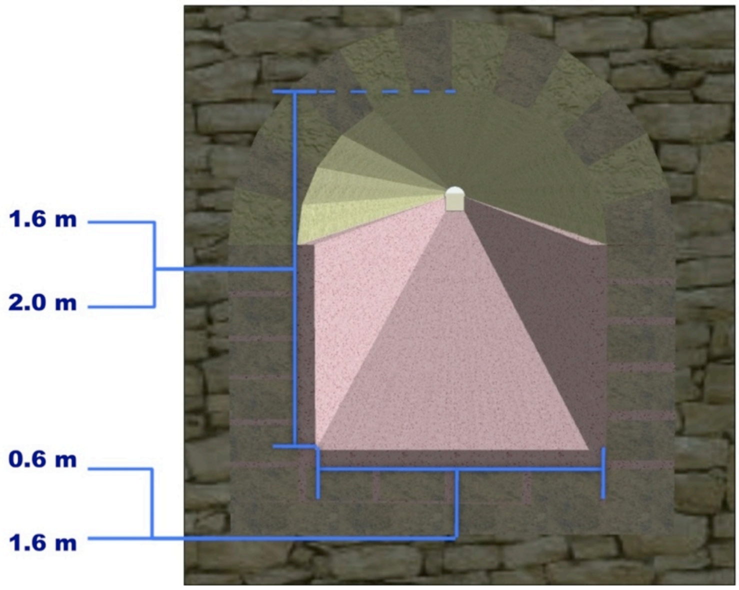


Figure 5.19 - Wide and narrow channel dimensions.

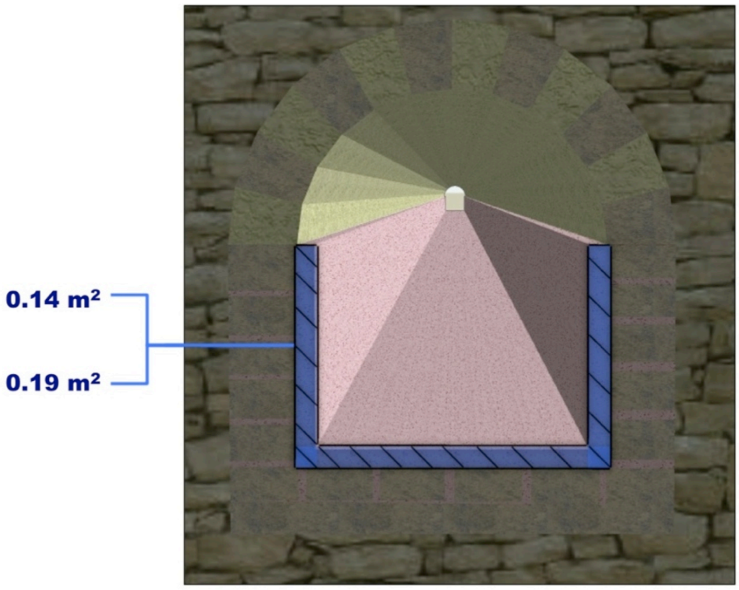


Figure 5.20 - Cross-sectional area of mortar lining in wide and narrow channels.

The length of each section had already been calculated when determining the structural volume of the channels. Instead of removing the total length of aqueduct bridges from these values, they were included due to the presence of channel lining mortar running across them. Since one of the crucial elements of engineering a hydrological system is to maintain a smooth surface over a long distance to cut down on water turbulence (Hodge, 1992: 98), channel lining mortar was the perfect material to link both channel and bridge across great distances.

Similar again to the previous method of calculating volume was gathering measurements from field surveys for cross-sectional area. By taking the average of the thickness recorded from field surveys of the mortar layer, height along the channel walls, and length along the bed of the channel, a cross-sectional area was assessed. This was another instance in which the narrow and wide channels had to be calculated separately due to variance in cross sectional area. By multiplying the cross-sectional area by the length of each section of channel, the total volume of channel mortar across a section could be determined.

5.7.5 - Anastasian Wall Structural Volume and Surface Area Calculations

Identifying the total structural volume of the Anastasian Wall was a much simpler task in comparison to any of the methods required for the water supply. In part, this was due to the simple and consistent nature of the design. Since the construction of the wall had a set height and width, with the exception of forts and towers, the length was the only factor that needed to be determined. This was done in a similar manner to the channel sections of the water supply, using maps and GIS.

Again, resulting from years of field surveys carried out by the Anastasian Wall Project team (Crow and Ricci, 1997; Bayliss and Crow, 2000; Crow, 2005; Crow, 2007; Maktav et al., 2009; Crow, forthcoming; Crow et al., forthcoming), a wealth of information was available to aid in this calculation. The wall was separated into two structural elements, similar to the method used to quantify the volume of the water supply. First was the wall itself, which stretched from the Sea of Marmara in the south to the Black Sea in the north. While there is no remaining evidence for the wall in certain sections in the south, it is assumed for these purposes that the height and width remain constant. The length of the total wall structure was measured using ArcGIS and then multiplied by the height and width.

The second structural element was defensive fortifications including towers and forts. Survey work on these structures, conducted by the Anastasian Wall Project team, provided much of the data necessary to calculate the volume of these elements. The set spacing of towers and forts, a feature of other long walls (see Chapter 2), allowed for an easily obtainable figure for their quantity along the line of the wall. In addition, a detailed survey including geophysical analysis of Büyük Bedesten presented much of the necessary data for forts.

5.8 - Methods of Quantifying Building Material

Once the total volumes had been calculated for the structures of the water supply and wall, quantities of individual construction materials could be broken down. Like so much of the work preceding this, much of the information used for this method of quantification came from the field survey data included in the 2008 study by Crow, Bardill, and Bayliss. The use of photographic evidence and image analysis was also a massive aid in estimating volumes of the core of the structures. After the initial phase of volume calculation was done for each of the construction materials, the second phase was implemented to break down composite materials into their individual components. Doing this brought together much of the work that had been done through petrographic analysis. The third and final phase of this deconstruction was to investigate the quantity of fuel required to fire the quantity of bricks and limestone used in these systems. This section will discuss in detail each phase of this methodology and the predicted implications of this endeavour.

5.8.1 - Quantifying the Materials used in Aqueduct Bridges

Estimating the amounts of individual construction materials for the aqueduct bridges of the water supply first required an understanding of their type and application within the structures. The monumental fifth-century aqueduct bridges were faced with metamorphosed limestone blocks held together with iron clamps set it lead (Crow, Bardill and Bayliss, 2008: 90, 94, 97). Bridges of the fourth century and smaller bridges of the fifth century used softer, non-crystalline limestone as facing stones. Materials used in the process of later repairs and rebuilding of bridges are not taken into consideration for this project. This is important to keep in mind for bridges like Talas that are completely rebuilt in the sixth century. Here, the evidence for the preceding fifth-century bridge, thought to have been constructed in a similar manner to the other monumental bridges of this phase, is encased by new construction (Crow, Bardill and Bayliss, 2008: 104).

To calculate the volume of facing stones for each bridge, a surface area calculation was needed. By multiplying the average depth of the facing stones by the surface area, this could calculate the amount of stone material and subsequently, by subtracting this figure by the total volume of the bridge, would provide the volume of the core. The formula used to calculate the surface area was very similar to the final ‘total volume’ formula of the bridge.

Methods used to calculate the materials used in the core structure of the aqueduct bridges were also used for the channels and the structures making up the Anastasian wall. Digital photographs of exposed sections of these features were cropped using Adobe Photoshop to isolate areas of interest. These areas were then broken down into their main material components by colouring the stone material black and the mortar white. Percentages were taken based on the amount of pixels of each colour. By applying these percentages to the total volume of the core material, a final value of the amount of mortar and large stone aggregate was determined.

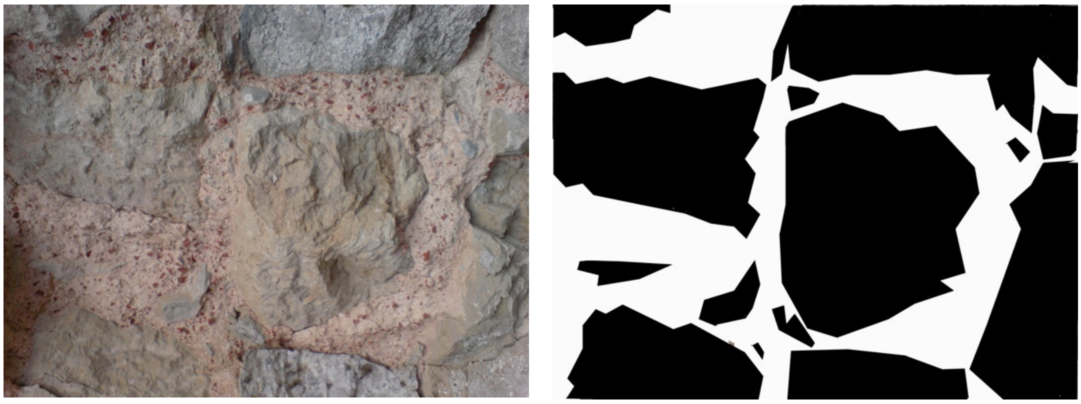


Figure 5.21 - Visual analysis of rubble stone and mortar core from Kurşunlugerme.

The last step was to obtain the total amount of each material used to make up the mortar by applying the volume of mortar for each structural feature to the corresponding percentage data gathered by petrographic image analysis. This included the amount of crushed brick, quicklime, sand and other aggregates making up this extremely important composite material. Breaking this down even further, by applying brick and lime production techniques (see Chapter 3), the total quantity of fuel would be calculated.

5.8.2 - Material Quantities of the Narrow and Wide Channels

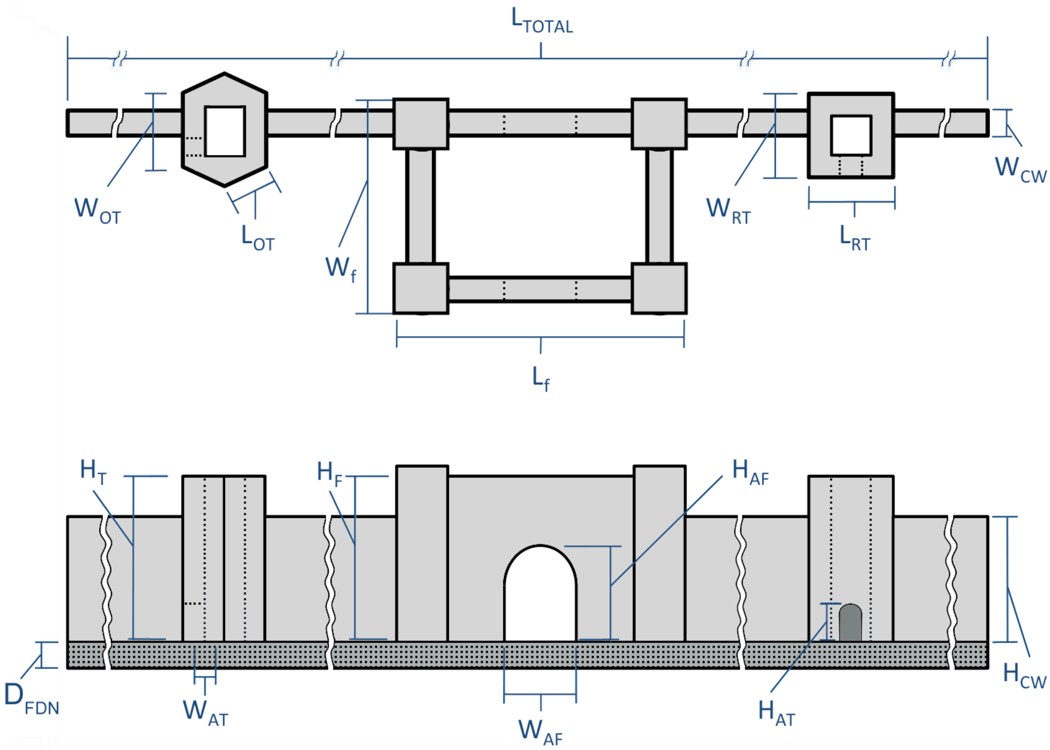
The structure of the channels was considerably simpler for calculating volume of individual materials. In the previous step of calculating the total volume of these channels, the cross-sectional area was calculated. By using photographic evidence and image analysis software, a percentage could be figured for the ratio construction materials making up sections of channels.

It was important to keep in mind that structural stone used in the channels was not uniform over the full length of the system. Channel walls and vaults were made from either slate, squared blocks, or rubble pieces of stones such as limestone, metamorphosed limestone, and schist (Crow, Bardill and Bayliss, 2008: 27, 51). This variation in stone type and shape was only observed in well-preserved sections of the channel that were exposed. All of the channels were constructed using the typical ‘cut and cover’ construction method (Crow, Bardill and Bayliss, 2008: 107), which meant that the channels were constructed in a trench cut in the earth and buried upon completion (Hodge, 1992: 93-94). This made it impossible to trace the construction methods and materials used over each section’s entire distance. This meant, like the methods used by the Anastasian Wall Project team to trace the channels’ paths, much of the calculations of volume for individual stone type could only be based on the recorded exposed examples from various points along the water supply.

5.8.3 - Calculating Material Quantities of the Anastasian Wall

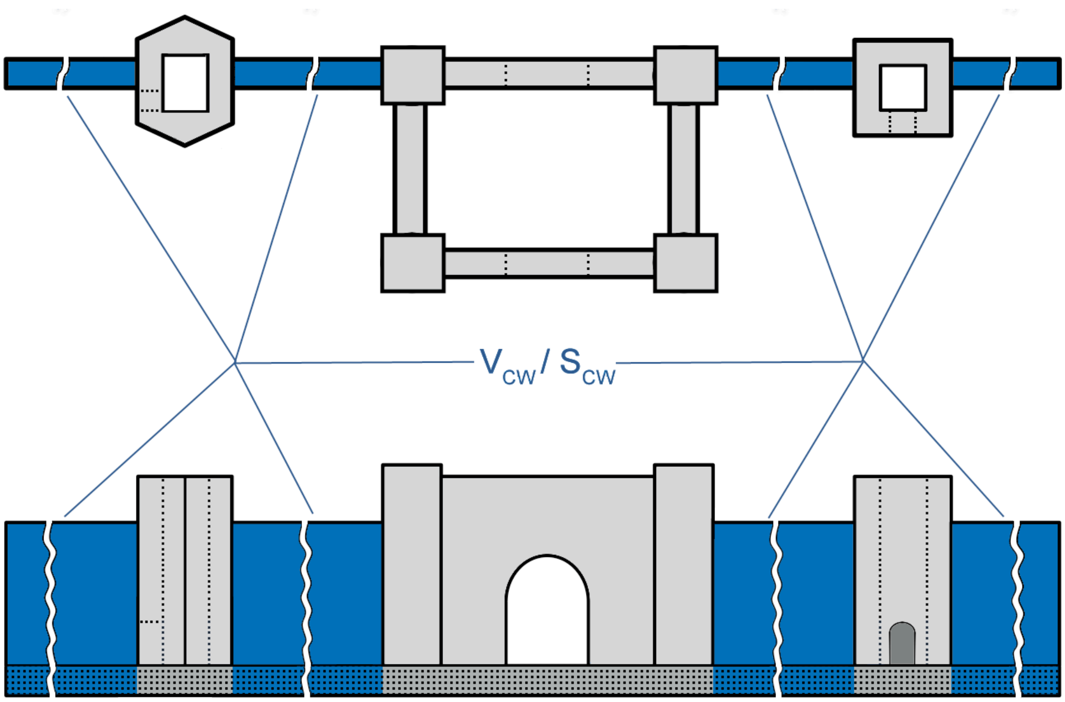
Despite the relative ease of calculating the total volume of the structures making up the Anastasian Wall, determining the amount of individual materials was significantly more difficult. Unlike the monumental bridges of the water supply, nothing of the wall complex survives with exceptional preservation except for a small stretch in the north near Evcik at Hisar Tepe (Crow and Ricci, 1997). Complicating things even more, construction methods and materials varied considerably between sections of the wall. For instance, sections of the wall to the south and evidence from towers and forts indicate that bricks were used structurally, while areas to the north show little or no of structural brick (Crow, forthcoming).

These changes in construction techniques and materials had to be incorporated into the volume calculations to ensure an accurate basis for determining the economic implications of such a monumental project. This was done by similar means used to calculate the varying types of stone used to form the narrow and wide channels of the aqueduct. Similar formulas to those used for aqueduct bridges were used to calculate the volume of facing and core materials, as well as the materials making up the mortars of the Anastasian Wall.



L_{TOTAL}	Total length of wall		H_T	Height of tower
W_{OT}	Width		H_F	Height of fort
W_{RT}	Width of rectangular tower		H_{AF}	Height of fort arch
W_{CW}	Width of curtain wall		H_{AT}	Height of tower arch
W_f	Width of fort		H_{CW}	Height of curtain wall
L_{OF}	Length		D_{FDN}	Depth of foundation

Figure 5.22 - Diagram of measurements used to calculate structural volume and surface area of the Anastasian Wall.



$$V_{CW} = L_{CW^*} \times W_{CW} \times (H_{CW} + D_{FDN})$$

$$S_{CW} = 2[L_{CW^*} \times (H_{CW} + D_{FDN})] + 2[L_{CW^*} \times W_{CW}] + 2[W_{CW} \times (H_{CW} + D_{FDN})]$$

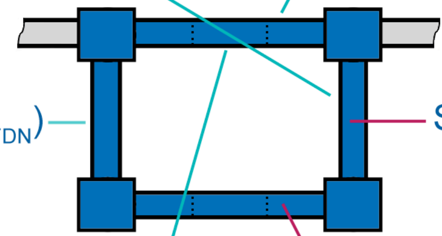
* $L_{CW} = L_{TOTAL} - (L_T \times N_T) - (L_F \times N_F)$

V_{CW}	Volume of curtain wall		L_{TOTAL}	Total length of wall
S_{CW}	Surface are of curtain wall		L_T	Length of tower
L_{CW}	Length of curtain wall		N_T	Number of towers
W_{CW}	Width of curtain wall		L_F	Length of fort
H_{CW}	Height of curtain wall		N_F	Number of forts
D_{FDN}	Depth of foundation			

Figure 5.23 – Formulae to calculate structural volume and surface area of the curtain wall.

$$S_{FWa\ in} = (W_F - 2W_{CW}) \times (H_F + D_{FDN})$$

$$S_{FWb\ out} = [L_F \times (H_F + D_{FDN})] - A_{AF*}$$

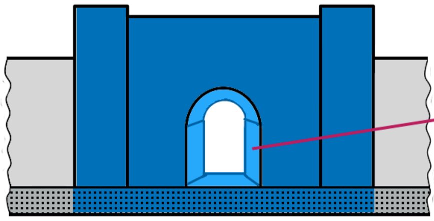


$$S_{FWa\ out} = W_F \times (H_F + D_{FDN})$$

$$S_{FTa} = W_F \times W_{CW}$$

$$S_{FWb\ in} = [(L_F - 2W_{CW}) \times (H_F + D_{FDN})] - A_{AF*}$$

$$S_{FTb} = (L_F - 2W_{CW}) \times W_{CW}$$



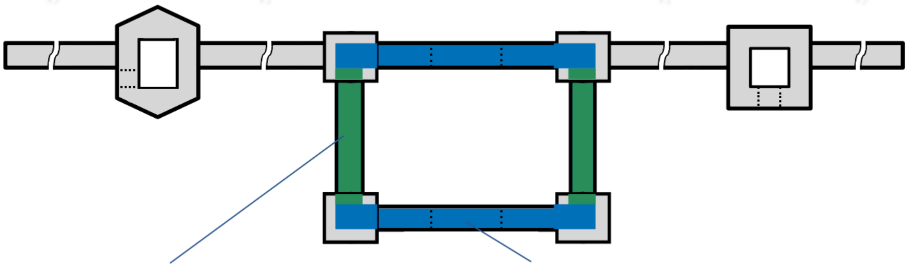
$$S_{AF} = \left(\pi \frac{W_{AF}}{2}\right) \times W_{CW} + 2(H_{AF} + D_{FDN} - W_{AF})$$

$$S_F = 2S_{FWa\ out} + 2S_{FWa\ in} + 2S_{FWb\ out} + 2S_{FWb\ in} + 2S_{FTa} + 2S_{FTb} + 2S_{AF}$$

$$*A_{AF} = \left(\frac{\pi W_{AF}^2}{8}\right) + \left[H_{AF} - D_{FDN} - \left(\frac{W_{AF}}{2}\right)\right] \times W_{AF}$$

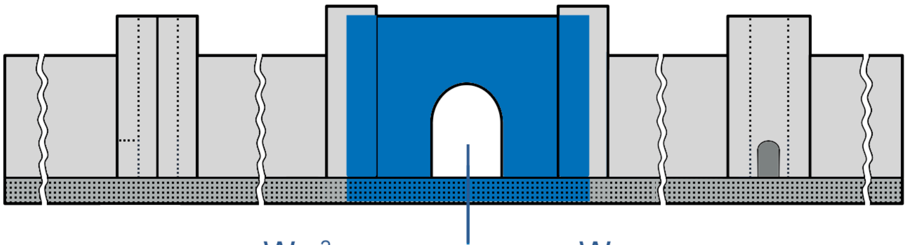
$S_{FWa\ in}$	Surface area of fort inner projecting wall
$S_{FWa\ out}$	Surface area of fort outer projecting wall
$S_{FWb\ in}$	Surface area of fort inner parallel wall
$S_{FWb\ out}$	Surface area of fort outer parallel wall
S_{FTa}	Surface area of top/bottom of projecting wall
S_{FTb}	Surface area of top/bottom of parallel wall
S_F	Total surface area of fort
W_F	Width of fort
W_{CW}	Width of curtain wall
L_F	Length of fort
A_{AF}	Area of fort arch
W_{AF}	Width of fort arch
H_{AF}	Height of fort arch
H_F	Height of fort
D_{FDN}	Depth of foundation

Figure 5.24 – Formulae to calculate surface area of the Anastasian Wall's forts.



$$V_{FWa} = (W_F - 2W_{CW}) \times W_{CW} \times (H_F + D_{FDN})$$

$$V_{FWb} = L_F \times W_{CW} \times (H_F + D_{FDN}) - 2V_{AF}$$

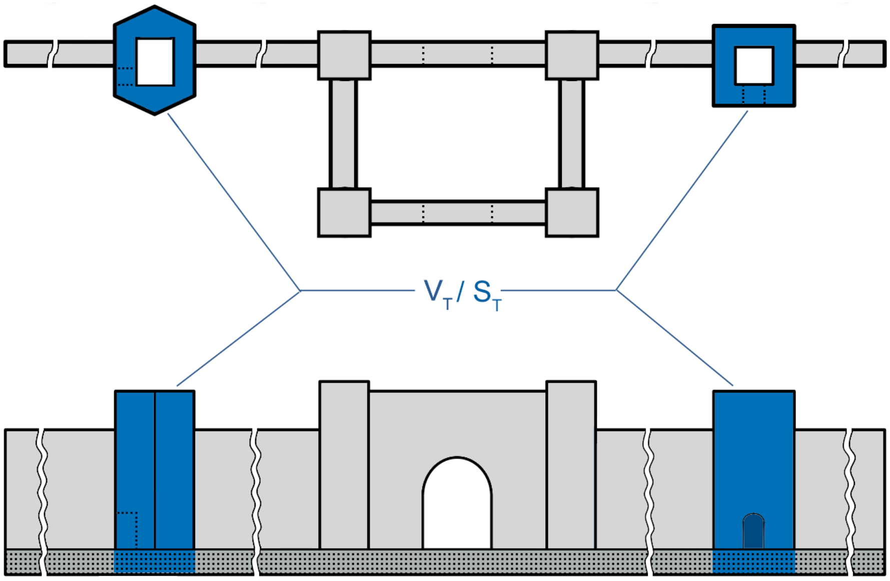


$$V_{AF} = \left(\frac{\pi W_{AF}^2}{8} \times W_{CW}\right) + \left(H_{AF} - \frac{W_{AF}}{2}\right) \times W_{AF} \times W_{CW}$$

$$V_{F\ Total} = 2V_{FWa} + 2V_{FWb} - 2V_{AF}$$

V_{FWa}	Volume of fort projecting wall
V_{FWb}	Volume of fort parallel wall
V_{AF}	Volume of fort arch
$V_{F\ Total}$	Total volume of fort
W_F	Width of fort
W_{CW}	Width of curtain wall
H_F	Height of fort
D_{FDN}	Depth of foundation
L_F	Length of fort
W_{AF}	Width of fort arch

Figure 5.25 - Formulae to calculate structural volume of the Anastasian Wall's forts.

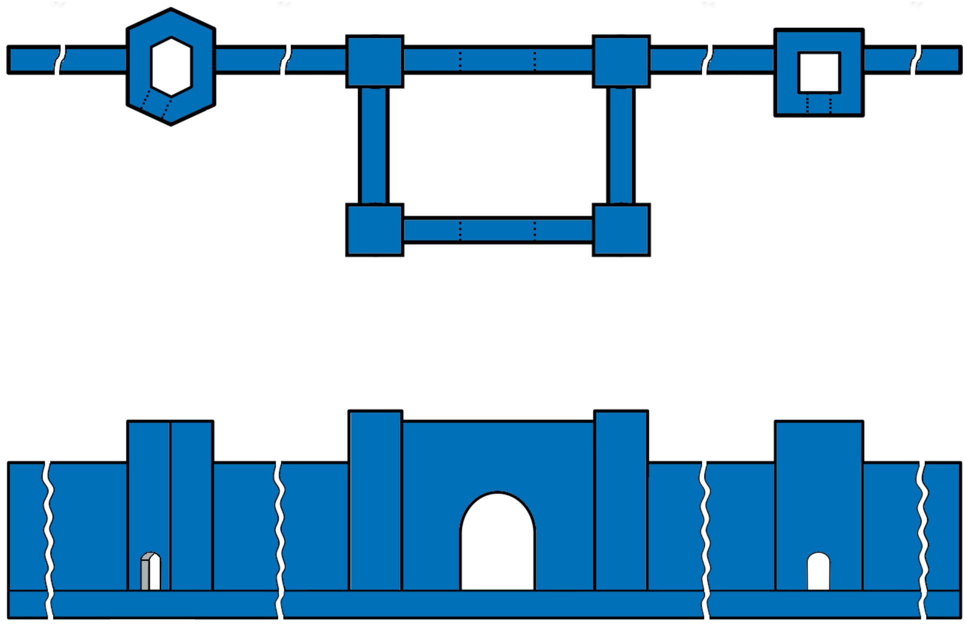


$$V_T = 2V_{TWa} + 2V_{TWb} - V_{AT}$$

$$S_T = 2S_{TWa\ out} + 2S_{TWa\ in} + 2S_{TWb\ out} + 2S_{TWb\ in} + 2S_{TTa} + 2S_{TTb} + S_{AT}$$

V_T	Total volume of a tower
S_T	Total surface area of a tower
V_{TWa}	Volume of tower projecting wall
V_{TWb}	Volume of tower parallel wall
V_{AT}	Volume of tower arch
$S_{TWa\ out}$	Surface area of tower outer projecting wall
$S_{TWa\ in}$	Surface area of tower inner projecting wall
$S_{TWb\ out}$	Surface area of tower outer parallel wall
$S_{TWb\ in}$	Surface area of tower inner parallel wall
S_{TTa}	Surface area of top/bottom of tower projecting wall
S_{TTb}	Surface area of top/bottom of tower parallel wall
S_{AT}	Surface area of tower arch

Figure 5.26 -- Formulae to calculate structural volume and surface area of the Anastasian Wall's towers. Formulae used to calculate $V_{TWa/b}$, V_{AT}, $S_{TWa/b\ out}$, $S_{TWa/b\ in}$, $S_{TTa/b}$, and S_{AT} are the same as those used for forts (See Figure 5.25).



$$V_{TOTAL} = V_{CW} + (V_F \times N_F) + (V_T \times N_T)$$

V_{TOTAL}	Total structural volume of wall
V_{CW}	Total volume of curtain wall
V_F	Volume of a fort
N_F	Number of forts
V_T	Volume of a tower
N_T	Number of towers

Figure 5.27 - Formula to calculate the total structural volume of the Anastasian Wall. The formula for surface area would be the same structure with 'V' replaced with 'S'.

5.8.4 - Foundations of the Water Supply and Long Wall

The volumes of foundations of the Water Supply of Constantinople and Anastasian Wall have been taken into consideration in each structure's overall calculation. These dimensions are described as 'H_F' in the case of the water supply and 'D_F' for the long wall (see Figure 5.9 through Figure 5.27). While these figures would naturally change throughout the distance of these structures, an average constant has been used based on the width of the surviving superstructures. In the case of the water supply, the foundation is only considered for aqueduct bridges as the foundation figure is combined with the thickness at the base of the channels.

In the case of the Anastasian wall, the foundation in considered for the curtain walls, towers, and forts over the entire distance. Because the heights of the structures are all roughly similar (within one or two meters) the foundation depth remains constant for all three types of structures.

For both systems, the volume of foundation is also used for another purpose. For the bridges of the water supply as well as all of the structures of the Anastasian Wall, digging the foundation (material excavated) would have to be taken into consideration. In addition, the ‘cut and cover’ construction method used for the majority of channels of the water supply would require the same excavation of materials. While this is not a material requirement for the structures, it is an essential aspect of the construction process (see pages 246-254). While the formulas of forts, vaults, and towers of the long wall are simple L x H x W (where ‘h’ is the depth of the foundation, or ‘D_F’), the formulas for the water supply are as follows:

Aqueduct Bridges $$\mathbf{V_{FE} = H_F \text{ x } W \text{ x } L_T - V_{ABF} \text{ x } N_{AB}}$$

V_{FE}	Volume of excavated earth for foundation
H_F	Height of foundation
W	Width of bridge
L_T	Length of bridge at the top
V_{ABF}	Volume of arch (below ground)
N_{AB}	Number of arches on bottom tier

Aqueduct Channels $$\mathbf{V_{CE} = (H_C + T_V + T_{CB}) \text{ x } W_C \text{ x } L_C}$$

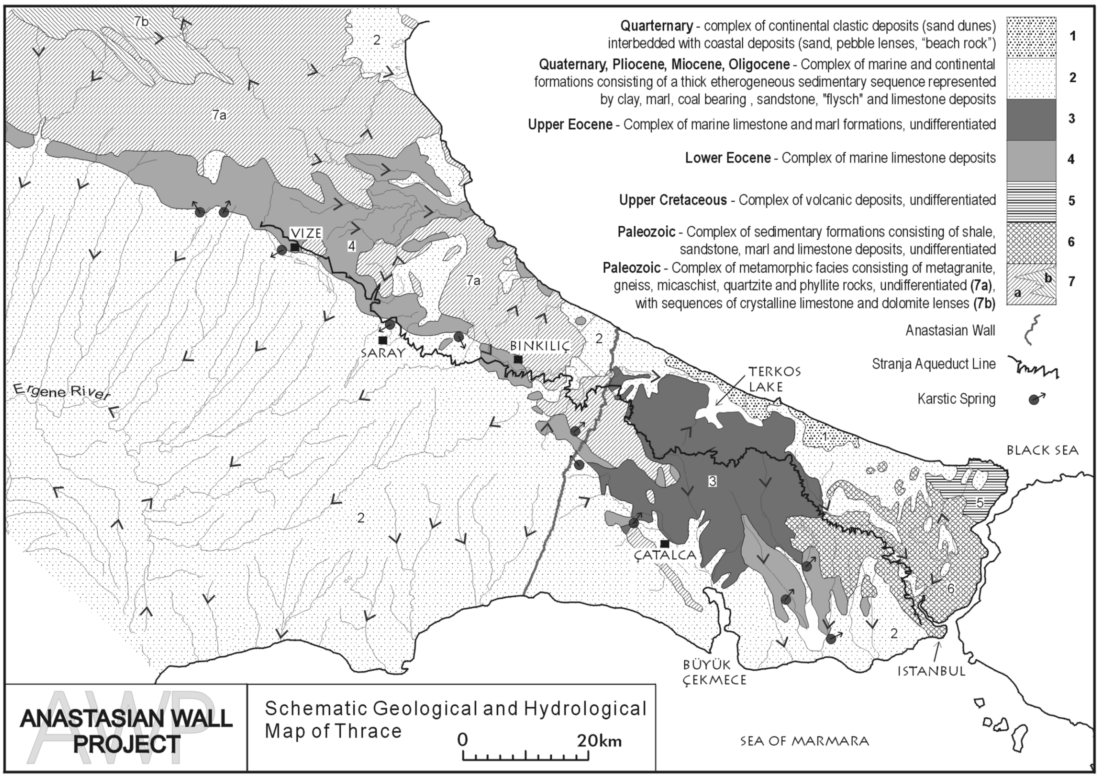
V_{CE}	Volume excavated earth for aqueduct channel
H_C	Height of channel
T_V	Thickness of channel vaulting
T_{CB}	Thickness of channel base
W_C	Width of channel
L_C	Length of channel section

5.9 - Comparative Methods

One of the characteristics of doing mortar analysis from two sites within a similar time period and geographical area was the prospect of identifying any differences between mortar recipe and application. Before collecting the samples, it was unclear what type of information could be gathered on these aspects. A general macroscopic observation of these structures indicates obvious similarities and differences in construction methods and material usage but is not sufficient for definitively answering any questions about mortar recipe or quality control during mortar manufacture.

5.9.1 – Geological Data and Distribution Maps

One of the interesting features of the mortars from both the Anastasian Wall and the Water Supply of Constantinople is the appearance of olive crystals that were most likely introduced with the addition quartz sand aggregate. By using current geological maps of Turkish Thrace (Türkecan and Yurtsever, 2002; also see Map 5.2), I will compare the occurrence of these crystals to the geological bedrock of the sites from which they were found. This will be done in hopes of finding any correlation between the geology of the area and the collection of local sand sources. Similarly, by comparing the size and crystalline structure, measured by petrographic analysis, of quartz sand additives in these mortars to geographical distribution maps, it is hoped that information can be gathered relating to the type of sand being utilised. The objective is to determine whether sand was specially selected from quarries, rivers or sea deposits.



Map 5.2 - Schematic Geological and Hydrological Map of Thrace (after Bono, Crow, and Bayliss, 2001: 1326)

Another comparison is to determine the type of brick aggregate being used in the mortars and how that may relate to geographical location. By applying the data from XRD analysis of brick samples from the water supply and wall to the their spatial relationship, the aim is to identify different sourcing of raw clay.

5.9.2 - Identification of Recipe Variations

Upon completing the image analysis of all of the thin sections of mortar samples from the Water Supply of Constantinople and the Anastasian Wall, percentages of their material makeup will be available for comparative investigation. The first goal will be to ascertain any demonstrable difference in proportions of sand, brick and lime between samples from the same site as well as distinctions in aggregate size and distribution.

The final intention is to compare these recipes to other documented historic mortars. As discussed in Chapters 3 and 4 of this thesis, many mortar recipes were studied from around the Roman and Late Antique world. By comparing samples from the water supply and wall in the hinterland of Constantinople with other historic mortars containing ceramic pozzolanic aggregate, a wider context of construction in late antiquity can be achieved through a discussion of material technology.

5.10 – Man-power Estimates

The vast majority of the labour estimations are heavily reliant on Janet DeLaine's 1997 book, "The Baths of Caracalla". Without such well-documented research, which is used as the bedrock of this project's man-power analyses, it would not have been possible to confidently and reliably estimate such an essential part of this body of work.

Based on the estimates of individual construction materials, the labour requirements of sourcing and producing materials will be calculated. While DeLaine (1997) occasionally used larger volumes, such as kiln loads of brick and lime, with the exception of facing stones, all man-power estimates used in this study will be converted to man-days per cubic meter. Due to the quarrying process and the impact of surface on the total time necessary to extract a single block, the man-power estimates for facing stones are based on the average volume of a single block from the water supply and long wall.

The labour required to transport construction materials to the building sites will be, by far, the most complicated. Having little evidence for the sources of raw materials is the first issue. Making things even more difficult is having no evidence for the route of transportation. This is a major issue for the discussion of late antique construction in Constantinople that DeLaine's (1997) study did not encounter because of the centuries of research carried out for classical Rome. The lacking evidence for material production sites and transportation networks of Constantinople would only be attainable through highly expensive remote sensing methods or years of further research. However, since this is a vital aspect of the construction process, it could not be ignored.

Steps were taken to provide a general basis for discussion to compensate for these shortcomings. Two hypothetical material transportation scenarios based on many comparative assumptions (see section 7.3.2 – Production Sites and Material Transport) will be introduced to calculate the associated man-power requirements. The first was the least difficult option for transportation and the second was the most demanding. These two scenarios were averaged in the hopes of obtaining a general idea of the transportation requirements, easily the most demanding aspects of the construction project.

Finally, the man-power estimates of building site preparation and construction are to be calculated. One of the aspects that will not be possible to address in this project was the labour requirement associated with surveying the lines the water supply and long wall. It can be stated, however, that this would have been a difficult and time-consuming process, especially in the case of the water supply. Keeping the line of the system running at a constant gradient over the inhospitable terrain would have been a formidable task and is of interest for future study.

Table 5.2 - 'Table of labour constants' (DeLaine, 1997: 268).

Action	*Unskilled*	*Skilled*	*Supervision*
Digging in clay and throwing behind	0.15 d per m^3		0.1 x unskilled
Digging foundations and throwing out, ≤ 1.6 m deep	0.14 d per m^3		0.1 x unskilled
Digging foundations, > 1.6 m deep	0.15 d per m^3		0.1 x unskilled
Shoring foundations	as skilled	0.015d per m^3	0.1 x skilled
Slaking lime, per volume of quicklime	1.2 d per m^3		0.1 x unskilled
Lay foundations, were d = depth of foundation	0.35 + 0.01(d-1) d per m^3		0.1 x unskilled
Mixing mortar, foundation	0.55 d per m^3		0.1 x unskilled
Lay brick and core for walls, h = height of wall	0.5 x skilled	4.18 + 0.13(h-1) d per m^3	0.1 x skilled
Mixing mortar, walls	0.7 d per m^3		0.1 x unskilled
Scaffolding, erect	2 x skilled	0.021 d per m^2 face	0.1 x skilled
Scaffolding, uprights	4 x skilled	0.25 d per upright	0.1 x skilled
Prepare and erect centering, small or simple vaults	as for skilled	0.1 d per m^2	0.2 x skilled
Prepare and erect centering, large or complex vaults	as for skilled	0.2 d per m^2	0.2 x skilled
Sawing timbers, average value per pair of sawyers	0.25 x skilled	0.06 d per m^2	0.1 x skilled
Load into baskets	0.06 d per m^3		0.1 x unskilled
Raising spoil from foundations, >1.6 m deep	0.018 d per m^3		0.1 x unskilled
Raising materials, h – height of wall	0.012(h-1) d per m^3		0.1 x unskilled
Carry over 105 m	0.0047 d per trip + 0.075 d per m^3		0.1 x unskilled

Site preparations began with clearing the site of forest and digging the foundations. Ultimately, this phase of construction involved all of the processes associated with erecting the physical structure by applying the building materials. Another aspect that will not be included in the man-power or material estimates is the tools. Ropes, hammers, chisels, baskets, pulleys, rakes, axes, and hoists were extremely important to the construction process but there is little way of knowing the minimum quantity required for this project. The variation in breakage and the unknown number of labourers makes the quantity (and ultimately, the production requirements) impossible to calculate.

Chapter 6 – MORTAR ANALYSIS

For things are produced in accordance with the will of nature; not to suit man's pleasure, but as it were by a chance distribution.

Vitruvius, *de Architectura* (2.4.5)

As stated in the previous chapter, the aim of testing the mortars used in the Water Supply of Constantinople and Anastasian Wall was to produce two types of results: qualitative and quantitative. Through qualitative analysis, descriptors such as colour, material makeup, and orientation were documented in the hopes of gaining a better understanding of these mortars' resilience, production process, and raw material provenance. Not all qualitative results came from visual or chemical analysis, as tactile responses during the preparatory methods, such as cutting mortar cores, provided important information about the materials that may not have been otherwise observable.

The majority of questions regarding the water supply and long wall revolve around the scale and logistics of the building projects. To help answer some of these questions, the second type of results from the examination of mortars was quantitative. This required building a large inventory of percentages, measurements, and calculations. The objectives of this regimen was to identify any variations in mortar recipe and ultimately, build an understanding of the material requirements for constructing the Water Supply of Constantinople and Anastasian Wall.

As there are numerous lists of secondary measurements and values used for calculations that would be unnecessary to address individually, only primary data will be provided in this chapter. For this secondary data, see Table A4.1 in Appendix A4.

6.1 - Mortar Collection and Preparation

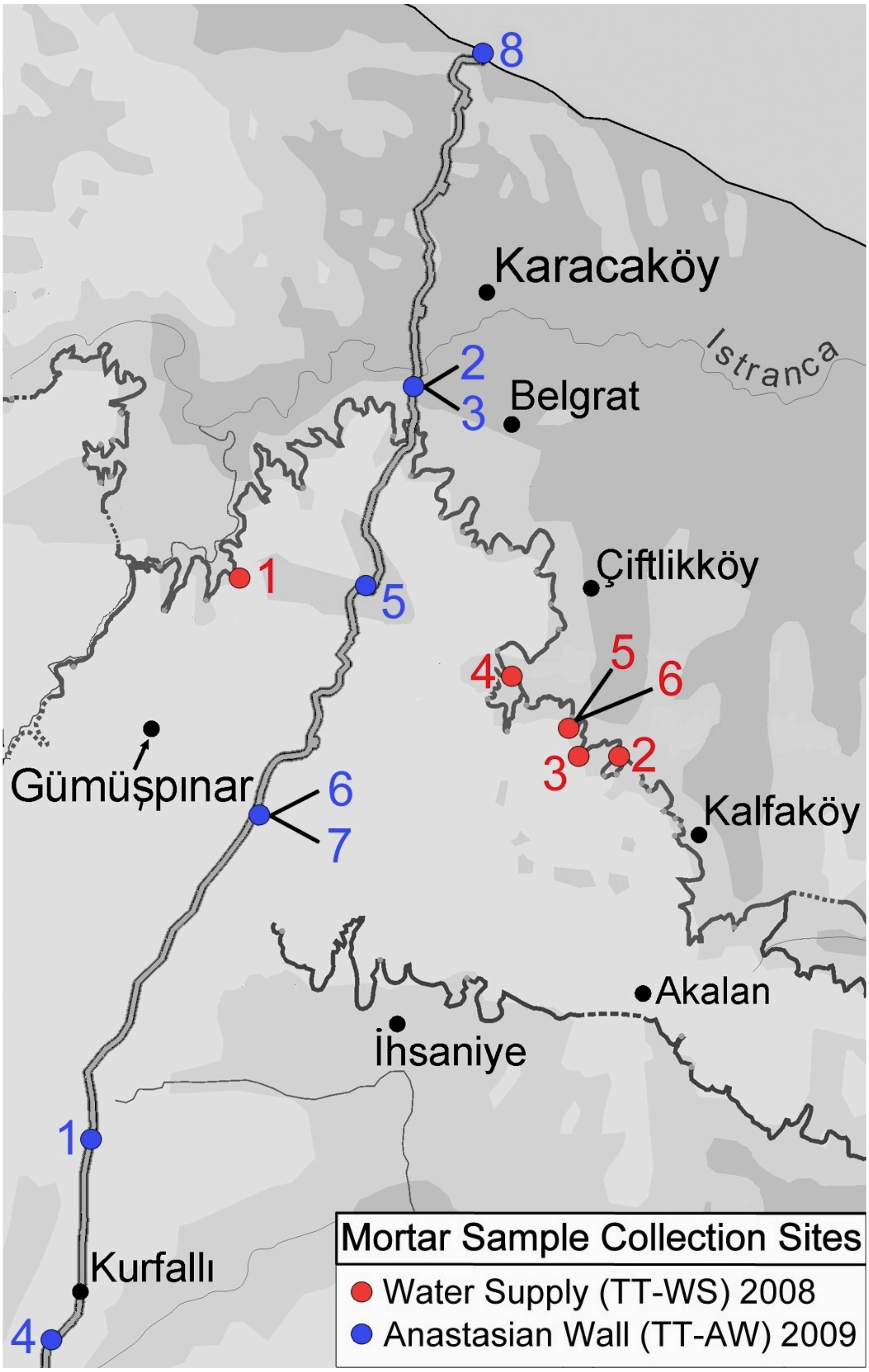
Before describing the sample locations, it is important to discuss the reasoning behind sample selection to put this into context greater than the methods employed. The collection sites and mortar samples were chosen based on four main factors. Firstly, the large geographical distances covered by these structures made it impossible to collect samples from every section within two seasons of fieldwork. This is especially true for the Water Supply of Constantinople where the problem was not just limited by the short fieldwork season, but more importantly, to survey permits, which limited the area of Thrace that we were allowed to work.

Secondly, mortar samples were taken from important areas of these systems. In the case of the water supply, most samples were collected from the monumental 5th-century bridges because of their impressive scale, engineering requirements, and modern state of preservation. Sampling sites of the Anastasian Wall were chosen mainly from well-preserved sections of the curtain wall, as well as one sample from a fort that had been thoroughly surveyed by the Anastasian Wall Project (TT-AW 5, discussion on page 150) and two samples associated with a tower structure (TT-AW 2 and 3, discussion on page **Error! Bookmark not defined.**).

The third factor of sample collection is based on the limits on the number of samples. While in some cases, it was possible to collect more than one sample of mortar from each site (TT-AW 2 and 3, TT-WS 5 and 6), it was necessary to keep a small overall number of mortar samples. This was because the Istanbul Archaeology Museum had to authorise each sample before they could be taken out of Turkey, which is becoming increasingly difficult for archaeological materials. Also, the time involved in scientific analysis limited how much material could be processed during this project, making it unfeasible to collect and test a large number of samples.

Finally, it was necessary that the collection of mortar samples did not jeopardise the remaining structure in any way. While the main goal was to collect good representative mortar samples (i.e. not overly exposed to the weather, association and and placement within the structure), permission would not have been granted to remove pieces that are structurally relevant to modern preservation (see discussion of mortar collection methods on page 85).

Due to the number of samples and sub-samples, abbreviations were developed for the fifth-century water supply phase and long wall. When labelling these samples for laboratory analysis, region and system were designated as ‘TT-WS’ (Turkish Thrace-Water Supply) and TT-AW (Turkish Thrace-Anastasian Wall) followed by the collection site number and core letter. These same abbreviations will be used in the discussion that follows.



Map 6.1 - Mortar sample collection sites (after Crow, 2007b: 269).

6.1.1 - Water Supply Collection Sites

Samples of mortar were collected from a total of five locations across the fifth-century phase of the Water Supply of Constantinople. With the exception of Karatepe, these sites are monumental aqueduct bridges of the fifth century, which are in a good state of preservation. As Map 6.1 indicates, the sampling sites for the water supply are located within a small geographical area of the water supply. While this may seem limiting to a discussion of the entire system, this region does contain the largest aqueduct bridges of the 5th century. Furthermore, this area includes the greatest concentration of bridges from both the 4th and 5th century construction phases, making it a vital region for the understanding the material needs of constructing the water supply. For further information on the dimensions of these bridges, see the rows outlined in yellow on Table A2.1.1 of Appendix 2. For more information from the survey of these bridges, see Chapter 4 of Crow, Bardill and Bayliss (2008: 89-108).

The first sample came from the Kurşunlugerme (K20), which is located 3.6 km northeast of Gümüspınar and is the most western collection site in Thrace (Figure 6.1). It is the longest and widest aqueduct bridge other than the Aqueduct of Valens in Constantinople, built of three tiers with 18 arches and eight buttresses extending up to the third tier (Crow, Bardill, and Bayliss, 2008: 93). This bridge carries the narrow channel on the top tier and wide channel on the middle (Crow, Bardill, and Bayliss, 2008: 93). The mortar sample, designated 'TT-WS 1', was collected from the exposed core on the inner face of the northern-most arch (18), which had been protected by the intact arch above.

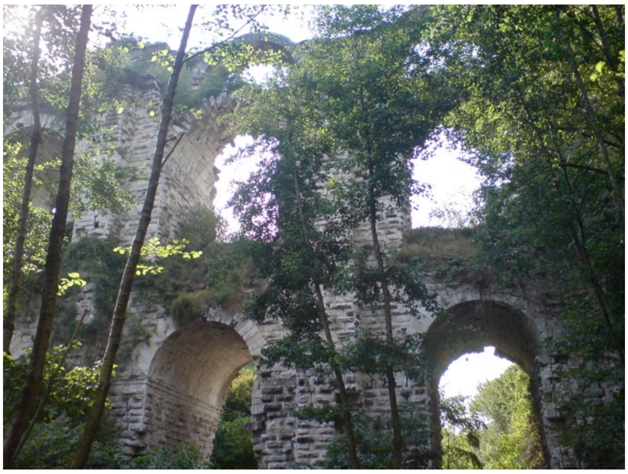


Figure 6.1 - Kurşunlugerme (K20).

The second sample, TT-WS 2, came from Kumarlıdere (K31), another bridge that illustrates the monumental nature of fifth-century aqueduct bridge construction (Figure 6.2). This bridge is located about 3 km northwest of the village of Kalfaköy and represents the eastern-most collection sites on the water supply. Kumarlıdere was two tier bridge with 11 arches on the upper and four taller arches on the lower. The bridge had long earthen embankments leading from the side of the hills to the ends of the bridge (Crow, Bardill, and Bayliss, 2008: 100). Sample TT-WS 2 was located on the western side of the bridge and had already completely fallen away from its original location. Based on the sample's proximity, it can be supposed to have come from a nearby exposed portion of the core structure on the first pier's southern face.

Figure 6.2 - Kumarlıdere (K31).

The third mortar collection site is less than one kilometre east of Kumarlıdere (K31) at Keçigerme (K30). This bridge is the smallest in terms of length and width of the monumental bridges used as collection sites in this project but is nevertheless important due to its towering height, comparable to both Kumarlıdere and Kurşunlugerme. Keçigerme (Figure 6.3) is situated in a deep and densely forested valley with only one lower arch and five tall upper arches (Crow, Bardill, and Bayliss, 2008: 99). A piece of structural core mortar was found *in situ* but naturally fractured away from the core matrix, making it a good candidate for minimally intrusive sampling. This sample, TT-WS 3, was taken from the south-western region of the lower tier of the aqueduct, about three metres up from the foot of the valley.

Figure 6.3 – Upper arches of Keçigerme (K31).

The fourth sample of mortar was taken from the second largest monumental bridge, Büyükgerme (K29), and is located 2.5 km southwest of the village of Çiftlikköy and 2.3 km northwest of Keçigerme. While most of the arches of the bridge are now collapsed, all but one pier still stands. Büyükgerme (Figure 6.4) would have had three arches on the lower tier and nine arches on the upper (Crow, Bardill, and Bayliss, 2008: 97). Sample TT-WS 4 was collected from the northern side of the valley and more than halfway up the embankment. This was found as a part of a pile of building materials that looked to have broken from the core during the same event that caused a few facing stones to fall away from lower portion of the second pier from the north of the upper tier.

Figure 6.4 - Büyükgerme (K29).

The fifth sampling site at Karatepe (K29.5), only 400 m north of Keçigerme, is unique in two respects. Firstly, it is the only mortar collection area that is not considered a monumental bridge. In fact, this bridge can be categorised as being only medium-sized when compared to the much smaller bridges of water supply's 4th-century construction phases (see discussion of average bridge size in section 7.1.2 – Total Volumetric Estimates and Table A2.1.1 or Appendix 2). The second reason that Karatepe is unique as a collection site is because two mortar samples, serving two distinct functional purposes, were collected. Both of these samples were found from locations with little evidence to their precise location within the bridge structure, but based on the mortar type, it was clear that one was from the channel and the other was from the core of the structure. Sample TT-WS 5 was found at the top of the northern hill, just past the remnants of the structure of the bridge. As will be described in greater detail further in this section, this sample was obviously a portion of the channel lining based on its flat surface with a thin coating of secondary calcite deposits from running water.

The second piece of mortar from Karatepe (K29.5), TT-WS 6, was found down in the valley close to the southern abutment of the bridge. This additional piece of mortar, likely part of the core due to its thick irregular nature, was collected with specific intentions. Mortar samples from the first four collection sites along the water supply also came from the structural core of each bridge. Since the first mortar sample collected from Karatepe played a different non-structural role it was decided that an additional piece of structural mortar would be necessary for comparative analysis. Also, unlike the mortar samples collected from the four monumental bridges, this sample has a unique fabric that will be described later in this chapter.

6.1.2 - Anastasian Wall Collection Sites

The methods of sample collection of the Anastasian Wall, as described in the previous chapter, were identical to those used in the previous year on the Water Supply of Constantinople. However, the size of the samples from the wall was typically smaller due to areas of collection, structural form, and the friability of the exposed mortar. Six different locations along a great extent (Figure 6.5) of the wall were chosen as mortar sampling sites. In total, eight separate mortar samples were collected from these locations.

The first collection site along the Anastasian Wall was about 3 km north of the village of Kurfallı at Karanlik Ayazma Sirti (Figure 6.5). Here, one mortar sample, TT-AW 1, was collected about 100 m south of an earthen mound where there were remains of a tower. The path of the curtain wall was identified by the abundance of rubble strewn about two adjoining planted field plots and the small grassy bump that served to separate them. Because there was no evidence of intact portions of wall in this area, the sample was collected from the debris of the western field, closest to the divider.


Figure 6.5 - Collection site of TT-AW 1 (Karanlik Ayazma Sirti).

The second location for sample collection provided two separate mortar samples. Both samples TT-AW 2 and TT-AW 3 were collected from a well preserved section of curtain wall immediately vicinity of Belgrat Tower (**Error! Reference source not found.**), located 2.3 km northwest of the village of Belgrat. Sample TT-AW 2 was collected from the northern end of a 2 m stretch where the upper facing stones had fallen away. This piece of core mortar was taken from behind the one of the disjointed facing stones and was already fractured free from the matrix, most likely from the event that caused parts of the wall's face to fall away. The second sample, TT-AW 3, came from an area about 5m down from the first sample site at Belgrat Tower at roughly the same course height of 1.5m from the current base of the wall. This location was different from the first as there was no embankment of rubble created from the exposed core materials. Instead, this are looked to be intentionally recessed into the wall with the facing stone perfectly accommodating this feature. The mortar sample was taken from the recessed area that looked to be made of similar materials as the mortared rubble core of the first collection site, possibly with the intention of rough courses of mortared rubble stone. This section of the wall was faced with large, cleanly cut soft limestone blocks.

Figure 6.6 – Mortar Collection site of TT-AW 2 and 3 (Belgrat Tower).

The next mortar sample came from the southernmost collection site of the Anastasian Wall. This location, known as Çilingir (Figure 6.6) is 1.5 km southwest of the village of Kurfallı and around 15 km from the southern terminus of the wall on the Sea of Marmara. The line of the wall was similar to Karanlik Ayazma Sirti but had a more pronounced mound with vegetation growing on the top, again seeming to be used to separate modern agricultural plots. Sample TT-AW 4 was found on the western embankment disassociated from any intact structural feature of the wall but in a pile of other rubble construction material close to where the core of the structure would be located.


Figure 6.6 - Collection site for mortar sample TT-AW 4 (Çilingir).

In many respects, sample TT-AW 5 is different from the others collected along the Anastasian Wall. It is the only piece of mortar that is known not to have come from a section of the curtain wall. Furthermore, the structural function of sample TT-AW 5 was also different from the rest of the samples, making it an important addition for comparative analysis. Its collection site is a fort on the line of the wall called Büyük Bedesten (Figure 6.7) and is located 2.7 km east of the monumental aqueduct of Kürsünlügerme (K20). While not *in situ* upon collection, based on its immediacy to the remains of the northeast tower of the fort along with which numerous whole bricks and stones were found, TT-AW 5 looked to be the remains of a mortar joint. Also, based on other observations of the morphology of the sample, which will be discussed in greater detail later in this section, it is most likely a whole joint from a vaulted brick arch.

Figure 6.7 - Collection site for mortar Sample TT-AW 5 (Büyük Bedesten).

The next mortar collection site comes from another curtain wall section just south of the Derviş Kapı fort (Figure 6.8). This site is located 2 km south of the Kücük Bedesten fort, 6 km south of Büyük Bedesten and around 3 km southeast of the village of Gümüşpınar. Two mortar samples were collected from a tall section of wall in an area of intense vegetation. The first sample, TT-AW 6, came from an exposed section about 1m from the modern ground level of the wall. Again, based on the surrounding architecture, this piece of mortar would have been applied to the inner core of a course made of large limestone blocks. The second sample, TT-AW 7, was collected from a location only 5 m away from the first and at height of roughly 2 m. This particular height of wall did not survive with facing materials still intact along the visible length. Because of this, it is difficult to say with certainty whether this was a part of the same small blockwork course or whether it was a part of the large limestone ashlar block courses as evidenced by other sections of the wall and the broken remains of ashlar blocks in proximity to the wall.

Figure 6.8 - Collection site of mortar samples TT-AW 6 and 7 (South Derviş Kapı).

The last collection site was at the northernmost section of the wall at Evcik (Figure 6.9). This area of curtain wall is located on the sandstone cliffs of the Black Sea coast 5 km north of Karacaköy and less than 50 m west of a small middle Byzantine Church. The sample TT-AW 8, taken from the exposed mortar core around 1.5m above the modern base on the wall's western side, could not be identified as a mortar joint or part of the large ashlar-faced mortared rubble known. This was due to the previous removal of facing stones most likely used for construction in the nearby church (Crow and Ricci, 1997), the poor preservation of the remaining wall matrices, and the overgrowth of vegetation along the entire section. Had there not been a visible area of the core, most likely exposed by weathering and crumbling of the surface material and subsequent vegetative cover, it would have been rather difficult to be able to identify this earthen mound as a section of wall.

Figure 6.9 - Collection site for mortar sample TT-AW 8 (Evcik).

6.1.3 - Macroscopic Observations of Mortar Samples and Cores

Following this tradition of Ward-Perkins (1958; see Table 3.1), when a sample was collected from a site and documented, I used these basic descriptive terms for colour, aggregate type, and functional role. The terms for colour are very subjective and are only a means of quick identification. A more reliable method of colour identification is used later in this chapter (see Table 6.6) for brick analysis. This was deemed unnecessary for the mortar samples based on the variation of colour of the sample's binder and the outer discolouration from weathering, soil, and organic growth.

As explained in the previous chapter, there were many preparatory steps in order to produce a thin section for petrographic. These revealed information through physical response of the preparation techniques coupled with the visible nature of the resulting objects. While drilling cores from the large mortar samples, it was noticed that adjustments had to be made to properly accommodate each sample. Large non-brick aggregates, size and quantity of sand grains, and friability of the binding material were each factors affecting the drilling process.
This section presents the characteristics of the original sample, directly followed by a discussion of the observations from coring.

TT-WS 1 – Original Sample: Very large piece of core structural mortar measuring roughly 306 x 202 x 103 mm. Very pink in colour from pulverised brick and also containing broken brick aggregate averaging 4.7 mm in diameter. Smoothed stone gravel aggregates of roughly the same size with the occasional piece being as large as 20 mm. One large piece of irregularly shaped metamorphosed limestone aggregate, matching the look of stone used to face Kürsünlügerme. Both front and back surfaces of the mortar show multiple impressions of rubble stone aggregate of the core. Hard mortar matrix but surface grains become dislodged easily to the touch.

Coring: A total of eight cores were taken from the Kurşunlugerme mortar sample due to its large size. While cutting these cores, it was immediately clear that the overall sample was strong but had weak bonds with non-reactive aggregates. Sand granules were large and frequent, making them prone to becoming dislodged in the coring process. Similarly, larger aggregate such as mica schist and hard limestone shared little cohesion with the surrounding lime. However, the larger brick aggregate indicated a strong bond with the lime binder, causing very few instances breaking away while coring. The last core (TT-WS 1i) was taken from the large piece of metamorphosed limestone. Surprisingly, this was bonded securely to with the mortar matrix and showed no signs of deterioration of mortar at the contact surface. The hardness of the metamorphosed limestone made cutting very time consuming.

TT-WS 2 – Original Sample: Large piece of structural core mortar measuring 164 x 92 x 69 mm. Pink in colour from crushed brick with small brick aggregate averaging 3.9 mm in diameter. One flat smoothed surface from contact with core stone rubble and other side is flat with a very thin white layer of calcite formation.

Coring: Three cores were extracted from this sample from Kumarlıdere. The mortar had a uniform matrix as well as small sand grain size. Cutting these cores and preparing the thin sections proved to be easy due to the continuity of the mortar mix.

TT-WS 3 – Original Sample: Medium piece of structural core mortar measuring 154 x 119 x 74 mm. During transport, two small pieces fractured away. All pieces are grey in colour on the surface and pink at the area of fracture. Broken and crushed brick used with the larger pieces averaging 3.8 mm in diameter. One surface is smooth from contact with core rubble. All other sides are jagged and seem to have fractured naturally well after hardening.

Coring: This mortar sample from Keçigerme was very similar to the sample from Kumarlıdere. The only distinguishing factor from this preparation work was the increased frequency of large pores. Since they were free of debris, these pores were most likely air pockets from the mixing process rather than from the deterioration of stone or organic material that had been observed in other samples.

TT-WS 4 – Original Sample: Medium piece of structural core mortar measuring 155 x 74 x 61 mm. Uniform Pinkish white colour under thin layer of pinkish orange residue. Crushed and sifted brick with medium sized broken brick aggregate averaging 3.6 mm in diameter. All surfaces seem somewhat smooth but only one small portion indicated direct contact with core rubble. One portion on the outer surface of the mortar has a layer of green algae and on an adjacent surface moss has grown into the crevasses.

Coring: Three cores were taken from the mortar sample from Büyükgerme. Once again, the small sand grains and solid matrix made producing thin sections quite easy. In core TT-WS 4c, a small crack was observed running three-quarters across the diameter. However, this had no effect on the cutting process and did not continue far beyond the core. Most likely, this was a pore that had been compacted by the weight of the materials placed on top during the early setting stages of the mortar.

TT-WS 5 – Original Sample: Medium piece of channel lining mortar measuring 157 x 111 x 52 mm. Very pink in colour throughout from both crushed and broken brick additives with the larger pieces averaging 3.6 mm in diameter. Top surface is very smooth with no indication of pores and has a uniform layer of white calcite. All other surfaces are jagged from fracturing and there is a possibility of two mortar layers making up the thickness of the sample.

Coring: The channel lining mortar sample from Karatepe yielded six cores. Small sand grains allowed for smooth cutting and all but one core was produced a solid core. In the instance of TT-WS 5f, the core broke after extraction from the coring bit. This core was taken perpendicular to the water channel surface and the break sheered half of this surface at an angle midway down the length of the core. Looking at the inside of these pieces, the break had bisected a large pocket measuring roughly 10 mm in diameter containing dark small-grained material. Until microscopic observations of materials were made (see section 6.2), nothing more was known about this material.

TT-WS 6 – Original Sample: Medium piece of structural core mortar roughly measuring 122 x 73 x 65 mm. White/light-grey in colour with seemingly little use of finely pulverised brick. Large pieces of broken brick aggregate mixed into the mortar matrix averaging 5.8 in diameter. The entire surface of this piece of mortar is smoothly rutted and looks as though it had not been properly compacted. In addition there is no indication on the surface of any proximate contact with stone rubble.

Coring: Only two cores were obtained from the second mortar sample from Karatepe because of its small size and friable nature. While cutting these cores, pieces regularly fractured off of the surface and disintegrated, leaving only small piece of brick. Upon investigation of the remaining cores, it was clear that there were regular large pores throughout the mortar matrix. The cohesion between the brick aggregate seemed to be sturdy whereas the rest of the lime binder was very friable.

Of the six samples from the water supply, this was easily the lowest quality.

TT-AW 1 – Original Sample: Medium sized piece of structural mortar measuring117 x 95 x 62 mm. Almost entire sample covered in a layer of dark brown dirt but very pink in colour in exposed areas. Crushed and sifted brick mixed throughout with larger brick aggregate averaging 3.7mm in diameter. Most surfaces are rough with the exception of two small indentations that look to be caused by large core aggregate.

Coring: Three cores were extracted from the mortar sample from Karanlik Ayazma Sirt. Analysis of the sample did not indicate any large aggregate other than brick but during the coring process and two large pieces of limestone aggregate with a diameter of around 14 mm. The aggregate had a relatively strong adhesion to the surrounding lime and crushed brick binder, which did not come loose during the cutting process. Large quantities of finely crushed brick seemed to be mixed well with the lime. In addition, small pieces of brick aggregate of consistent size had very strong adhesions to the surrounding binders. While the size of the sand grains was larger than the majority of the samples from the water supply, this did not have a noticeable affect on thin section production.

TT-AW 2 – Original Sample: Small piece of structural core mortar measuring 49 x 49 x 31 mm. The overall colour is pinkish brown and is very friable. Large sand grains mixed with finely crushed brick and large brick aggregates averaging 5.3mm in diameter. Surfaces are very granulated and are extremely friable with no discernible evidence of immediate contact with stone aggregate.

Coring: The two samples of mortar from Belgrat Tower produced three pieces each for thin section analysis. Due to the very large sand grains, numerous pieces of hard aggregate, and the very friable binder of both of these samples, it was almost impossible to produce solid cores. Instead, pieces from the attempted coring were used in the place of cores. Producing thin sections from these pieces was just as problematic. Even with extra care, sand grains easily became dislodged during the cutting and polishing process. Surprisingly, the largest pieces of stone aggregate seemed to have a good bond with the surrounding binder. This sample contained large brick aggregate pieces with good cohesion to the binder and a seemingly ample amount of finely crushed brick, despite the friability of the mortar.

TT-AW 3 – Original Sample: Small piece of structural mortar measuring 41 x 33 x 23 mm. Pinkish white in colour and very friable overall. Similar to TT-AW 2 with large sand grains, crushed brick and large brick pieces averaging 6.9 mm in diameter. All surfaces are very granulated, very porous, and binder is quite friable. One surface looks to have been smooth and compacted by core aggregate stone at some point during its application.

Coring: see TT-AW 2 (above).

TT-AW 4 – Original Sample: Small to medium piece of structural mortar measuring 71 x 62 x 45 mm. Relatively hard binder that is pink in colour with finely pulverised brick mixed evenly throughout. High quantity of large-grained river sands with brick aggregates averaging 5.7 mm in diameter. Two extremely large pieces of brick measuring 21 and 28 mm in diameter. One surface of the sample is smooth and compacted from large stone aggregate while all other surfaces look to be freshly fractured from the surrounding mortar matrix.

Coring: The three cores from the Çilingir mortar sample were relatively easy to extract. A mix of sand as well as large and small brick aggregate were securely bonded in the mortar matrix. However, the one distinction from the cutting process was the large proportion of lime that has not been properly hydrated for incorporation into the mortar mix. A large portion of the top of core TT-AW 4c was made up of a single lump of lime measuring at least 7 mm in diameter. The majority of this lump broke away from the core before further thin sectioning preparations could be made. Because of the consistent distribution of finely crushed brick throughout this sample, it was concluded that it was not poorly mixed but most likely a case of improper slaking.

TT-AW 5 – Original Sample: Large piece of structural joint mortar measuring 197 x 159 x 62 – 74 mm. Very pink in colour from finely crushed brick thoroughly mixed through. Medium to large pieces of broken brick aggregate measuring 6.8 mm in diameter. Top and bottom surfaces both entirely flat and smooth resulting from being compacted between two uniform materials. Each side gently slopes over its length to form a partial wedge shape. Light weight for its size yet quite strong.

Coring: The large size of the mortar sample from Büyük Bedesten allowed for a total of four cores to be produced. As previously mentioned, this mortar sample was likely a mortar joint for a brick arch, thus having a different structural function from the other core mortars. Even though the mortar seemed to be strong on the larger scale, surprisingly, the coring process proved to be quite challenging. The bonds of all of the numerous large sand grains as well as the brick aggregate were quire strong but the mortar matrix had some of the largest and most frequent pores. The entire matrix of the system would have functioned well structurally but when cutting the cores, many of the large pores caused small pieces of brick to become dislodged. In addition, the amount of finely crushed and aggregate brick material appeared to be higher than any other sample. These factors would have contributed greatly to the sample's light weight.

TT-AW 6 – Original Sample: Small piece of structural core mortar measuring 48 x 45 x 38 mm. Very pink in colour with a large quantity of pulverised brick mixed throughout. Numerous pieces of broken brick aggregate averaging 6 mm in diameter. The sample is generally quite friable and broke into three smaller pieces during transport. While the surface is friable like many of the others, the subsequent debris is a fine powder unlike the granule nature of samples TT-AW 2 and TT-AW 3. There is no evidence of the surfaces of the sample having any contact with stone aggregate material.

Coring: Three rough cores were produced from the first sample of mortar from South Derviş Kapı. The coring process was very delicate for this mortar due to many large pores and the weak matrix of the binder. Both large and small brick aggregate were used and showed durable bonds with the surrounding lime. Despite relatively high quantities of pulverised brick thoroughly mixed with the lime, the overall impression of this mortar from preparing thin sections was that is was too friable to be classed as a high-quality mortar.

TT-AW 7 – Original Sample: Small to medium piece of core structural mortar measuring 81 x 62 x 44 mm. Very pink in colour with evenly distributed pulverised brick. Very similar to TT-AW 6 with the exception that this sample seems to be quite strong. Well-distributed broken brick aggregate averaging 5.8 mm in diameter with one large observable piece measuring 17 mm. Two opposite surfaces are smooth and compacted from stone aggregate with one covered in a thin layer of calcite. All other surfaces look to be recently fractured from the surrounding mortar matrix.

Coring: The second piece of mortar from South Dervis Kapı produced three solid cores. The sand, while large grained, were infrequent. Brick aggregate was evenly distributed throughout the binding matric and did not exceed seven millimetres in diameter with the exception of one large brick piece found in TT-AW 7a the measures close to 12 mm across. Large quantities of finely crushed brick were also mixed thoroughly with the lime. Other than a few instances of medium-sized pores, the surfaces of the cores were intact and relatively smooth. Pieces of stone aggregate were not identified in the overall samples or the produced cores and thin sections. Good cohesion of the aggregate material allowed for easy thin section production.

TT-AW 8 – Original Sample: Small piece of curtain wall core mortar measuring 66 x 46 x 38 mm. Immediately after collection, sample fractured into 3 similar shaped pieces. White in colour with little evidence of pulverised brick mixed into the lime binder. Large pieces of broken brick aggregate were sparsely distributed in the mortar averaging 7.4 mm in diameter with instances of brick fragments as large as 24mm. Very friable mortar with large an abundance of large quartz sand grains spread throughout the binder. All surfaces are rough and look to have been recently fractured from the matrix with no evidence of weathering or organic growth.

Coring: The sample of mortar from the end of the Anastasian Wall at Evcik yielded four pieces for thin sectioning analysis. Similar to Belgrat Tower, cutting cores was impossible. Preparing these pieces for thin section petrographic analysis provided little further information about the sample. The sample contained the highest quantities of sand of all of the samples from the Anastasian Wall as well as the Water Supply. Brick was only used as large pieces of aggregate, one measuring least 22 mm in diameter, and did not show and significant adhesion to the binder. Because of the frequency of the sand grains and the marked difference in hardness from the surrounding binder, producing a thin section of this material was very difficult. It was postulated that the friability of this mortar sample's matrix could possibly be attributed to the negative effect of salt from the water or sand used in its production, due to its extremely close proximity to the Black Sea.

6.1.4 – Conclusions

Without having performed any scientific testing of mortars collected from the Water Supply of Constantinople and Anastasian Wall, some general macroscopic observations have been made. All mortar samples use brick to some degree. In most cases, finely crushed brick powder and broken brick aggregate seemed to be used liberally, especially in the case of TT-AW 5 (Büyük Bedesten). However, also from the Anastasian Wall, TT-AW 8 (Evcik) showed very little finely crushed brick and intermittent pieces of very large brick aggregate. This could be related to possible later repairs to the wall or to inavailability of brick at this construction section. Further analysis of the amount of sand, lime, and brick used in these mortars should provide more data on the use and availability of these constituent materials.

The average size and quantity of sand grains noticeably varied between mortars from the water supply and long wall, which are an indicator of a variation in collection sites (i.e. quarried versus sea sand). While these are only preliminary findings, microscopic observations are hoped to shed more light on the nature of raw material procurement and technological variations in recipe based on function and geographical position of the collection site.

It is possible, however, to address the differences of some mortars based on the use of materials. In the case of TT-WS 1, larger pieces of metamorphosed limestone and mica schist were used as aggregate. Since the facing stones of Kurşunlugerme are of similar (if not the same) metamorphosed limestone, these aggregates may be a by-product quarrying or dressing the facing stones. Without further analysis, it is unclear from macroscopic observation whether this played any significant role in the mortars' overall quality or whether these variations indicate any intentional adaptations to the mortar mix.

6.2 – Petrography: Material Identification and Measurements

Macroscopic observations proved to be beneficial in understanding some of the basic physical qualities of the mortars (such as friability and basic constituent materials) used in the large bridges of Water Supply of Constantinople and structures of the Anastasian Wall. However, scientific studies of mortar such as Moropoulou, Bakolas, and Aggelakopoulou (2001), Pavia and Caro (2008), and Valetti, Bontempi, Picciolim and Depero (2004), showed that much more could be understood about these mortars from microscopic analysis (see Chapter 4).

Other than lime, brick, sand and stone aggregate, what materials are included in these mortar mixtures? What is the degree of the pozzolanic reaction between lime and brick? Where their obvious differences in the types of sand and brick used in the samples? What were the proportions of materials used to make these mortars? The objective of this section is to address these questions through microscopic analysis.

6.2.1 – Material Identification and Examination

LIME

All of the samples analysed under the microscope consisted of three primary materials: lime binder, broken or crushed ceramics, and sand. Using thin section petrography, more information could be determined about the specifics of these materials. In the case of the lime binder, most mortar samples included small lumps of burnt lime that had not been properly slaked. Unfortunately, due to the burning process, little could be determined about the original carbonate rock. However, the cores from the channel lining mortar of Karatepe (TT-WS 5) included pieces of unburned lime with the peripheries of these surrounded by reacted lime and crushed brick. This meant that they were most likely portions of limestone that had not been burned sufficiently instead of being included through the addition of aggregate. Interestingly, these unburned lime pieces contained microfossils (Figure 6.10) with no evidence of morphological distortion, indicating that the lime was produced from non-metamorphosed limestone.

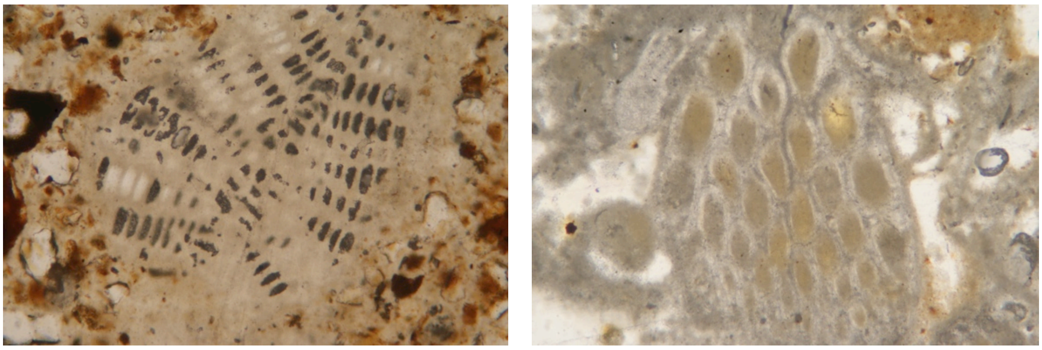


Figure 6.10 - Microfossils from sample TT-WS 5b (left) and TT-WS 5e[1] (right). Scale of micrographs is 3 mm by 2 mm.

The microscopic investigation of the channel lining mortar from Karatepe (TT-WS 5) also revealed some interesting and important information about lime. The surface of the mortar on which the water would run clearly shows multiple events of limescale deposits (Figure 6.11).

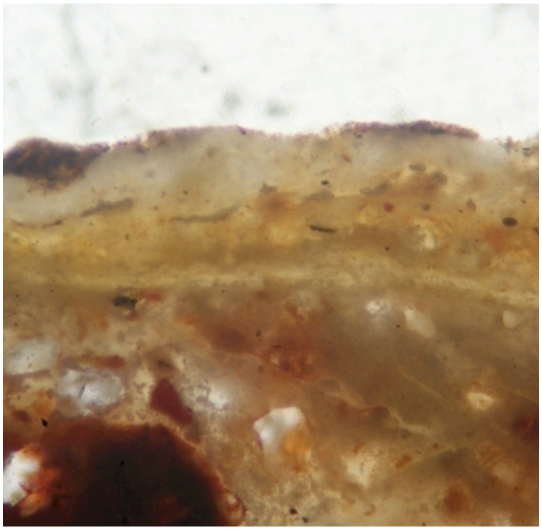


Figure 6.11 - Layers of limescale deposits from channel surface of mortar sample TT-WS 5d[1] from Karatepe. Scale of micrographs is 2 mm by 2.1 mm.

This could reflect periods of disruption in supply, stagnated water flow, or changes in water mineralogy, especially due to the defined colour and inclusions. The upper-most layer of off-white limescale measured 0.21 mm thick and had small pockets of sinter (dark brown) on its surface. Immediately below, another line of sinter traces the outline of a yellow-orange limescale deposit measuring 0.17 mm thick. The last two layers are both around 0.8 mm thick, the top being an opaque yellow-grey and the bottom a very light yellow. It is most likely that at least two separate events caused the build-up of distinctive limescale deposits of the top layer.

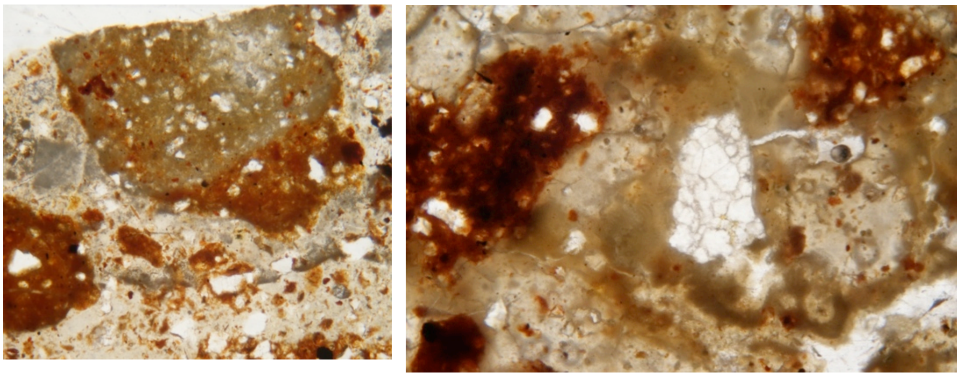


Figure 6.12 - Possible mortar fragment from previous construction phase in channel lining mortar from Karatepe (TT-WS 5). Scale of micrographs is 2 mm by 2 mm

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Another conclusion that was made about the channel lining mortar sample from Karatepe was the poor care and quality control that was used in its production. The first indication of this was the use of large sand and brick aggregates compared to the relatively small proportion of finely crushed brick. Because of the limited pozzolanic reaction between brick and lime as well as silica sand having no reaction, much higher quantities of pulverised brick would be needed to produce a quality waterproof plaster. The second indication of poor quality control is evidenced by the possible use of older mortar as aggregate, possibly from an earlier building phase. These are indicated by cohesions between the mortar's lime binder surrounding distinctively different brick and lime matrices (Figure 6.12).

The final case of poor quality control comes from core TT-WS 5b. As previously mentioned, when the core was extracted from the surface of the channel lining mortar, a portion fractured off the side of the sample. This revealed a large pocket filled with a dark brown, fine-grained material that had no noticeable cohesion to the mortar sample. Thin section analysis provided a much clearer view of this material (Figure 6.13).

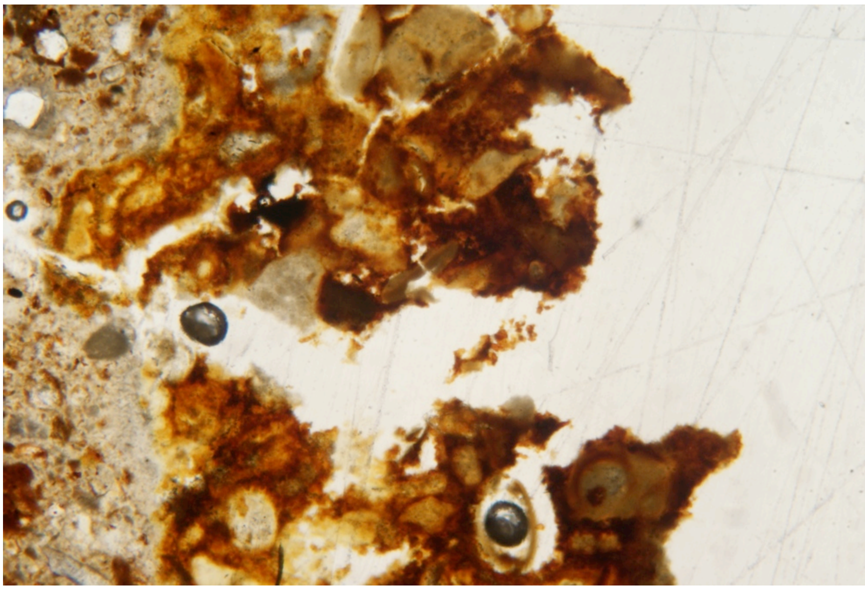


Figure 6.13 - Possible decayed organic material in mortar sample TT-WS 5b. Scale of micrographs is 3 mm by 2 mm.

Polarised light microscopy provided little information on the material's mineralogy. The granules were not silica and fabric was unlike brick, despite the dark red colour. This material did not look like an intentional addition to the mortar, especially because it was located in the thin layer of channel lining plaster. Most likely, this pocket was originally plant material such as a seed or twig that had gotten into the mortar mixture inadvertently. Over time, the material would have decayed and broken down into small granules. This would have reduced the overall volume of the material, creating the half-filled pocket. This pocket was located very close to the channel surface at only 1.1 mm, making it likely that it was introduced during the mortar mixing or plastering process.

SAND

Sand grains in the binder of the mortar varied in size considerably from sample to sample but almost all of them were identified as silica. During the earlier discussion on sample preparation, the size of the grains played a large role in the success of producing an intact core. Using image analysis software, sand grains from each sample were measured to see how much of a difference there was in size. Most samples of the water supply had sand grains that averaged a diameter of close to 0.35mm. The one exception came from TT-WS 1 where the average sand grains were almost twice the size at 0.63 mm (Figure 6.14).

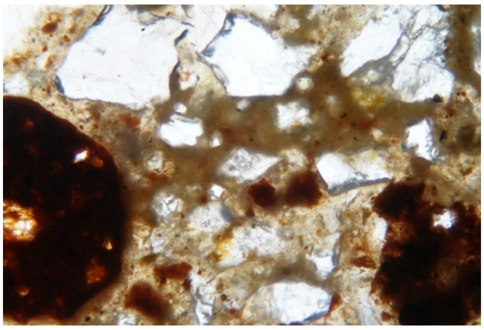
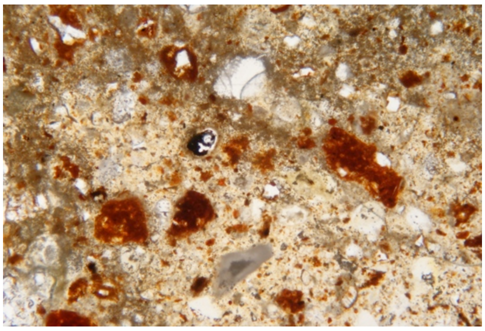



Figure 6.14 - Size difference of sand grains of sample TT-WS 1b (left) and TT-WS 3c (right). Scale of micrographs is 3 mm by 2 mm.

While samples TT-AW 5 (Büyük Bedesten), 6, and 7 (South Derviş Kapı) had an averaged 0.32 mm in diameter, sand grains from most of the Anastasian Wall mortars were found to be larger than those of the water supply. Most notably, mortar from Evcik (TT-AW 8) and Belgrat Tower (TT-AW 2 and 3) had the largest sand grains with diameters of 0.63 mm and 0.87 mm respectively.

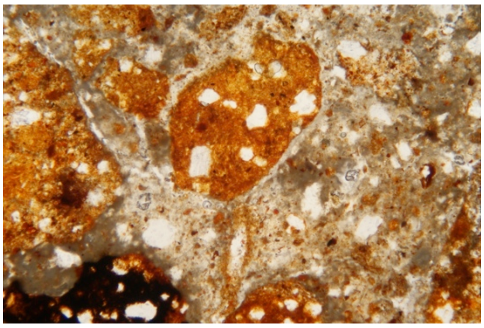
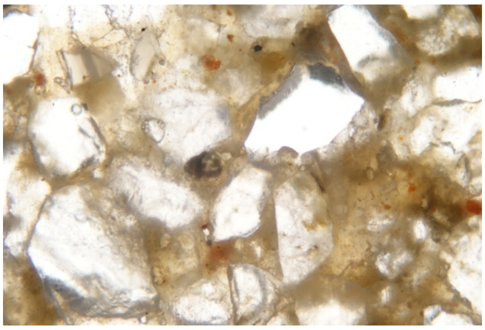



Figure 6.15 - Size difference of sand grains of sample TT-AW 6a (left) and TT-AW 8b (right). Scale of micrographs is 3 mm by 2 mm.

The shape of the sand grains was also taken into consideration. In almost every sample, sand grains were typically coarse and angular. Even in large-grained sand from Kurşunlugerme (TT-WS 1) showed sharp and irregular edges (see Figure 6.16). However, samples from Evçik and Belgrat Tower (TT-AW 6, 7, and 8) contained comparatively smooth edges and in some cases, the crystalline structure has been significantly rounded (Figure 6.15).

BRICK

One of the initial interests of the microscopic investigations of these mortars was identifying what types of ceramic materials were being used as aggregate and pozzolana. From the macroscopic examinations, the term 'brick' was used for all ceramic materials found in the samples but this had yet to be verified. Since roof tiles, amphorae, and pottery could be used in mortars according to classical sources such as Pliny (*Natural History 36.175*), Cato (*On Agriculture* 18.6-8) and Vitruvius (*On Architecture* 2.5.1), it was important to identify the type used in these mortars. Investigations of the type of temper used in the ceramic material concluded that only large quantities of silica sand were used. These grains were measured in the same manner as the sand aggregate in the binder, but yielded different results. Surprisingly, the silica temper for the ceramic pieces used in all of the samples had a very small range in size. For the water supply, sand temper averaged a diameter of 0.26 mm with a range of ± 0.06 mm. The sand temper from the long wall averaged 0.32 mm and also had a range of only ± 0.06 mm.

Examination of the fabrics revealed that almost all of the ceramic material in these mortar samples was homogeneous and porous. In addition, large pieces of carbonised organic material were identified, the details of which will be discussed later in this section. Based on the exclusive use of silica sand temper throughout the ceramic aggregates, as well as the porousness and homogeneity of the fabrics, the mortar samples of the Water Supply of Constantinople and Anastasian Wall were assumed to have only used brick as a pozzolanic material.

The average size of the largest brick aggregate was also measured. The size of these made it impossible to measure through thin section petrography so micrographs of the polished cores were used instead. The largest of these brick aggregate pieces found in the water supply mortar samples came from Kurşunlugerme (TT-WS 1) with a diameter of 10.84 mm and an overall average of 7.22 mm. However, the second sample of mortar from Karatepe had consistently larger pieces of broken brick, averaging 9.59 mm in diameter. All of the other mortar samples had a similar size with an average diameter of 5.40 mm with a range of ± 0.40 mm.

The largest pieces of brick temper from the Anastasian Wall mortar samples were typically bigger in size than the water supply. With the exception of sample TT-AW 1 from Karanlik Ayazma Sirti, which had brick pieces averaging 5.54 mm in diameter, the mortars of the long wall had brick aggregate averaging 10.40 mm ± 1.20 mm. The largest piece of brick aggregate was found in the mortar from Evcik (TT-AW 8), measuring at least 22 mm in diameter.

After the sand aggregate and sand temper had been measured, an intriguing question arose: were these two types of sand actually the same thing? Since brick was crushed before being added to the mortar mixture, it was inevitable that the sand temper of the brick would be mixed in as wall. The only way to know whether the sand in the binder was an intentional addition or just the loose sand temper was to compare their average sizes (Table 6.1). There was no doubt that sand aggregate was added to sample TT-WS 1 from the water supply and TT-AW 1, 2, 3, and 8 from the long wall. The sand in these mortar samples' binders was consistently much larger by an average 0.44 mm. To a smaller degree, but no less significant, the remaining samples of the water supply and TT-AW 4 (Çilingir) showed a difference in diameter between brick temper and sand in binder of 0.10 mm. However, TT-AW 5, 6 and 7 from Büyük Bedesten and South Derviş Kapı showed little difference between brick temper and sand found in the binder.

Table 6.1 - Size of sand aggregate from binder versus sand temper of bricks from mortar samples of the Water Supply of Constantinople and Anastasian Wall.

Mortar Sample	Site Name	Brick Temper Ø (mm)	Sand in Binder Ø (mm)	Ø Difference (mm)
Water Supply of Constantinople				
TT-WS 1	Kurşunlugerme	.19	.63	.44
TT-WS 2	Kumarlıdere	.24	.33	.09
TT-WS 3	Keçigerme	.23	.34	.11
TT-WS 4	Büyükgerme	.29	.38	.09
TT-WS 5	Karatepe	.28	.36	.08
TT-WS 6	Karatepe	.35	.47	.13
Anastasian Wall				
TT-AW 1	Karanlik Ayazma Sirti	.29	.59	.30
TT-AW 2	Belgrat Tower	.26	.84	.58
TT-AW 3	Belgrat Tower	.34	.91	.57
TT-AW 4	Çilingir	.37	.49	.12
TT-AW 5	Büyük Bedesten	.32	.28	-.04
TT-AW 6	South Derviş Kapı	.32	.36	.04
TT-AW 7	South Derviş Kapı	.32	.31	-.01
TT-AW 8	Evçik	.30	.63	.33

6.2.2 - Objects of Interest

In addition to the typical brick, sand and lime, there were other materials found through petrographic analysis of the mortar samples from the Water Supply of Constantinople and Anastasian Wall. For example, burnt organic materials and grains of various minerals were found within the matrix of many of the thin sections. In most cases, these would account for less than 0.5% of the total sample area, meaning that they would have played little to no role in the quality and success of the mortars. However, it was important to document these materials, which have been called 'objects of interest', for a qualitative and quantitative discussion of the mortars and their possible implications in material manufacture and sourcing.

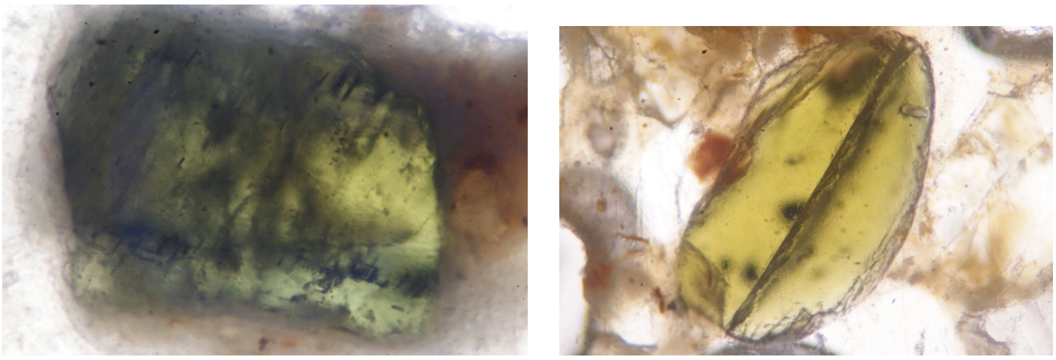


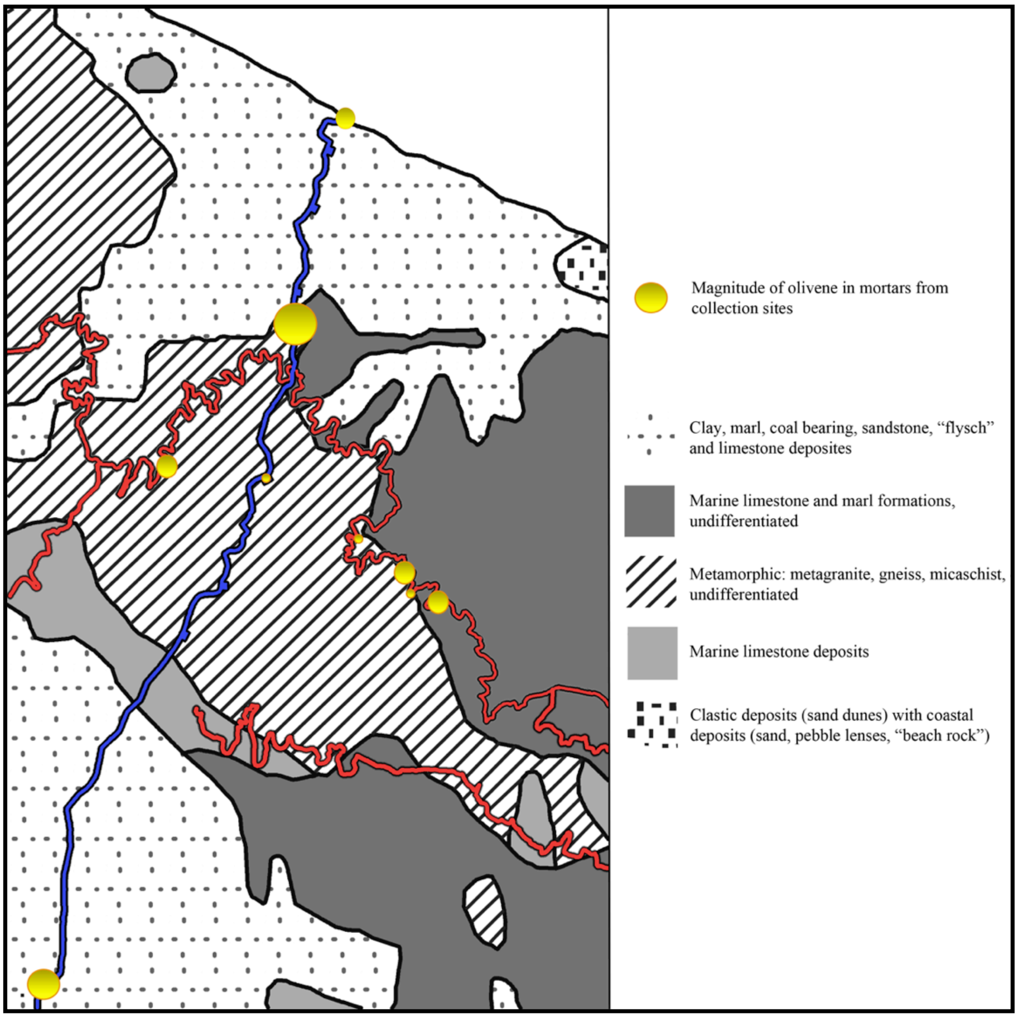
Figure 6.16 - Olivine in mortar samples TT-AW 4c (left) and TT-AW 8b (right). Scale of micrographs is 1 mm by 0.66 mm.

One of the most prevalent objects of interest was olivine (Figure 6.16); a magnesium rich constituent of igneous and metamorphic rocks, typically colourless to dark green (Mackenzie and Adams, 1994: 1-2). This material was found in every sample of mortar from the water supply and long wall with the exception of TT-AW 6 and 7 from South Dervis Kapı. It is most abundant in samples TT-AW 2 and 3 from Belgrat Tower averaging over seven granules per core (Table 6.2). Sample TT-AW 4 from Çilingir is the next highest with an average of five granules per core.

Table 6.2 - Averages instances of olivine granules per core in mortar samples from the Water Supply of Constantinople and Anastasian Wall.

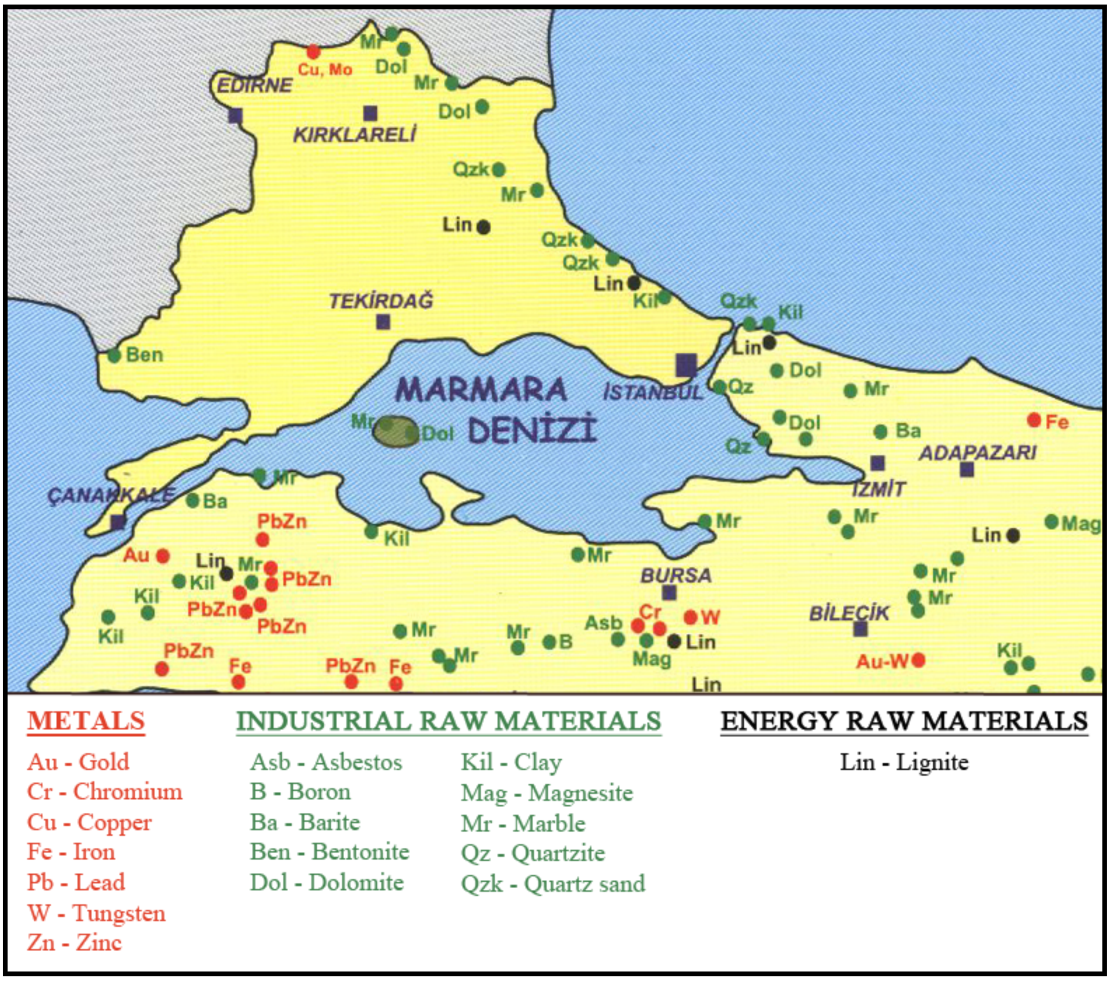
Mortar Sample	Site Name	Olivine Granules per Core
Water Supply of Constantinople		
TT-WS 1	Kurşunlugerme	3.1
TT-WS 2	Kumarlıdere	3.3
TT-WS 3	Keçigerme	0.3
TT-WS 4	Büyükgerme	0.3
TT-WS 5	Karatepe	0.4
TT-WS 6	Karatepe	3.0
Anastasian Wall		
TT-AW 1	Karanlik Ayazma Sirti	1.3
TT-AW 2	Belgrat Tower	7.3
TT-AW 3	Belgrat Tower	7.0
TT-AW 4	Çilingir	5.0
TT-AW 5	Büyük Bedesten	0.5
TT-AW 6	South Dervis Kapı	0.0
TT-AW 7	South Dervis Kapı	0.0
TT-AW 8	Evçik	3.3

These totals were plotted on a geological and hydrological map of Thrace produced by (Bono, Crow, and Bayliss (2001: 1326) at the locations of mortar collection sites to see if there was any clear correlation between the bedrock, rivers, and concentrations of olivine (Map 6.2). Unfortunately, no relationship between these was found using this method. While it is most likely the case that olivine fragments were introduced with the addition of sand aggregate since there are no examples of olivine in brick, without a detailed sampling of sand and stone deposits close to the collection sites, nothing more can be concluded at this point.



Map 6.2 – Amount of olivine at each sampling site compared to bedrock geology.

Another example of an object of interest is carbonised organic material. These are found in brick aggregate pieces and the lime-based binder of every mortar sample collected from the water supply and long wall. There are three distinguishable types of organic materials found in these mortar samples. The first is found in the binding matrix of the mortar as very dark and dense material (Figure 6.17), possibly a fossil fuel. According to a map of the mineral deposits of Turkey (Map 6.3) produced by Maden Tetkik ve Arama Genel Müdürlüğü (Directorate General of Mineral Research and Exploration), there are large deposits of lignite in northern Thrace close to Evcik, further west near Vize, and on the eastern side of the Bosphorus near Cayagzi. Since there is no indication of other forms of fossil fuels in the area, such as coal or peat, it is assumed to be lignite.



Map 6.3 - Mineral deposits in northwest Turkey (after Engin, 1986)

There is strong evidence of the use of coal and lignite in Roman Britain (Dearne and Branigan, 1995), meaning that the knowledge of such a material had been introduced long before the construction of the Water Supply of Constantinople and the Anastasian Wall. However, there no archaeological or historical evidence confirms the use of these fossil fuel deposits. Furthermort, when organic materials were identified as probable lignite, it was impossible to classify conclusively. Very small and dense samples within the matrix (less than 0.1 mm diameter) would have required that the thin section be polished down even further, risking losing the fragile organic material as well as significant data pertaining to the overall mortar sample. This made quantifying the total instances of lignite in the samples almost impossible, though it can be stated that the possible and probable examples of lignite were still far less frequent than other organic materials.

The second type of organic material found in samples from the water supply and long wall is burnt plant material. This is likely spent fuel introduced to the mortar by inadvertent mixing with the lime when being gathered from the bottom of the kiln. Determining whether this was originally raw wood, charcoal, or other plant material is very difficult because the examples only occur as very small fragments in thin section, no bigger than 0.2 mm in diameter. Furthermore, plant material such as brush and wood would be carbonised in a similar manner to charcoal during the burning process, distinguishing between the two types of fuel extremely difficult.

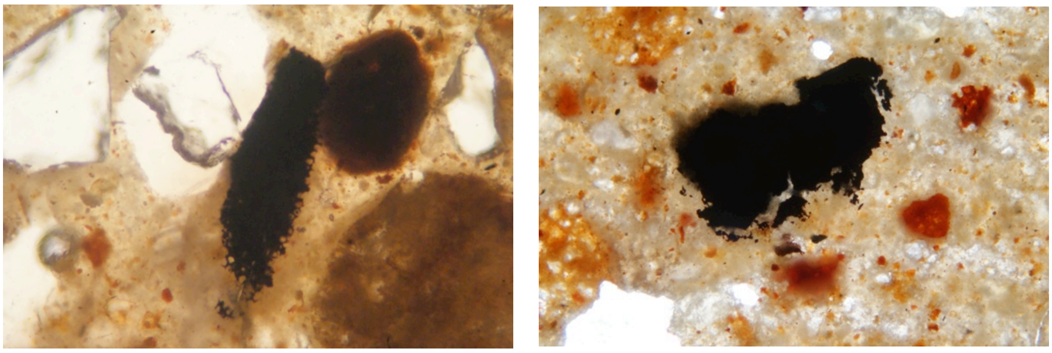


Figure 6.17 - Possible lignite in sample TT-WS 1(left) a and TT-WS 3c (right). Scale of micrographs is 1 mm by 0.66 mm.

An argument could be made for the use of charcoal or wood, however. Much of the area of the Thracian peninsula is covered in dense forests as well as a long tradition of charcoal production. Many of today's residents of the region make their living producing mass quantities of charcoal for sale in large cities such as Istanbul (Byfield, 1995). Also, the efficiency of charcoal is higher than regular wood and would require less total fuel material to achieve the necessary temperatures (Olson, 1991: 412). On the other hand, the additional time and labour needed for the production of charcoal means the cost for charcoal would be significantly more than wood.

Table 6.3 - Averages instances of carbonised organic material per core in mortar samples from the Water Supply of Constantinople and Anastasian Wall.

Mortar Sample	Site Name	Carbonised Organic Material per Core
	Water Supply of Constantinople	
TT-WS 1	Kurşunlugerme	3.1
TT-WS 2	Kumarlıdere	3.3
TT-WS 3	Keçigerme	0.3
TT-WS 4	Büyükgerme	0.3
TT-WS 5	Karatepe	0.4
TT-WS 6	Karatepe	3.0
	Anastasian Wall	
TT-AW 1	Karanlik Ayazma Sirti	1.3
TT-AW 2	Belgrat Tower	7.3
TT-AW 3	Belgrat Tower	7.0
TT-AW 4	Çilingir	5.0
TT-AW 5	Büyük Bedesten	0.5
TT-AW 6	South Dervis Kapı	0.0
TT-AW 7	South Dervis Kapı	0.0
TT-AW 8	Evçik	3.3

The third type of organic material found in these mortars is small plant vegetation (Figure 6.18) such as grasses or brush. These are only found in larger pieces of brick aggregate and do not have the typical indications of being burnt. Instead, like the surrounding brick, they are typically red, fibrous, and of a larger size than organic materials found in the lime binder.

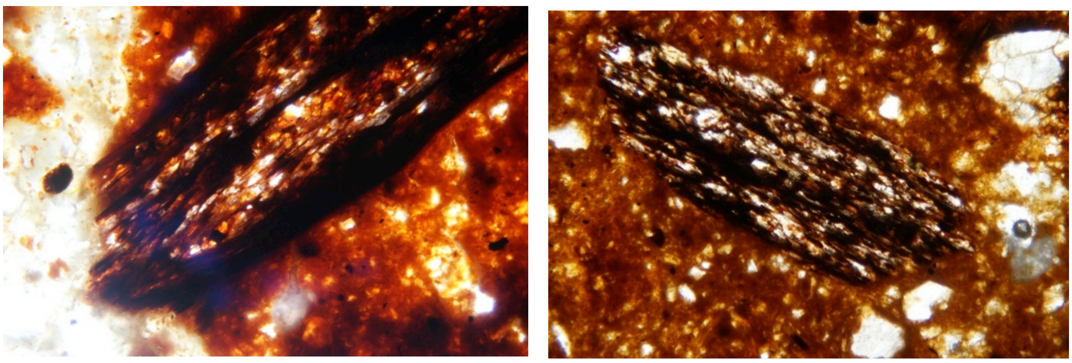


Figure 6.18 - Organic material in brick aggregate of sample TT-WS 1b (left) and TT-AW 3a (right). Scale of micrograph is 1 mm by 0.66 mm.

6.3 - Constituent Quantification

Using the digital image analysis, the quantity of the main materials of each mortar core was estimated using the point counting method. The statistical results of each core were compiled to reflect an average percentage of lime, brick, and sand throughout the entire sample. For a full list of the data obtained from point counting analysis, see Table A3.1 – Table A3.4 of the Appendix 3.

Table 6.4 - Percentages of primary constituents of mortars from the Water Supply of Constantinople and Anastasian Wall.

Mortar Sample	Site Name	Lime	Sand	Brick
Water Supply of Constantinople				
TT-WS 1	Kurşunlugerme	43%	21%	36%
TT-WS 2	Kumarlıdere	37%	11%	52%
TT-WS 3	Keçigerme	49%	8%	43%
TT-WS 4	Büyükgerme	32%	9%	59%
TT-WS 5	Karatepe	43%	8%	49%
TT-WS 6	Karatepe	37%	13%	50%
Anastasian Wall				
TT-AW 1	Karanlik Ayazma Sirti	38%	13%	49%
TT-AW 2	Belgrat Tower	26%	27%	47%
TT-AW 3	Belgrat Tower	30%	33%	37%
TT-AW 4	Çilingir	36%	8%	55%
TT-AW 5	Büyük Bedesten	25%	5%	69%
TT-AW 6	South Dervis Kapı	24%	9%	67%
TT-AW 7	South Dervis Kapı	33%	8%	59%
TT-AW 8	Evçik	25%	35%	40%

The proportions of the primary materials estimated by point counting analysis showed variations between all samples. This can be attributed to a number of factors such as a limited sample area, poor amalgamation of materials on the microscopic levels, and typical statistical variations of the point counting methods. However, some important observations were made.

Firstly, compared to the to the rest of the mortars of the water supply, the sample from Kurşunlugerme (TT-WS 1) had the least amount of brick material. To make up for this low percentage, the highest quantity of coarse sand grains of all of the water supply samples was used. Keçigerme (TT-WS 3) had the lowest percentage of sand but the highest quantity of lime. The most surprising aspect from the samples of the water supply came from Karatepe (TT-WS 6). Despite being classified as the poorest quality mortar from observations made while preparing the sample for thin section, the ratio of sand, brick, and lime are average. Only looking at these figures, it could be assumed that the structural mortar from Karatepe would be no different than the sample from Kumarlıdere. This is a clear indication of the limitations of relying solely on mortar proportions for quality standards.

Table 6.5 - Amount of sand temper versus sand aggregate of the mortar samples of the Water Supply of Constantinople and Anastasian Wall.

Mortar Sample	Site Name	Sand in Brick	Sand in Lime	Quantity Difference
Water Supply of Constantinople				
TT-WS 1	Kurşunlugerme	4%	21%	17%
TT-WS 2	Kumarlıdere	7%	10%	3%
TT-WS 3	Keçigerme	6%	8%	2%
TT-WS 4	Büyükgerme	10%	9%	-1%
TT-WS 5	Karatepe	9%	8%	-1%
TT-WS 6	Karatepe	9%	13%	4%
Anastasian Wall				
TT-AW 1	Karanlik Ayazma Sirti	4%	13%	9%
TT-AW 2	Belgrat Tower	6%	23%	17%
TT-AW 3	Belgrat Tower	4%	31%	27%
TT-AW 4	Çilingir	8%	8%	0%
TT-AW 5	Büyük Bedesten	11%	5%	-6%
TT-AW 6	South Dervis Kapı	12%	8%	-4%
TT-AW 7	South Dervis Kapı	10%	6%	-4%
TT-AW 8	Evçik	7%	32%	25%

The samples from the Anastasian Wall show the most variation in material proportions. Samples TT-AW 4, 5, 6, and 7 have relatively low quantities of sand but very high quantities of brick material. Samples 2, 3, and 8 have very high quantities of sand and a relatively low proportion of lime. The most interesting aspect of this investigation is the findings from Büyük Bedesten (TT-AW 5). During the initial examination of the mortar, it was obvious that it was a very light and durable material. From this analysis, it showed the highest value of brick of all samples from the water supply and long wall at almost 70%, 10% more than the mortar sample from the water supply with the highest brick content. In addition, TT-AW 5 had 38% less sand then the next lowest sample. These two factors are key indicators of the noticeable lightness of the mortar sample from Büyük Bedesten. Again, while the mortar samples from South Derviş Kapı had very similar proportions of materials, the conclusions made from thin section preparation show that these were of poor quality.

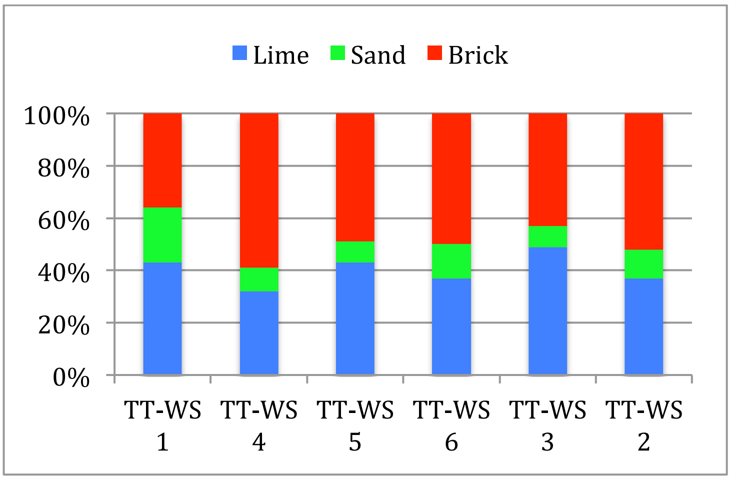


Chart 6.1 - Proportions of brick, sand, and lime of mortar samples from the Water Supply of Constantinople, ordered west to east.

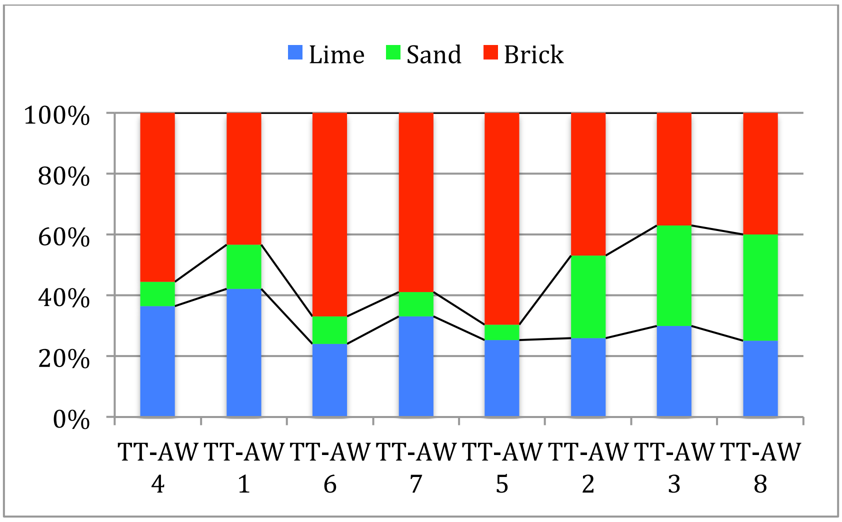


Chart 6.2 - Proportions of brick, sand, and lime of mortar samples from the Anastasian Wall, ordered south to north.

Since these tables are set up in numerical order, these is little that can be said about the change in material proportion based on location. To investigate whether there was any corrolation, the proportions of materials used in the mortars were charted based on geographical location. For the Water Supply of Constantinople, samples were plotted from the western-most collection site at Kusunlugerme to the

Kumarlıdere in the east (Chart 6.1). Similarly, the material constituents of the mortars from the Anastasian Wall were plotted from the southern-most collection site at Cilingir to the northern terminous at Evcik (Chart 6.2).

Unfortunately, little can be said about the relationship between the geographical situation of the collection sites and their mortars' material components. However, the plot for the Anastasian Wall revealed an interesting shift. In the three mortar samples from the two collection sites (Belgrat Tower and Evçik) closest to the Black Sea coast, there is a drastic increase in the percentage of sand. Samples TT-AW 2, 3, and 8 also had the largest sand grains. Since the area around Evçik is made up of weathered sandstone cliffs, larger quantities of sand were being used, and thin section analysis indicated that the sand grains were both larger and smoother in samples TT-AW 2, 3, and 8, it can be assumed that local sand resources were used.

6.4 - SEM/EBSD

Following the standard methods employed by many of the scientific mortar studies (such as Baronio and Binda, 1997; Cazalla et al., 2000; Moropoulou et al., 2002; Böke et al., 2006) explained in Chapter 4, SEM/EBSD analysis was performed on selected specimens of the mortar samples and brick aggregate collected from the Anastasian Wall and Water Supply of Constantinople. The results of such approaches did not always yield significant results for answering the large research question regarding this project. However, they all succeeded in providing evidence for the understanding of the microscopic characteristics of these mortars.

Not surprisingly, the analysis of mortar materials from both sites proved useful in understanding the porosymetry and microcrystalline structure of mortar samples from both sites. All of the samples indicated that the mortar was quite dense with few areas of large pores.

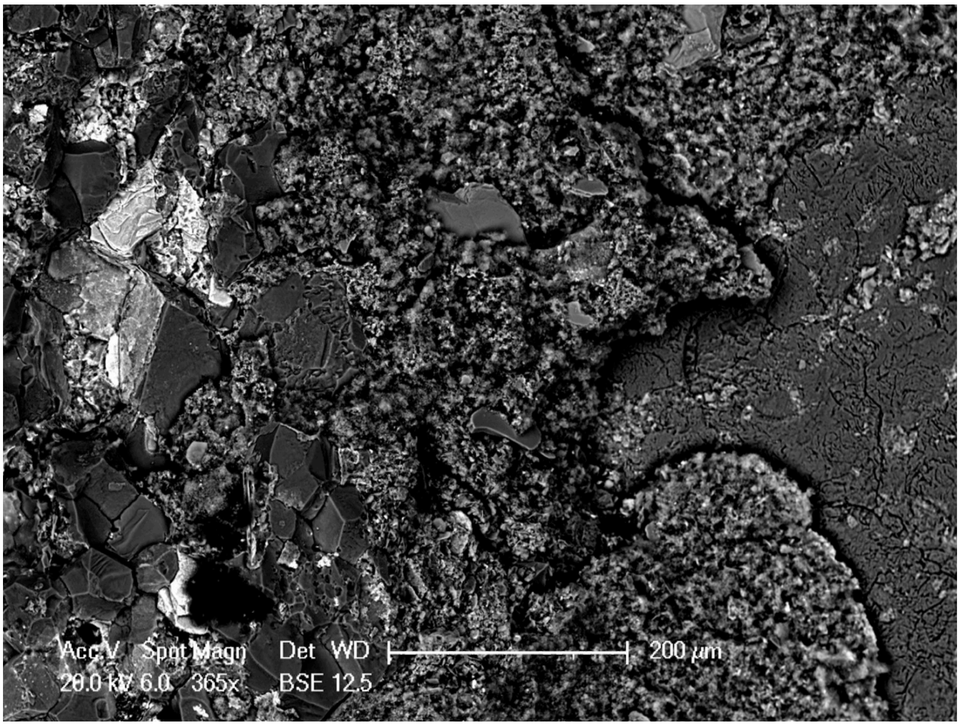


Figure 6.19 - SEM photograph of sample TT-WS 1 (Kurşunlugerme)–

It was clear in many areas that the quartz sand grains showed little weathering, indicated by the defined crystalline structures (Figure 6.19). In cases of large pores, leaching of lime is indicated by the secondary formation of calcite crystals (Figure 6.20). This is most likely due to moisture percolating through the mortar matrix.

Figure 6.20 - SEM photograph of large pore from sample TT-WS 4 (Büyükgerme) with secondary calcite crystal formations.

Much of the results of EBSD reaffirmed the petrographic analysis that had been performed prior. However, this did provide more detailed information regarding the presence of key minerals necessary for a pozzolanic reaction. For instance, all results taken of brick aggregate and the binding material showed high levels of aluminates and silicates. These elements were identified at their highest levels in pieces of brick aggregate, along with low quantities of iron, potassium, and magnesium (Chart 6.3).

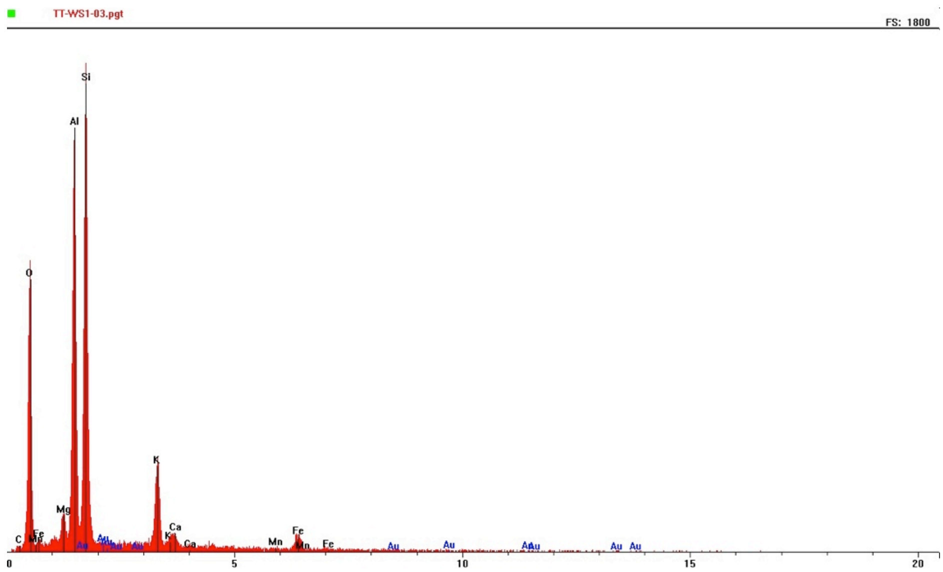


Chart 6.3 - EBSD chart of brick from sample TT-WS 1.

The lime-based binder also showed high levels of aluminates and silicates from the large quantity of pulverised brick used as pozzolana (Chart 6.4). The large peaks of calcium with no significant quantities of magnesium suggests that the limestone was most likely not dolomitic. This will be an important piece of information in future analysis of local stone materials for determining the provenance of lime-producing stone materials.

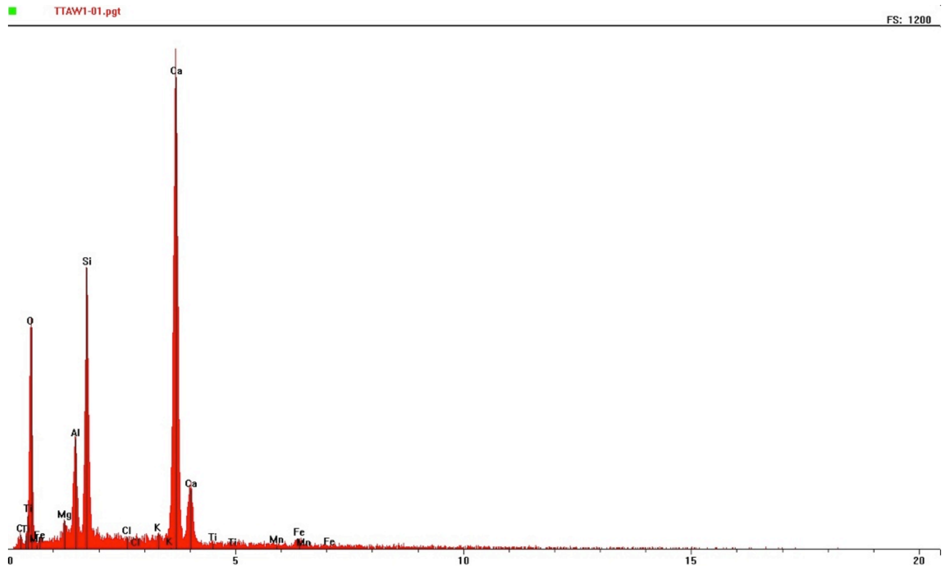


Chart 6.4 - EBSD chart of lime-based binder from sample TT-WS 1.

In the case of the sand grains, EBSD analysis showed that they were exclusively silica (Chart 6.5). However, as indicated in the previous section on thin section petrographic analysis, there was evidence of other materials most likely included with the sand grains, most notably iron and magnesium-rich olivine. Because of the infrequency of these materials in all of the samples tested and the extremely small area of focus used in SEM/EBSD analysis, these were not identified during this analysis.

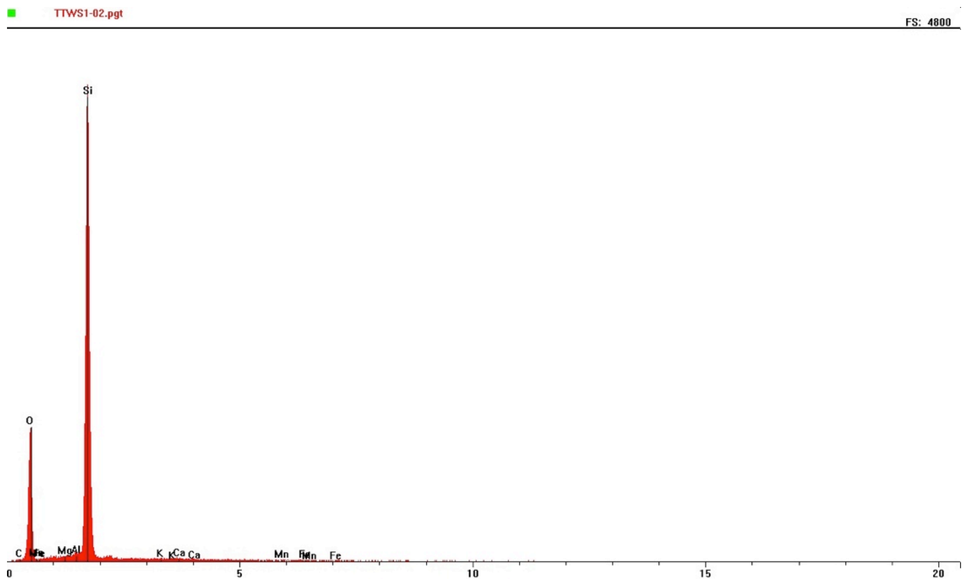


Chart 6.5 - EBSD chart of quartz sand grain from sample TT-WS 1.

Comparatively, all of the samples provided similar data. It was found that the magnitude of aluminates and silicates in the binder varied slightly in every test.

However, this did not prove to be significant since these differences were found within the same mortar samples, most likely due to variations in frequency of pulverised brick within the same sample observed from petrographic analysis. Also, based on the limited number of mortar samples analysed and the few charts available for each sample, no solid conclusions can be made about any major differences in materials such as the type of carbonate rock used to produce the binder or brick mineralogy.

6.5 - XRD Analysis of Brick Aggregate

Because of the limitations of SEM and EBSD analysis in producing comparative data for raw material provenance, brick aggregate samples from a selection of the mortar samples were prepared for XRD analysis. Brick specimens were prepared by extracting them from the surrounding mortar matrix and polished to remove the outer layer that would have chemically reacted with the lime binder. This provided the ability to record the macroscopic attributes of original brick fabric before being analysed.

First the colour of these prepared brick samples was recorded using a Munsell Soil Colour Chart. This was done in order to identify if there were any discernible patterns between brick colour and mineralogical data from XRD analysis. In addition, this could be used to test the usefulness of the method applied by Peacock (1977) in describing the clay sources of stamped bricks along the English Channel. The results of the colour matching of brick aggregate specimens from the Water Supply and Long Wall are as follows (Table 6.6):

Table 6.6 - Colour values for brick aggregate samples from mortars of the Water Supply of Constantinople and Anastasian Wall.

Mortar Sample	Brick Sample	Site Name	Colour Hue	Value/ Chroma
Water Supply of Constantinople				
TT-WS 1	A	Kurşunlugerme	7.5YR	7/6
TT-WS 1	B	Kurşunlugerme	7.5YR	6/8
TT-WS 2	A	Kumarlıdere	7.5YR	6/6
TT-WS 2	B	Kumarlıdere	7.5YR	7/6
TT-WS 5	A	Karatepe	7.5YR	7/4
TT-WS 5	B	Karatepe	5YR	7/8
Anastasian Wall				
TT-AW 5	A	Büyük Bedesten	7.5YR	7/6
TT-AW 5	B	Büyük Bedesten	5YR	5/6
TT-AW 6	A	South Dervis Kapı	7.5YR	7/6
TT-AW 6	B	South Dervis Kapı	7.5YR	7/6
TT-AW 8	A	Evçik	7.5YR	7/6
TT-AW 8	B	Evçik	7.5YR	7/6

Almost all of the brick aggregate specimens were matched to colours in 7.5YR colour hue of the Munsell Soil Colour Chart. Breaking it down even further, all but one of the specimens from the Anastasian Wall was of the same hue, value and chroma. From the colour comparison, the greatest differences in colour were found in pieces of brick within the mortar samples TT-WS 1, TT-WS 2 and most significantly TT-AW 5.

Of these specimens of brick aggregate, TT-WS 1 A and B, TT-WS 2 A and B, and TT-AW 5 A and B were chosen for XRD analysis. These represented the greatest differences in colour among specimens within the same mortar sample as well as throughout all that were recorded for colour comparison. It was suspected that these brick samples would indicate a difference in the mineralogical composition of brick samples with stark colour contrasts. However, after the analysis was completed, they were all found to be of the same composition. Below, each of the samples have been overlaid on the same chart to show their similarities:

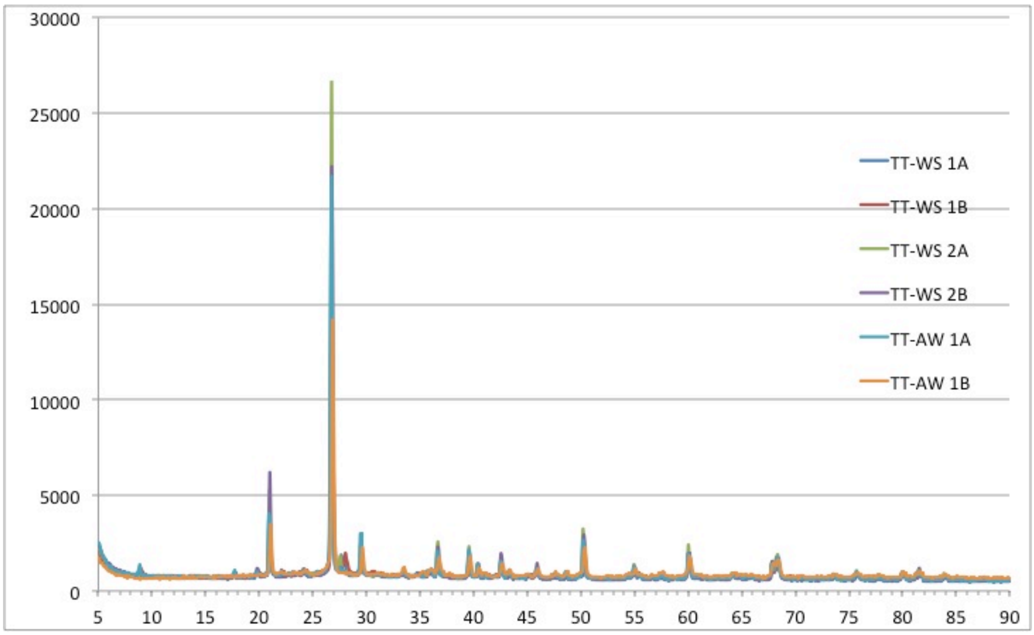


Chart 6.6 - Overlap of x-ray diffraction pattern. For the XRD patterns of individual brick samples, see charts in section A4.2 in Appendix 4.

The resulting data for each brick specimen was compiled and compared with a database of XRD results from a wide range of materials. The closest match for all of these brick specimens is a substance called nontronite, which is the product of weathered biotite (mica group) and basalt (see Bischoff, 1972 for detailed discussion).

The first clear conclusion from the XRD analysis is that, at least in the case of samples TT-WS 1, 2, and TT-AW 1, the brick aggregates must have come from the same raw clay source. The second conclusion is that colour had absolutely no bearing on the type of raw clay used from brick production and should only be attributed to firing conditions such as temperature and oxygen levels. Finally, from a general comparison with the XRD results of bricks from Hagia Sophia (Moropoulou, Çakmak, and Polikreti, 2002: 368), they had very similar presence and intensities of minerals such as feldspar, illite, diopside, anorthite, and hematite. Because of the variations of clay mineral types in Turkish Thrace (Ataman and Gökçen, 1981), it is no coincidence that these are similar. It can be safe to assume that the brick material used in the mortars for the Water Supply of Constantinople and Anastasian Wall come from the same clay sources, and likely even the same production sites.

6.6 - Conclusions

Investigations into the basic qualities and makeup of mortars from the Water Supply of Constantinople and Anastasian Wall have revealed some important aspects of material production and technology. Macroscopic observations from mortar sample collection and preparation indicated variations in the friability of the mortar matrixes, the types of small aggregate, and the differences in colour and morphology. For instance, it was evident that all mortars from both the water supply and long wall contained three main components: brick, lime, and sand. Only the sample from Kurşunlugerme (TT-WS 1) had an addition to these in the form of small pebble aggregate. Because of the smooth nature of these pebbles, it is assumed that they came from river beds. However, it was the combination of scientific techniques that revealed the most about these mortars.

Almost all of the mortars from the water supply and long wall showed evidence of being produced with care and purpose. The absense of large pores indicated the mortar was compaceted sufficiently. The distribution of sand, brick aggregate, and brick dust, showed that the great majority of mortars were mixed thoroughly. Also, tmortars from both structures generally contained little quantities of poorly burnt or slaked lime. While these factors indicate that quality control was an important aspect of the material production and construction processes, two related samples stand out as the exceptions. Both samples from the small aqueduct bridge of Karatepe (TT-WS 5 and 6) were examples of poor mortars, unrelated to their constituent materials. First of all, sample TT-WS 6 had little finely crushed brick powder within its binding matrix and had extremely large pores. These were clear indications of inadiquite compression of the mortar and little care for the pozzolanic properties of available from crushed ceramic materials.

Second, sample TT-WS 5 from Karatepe was the most decieving mortar sample. It was only through petrographic preparation and analysis that it was noticed that this piece of channel lining mortar had evidence of hasty production and application. This was first noticed during the coring process when a large pocket was found dirrectly under the surface that the water would have passed over (Figure 5.2 on page

89). Through petrographic examination, this pocket was found to be filled with organic material (Figure 6.13), and then paved over. While this should not be considered an intentional addition, it does show the lack of quality control during on the most important aspect to the construction of the water supply: the waterproofing layer linging the channel. This, along with the inclusions of possible fragments of mortar from a previous phase (Figure 6.12) shows that both mortars from Karatepe were examples of hasty work. This would most likely indicate repairs in order for water to continue to flow to Constantinople as quickly as possible.

Other petrographic observations include more clues to the material production processes. The inclusion of organic materials in the binding materials of the mortars were determined to be spent fuels. While it was not possible to conclusively determine whether lignite (Figure 6.17) was used alongside wood or charcoal fuels, since deposites are known in the area, it is still a strong possibility.

Probably the most interesting conclusion from the study of mortars from the water supply and long wall was the XRD results of brick aggregates. Despite the brick aggregate samples coming from mortars collected from regions furthest apart, from two distinct structurs with decades separating their construction, and the the differences in colour (Table 6.6) it was likely that all of the brick material came from the same raw clay source. Even more interesting is the relationship with mortars from sites within the city of constantinople, such as the land walls and Hagia Sophia, indicating that there was some form of centralised organisation of raw material resources. Most likely, this represents something more important: since brick production sites were usually located near the source clays (Bardill, 2004: 3-4) it is probably that the brick production industry of Constantinople was also an essential aspect of the construction of the city's water supply system as well as the Anastasian Wall.

What does all of this say about the production and workforce? A variation in the proportions mortars constituents indicates that both local (sand) and regional raw (brick) materials were being used. Care was taken to produce high quality mortars depending on the necessary function, like the case of the mortar joint from Büyük Bedesten. However, possible hasty repairs of the water supply channel at Karatepe seemed to have an affect on quality control. The most basic evidence for the construction organisation of these sytems is the continuity of materials used in the mortars. Despite the differences in proportions of materials and overall quality, every mortar sample tested used the same three main mortar components: sand, crushed brick, and lime.

Chapter 7 - SCALE AND MAN-POWER ECONOMY

I ask you! Just compare with the vast monuments of this vital aqueduct network those useless pyramids, or the good-for-nothing tourist attractions of the Greeks!

Frontinus, *De Aquaeductu*, I 16

The technology of building materials and what they say about the organisation of construction and quality control is only the first step towards understanding the larger picture—the building history of a great city like Constantinople. In the case of the Water Supply of Constantinople and the Anastasian Wall, the construction materials played a vital role in our understanding and evaluation of their overall scale and longevity. However, in order to fully understand the scale of these building projects, it is necessary to calculate and estimate their total size. This, in turn, provides an idea of the material and labour requirements of the building operations.

While the previous chapter on mortar analysis only looked at the fifth-century phase of the water supply and the long wall, this chapter also includes the first long-distance phase of the water supply from the fourth century. The reason for adding this system was primarily in order to have another case study for further structural comparisons. In addition, this provides a prime opportunity to expand on the relationship between the two phases of the long distance water supply from structural, organisational and logistical perspectives.

What is the true scale of these structures? One of the recurrent issues that arose while studying the mortars of these systems was trying to understand their true scale. In the hope of gaining an understanding of the magnitude of these structures, the survey data from the Anastasian Wall Project, as well as comparative analysis of similar structural forms of the classical and late antique world (other water supply systems and fortification walls) were analysed and measured. By calculating the length and, ultimately volumes of the fourth and fifth-century phases of the water supply and long wall, this chapter aims to provide a new perspective on monumentality in the Late Antique world.

The next question arising from the analysis of these systems is what we can deduce from their scale in terms of material and production requirements. This chapter continues by applying the estimates of the total structural volume, surface area and dimensions of individual architectural elements of the water supply and long wall, in the hope of deconstructing these systems into their individual material components.

Finally, can an understanding of the labour requirements of the Water Supply of Constantinople and Anastasian Wall be obtained through the analysis of their scale and material requirements? The final objective of this chapter is to investigate the man-power requirements of these systems through the stages of material production, material transport, and construction. This is by far the most hypothetical aspect of this study and relies on numerous assumptions. Without knowing the exact sources of most raw materials (see section 2.2.3 – Architecture of the Anastasian Wall) the discussion of transportation must rely on hypothetical scenarios based on comparative evidence generalities.

Before beginning a detailed discussion of the evidence, it should be clearly noted that all figures used in this chapter are estimates, and to a greater or lesser degree hypothetical. While to my knowledge, all formulae, measurements, calculations and constants accurately reflect the original sources and integrity of their scholarship, any miscalculations, inconsistencies or omissions found in this chapter are the sole responsibility of the author. Janet DeLaine (1997: 175) addressed this important issue, saying that this type of work is built “on the understanding that all which follows will in fact be read as hypothesis.”

7.1 - Understanding the Scale of the Systems

Both the Water Supply of Constantinople and the Anastasian Wall can easily be considered monumental structures. Not only are they modern testaments to the former glory of the city of Constantinople but also to the architects, administration, and workforce that constructed these enormous systems. Like the colossal aqueduct bridges of Kurşunlugerme and Büyük Germe or the prominent curtain wall running beside the road to Evcik, these surviving relics are reminders of the importance of the infrastructural works in the hinterland of Constantinople.

While there is little question that these two construction projects would have been monumental in scale based on the features that still dot the landscape of Turkish Thrace, there is much more that either no longer survives or is not immediately visible. To fully understand these structures in regards to their total material and logistical construction requirements, it is the intention first to reconstruct and estimate the overall scale of the fourth and fifth-century phases of the Water Supply of Constantinople and the early sixth-century Anastasian Wall. Once an estimate of the overall sizes is determined, the second part of this section follows by deconstructing these systems into individual building material components. Furthermore, composite construction material such mortar and bricks are then broken down into their individual raw components, all in preparation for the second section of this chapter on site management, production, and construction requirements of these structures.

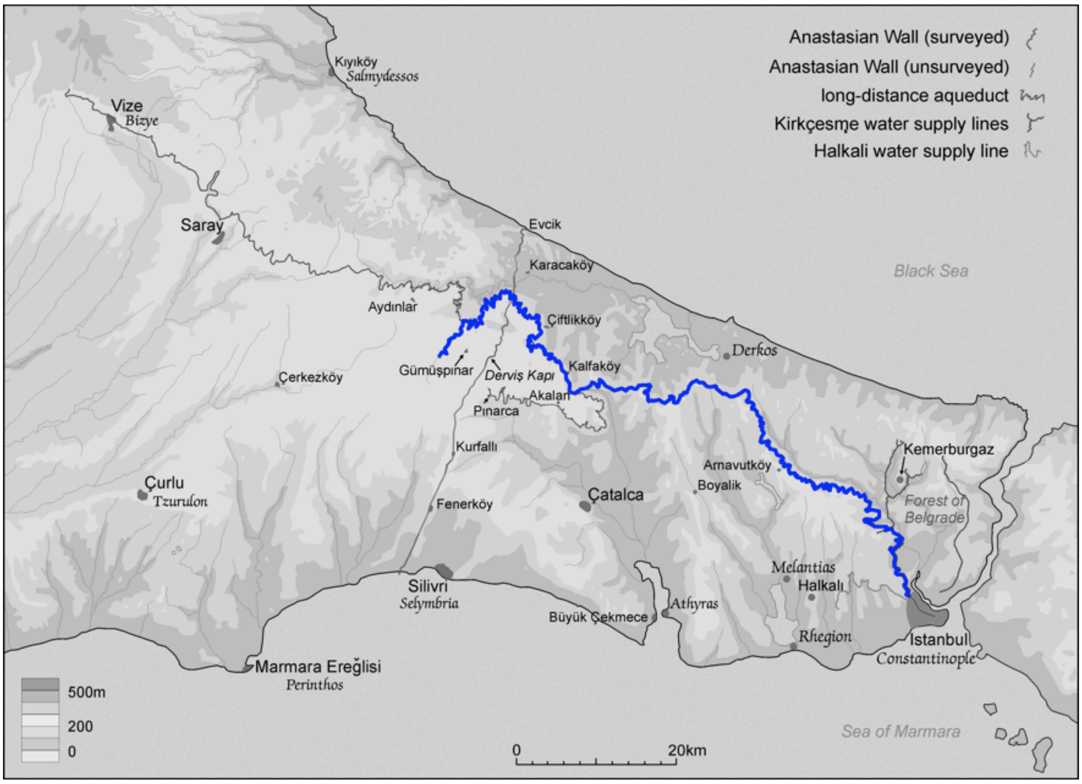
7.1.1 – Length Estimates

The first step in understanding the magnitude of the construction of the Water Supply of Constantinople and the Anastasian Wall is to obtain accurate measurements of length of the structures. However, especially in the case of the water supply, this is not as straightforward as it may seem on the surface. If one were to measure a straight line from the spring source of the water supply system at Pazarlı to the Binbirdirek cistern in Constantinople, the resulting distance would be a very poor representation of its actual length. In order to maintain the necessary slope for optimum water flow, the narrow and wide channels snake along the steep hills and valleys of northern Thrace, considerably increasing its east-west length. Even more important for this particular study is to independently study each element of the systems such as the channels and bridges that make up each phase of the water supply as well as the sections of curtain wall, towers, and forts of the long wall. Again, considering the complexity of the water supply, a substantial portion of the fourth and fifth-century lines run parallel to one another, also decreasing the direct geographical length. For a discussion of the system over time, see Chapter 2 (Figure 2.1).

FOURTH-CENTURY PHASE OF THE WATER SUPPLY

As explained in Chapter 5, the only possible way of understanding the complexity of the long distance channels of the water supply was to break them down into construction phases and channels width using the survey data and maps collected by the Anastasian Wall Project. Figures for the distances of the entirety of the water supply system have been estimated by Çeçen (1996) at 242 km, and more systematically calculated by Crow, Bardill, and Bayliss (2008) at 551 km (see Chapter 2 for further discussion). Because of the wide discrepancy of these two figures, each line of the water supply was calculated using survey maps analysed using image analysis software.

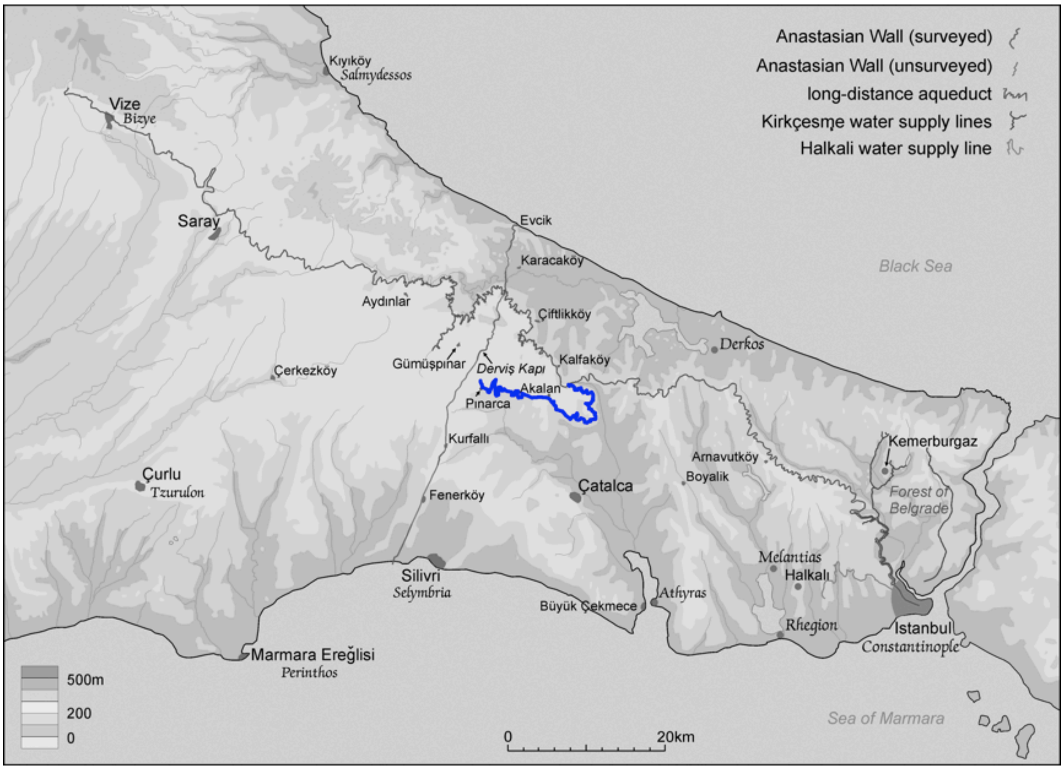
Danamandıra to Constantinople



Map 7.1 – Section of 4th-century phase of the water supply from Danamandıra to Constantinople.

By far the longest section measured, this length of channel stretched from the water source of Kaynarca Spring, just east of the village of Danamandıra, to the Theodosian land walls of Constantinople. A tributary channel from springs at Pınarca joined the main channel 60 km from the city (see below). In addition, portions of the later supply line run parallel. At a distance of over 227 km, this section is longer than the total of the fifth-century sections. However, over this distance, only 30 bridges are known to have existed with many rebuilt or replaced during the fifth century. The entire distance of this section consists of a narrow channel averaging .70 m in width.

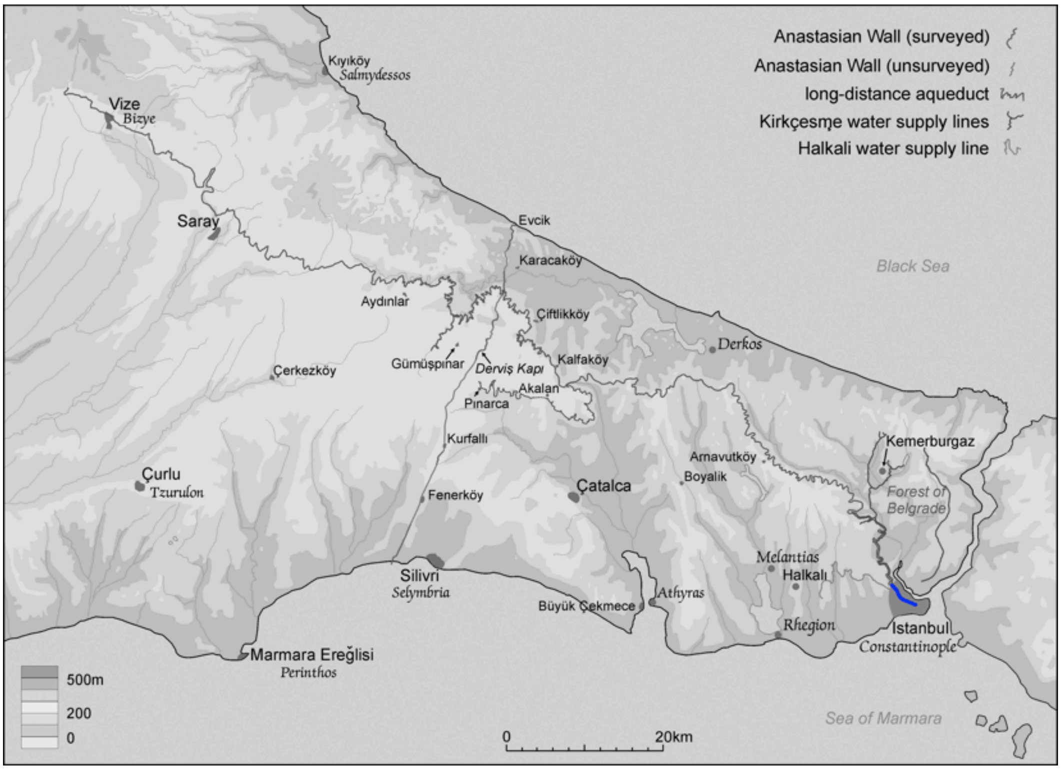
Pınarca to the junction near Dağyenice



Map 7.2 - Section of 4th-century phase of the water supply from Pınarca to Dağyenice.

This section from the fourth-century water supply line is a tributary from the springs at Pınarca, located north of the village of Pınarca and only 1.5 km east of the Anastasian Wall. Crow, Bardill, and Bayliss (2008: p) postulated that this line connected with the Danamandıra-Constantinople section at the junction 2 km west of the village of Dağyenice. Similar in build to the entire length of the fourth-century line, this is a narrow channel, averaging a little less than the previous section at .6 m wide. The total length of this section of the channel was measured at just under 41 km and contained only five aqueduct bridges.

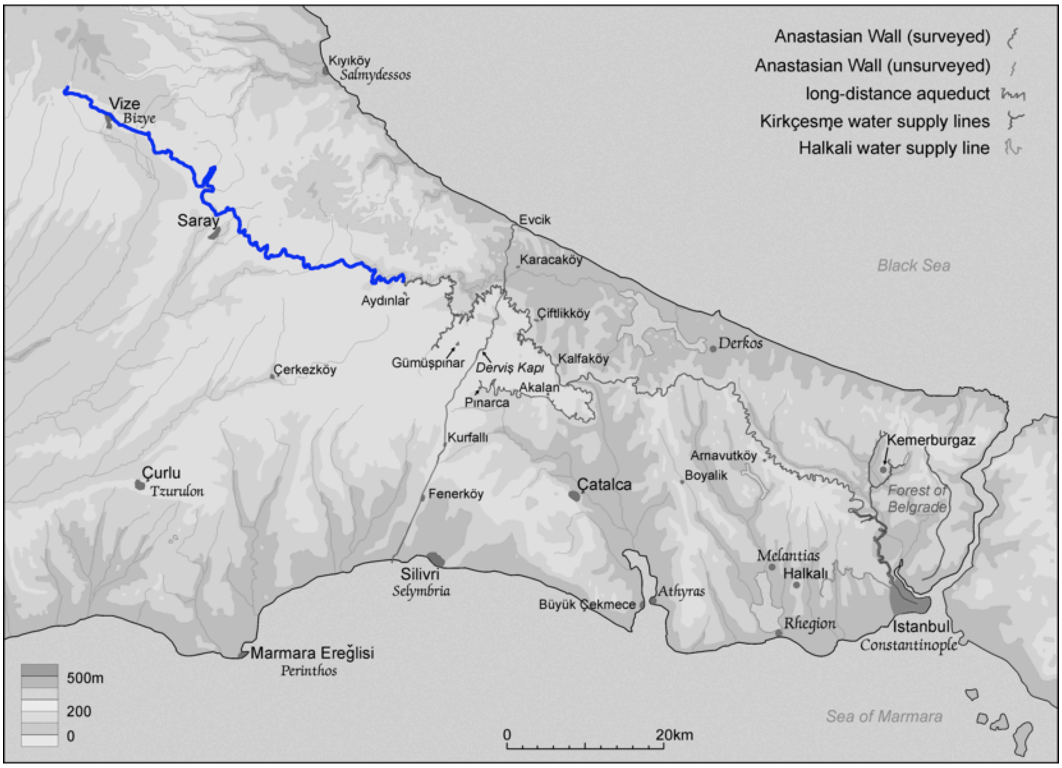
Within the City: Land Walls to Binbirdirek Cistern



Map 7.3 - Section of 4th-century phase of the water supply in Constantinople (Theodosian Land Walls to Binbirdirek Cistern).

The last section of the water supply system to be measured was from the Theodosian land walls to the Binbirdirek Cistern. While this is the shortest of all of the previous sections, it is the most important to the system's intended function: the distribution of water within the city. There is little difference between this line of the aqueduct from the previous sections apart from the significant portion that is made up of the well-known and well-preserved Aqueduct of Valens. The narrow channel averages .7 m wide and only contains the one aforementioned aqueduct bridge. This final line within the city walls measures about 3,350 m in total but spans more than three-quarters of the city of Constantinople. It should be noted that this figure only takes the main supply line in to consideration and does not include the secondary supply networks to the many cisterns along its path.

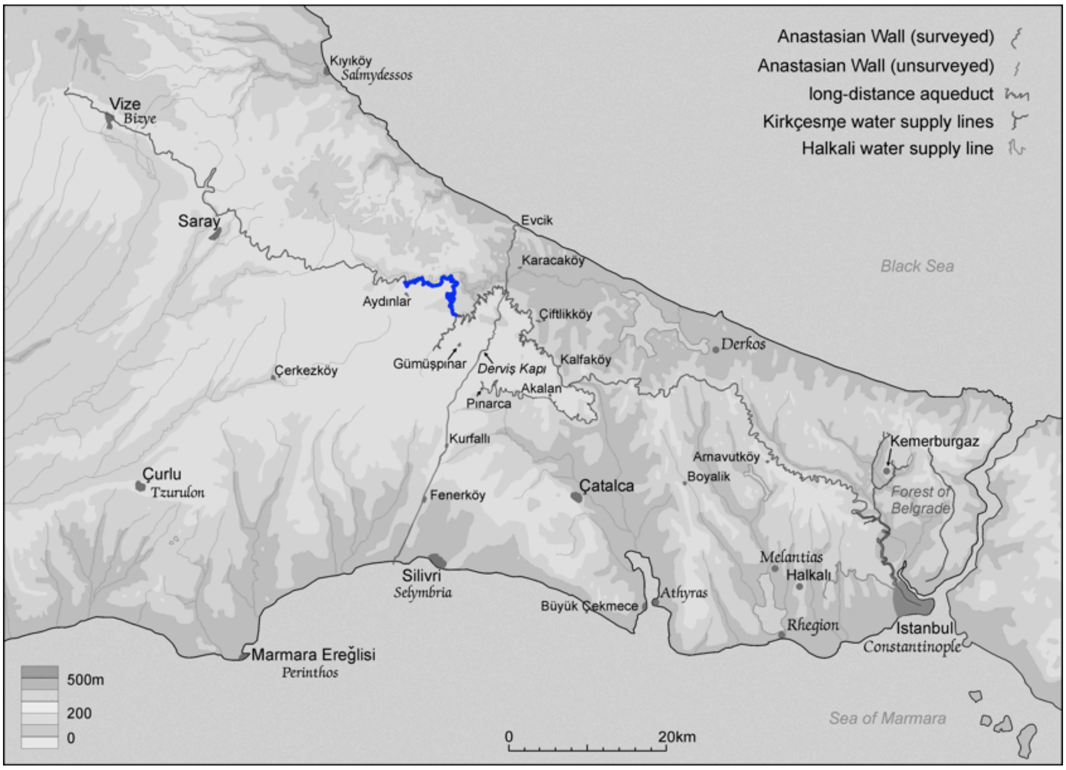
Pazarlı Spring to Manganez Dere (K9)



Map 7.4 - Section of 5th-century phase of the water supply from the furthest water source (Pazarlı spring) to Manganez Dere bridge (K9).

The first part of the water supply to be measured was the narrow channel line that extends furthest west. This begins at the spring source at Pazarlı spring (240 m ASL), continues through the town of Vize to the aqueduct bridge of Manganez Dere. With little variation, this channel averages a width of 0.7 m, qualifying it as a narrow channel. The total length of this stretch of channel measures a little over 51 km, which included 13 bridges (Crow, Bardill, and Bayliss, 2008: 29-42).

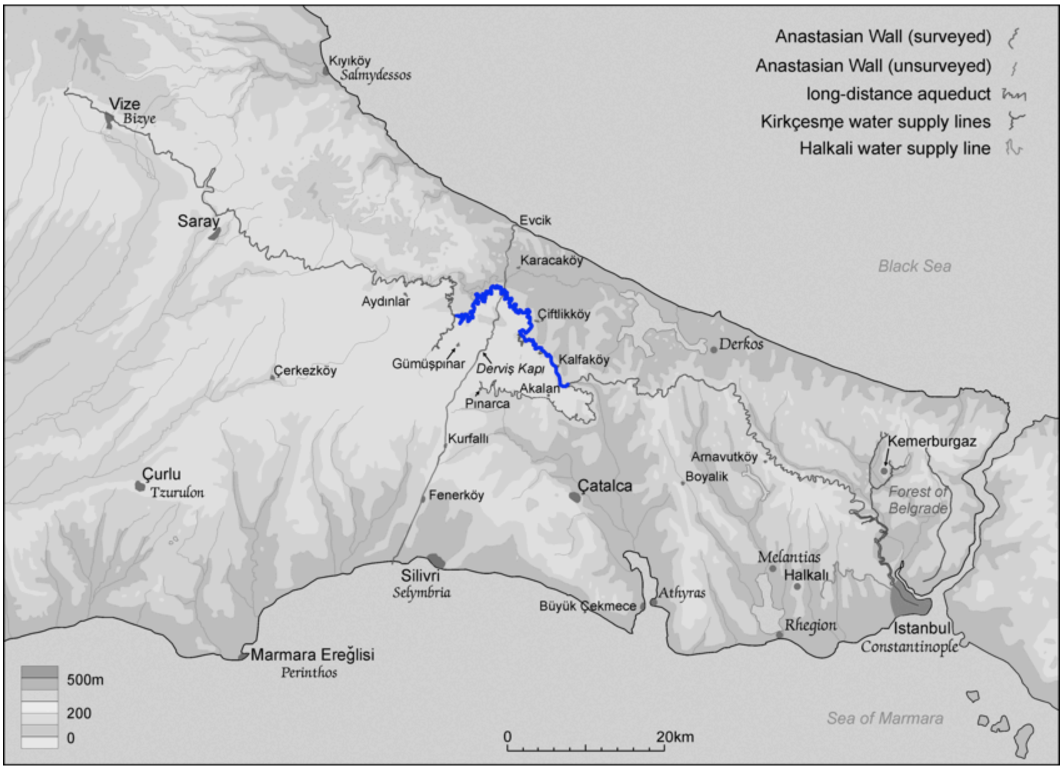
Manganez Dere (K9) to Ballıgerme (K18)



Map 7.5 - Section of 5th-century phase of the water supply from Manganez Dere (K9) to Ballıgerme (K18).

This next section of the fifth-century line of the water supply line continues from the last measured section at the beginning of Manganez Dere. A small length of broad tunnel was observed on the east side of the site of the bridge, marking the beginning of the calculations for the length of this stretch. Over the entire distance of this section, the channel remains wide at an average of 1.6 m. The distance from the last measured section to Ballıgerme was found to stretch over 80 km and included 13 bridges (Crow, Bardill, and Bayliss, 2008: 42-53).

Ballıgerme (K18) to Kalfaköy



Map 7.6 - Section of 5th-century phase of the water supply from Ballıgerme (K18) to Kalfaköy.

The final section of channel from the fifth-century addition to the water supply system of Constantinople continues from Ballıgerme and for the majority of the distance, runs parallel with the fourth-century phase, but for much of its length at a lower level. The channel, averaging 1.5 m wide, travels a distance of a little over 51 km to its furthest known location near the village of Kalfaköy. The exact location where the fifth-century stretch merges with the fourth-century line is unknown but based on the surviving evidence, it was most likely somewhere from Karılpınar Bridge (K32) and the line southeast of Kalfaköy. Not only does this section have the most bridges at 31 (Crow, Bardill, and Bayliss, 2008: 54-75), it also contains all of the largest bridges from the entire water supply system with the exception of the Aqueduct of Valens in Constantinople.

Table 7.1 - Channel type and length of the different lines of the Water Supply of Constantinople by construction phase.

Line	Channel	Length (km)
4th Century System		
Danamandıra to Constantinople	Narrow	227.24
Pınarca to junction near Dağyenice	Narrow	40.64
Land Walls to Binbirdirek Cistern	Narrow	3.35
5th Century System		
Pazarlı to Manganez Dere (K9)	Narrow	51.19
Manganez Dere (K9) to Ballıgerme (K18)	Broad	80.26
Ballıgerme (K18) to Kalfaköy	Broad	51.26
2nd Century System		
Hadrianic System		46.69
Total Length		**500.63 km**

Table 7.1 provides the measurements for each section discussed above of the fourth and fifth-century lines of the water supply as well as the calculations for the separate Hadrianic system that was still in use through the Early Ottoman times. The final totals (Table 7.2) indicate that there is a marked difference in the total length of the fourth and fifth-century lines of the water supply. As mentioned in Chapter 2, the length of the entire functioning system of the water supply in the fifth century is just over 500 km. This was made up of the fourth and fifth-century phases as well as the second century Hadrianic water supply system. The fourth-century lines, which begin the long distance supply, make up 271 km of this length. For comparison, if all of the lines of this phase were pulled into a straight line, it would reach from the Trafalgar Square in London to York Minster in York. This is almost three times longer than Rome's longest aqueduct; the 91 km-long Aqua Marcia (Hodge, 1992: 347) and over 100 km longer than Jordan's Gadara Aqueduct (Döring, 2007). Over the long distance of the fourth-century phase, 36 bridges were built to carry the water over the varying terrain of Constantinople's hinterland.

Table 7.2 - Total length of the fourth and fifth-century phases of the Water Supply of Constantinople.

Water Supply Line	Length
4th Century	**271 km**
5th Century	**183 km**

Compared to the 36 bridges from the fourth-century phase of Valens, the fifth-century water supply required 52 new locations for aqueduct bridges and 16 fourth-century bridges to be rebuilt. However, the fifth-century addition is much shorter than the fourth-century line at 183 km. This is still twice as long at the Aqua Marcia and around 13 km longer than the Gadara Aqueduct. With this 88km difference between the two systems of the two phases of the long-distance Constantinopolitan water supply system, it is difficult to keep from categorising the fifth-century line as 'smaller'. As we will see in the next section on volume estimates, it can be deceiving to base the construction requirements of these structures solely on their length.

ANASTASIAN WALL

The length of Anastasian Wall was considerably easier to calculate. This should not imply that the structure of the wall is any less intricate. It does, however, reflect the difference in function of the two structures. Simply put, while the water supply system has to follow a set path to ensure the necessary gradient for water flow, the long wall has very little decreeing its intended path. The key features of the path of the water supply such as harsh twists, turns, and double backs simply do not exist along the wall. Usually any significant deviation from a straight line is to avoid large valleys and to maintain a prominent position on high ground.

The starting point for measurement was at the southernmost location of the wall, which extends some 160 m out into the Sea of Marmara, just west of the city of Silivri (see Crow et al., forthcoming). The total distance from this point in the south to the northernmost extent at Evcik along the Black sea coast was calculated at over 52 km. A straight line drawn from the beginning of the wall at the Sea of Marmara to the end at the Black Sea, measures 47 km, meaning that there is only 5km discrepancy. Compared to the 227 km distance calculated for the stretch of channel from Danamandıra to the land walls of Constantinople, a straight line only measures a little less than 80 km. This 5km difference shows just how little the direction of the wall changes compared to the 65% decrease in east to west distance of this section of the fourth-century water supply.

7.1.2 – Total Volumetric Estimates

Having established estimates of the total distances of the fourth and fifth-century water supply lines and the Anastasian wall, it is now possible to ascertain a total volume of these structures. However, the most intricate portion of these calculations comes from the numerous bridges that play a more than significant role in the water supply.

Since the methods used to calculate the volume and surface area of all of these structures have already been reviewed in Chapter 5, this section will not go into the details of individual bridges or other singular units of the water supply or long wall. Instead, the data obtained from these formulas will be discussed as whole sections of channel or wall and collective structural features. For more information on individual bridges, see tables in section A2.1.1 of Appendix 2.

WATER SUPPLY - AQUEDUCT BRIDGES

Since there are no set standards for the size of the bridge structures due to their function as elevated spans across natural terrain, it would be impossible to choose a single aqueduct bridge as an average representation for the whole system. Fortunately, extensive data obtained through surveys of the water supply facilitated the calculations of many of the bridges. Topographical data of the water supply lines, as well as comparative analysis of similar bridges also proved advantageous for estimating bridges that were either unable to be surveyed or had insufficient data.

There are seven main variables used to measure these bridges, as outlined in greater detail in Chapter 5. These are width of the bridge, height of the bridge, length of the bridge at the top, length of the bridge at the base, arch height of the tier, arch width of the tier, and number of arches of the tier. For the primary source of the measurements collected on the bridges outside the land walls, see Crow, Bardill, and Bayliss (2008). For the primary sources of the data used in the chapter regarding the Aqueduct of Valens, see Dalman and Wittek (1933). All of these measurements (in black), as well as the measurements estimated for this project (in red), are also catalogued in Section A3 of the Appendix.

The fourth-century network of the water supply had a total of 36 bridges over its full length of 271 km. All of these bridges, including the largest bridge, the Aqueduct of Valens, can be combined to provide a total structural volume of over 115,000 m^3. Interestingly, 67% of this is made up of the Aqueduct of Valens, which was estimated to be almost 78,000 m^3. Without including this massive aqueduct bridge, the average structural volume for the other bridges of the fourth century is a little over 1000 m^3.

For the fifth-century water supply, four sections with a total of 68 bridges added up to almost 300,000 m^3. The combination of the channels spanning more valleys, the monumentality of many bridges, and numerous rebuilt bridges along the fourth-century line makes the total volume of the fifth-century structures almost three times larger than the fourth century. Averaging 4400 m^3 per bridge, the fifth-century phase quite clearly illustrates the capabilities of late-antique architects and masons, surpassing that of the impressive construction of the fourth century phase.

Table 7.3 - Number and total structural volume of aqueduct bridges by construction phase and line of the Water Supply of Constantinople.

Stretches of Channel	Number of Bridges	Channel	Structural Volume (m^3)
4th Century Bridges			
Land Walls to Binbirdirek Cistern	1	Narrow	77,500
Danamandira to Constantinople	30	Narrow	34,500
Pınarca to junction near Dağyenice	5	Narrow	3,000
Total			***115,000***
5th Century Bridges			
Pazarli to Manganez Dere (K9)	13	Narrow	50,000
Manganez Dere (K9) to Balligerme (K18)	13	Broad	46,000
Ballıgerme (K18) to Kalfaköy	31	Broad	190,000
Danamandira to Constantinople (rebuilt)	11	Narrow	13,000
Total			***299,000***

WATER SUPPLY - CHANNELS

The second calculation that has to be made in order to understand the total size of the fourth and fifth-century phases of the water supply is the structural volume of the long sections of channel. This is the most vital section in regards to the difference in the width of these channels. As briefly discussed with the calculations for distance, the average width of the channel differs considerably from section to section in the fifth-century phase. On the other hand, the total length of these sections is 88 km shorter than those of the fourth century.

Fourth-century Channels

Unlike the fifth-century phase, the fourth-century channel sections are largely similar in dimensions. The height and width of the opening, wall thickness, and vault thickness of the channel opening averaged 1.55 m, 0.7 m, 0.7 m, and 0.3 m respectively for both the Danamandira to Constantinople and Land Walls to Binbirdirek Cistern sections. These sections both had a cross-sectional area of 3.46 m^2. However, the third section from Pınarca to the junction near Dağyenice had the smallest cross-sectional area of all the channels of the fourth and fifth-century phases, averaging only 2.63 m^2. This can be attributed to the narrowest width of 0.6 m and height of 1.3 m of the channel opening. The total structural volume for the longest section of the fourth century, from Danamandira to Constantinople, was 787,000 m^3. From Pınarca to the junction near Dağyenice—the second longest section but with the smallest surface area—measured 107,000 m^3. Finally, the short stretch from the Theodosian Land Walls of Constantinople to Binbirdirek Cistern had an estimated structural volume of 12,000 m^3. It should be noted that the only surviving evidence for the channel within the city walls are from the Aqueduct of Valens itself. The length of the channel, with the exception of this aqueduct, is based on the hypothetical course plotted in Crow, Bardill, and Bayliss (2008: 110-115).

Fifth-century Channels

Pazarlı Spring to Manganez Dere (K9)

The narrow channel averages 0.68 m wide and 1.4 m high. These figures only reflect the channel opening and not the channel structure. Here, the thickness of the vaulting averages 0.3 m, the side walls are around 0.65 m and the base around 0.7 m. In addition to these structural elements, a layer of channel lining mortar coated the inside of the channel from the base to the vaulting with an average thickness of 1.5 cm. The cross-sectional area of the channel structure was calculated at 3.02 m^2, while the channel lining mortar was 0.06 m^2. It may seem like the channel mortar makes up a small portion of the total volume based on the cross-sectional area but in reality, this small figure adds up to a little over 13,600 m^3 for the entire fifth-century phase of the water supply. Combining the channel structure with the mortar lining from this section, the structural volume of this section of narrow channel was calculated at over 154,000 m^3.

Manganez Dere (K9) to Balligerme (K18)

This stretch of channel is the longest of the fifth century and is the first section of broad channel from the main water source at Pazarlı Spring. The channel opening averages 2.1 m high and a width over two times that of the narrow channel at 1.6 m. This larger channel area required increased structural stability through increasing the thickness of the walls and base to around 1.5 m as well as a thicker vault of 0.7 m. This significantly increased the cross-sectional area from 3.02 m^2 in the previous narrow section of channel to 12.77 m^2 for this first wide section of channel. Over this distance and counting the channel lining mortar, the structural volume was calculated to be over 1.8 million m^3.

Ballıgerme (K18) to Kalfaköy

The final section of channels, running predominantly parallel to part of the fourth-century phase, was also broad channel. It was of similar dimensions to the stretch from Manganez Dere to Balligerme, with and average width of the opening of 1.5 m and a height of 2 m. The thickness of the channel walls, base, and vault all averaged the same as the previous section, giving a cross-sectional area of 12.32 m^2. The total structural volume of this stretch of channel was calculated at over 631,000 m^3. Having almost the exact total length as the section of channel from Pazarlı to Manganez Dere yet having a significantly larger cross sectional area makes causes this channel to have a structural volume more than four times larger.

Table 7.4 - Structural volume of channels by phase and line of the Water Supply of Constantinople.

Stretch of Channel	Channel	Structural Volume (m^3)
4th Century Channels		
Land Walls to Binbirdirek Cistern	Narrow	12,000
Danamandira to Constantinople	Narrow	786,000
Pınarca to junction near Dağyenice	Narrow	107,000
Total		***905,000***
5th Century Channels		
Pazarlı to Manganez Dere (K9)	Narrow	154,000
Manganez Dere (K9) to Balligerme (K18)	Broad	1,025,000
Ballıgerme (K18) to Kalfaköy	Broad	631,000
Total		***1,810,000***

ANASTASIAN WALL

In the same way that the key components of the water supply have been considered for volumetric calculations, the Anastasian Wall system was broken down into three distinctive structural elements: forts, towers, and the curtain wall. Because evidence of only a few forts and towers remain throughout the length of the wall, only estimates of their total numbers could be used for volumetric calculations.

Towers

One of the most difficult aspects of determining the structural volume of the towers is their known variation in size and shape as well as the missing sections of the wall, especially in the southern sector. Because of these issues and in order to make a general calculation, a 'model' tower was compiled from dimensions of surveyed towers. Without having data for each individual tower, it is clear that a single 'standard' tower will not yield absolute figures. However it is hoped that the chosen dimensions will be reliable for the structural volume estimates of all of the towers along the Anastasian Wall.

The height of this 'model' tower was taken from the estimates of the polygonal towers at 11.5 m. The shape, however, was based on a square planned tower with dimensions of 11 m by 11 m. The thickness of the walls of the fort was most probably similar to the average width of 2.5 m for the wall's curtain. The foundation of the structure was found to be 1.5 to 2.5 m deep in areas that were exposed by road construction or holes dug by treasure hunters (Crow et al., forthcoming). However, since these towers were similar in height to the largest towers of the ancient world (Crow, forthcoming), it would be safe to assume that some sections could have a deeper foundation depending on the terrain. An average of 3.25 m was chosen for the depth of the foundations for all portions of the wall.

A single arched entrance to the tower from the original construction phase was measured at 2.4 m wide (Crow, forthcoming). The height of the arched entrance can then be estimated at 3.6 m, based on the width. From all of these dimensions, the structural volume of this 'model' tower was calculated to be a little over 1,200 m^3.

After obtaining a structural volume estimate for an average tower, the total number of towers along the wall will determine the volume of all of the towers along the Anastasian Wall. According to the Anastasian Wall project's survey analysis, towers were spaced between 80 and 100 m apart. Crow (forthcoming) suggests that, based on this spacing, approximately 340 towers were located along the entirety of the wall. Using this number, a total structural volume of the towers was determined to be over 419,000 m^3.

Forts

Due to the similar layouts and dimensions of Kücük and Büyük Bedestens (see Chapter 2 for a brief discussion), it can be assumed that these are fairly good representations of most of the forts along the Anastasian Wall. Through survey and planning of these forts, they were found to stretch 64 m along the wall and extend 32 m perpendicular to the back wall. Both of these forts also had a rectangular tower at each of the four corners that were most likely similar to the 'model' tower discussed previously. The two sides of the forts parallel to the line of the wall would have had large gateways, roughly 6 m wide based on the topographical survey and 3D site plan of Bayliss and Crow (2000: 26). The structural volume of a fort based on the plans of Büyük and Kücük Bedestens was estimated to be almost 12,000 m^3. Not counting the fort's corner towers, it is almost six times the structural volume of a single 'model' tower.

From the six known locations of forts along the wall, including the two on which the calculations for structural volume were made, the spacing of these forts were estimated to be at intervals of around 3.5 km. Applying this figure to the total length of the wall calculated in the previous section, the total number of forts was assessed at 15. Thus, the total structural volume of forts along the Anastasian Wall was estimated to be 178,000 m^3.

Curtain Wall

The final and most important element of the long wall was the curtain. This structure stretched over the entire distance linking forts and towers to limit access. The total length of the wall was measured at over 52 km but the lengths of the forts and walls have already been calculated. By removing the total length of the forts (960 m) and the total length of the towers (3,740 m) from the total length of the Anastasian Wall, the length of the curtain wall is was estimated to be almost 48,000 m.

Unfortunately, one of aspect of the wall that does not survive is the height of the curtain wall. However it can be assumed, based on comparative studies of dimensions and structure of other long walls of the time (such as Resafa in Syria), that the curtain wall could easily have a height of 10 m (Crow, forthcoming). The width of the wall was calculated based on the average of the minimum measured width of 1.8 m and maximum of 3.2 m (Crow, forthcoming). The width of 2.5 m used for the volumetric calculation was also chosen in hopes of compensating for cases were the foundation or height of the wall may have varied considerably.

Unlike the forts and towers, it was both impossible and unnecessary to calculate each stretch of the curtain wall from fort to fort or tower to tower (discussed in the section on calculation methods in Chapter 5). Simply multiplying the average width of 2.5 m by height 10 m plus the 3.25 m foundation yields a cross sectional area of a little over 33 m^2. Multiplying this by the estimated length of curtain wall gives a total structural volume of almost 1.58 million m^3. This makes up the vast majority of the total structural volume of the Anastasian Wall at close to three times larger than the total towers and forts combined.

Table 7.5 - Total volume of Anastasian Wall by structural unit.

Wall Structure Type	Volume per Unit (m^3)	Number of Units	Total Volume of Units (m^3)
Towers	1,200	340	419,000
Forts	12,000	15	178,000
Curtain Wall	--	--	1,578,000

TOTAL STRUCTURAL VOLUMES

The channels of the water supply of Constantinople and the Anastasian Wall have now been deconstructed into individual elements: channels, aqueduct bridges, forts, towers, and curtain walls. By individually evaluating these elements through survey data and topographical analysis and thereby calculating their collective structural volumes, it was clearly exhibited that their lengths are not indications of their true monumentality. In order to fully understand their magnitude, these elements need to be placed back into unified systems.

The fifth-century phase of the water supply, including bridges and channels was calculated to be a little over 2.12 million m^3. The considerably longer phase of the fourth century totalled less than half of the fifth-century structural volume at a fraction over one million cubic meters. The sixth-century Anastasian Wall was measured to be only 52 km long but exceeds the structural volume of the fifth-century phase of the water supply. At almost 2.18 million m^3, the long wall is the largest structure of this project by just a little over 52,000 m^3.

Table 7.6 - Structural volume of the fourth and fifth-century phases of the Water Supply of Constantinople and Anastasian Wall.

Phase	Total Length (km)	Total Volume (m^3)
Water Supply - 4th Century Line	271	1,039,000
Water Supply - 5th Century Line	183	2,124,000
Anastasian Wall	52	2,176,000

7.2 - Construction Material Quantification

Calculations of the structural volume of the Water Supply of Constantinople and the Anastasian Wall, while important to understand their scale, are actually more of a means to an end. Much more can come from such analyses such as construction material, man-power, and logistical requirements. The goal here is to determine the amount of individual materials used in the construction of the water supply and long wall so that a solid foundation is put in place for future discussion of man-power requirements.

This section discusses the results of the three-stage breakdown of individual elements from the structural volumes calculated in the previous section. The first stage was to break the water supply and long wall systems down into the volume, units, and mass of each primary building material. Since mortar is a composite material made up of multiple ingredients, the second stage was to apply the information from the mortar examination discussed in the previous chapter to obtain estimates for the quantity of these raw materials. The last stage describes the secondary materials and processes necessary for the production bricks, lime, and iron. See Chapter 5 for more information on the applied methods.

7.2.1 – Primary Building Materials

Primary building materials refer to finished structural elements that are used to construct these systems. These materials include channel lining mortar, structural mortar, facing stones for block work, rough structural stone, and iron clamps. This breakdown of materials starts from the face of the structure to the core, meaning that the first material to be discussed is the facing stones.

The first step was to determine an average size block used for construction. While the blockwork of the fourth and fifth-century phases of the water supply varies in size, the goal was first to determine the average depth of these stone facings. This depth was determined to be roughly 0.4 m for the large blockwork construction of the water supply bridges and most of the long wall. There are instances when smaller blocks are used as facing stone, particularly in the middle courses of the surviving portions of the northern end of the Anastasian Wall leading to Evcik. However, for the purposes of calculating the volume of facing stone, the average of 0.4 m could be used for both systems.

While estimating the structural volume of the bridges of the water supply and the forts, towers, and curtain of the long wall, surface area was also calculated. It should be kept in mind that facing stones were only used for the construction above ground structures of these systems. This means that the volume of the channels, which primarily ran below ground, as well as the volume of the foundations of both the aqueduct bridges, forts, towers, and curtain walls were not included in the surface area calculations of facing stones. The dimensions of an average block used in these systems were selected to be roughly 40 cm by 40 cm by 65 cm, or a total volume of 0.1 m^3.

FOURTH-CENTURY PHASE OF THE WATER SUPPLY

The fourth-century phase of the water supply, with an above ground surface area almost half that of the fifth-century phase (almost 84,000 m^2), was estimated to have a total blockwork facing volume of almost 34,000 m^3. This equates to almost 339,000 limestone blocks of similar size to those of the fifth century, weighing in at roughly 89,000 tonnes. Holding these blocks together were 305,000 iron clamps weighing a total of 1,700 tonnes.

The cores and foundations of the aqueduct bridges formed a volumetric total of 82,000 m^3. Of this, almost 30,000 m^3 was mortar while stone rubble made up 52,000 m^3. The lines of channel were broke down to yield almost 332,000 m^3 of mortar and 573,000 m^3 of rough structural stone. The entire fourth-century phase of the water supply of Constantinople required 625,000 m^3 of rubble stone and 362,000 m^3 of structural mortar.

Finally, the remainder of the structural volume of the fourth-century phase of the water supply of Constantinople consisted of the channel lining mortar. Over the entire 271 km distance of this phase, almost 19,000 m^3 of channel lining mortar was needed. Interestingly, because it is 88 km longer, this is the one instance when length proved to require a larger volume of construction materials than the fifth-century phase.

FIFTH-CENTURY PHASE OF THE WATER SUPPLY

The aqueduct bridges of the fifth-century phase of the water supply had a total aboveground surface area of over 166,000 m^2. The thickness of the blockwork facing was applied to this figure, producing an estimate of almost 67,000 m^3 for the total volume of facing stones necessary for construction. Roughly 666,000 stones of average size, weighing of 174,000 tonnes, would need to be quarried, transported and placed to construct the 68 aqueduct bridges of this phase.

Figure 7.1 - Clamp socket from Cineviz Dere (K11) (after Crow, Bardill, and Bayliss, 2008: 46)

Now that we have established roughly how many stones were necessary, we can make an inference about the total quantity of iron clamps were needed to hold them together, under the assumption that iron clamps were used at each bridge (see Chapter 2 for a discussion of evidence). It is estimated that each stone would have one entire iron clamp, with the exception of the vaulting stones. This amounted to an estimated total of a little over 610,000 clamps. An iron clamp socket (Figure 7.1) from Cineviz Dere (K11) was measured at a volume of roughly 720 cm^3, taking into account a small margin for sealing lead. The total mass of iron clamps necessary for the faces of the aqueduct bridges would have been approximately 3,400 tonnes. Interestingly, the name of the monumental aqueduct bridge of Kurşunlugerme (K20) means “the leaded span”, referencing the clamps and lead settings recovered during later robbing (Crow, Bardill, and Bayliss: 58).

Now that the volume of face of the bridges has been removed from the total structural volume, we are still left with 2.06 million m^3. This consisted of the foundation materials and the mortar and rubble core, which for the purposes of this calculation are assumed to be similar in construction. The first step was to break this down into the two main components—mortar and stone rubble—using photographic analysis (see Chapter 6). From five total photographs of exposed core from the water supply of Constantinople and the Anastasian Wall, this yielded an average mortar-stone ratio of 1:1.75 for the two phases. Surprisingly, the standard deviation was only 3.12% between all five photographs. The estimated volume of rubble stone from the core of the aqueduct bridges was over 148,000 m^3 and almost 1.15 million m^3 for the channel masonry, totalling almost 1.30 million m^3. The core mortar from the aqueduct bridges was estimated at 85,000 m^3 and 645,000 m^3 for the joints of the channel masonry, tallying almost 750,000 m^3.

The final portion of the total structural volume of the fifth-century phase of the water supply is the layer of fine, waterproof mortar lining that covers the full length of the channels and bridges. As was discussed in the previous section, the total volume was estimated to be 13,600 m^3.

One topic that should be addressed before continuing is the use of spoliated materials from fourth-century bridges in fifth-century construction. While the fifth-century stretch of the water supply replaces many fourth-century aqueduct bridges, it is highly unlikely that these materials were reused in this phase. Spoliation of these bridges would require a break in the water supply line, stopping the flow of water until the new bridge was completed. This would have caused a significant period of disruption of water flow to the city, leading to the assumption that all construction materials used in the fifth-century were produced for this purpose.

ANASTASIAN WALL

Calculating the individual materials of the Anastasian Wall was quite similar to the methods employed for the fourth and fifth-century phases of the Water Supply of Constantinople. The only exception is that, unlike the masonry walls of the channels, all of the structures of the walls would have been stone faced with mortared rubble cores. While the portions of northern stretch of the curtain wall have courses that used differing sized stones (Chapter 2, Figure 2.3), as well at the possibility that brick may have played a role in courses or arcades of the southern sector of the wall (Crow et al., forthcoming), it is impossible to identify accurately the extent of these variations using the limited surviving data. For the sake of material estimates and the subsequent man-power analysis, the wall has been hypothetically typed as a homogeneously constructed system. This means that the same type of blockwork construction of the aqueduct bridges using 0.1 m^3 stones, which is also found at surviving sections of the wall, will be used as the general blueprint for volumetric calculations of individual materials.

With a total estimated aboveground surface area of almost 1.87 million m^2, it is to be expected that the scale of the entirety of the wall was significantly more visually dominating than the entirety of the fourth and fifth-century phases of the water supply. This figure equates to a face volume of 214,000 m^3, or almost 2.14 million stone blocks. No evidence has been found to indicate that iron clamps would have been used in the construction of the Anastasian Wall (Crow et al., forthcoming).

The wall system had a core and foundation volume of just over 1.96 million m^3 including the curtains, forts, and towers. When broken down into its two parts, the core of the structure was made up of 1.25 million m^3 of stone rubble held together by over 712,000 m^3 of mortar.

Table 7.7 - Volume, units, and mass of construction materials used in the Water Supply of Constantinople and Anastasian Wall.

Material	Volume (m^3)	Number of Units	Mass (Tonnes)
Water Supply - 4th Century Line			
Channel Lining Mortar	18,500	--	--
Structural Mortar	362,000	--	--
Facing Stones	34,000	339,000	88,500
Rubble Stone	626,000	--	1,633,000
Iron Clamps	220	305,000	1,700
Water Supply - 5th Century Line			
Channel Lining Mortar	13,600	--	--
Structural Mortar	749,000	--	--
Facing Stones	66,000	666,000	174,000
Rubble Stone	1,295,000	--	3,380,000
Iron Clamps	440	610,000	3,400
Anastasian Wall			
Structural Mortar	712,000	--	--
Facing Stones	214,000	2,141,000	559,000
Rubble Stone	1,250,000	--	3,263,000

7.2.2 – Mortar Components

Mortar was the most important material for the lasting success of the water supply and Long Wall of Thrace. In the previous chapter, samples of mortar from these structures were examined on the microscopic level to better understand their manufacture technology. Since the ultimate goal of this chapter is to provide an insight into the man-power requirements from obtaining raw materials to the final stage of site construction, the microscopic examination can be used to break down the composite materials into individual elements.

The first step was to identify the main components of the mortars used in the Anastasian Wall and Water Supply of Constantinople. The mortar analysis showed that the three main components of the mortar were lime, brick, and sand with almost no additional aggregates (see section 6.2.1 – Material Identification and Examination). This was consistent between the mortars of both structures and, because no samples were available from the fourth-century phase of the water supply, it is assumed that the proportions of materials in the fourth-century mortars were similar to the mortar of the fifth century. This is bolstered by the description of fourth-century mortars from the surveys of the fourth-century phase of the water supply, where mortar was described as being "...rubble set in a hard pink mortar" from features such as the mortar lining of the basin from Pınarca Spring or the aqueduct bridge at Kale Dere (Crow, Bardill, and Bayliss, 2008: 78 and 79).

The tests of mortar samples from the fifth century yielded an average of 40% lime, 12% sand, and 48% crushed brick. Applying the total mortar used to these percentages, the volume of material components is estimated at 305,000 m^3 of lime, 91,500 m^3 of sand, and 366,000 m^3 of brick. Using the same proportions as the fifth-century mortars, the volumes of individual materials of mortars from the fourth-century phase were estimated to be 152,000 m^3 of lime, 46,000 m^3 of sand, and 183,000 m^3 of crushed and powdered brick material.

The total mortar for the Anastasian Wall's core and foundation structures total 712,000 m^3. The results of the mortar testing indicated different proportion of materials from the fifth-century phase of the water supply. There was a smaller proportion of lime at an average of 31% while the quantity sand and brick increased to 17% and 52% respectively. This generated an estimated volume of 221,000 m^3 of lime, 121,000 m^3 of sand, and 370,000 m^3 of brick.

Table 7.8 - Volume, units, and mass of mortar components of the Water Supply of Constantinople and Anastasian Wall.

Structural Mortar Component	Volume (m^3)	Number of Units	Mass (Tonnes)
Water Supply - 4th Century Line			
Lime	152,000	--	129,000
Brick	183,000	28,524,000	301,000
Sand	46,000	--	73,000
Water Supply - 5th Century Line			
Lime	305,000	--	259,000
Brick	366,000	57,201,000	604,000
Sand	92,000	--	147,000
Anastasian Wall			
Lime	221,000	--	187,000
Brick	370,000	57,864,000	611,000
Sand	121,000	--	194,000

7.2.3 – Secondary Material and Production Requirements

Three types of construction materials need to be addressed in regards to the additional production requirements. These are bricks and quicklime for the mortar, as well as iron clamps held in lead. Each of them requires a process involving the application of high temperatures in a controlled environment to produce the desired end product. Here, we will look at the quantity of raw materials necessary to produce the end product, the number of kiln or furnace firings, as well as the amount of fuel necessary for the production process. The lead required to set the iron clamps in their sockets would have also been vital to the construction of these systems, especially in terms of cost. However, based on the limited data for the magnitude of its use within these structures and the small timeframe for research, the impact of the use of lead will be addressed in future research.

The first material to be examined is quicklime. While estimates for the total lime within the mortars of these systems has already been discussed, this is misleading in regards to the total raw limestone necessary for production. According to DeLaine (1997: 112), one cubic meter of limestone would only produce 0.91 m^3 of lime. During the slaking process, the lime will expand but ultimately, will only permanently gain a fraction of this 9% loss in volume. In total, this means that roughly 243,000 m^3 of limestone were needed to produce the almost 221,000 m^3 of lime used in the mortars of the Anastasian Wall. Similarly, the fifth-century phase of the water supply would require 336,000 m^3 of limestone and 167,000 m^3 for the fourth-century phase of construction.

In the case of bricks, little variations in volume occur between the raw clay and the fired brick. While processing the clay to remove stone and organic materials takes out a significant portion of the total quantity, large quantities of sand temper would have been mixed in to significantly reduce shrinking and warping during the drying and firing process (DeLaine, 1997: 114, Ousterhout, 2008: 129-130).

The production of iron requires a large quantity of iron ore. However, this is dependant on the type of ore being smelted. Without knowing the exact source of the ore, it is difficult—if not impossible—to infer the type. However, using data obtained from experimental testing of iron smelting, carried out by Cleere (1971), an ore to metal ratio was found to be 6:1. Also used by DeLaine (1997: 122), this ratio was chosen as a representative figure for this study. For the amount of iron ore needed to produce iron clamps, this calculates to a volumetric figure of 2,640 m^3 for the fifth-century phase of the water supply and 1,320 m^3 for the fourth-century phase.

Before proceeding to the amount of fuel necessary to produce these masses of material, the kilns and furnaces should be discussed. Without any evidence for these production sites around the wall or over the larger geographical area of the fourth to sixth-century hinterland of Constantinople, it is impossible to determine the exact size of the kilns or furnaces. For the sake of estimating the quantity of fuel, I have relied on the figures for kiln and furnace size used by DeLaine (1997) in her work on the Baths of Caracalla.

DeLaine uses a figure of 100 m^3 (1997: 112) for a moderately large lime kiln (see discussion of kilns in Chapter 3 for comparison) that could hold roughly 66 m^3 of limestone and produce 60 m^3 of lime. The volume of lime from these systems would require 5,085 kiln loads for the fifth-century phase of the water supply, 2535 for the fourth century, and 3680 for the Anastasian Wall. A volume of 65 m^3 (DeLaine, 1997: 117) is assumed as the capacity for a moderately large brick kiln, which was estimated to require 8,200 firings for the fifth-century water supply, 4,100 firings for the fourth-century phase, and 8,300 for the wall.

Based on the experimental work of Cleere (1971), DeLaine (1997: 122) uses the figure of 30 kg of iron produced from a typical iron furnace. The total volume of iron necessary and based on its density of 7.85 tonnes/m^3 according to Walker (1998), the fifth-century water supply phase required 3,420 tonnes of iron, 1,710 tonnes for the fourth century, and 9,710 tonnes for the Anastasian Wall. This equates to 113,900 and 57,000 furnace loads for the fourth and fifth-century phases of the water supply of Constantinople and 324,000 furnace loads for the Anastasian Wall.

Fuel was crucial for producing the amounts of quicklime, brick, and iron required for the two systems. Despite possible evidence of traces of lignite in the mortar samples, as well at the lignite deposits found within reach of the water supply and long wall (Engin, 1986), it remains uncertain if it was used as a fuel source (see Figure 6.17). For the purposes of estimating quantities of fuel resources, wood and charcoal were chosen based on the availability from the heavily forested areas of northern Thrace as well as data from experimental testing or historic documentation of kilns and furnaces (charcoal: Cleere, 1971; brick kilns: Table 8 of DeLaine, 1997: 117; lime: discussion in DeLaine, 1997: 112, 113).

The quantities of required wood fuel rely on the time and temperature needed to properly fire limestone, clay, and iron ore. This hinges on the calorific values of the wood used for firing and smelting and since the forests of the Thracian Peninsula are predominantly oak and beech, these were chosen as the representative woods used as fuel. All tree species have uniform calorific values of 4.5 Kcal/gm if dry and around 3.5 Kcal/gm if still green. Wood has been chosen as the primary fuel for producing lime and bricks based on the additional labour involved in producing charcoal. However, it should be noted that charcoal is 2.5 times more efficient than green wood, producing a higher and longer lasting heat (Olson, 1991: 412).

According to DeLaine (1997: 113), the total firing time for a lime kiln with the capacity of 66 m^3 is around seven days and would require 165 tonnes of wood. This means that an average of 2.5 m^3 of wood fuel would be required to produce 1 m^3 of lime. This ultimately means that to produce the volume of lime for the fourth and fifth-century phase of the water supply would require 418,346 tonnes and 838,945 tonnes of wood fuel respectively and 607,000 m tonnes for the Anastasian Wall.

Brick production, on the other hand, is not as energy intensive as lime production needing a lower minimum temperature and less time. This required only two and a half days and 40 tonnes of wood fuel to fire a kiln with the capacity of 65 m^3 according to 19th century records from Italy (DeLaine, 1997: 117). By applying the estimated number of kiln loads required to produce the compulsory quantity of brick material for these systems, the mass of wood fuel requires for the fourth and fifth-century phases of the water supply can be calculated at 327,000 tonnes and 163,000 tonnes respectively. The Anastasian Wall would require 331,000 tonnes of wood fuel to produce the estimated 57.9 million bricks used in the structural mortar.

It is necessary to identify the fuel requirements in the production of iron clamps. It was common to use charcoal in the roasting and smelting processes to produce iron from iron ore since it could easily reach the 1200 to 1300 degrees needed for smelting (Thompson and Young, 1999: 222). Cleere (1971) found that these processes required a ratio of one part ore to two parts charcoal. The fuel requirements for each system equate to 41,000 tonnes of charcoal for the fifth-century phase of the water supply, 21,000 tonnes for the fourth-century phase, and a massive 117,000 tonnes of charcoal for the Anastasian Wall.

A key fuel, especially for iron production, was charcoal (Cleere, 1971; Thompson, 1999; Mattingly, 2001: 132-133). The forests west of Catalca remain a major centre for charcoal production (Byfield, 1995) and it is reasonable to assume these regions were important for the late antique city as well. The process of making charcoal will be considered in the next section on man-power but we can deduce the amount of raw material based on the mass. If charcoal has an average density of 208 kg/m^3 (Walker, 1998) and oak species have an average density of 760 kg/m^3 (Walker, 1998) this means that the production process causes a 73% loss in mass. Thompson and Young (1999: 229) claimed that the maximum yield of a charcoal kiln would be one part charcoal from two parts wet hardwood. For the sake of a reasonable estimate of necessary wood fuel, the average charcoal yield of 37% of the total wood mass was chosen for this study. Thus, 108,000 tonnes of oak timber was needed to produce the necessary charcoal for the fifth-century phase of the water supply. Similarly, 54,000 tonnes of wood were needed for the fourth-century phase.

We can now estimate the total mass of wood required for the production of lime, brick, and iron clamps for each of the systems. While not having the fuel requirement for the production of iron clamps, the production of the Anastasian Wall would still have required the second highest mass of fuel at 938,000 tonnes. Ranking third, yet having the greatest overall length, the fourth-century phase of the water supply would have consumed 635,000 tonnes of wood for material production. The most fuel intensive system of this study was the fifth-century phase of the water supply of Constantinople, requiring over 1.27 million tonnes of wood.

Table 7.9 - Kiln loads, fuel type, and fuel mass requirements for the production of materials used in the Water Supply of Constantinople and Anastasian Wall

Product	Kiln/Furnace Loads	Fuel Type	Fuel Mass (Tonnes)
Water Supply - 4th Century Line			
Quicklime	2,500	Wood	418,000
Bricks	4,100	Wood	163,000
Iron Clamps	57,000	Wood/Charcoal	54,000/21,000
Water Supply - 5th Century Line			
Quicklime	5,100	Wood	839,000
Bricks	8,200	Wood	327,000
Iron Clamps	114,000	Wood/Charcoal	108,000/41,000
Anastasian Wall			
Quicklime	3,700	Wood	607,000
Bricks	8,300	Wood	331,000

7.3 - Estimating Man-power Requirements

The estimations of the scale and building material requirements discussed in the previous sections offer radically different insights into the construction of the long distance phases of the Water Supply of Constantinople and Anastasian Wall. Looking at the remnants of these systems over the modern Thracian landscape, it is easy to imagine but difficult to grasp the great quantities of resources needed for their construction. Furthermore, visual investigation offers very little insight into the required labour force charged with these systems' conception and completion. In the same manner as the previous section made these structures more accessible in a physically quantitative sense, this section aims to offer insight into the man-power requirements of these systems. Through the combination of material volume estimates calculated in the previous section, historical data collected primarily by DeLaine (1997) in her work on the Baths of Caracalla, and developing hypothetical scenarios for material transport, attention will be turned from the material to the human investment of the Water Supply of Constantinople and Anastasian Wall.

A building project can be divided into three major divisions: construction material production, material transport, and construction. The first division includes the man-power for obtaining facing stones, rough structural stone, and sand, as well as the processes for producing composite materials such as lime, brick, and iron clamps. The second division includes material provenance, locations of production centres, transportation methods, and distances travelled. The geographical area covered coupled with the lack of evidence for production sites makes this the most complex and assumptive aspect of estimating the required man-power. However, being a vital aspect of the overall labour requirements for these projects, various plausible scenarios for the transportation of materials can be applied. The final division consists of four distinct phases. These are site planning and preparation, mortar preparations, building preparations, and construction. These phases include everything from clearing sites of vegetation to constructing the edifice. This section does not intend to be an analysis of these construction processes as they relate to the building of the water supply or long wall. Instead, it will provide a look at the magnitude of the labour required for these processes, which is essential to understanding the scale of the construction projects for the Water Supply of Constantinople and Long Wall of Thrace. Future research will address the logistics of these construction projects, such as building scheduling, material distribution, and workforce organisation.

Assumptions:

Many assumptions have to be made regarding the investigation of the required labour for the construction of these two systems. Since the figures used to calculate the estimated man-power come from DeLaine's (1997: 105) book *The Baths of Caracalla,* her assumptions are similar to those of this study.

1- "The average output of a man at work at a given task, using equivalent tools, was the same during the Roman empire as during any later period before the 20th century."

2- "The average working year on the construction site is assumed to consist of 9 months totalling 220 days."

3- "The average working day is assumed to be 12 hours, including 2 hours for breaks…"
4- "…the nature of the man-power sources constrains me to assume that the work-force is composed entirely of men."

In regards to the fourth assumption, it is unclear who comprised the workforce of the water supply and long wall. It is entirely possible that women and children contributed by producing baskets and ropes or collecting wood fuel (DeLaine, 1997: 105) but without textual or conclusive archaeological evidence, this is impossible to determine.

Qualifications:

In addition, a few qualifications have to be addressed. The time of year for production of brick and lime, transportation of materials, and construction is not considered in this study but plays a significant role in the scheduling of work, and ultimately the length of time in years required. For instance, the production of brick and lime would require the dry weather of the summer months to ensure moisture does not interfere with the slaking process for lime and the drying of the brick clay. Furthermore, the winter months would be an inhospitable time for the construction process as well as the transportation of materials, especially in the mountainous terrain of northern Thrace. For information regarding the scheduling of work for large-scale construction, see Delaine's (1997) Baths of Caracalla (specifically Part 2, Chapter 7: 182-194).

The second qualification is that the production of large tools (counterbalances, hoists, sleds etc.) and small tools (hammers, axes, chisels, wedges, baskets, ropes, weights, mixing paddles, survey instruments etc.) will not be addressed. Because they are generally multi-use items with many possible factors leading to their damage and disuse, it would be impossible to quantify the amount required. Erecting scaffolding has been included in this study due to its necessity in the entire distance of the Anastasian Wall and the aqueduct bridges of the water supply.

The third qualification is the exclusion of man-power estimates for the design and survey of the Water Supply of Constantinople and Anastasian Wall. Again, without direct textual references, it is impossible to conclude the labour required to accomplish these tasks. For a discussion of the methods used to survey the land in preparation for aqueduct construction, see Hodge (1992: 171-214).

The last qualification is about the nature of the workforce associated with the construction of the long distance phases of the Water Supply of Constantinople and the Anastasian Wall. Unfortunately, it is still unknown whether the workforce was comprised of military, slave, or free workers. We do have information about repairs of the water supply. Theophanes (*Chronicle* AM 6258) writes that a large number of artisans and labourers were brought in from great distances to repair the water supply in the 8th century (see Dalman, 1933, page 6 for a discussion of this workforce). However, this is not analogous to the original construction of these structures. One thing that can be said about the workforce, which is taken into consideration in this section, is that it would be comprised of both skilled and unskilled labourers.

7.3.1 – Material Acquisition and Production

Since the process of obtaining or producing different construction materials varies greatly, the required man-power will also vary. In order to maintain a coherent discussion of these materials, each will be discussed independently, despite having some of the same steps. However, the resulting figures for man-power of the fourth and fifth-century phases of the Water Supply of Constantinople, as well as the Anastasian Wall, will be discussed together since it is assumed that the methods of production are the same between these three systems.

FACING STONES

The man-power requirements for readying rough-cut facing stones (dressing will be addressed in later in the last building project division, with the assumption this was done on-site) can be separated into three categories. The first and most energy intensive of these was the process of quarrying. Kozelj (1988: 39) was able to calculate through experimental quarrying that it would take 22.5 hours (0.937 days) to extract a marble block from an antique quarry at Thasos measuring 0.125 m^3. Converting this figure to the 0.1 m^3 crystalline limestone block that was used as an average for the blocks of this project, it can be assumed that it would require 0.75 man-days to extract one block. This time would vary depending on the stone type but for a hard material like marble might have taken less time with a seasoned quarryman. Taking into consideration these variations, the figure of 0.75 man-days will serve as a reasonable estimate for the immense quantities of facing stones needed for these systems. It can be assumed that the type of labour needed to quarry stone blocks would require almost entirely skilled workers. Workers would have to be practiced with both the tools they used, such as iron picks, the type of stone being quarried, and the ultimate use for the resulting cut stone (Fant, 2008: 122; Asgari, 1992).

Readying the stone for transportation is the next man-power category. This involves moving and loading the rough-cut quarried stones from the quarry face to the carts.

The average density of limestone is somewhere between 2.5 to 2.6 tonnes per m^3 (Walker, 1998) meaning that a single stone measuring 0.1 m^3 would weigh roughly 255 kg. Since a reasonable maximum load of a human is around 50 kg (DeLaine, 1997: 107) and a large mule can carry little more than 135 kg (Delaine, 1997: 108), it is likely that sleds were used over short distances. DeLaine (1997: 111) discusses the transport and loading of quarried material such as pozzolana, tufa, selce, and pumice. Unfortunately, these man-power figures cannot be directly translated to the stone blocks used in the water supply or long wall because, as DeLaine (1997: 121) notes, the total man-power can significantly vary depending on the terrain and location of the quarry site. Since the quarry locations are unknown for these sites, the figure of 0.200 man-days per block was selected, assuming that it would take two workers pulling a sled roughly the same amount of time for one worker to carry one cubic metre (over multiple trips) of rubble stone 25 m.

The final category of man-power analysis for extracting stone blocks is also universal for all steps of the construction process. Supervision and administration encompasses all of the duties of overseeing a process—in this case the quarry and the stone masons—as well as regulating the working hours, conditions, and payment of the labourers. For all of the categories within each phase of the building process, DeLaine's (1997: 107) established average man-power requirement for supervision and administration has been chosen at 10% of the total man-power.

The total estimated man-power required to obtain rough cut stone blocks for the two phases of the water supply is 352,000 man-days for the fourth century and over 695,000 man-days for the fifth-century. However, more than doubling the combined total of the water supply, the man-power required for the facing stone quarrying for the Anastasian Wall would have been almost 2.24 million man-days.

RUBBLE STONE

Many elements of the water supply and long wall consist of stone rubble. As discussed in the previous section, these can be found in the foundations and cores of above ground structures as well as in the masonry walls of the water supply's channels. The term 'rough structural stone' refers to the stone material that is quarried in non-uniform pieces that can be easily carried by a single worker or pack animals in the cases of the larger stones used in the foundations of higher structures.

The labour requirements for obtaining this material, like most other quarried materials, involve two steps: quarrying and preparing for transport. The stone type varies over the entirety of these systems but for the purpose of estimating the required man-power, a hard semi-crystalline limestone was used to represent the hypothetical scenario of extraction. This was chosen based on the availability of similar data pertaining to labour requirements, as well as representing fitting between the soft limestone and hard metamorphosed limestone used as rubble stone in the water supply and long wall.

Unlike extracting facing stones, little skill was needed to obtain these stones. In terms of man-power requirements, it is assumed that quarrying this material would be somewhere close to the figures given for other solid materials by Delaine (1997: 111). For quarried materials with lesser requirements, she uses 0.063 man-days for pumice and 0.250 man-days for quarrying tufa. On the high end of the scale, the figure of 1.880 man-days is given for extracting *selce*, a stone rich in potassium and alumina silicates produced by cooled lava from the volcano of the Alban Hills (Jackson and Marra, 2006: 406). It was decided to average these to obtain a safe, albeit conservative, figure for the man-power requirements, resulting in a figure of roughly 0.750 man-days per m^3. Later, Delaine (1997: 113) provides a figure of 66 man-days to quarry and break enough stone to fill a 66 m^3 capacity kiln. By removing the step of breaking the limestone in a kiln, it is reasonable to assume that 0.750 man-days of unskilled labour is a sufficient figure.

Carrying and loading this quarried stone would also require only unskilled labour. It can be assumed that this stone would need to be carried similar distances to the aforementioned stone blocks. Again, based on Delaine's (1997: 113) figures for transporting limestone to the kiln sites, the man-power requirements for rubble stone were estimated to be 0.104 man-days per m^3 (or one quarter of man-days required to carry 1 m^3 of limestone 100 m).

The labour requirements for producing the total quantity of rubble stone for the fourth-century phase of the water supply, including supervision and administration, was estimated to be a little over 587,000 man-days. At almost 1.22 million man-days, the fifth-century phase of the water supply required more than double the labour as the fourth century. However, not far behind, acquiring this stone for the Anastasian Wall was estimated to have required over 1.17 million man-days.

LIME

Producing lime is a very energy intensive process in terms of both the necessary chemical transformation and requisite labour. The first step is to quarry the limestone and break it into pieces that will fill the kiln. As previously mentioned, DeLaine (1997: 113) uses 66 man-days as the labour required to quarry and break enough stone to fit in a kiln. This simply equates to one man-hour per m^3.

Also mentioned in regards to rough structural stone, DeLaine (1997: 113) uses a figure of 25 man-days to transport the 66 m^3 of stone 100 m. As she aptly points out, the distance from the quarry face to the kiln or cart is the “largest element of uncertainty” (DeLaine, 1997: 112) for all quarried materials. In order to remain consistent with DeLaine’s estimates, the equivalent of 0.417 unskilled man-days per m^3 was chosen as the labour requirement to transport limestone to the kiln. Once the stone arrived at the kiln it would require an average of skilled and unskilled labourers 0.159 man-days to load a kiln with 1 m^3 of limestone. This is according to DeLaine’s estimation that it would take 14 unskilled man-days or 7 skilled man-days to load a kiln with a capacity of 66 m^3.

Properly firing limestone is one of the most important steps to ensure the success of a mortar. The kiln must have been constantly watched and the fire continuously stoked over the seven-day process (DeLaine, 1997: 114). This would have required a combination of skilled and unskilled labour 14 man-days or two workers working 12-hour shifts over the seven days period per kiln load (Delaine, 1997: 113). Per 1 m^3 of limestone, this equates to 0.212 man-days.

Once the kiln had been allowed to cool over a five-day period, the kiln would need to be unloaded and the lime slaked. Unloading the kiln and carrying the lime to the slaking pit would be roughly equivalent to the figure of 0.242 man-days per m^3, which DeLaine (1997: 113) uses for unloading the kiln and loading carts. She (1997: 113) chooses to address slaking lime later but I have chosen to include this process as taking place before being transported to the site. Since lime is very volatile after burning, it can absorb moisture from the air, inadvertently beginning the slaking process. This will cause the lime to become inert over long periods of time so slaking of quicklime was typically done soon after burning (Ousterhout, 2008: 133). Information regarding man-power requirements for slaking lime (and many other labour constants) are estimated in Pegoretti's 1869 work, *Manuale practico per l'estimazione dei lavori architettonici, stradali, idraulici e di fortificazione, per uso degli ingegneri ed architetti* (quoted in DeLaine, 1997: 268). He categorised this process as unskilled labour requiring 1.2 man-days per m^3 of quicklime. It should be noted that large quantities of water would be needed to produce quicklime and, in turn, require substantial man-power to carry to the slaking site. While, the quantity of water is attainable, the man-power analysis is much more complex and will be addressed in future research.

Including supervision and administration, the total labour requirements for lime production were calculated. The fourth and fifth-century phases of the water supply would have required almost 595,000 man-days and 1.19 million man-days respectively. The Anastasian wall was estimated to have required close to 863,000 man-days to produce the almost 221,000 m^3 of required lime. It should be noted that obtaining fuel was not included in the man-hour estimates for lime or brick production. Instead, it is included in upcoming discussion material provenance and transportation.

BRICKS

The first step in producing bricks is obtaining the clay. DeLaine (1997: 118) uses the figure of 14 man-days to quarry 93 m^3 of clay or .151 man-days per m^3. Like all other quarried materials, clay had to be transported from the quarry location and in this case to the processing area and then to the kiln. Using her (DeLaine, 1997: 118) average distance of 25 m, an estimated 0.634 man-days were required per m^3.

The next step was to process the clay by removing all of the larger stones and organic material. Sand would then have been mixed into the clay for temper and then placed in clay forms. DeLaine's (1997: 118) estimate of 104 man-days for 93 m^3 to prepare and form clay equates to about 1.118 man-days per m^3. To ensure the proper consistency of the clay and to ensure that the dimensions were even for all brick forms, this process would have most likely required skilled workmen. After, the bricks would have been left to dry for around 28 days (Delaine, 1997: 118). Brick stamps could then be applied when they had become leather-hard (Delaine, 1997: 115).

Similarly, loading the dried bricks into the kiln would have required a combination of skilled and unskilled labourers. In this state, pre-fired bricks would have been brittle and easily broken if not stacked properly. DeLaine (1997: 118) calculates the man-man power requirements for loading bricks according to four typical Roman brick sizes: bessales, sesquipedales, bipedales, and tubuli. Since the bricks produced for the Water Supply of Constantinople and the Anastasian Wall have already been determined to be from the same clay sources as the bricks used around Constantinople (see previous chapter), the dimensions of fifth-century bricks from the capital city have been chosen as an average representative size for these systems. The average dimensions of 374 mm by 374 mm by 46 mm were calculated by Bardill's (2004: 105) investigation of bricks and brickstamps of Constantinople. This means that the bricks used in the water supply and long wall are closest in size to bipedales and therefore, the man-hour figures for loading a kiln has been estimated to be 0.118 man-days per m^3.

Again, similar in nature to the requirements of lime burning, brick firing would have required constant attention by skilled and unskilled labourers. DeLaine (1997: 118) estimated that it would have taken around two days to fire a kiln full of bricks, requiring a total of 10 man-days. Per cubic meter of clay, this equates to 0.108 man-days.

After a cooling time of four days (DeLaine, 1997: 118), the brick would have needed to be unloaded from the kiln and loaded into a cart. Assuming that the bricks were whole at this point, DeLaine's (1997:118) figure of around 0.065 man-days per m^3 for unloading the kiln and preparing for transport is reasonable estimate. It is reasonable to assume that the man-power for this step of the production process would have been carried out by unskilled labourers, especially considering the use of bricks in the mortar of these systems would not have required that they be whole.

Bricks used in the water supply and long wall would have been crushed and sieved for use in mortar, this process also has to be taken into consideration. However, it is uncertain whether this is done prior to leaving the brick yards or done on site. As long as this is included somewhere in the man-power estimations, the order should have no effect on the outcome of the estimations. Fortunately, estimates for the labour required to crush brick was available from DeLaine's (1997: 180) estimates for crushing terracotta to be used in mortar bedding of marble slabs. Since this would be an almost identical process to crushing brick, this figure of 0.220 man-days was used for this analysis.

The final man-power estimates for the production of brick material, with the additions of supervision and administration, can now be calculated for the Water Supply of Constantinople and Anastasian Wall. Starting with the fourth-century phase of the water supply, the production of the 28.52 million bricks needed for the mortar would have required almost 485,000 man-days. Needing 57.20 million bricks for the amount of mortar used in the fifth-century phase would have necessitated 972,000 man-days. However, the highest man-power requirement was over 983,000 man-days to product the 57.86 million bricks needed for the mortars of the Anastasian Wall.

As a side note, it is entirely possible that a large proportion of bricks used to make mortar were broken or under-fired wasters and not produced with the intension of mortar production. In fact, these wasters can account for 17% of the total kiln load (Ousterhout, 2008: 131), suppling large quantities pozzolanic brick material without sacrificing all of the structurally viable bricks. Due to the quantity of bricks necessary for these projects, wasters may have had to been supplemented with properly fired and/or spoliated bricks. However, it is impossible to determine the degree in which waster, spoliated, or structural bricks were used based on the small fragment sizes represented in mortar. The very extensive and ubiquitous use of both structural brick and brick-based mortars throughout the Late Roman and Byzantine world would indicate the likelihood of using all of these resources.

IRON CLAMPS

Producing iron clamps for the aqueduct bridges of the Water Supply of Constantinople would have been another labour-intensive endeavour. The steps included in this analysis are mining ore, carrying the ore to the production site, produce charcoal, roasting and smelting the iron ore, casting the iron clamps, and loading the carts with the clamps for transportation to the site.

Much of the data used in this man-power analysis comes from Cleere's "Ironmaking in a Roman Furnace" (1971) and Cleere and Crossley's *The iron industry of the Weald* (1986) as well as DeLaine's (1997: 122) analysis of these figures. Starting with mining ore, Cleere found that it would take roughly 14 to 15 man-days to obtain the six tonnes of iron ore needed to produce one cubic meter of iron. This equates to roughly 2.333 man-days per m^3 iron ore. Iron ore would then need to be carried to the furnaces. To stay consistent with the other materials that required some form of processing, a distance of 25 m transport was chosen. The labour requirement was assumed to be similar to other materials discussed by DeLaine regarding locally quarried materials at an estimate of 0.180 man-days per tonne of iron ore.

The next process was to produce charcoal for the roasting, smelting, bloom preparation and casting. Since the figures for the amount of wood needed to produce charcoal have already been calculated, Cleere's estimate that it would take 70 to 75 man-days to cut enough wood and produce 12 tonnes of charcoal will be fitting for the labour calculations of this study. This equates to 5.830 man-days per tonne of charcoal to cut wood and produce charcoal fuel.

Once the ore had been obtained and the charcoal produced, iron ore needed to be roasted and smelted. At a figure of 180 man-days per m^3 of iron, DeLaine's analysis of Cleere and Crossely's estimates show a major upshift in labour requirements. This clearly illustrates the intensity of the process. However, once finished with the smelting process, the most labour-intensive activity of all material processes is preparing the iron bloom and casting the iron clamps. According to DeLaine (1997: 122), it was likely to require 570 main-days to produce one tonne of iron clamps, including the preparation of additional charcoal.

Using similar figures to those used for loading the other materials as well as adding in the man-power needed for supervision and administration, the total estimates for the labour requirements of producing iron clamps is astonishing. The iron clamps for fourth-century phase of the Water Supply of Constantinople were estimated to take 1.55 million man-days. More than doubling this figure, however, the fifth-century phase of the water supply would have required a record for the production of a single material at 3.10 million man-days. Considering that the total volume of iron clamps used in the fifth century is 0.7% of the total volume of facing stones, it would have required almost four and a half times the amount of labour.

SAND

Sand is the final construction material that needs to be addressed in terms of man-power requirements. Although making up the least of the bulk, it is one of the three primary components of mortar and required quarrying and processing before being mixed in. The first step is obtaining sand, in this case, through quarrying. As mentioned in the previous chapter, it is unlikely that sand used in the water supply and long wall (with the exception of Evçik – see p. 154) was sea sand. For the purposes of estimating the labour requirements, quarry sand has been chosen as the representative sand type due to the angular crystalline structure that would have been significantly weathered if sea sand.

While not being a catalyst for a chemical reaction, the process for obtaining sand was most likely very similar to pozzolana. Under this assumption, DeLaine's (1997: 111) estimations of man-power requirements for acquiring and processing pozzolana have been used here. Per cubic meter of pozzolana (or sand in this case), she estimated that it would have taken 0.090 man-days to quarry. Like shallow pozzolana deposits found, sand would likely have weak cohesive matrix, making it very easy to extract.

Once sand has been removed from the quarry, it would have been loaded and carried to the processing site. Again, using 25 m as a standard distance of travel within the quarry site, DeLaine's (1997: 111) estimate for transporting pozzolana of 0.165 man-days per m^3 has been selected for the sand needed for the water supply and long wall.

To ensure that sand had been broken up properly and free from larger stones, it was likely processed and sifted. DeLaine's figure of 0.120 man-days per m^3 (1997: 111) for pozzolana was used as the estimated labour requirement for processing and sifting sand. Additionally, DeLaine's (1997: 111) estimate for the man-power required to load pozzolana into carts for transportation to the construction sites were used for sand at 0.050 man-days per m^3.

Sand was calculated to have the least total labour requirements for the material acquisition and production phase at over 21,000 man-days for the fourth-century phase of the water supply, 43,000 man-days for the fifth-century phase, and 57,000 man-days for the Anastasian Wall. This is not surprising considering that the required sand for these systems also had the smallest total volume aside from the iron clamps. Nevertheless, sand is not insignificant for the structural volume or man-power estimates, especially considering the transportation requirements that will be discussed next.

Table 7.10 - Man-power requirements for the production of construction materials used to build the Water Supply of Constantinople and Anastasian Wall.

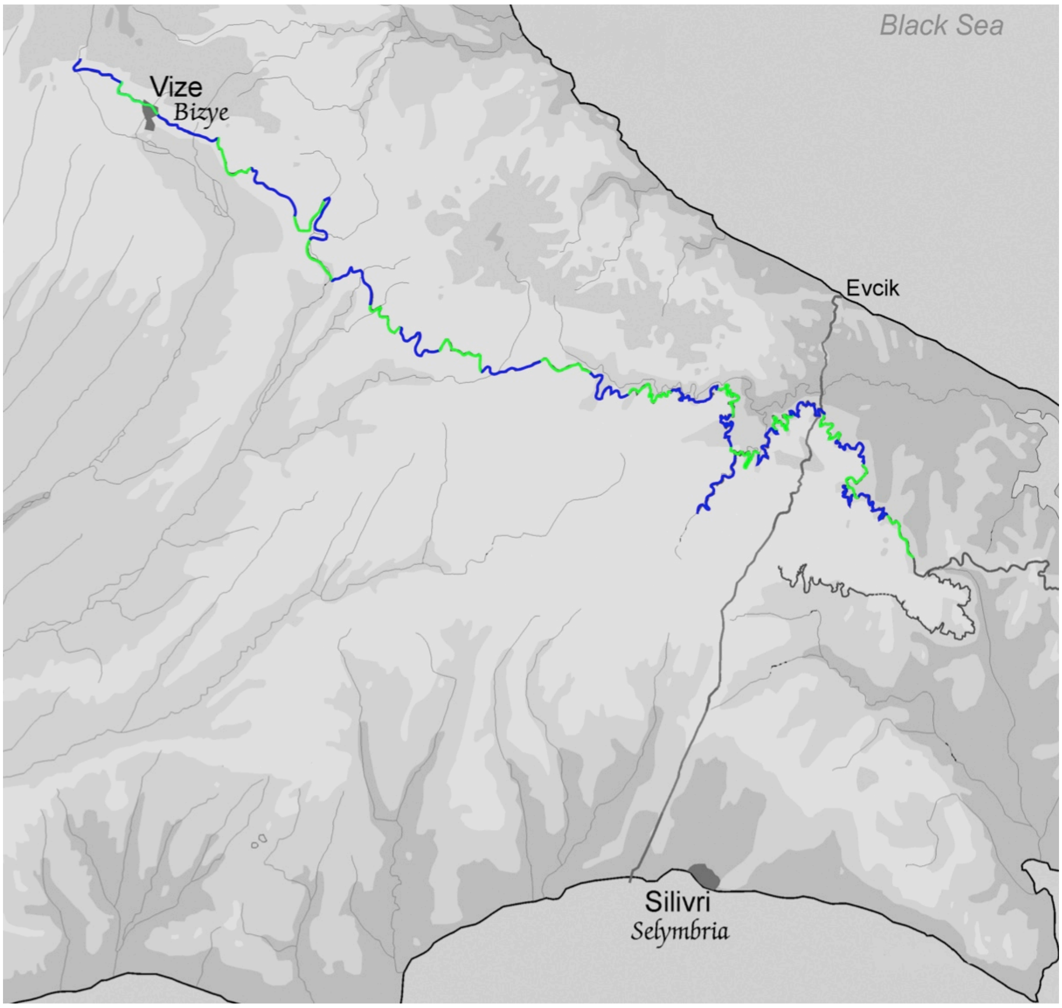
Material	Man-days (in thousands)
Water Supply – 4th Century	
Facing Stone	421
Rough Structural Stone	911
Lime	595
Bricks	465
Iron Clamps	102
Sand	21
Total	***2515***
Water Supply – 5th Century	
Facing Stone	833
Rough Structural Stone	1,888
Lime	1,193
Bricks	932
Iron Clamps	201
Sand	42
Total	***5,089***
Anastasian Wall	
Facing Stone	2,214
Rough Structural Stone	484
Lime	229
Bricks	250
Sand	15
Total	***3,192***

7.3.2 – Production Sites and Material Transport

Janet DeLaine (1997), in her work *The Baths of Caracalla*, was able to assess the sourcing and distribution of materials based on a centralized construction complex in Rome, as well as the vast geological, architectural, and archaeological work that has been carried out in central Italy for centuries. By linking the locations of quarries, kiln sites, and forests to the well-documented roads of Rome leading to the site of the baths, she was able to determine the distance each material would have to travel. Unfortunately, little is known about the precise provenance of construction materials, production sites, and the subsequent routes taken to transport them to the building sites of the Water Supply of Constantinople and Anastasian Wall. It would be a hapless pursuit to delve into a discussion of the labour requirements of transporting materials for the systems without first addressing the origins and destinations of these materials.

Hodge (1992: 191-194) makes reference to the Eifel Aqueduct of Cologne in regards to the logistics of building aqueducts. By 'contracting' pieces of the construction to groups of workers, he says that multiple stretches of the aqueduct were built simultaneously to speed up the process of construction. In the case of 130km-long Eifel aqueduct, it was built in about 15 sections, each spanning between 4.44 and 5.33 km of length (Hodge, 1992: 194). Unlike the Eifel aqueduct, however, there is no clear indication that the two long distance phases of the water supply were built in section. The Eifel aqueduct shows a 40cm discrepancy between 2 joining sections of the channel (Hodge, 1992: 192) whereas no clear evidence has been identified for the systems of Thrace. It is possible that the joining sections did not always match up in the Aqueduct of Constantinople and that the evidence could only be visible through excavations of the channels buried below ground.

It is quite conceivable that the channels and bridges of the fourth and fifth-century phases of the Water Supply of Constantinople as well as the Anastasian Wall were built in sections. For the purpose of estimating the man-power for material transportation, each system of this study has been broken down into a number of hypothesized ‘contract’ sections similar to the Eifel Aqueduct in estimated sections of 10 km due to the great length of these structures. The Water Supply of Constantinople has been estimated to have 27 sections for the fourth-century phase and 18 for the fifth-century phase. The much shorter Anastasian Wall was calculated as having an estimated five sections.



Map 7.7- Example of contract section divisions for the fifth-century phase of the Water Supply of Constantinople (after Crow, 2007b: 269)

Before continuing to the discussion of transportation and associated man-power requirements, general assumptions of this analysis need to be stated:

- Ox-carts and cargo ships were chosen as the methods used to transport construction materials from the sources to the contract sections. Ox-carts were typically used for the transport of lime in late-antiquity and would have carried a maximum load of 1500 librae or almost 500 kg (*Codex Theodosianus* 8.5.30). Large cargo ships had a maximum cargo of 300 to 400 tonnes and were common in coastal transport (DeLaine, 1997: 108; also see shipwreck YK 3 from excavations at Yenikapı in Kocabas, 2012).

- Ox-carts required two oxen and one man, traveling an average distance of 30 km a day (Delaine, 1997: 108). Cargo ships required a minimum crew of men and traveled a maximum distance of 78 nautical miles per day (DeLaine, 1997: 108; Casson, 1951: 141-143). These distance figures will be used to determine how long one trip would take from the hypothetical material sources

- The route of the ox-carts and cargo ships would have taken the path of the shortest distance, taking terrain into consideration. There is no evidence for supply paths and little on the secondary roads of Late-Antique Thrace.

- The average of the measured lengths from the material source or manufacturing site to the closest and furthest contract sections indicate the mean distance traveled for transporting materials to the construction sites of the water supply and long wall.

- Each contract section would require the same quantity of building materials. While this would not have been the actual case during the construction of the water supply due to the varying occurrences of bridges or for the long distances between forts along the Anastasian Wall, the routes and distances traveled remain very hypothetical. Because of this, calculating specific quantities of materials needed for hypothetical contract sections would be an unnecessary exercise.

MATERIAL PROVENENCE AND LOCATIONS OF PRODUCTION SITES

Stone

The precise location of quarry sites associated with the water supply and wall is largely unknown. Almost no conclusive evidence exists for large quarries needed to produce the vast quantities of stone required for the facing, core, and production of mortars (Crow, Bardill, and Bayliss, 2008: 90). There is possible evidence of a small quarry near Babadar Dere along the end of the fourth century and the beginning of the fifth-century water supply lines (Crow, Bardill, and Bayliss, 2008: 46, 107). However, it would be impossible to conclusively state that similar small quarries were the locations of the initial construction of the whole systems or stone sources for small structures and/or later repairs. In addition, large depressions found in the middle and northern sectors of the Anastasian Wall (Crow et al., forthcoming) are also likely to have been quarry sites.

As previously discussed in Chapter 6 on the mortar analysis, geological bedrock maps (Türkecan and Yurtsever, 2002; Bono, Crow, and Bayliss, 2001: 1326;) of the area show that large portions of north-central, and northwestern Thrace are rich in metamorphic and limestone deposits. Evidence of stones used to construct the long wall and water supply has been categorised as mica schist, metamorphosed limestone, and non-crystalline limestone (Crow, Bardill, and Bayliss, 2008: 90, 103, 107). Further to the north, sandstone bedrock is widely available but construction using this material seems to be limited only to lime mortars from the northernmost section of Anastasian Wall, close to the Black Sea coast.

The wide coverage of viable sources of structural stone and the lack of evidence of large quarries has led to two hypothetical scenarios stone sources. The first scenario was that there was one central source of stone, which was distributed among the contract sections of the two systems. This was assumed to be in a region closest to the middle of the length of the system. The second scenario was that numerous locations of stone quarries were located over the entire length of the systems, requiring much shorter trips distribute materials to the contract sections.

Lime Production

The process of producing quicklime from limestone is a thorough process that drastically changes the composition of the original material. Furthermore, the rehydration and mixing with other materials makes it almost impossible to determine the origin of the stone with the naked eye. However for this analysis, it has been assumed that the limestone used to produce quicklime came from the same quarry sites at the structural stone material. Furthermore, since burning lime was most likely done at or close by the quarry (Lancaster, 2005: 53), the distribution of the quicklime to the site would follow the same paths as the structural stone used in the core and the facing stones.

Based on the scientific analysis (see Chapter 6) of the mortars from these systems— specifically the XRD analysis of the brick aggregates— it is safe to assume that the location of the raw clay and brick production sites for these systems were the same as the those producing the bricks for construction around Constantinople. Unfortunately, little more can be said with definitely about the provenance of the remaining construction materials used in the water supply and wall.

Brick

As mentioned in the previous chapter, it is likely that the crushed brick material used in the mortars of the water supply and the long wall came from similar raw clay sources as the bricks used in structures within Constantinople based on XRD analysis of brick aggregate (see page 182). This does not guarantee that all of brick material used in the construction was from Constantinopolitan production sites. Brick wasters deposited on the southern terminus of the wall, and the remains of a brick kiln were identified from surveys carried out near Silivri (Anastasian Wall Project; Crow et al., forthcoming). It might be possible, if this and other neighbouring kilns was producing bricks for the wall, that they could have been used structurally as brick courses or arcades from section of the southern sector where there is little surviving evidence of the wall structure for the first 20 km north from the Sea of Marmara.

For the sake of estimating the man-power requirements of transporting materials, all bricks are assumed to have come from brickyards located near the Theodosian Land Walls. In both scenarios for transporting bricks for the construction of the water supply and long wall, it is assumed that bricks were shipped from harbours near Constantinople. Destinations of materials will be addressed further in this section.

Iron

Because special furnaces were needed to smelt the large quantities of iron necessary for construction around Constantinople, it is assumed that, like brick production, iron smelting and casting was carried out at pre-existing sites close to the capital city. This is not to say that ironwork could not have taken place closer to the site but the logistical problems created by setting up multiple smelting sites, transporting iron ore and casting iron clamps along the great distances of the wall and water supply would drastically increase the time and cost.

According to a map of mineral deposits in Turkey produced by the Maden Tetkik ve Arama Genel Müdürlüğü (Directorate General of Mineral Research and Exploration), the closest source of iron ore is about 150 km from Istanbul, near the Black Sea coastal town of Karasu (Engin, 1986; see Map 5.1). Without further information regarding the sources of ore for Late Antique Constantinople, the transport of iron ore will not be considered in the man-power calculation. However, under the assumption that large-scale iron ore processing and clamp casting is performed at production centers close to Constantinople, the transportation of the iron clamps follow the same hypothetical routes as brick.

Sand

Sand is another very difficult material to pinpoint the exact location of quarrying. As Pliny (*Natural History* 36.175-177) and Vitruvius (*On Architecture* 2.4.1-3) pointed out, there are three forms of sand that could be used for the production of mortars:

quarried sand which is most recommended, river sand, and sea sand which he says to avoid if at all possible. In Thrace, all three of these types of sand are available over large portions of the peninsula. Based on the study of mortars from these systems discussed in the previous chapter, almost every sample indicates coarse quarry or river sand. The single exception is sand found in the samples from Evcik where they were larger-grained with smoothed crystalline structures. Like stone quarries, the two hypothetical scenarios for sand quarry sites and distribution networks have been applied for the man-power requirements for transportation.

Wood Fuel

The source of wood fuel for the production of building materials for the Water Supply of Constantinople and the Anastasian Wall is assumed to be needed for two main production locations: brick and iron production sites near Constantinople and lime production sites at or near stone quarry(s). Relating to these production centres, the forest areas yielding timber for such exploits were likely chosen based on their proximity to production sites. However, even having estimated a quantity of fuel necessary for iron and brick production, it is assumed that the city of Constantinople would have a constant influx of timber to suit a myriad of needs. Thus, only the transport of wood fuel, assumed to be within easy access to the production sites, will be included in this calculation.

DISTANCES AND NUMBER OF TRIPS

Calculating the transport distances of construction material is of particular importance for labour requirements. Unfortunately, the routes of travel are virtually unknown for the Water Supply of Constantinople and Anastasian Wall. However, using the many assumptions listed earlier, rough calculations can be made for the distances traveled and the total trips needed to distribute the construction materials. The discussion that follows will identify the estimated distances travelled and number of trips necessary for each of the construction materials based on the average of the two following hypothetical scenarios:

‘Hypothetical Scenario 1’

- *Water Supply (both phases)*

  Stone and sand are transported from a single quarry source located within close proximity to the particular phase of construction. Iron and brick are transported by cargo ship from Constantinople along the coast of the Sea of Marmara to Büyükçekmece Lake and then distributed by land transport. Wood fuel for lime production is collected from the environs of the single stone source.

- *Long Wall*

  Stone and sand are transported from a single source located within close proximity to the wall. Brick is transported by cargo ship from Constantinople along the coast of the Sea of Marmara to Silivri and distributed by land transport. Wood fuel for lime production is collected from the environs of the single stone source. (Figure 7.3)

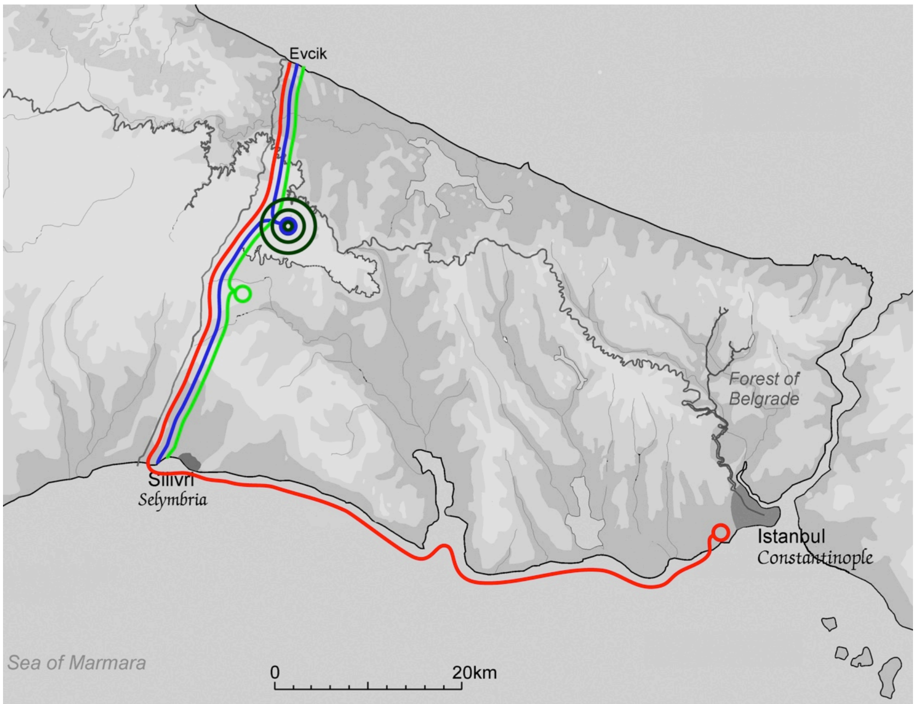
‘Hypothetical Scenario 2’

- *Water Supply (both phases)*

  Stone and sand are transported from multiple sources all located within close proximity to the smaller groups of contract sections. In the fourth-century phase, iron and brick are transported by cargo ship from Constantinople up the Golden Horn, and then distributed by land. The fifth-century phase follows the Bosphorus north, west along the Black Sea coast to around the village of Yalıköy, and then distributed by land transport. Wood fuel for lime production is collected from the environs of each stone source.

- *Long Wall*

  Stone and sand are transported from multiple sources located within close proximity to the wall. Half of the brick is transported by cargo ship from Constantinople along the coast of the Sea of Marmara to Silivri and distributed to the southern half of the contract sections by land transport. The other half of brick is transported by cargo ship up the Bosphorus and along the Black Sea coast to Evcik, where the materials are distributed to the northern half of the contract section. Wood fuel for lime production is collected from the environs of each stone source.



Map 7.8 - Example of 'Hypothetical Scenario 1' for the Anastasian Wall (after Crow, 2007: 269). Red = brick, light green = sand, blue = stone and lime, dark green = wood for lime production.

These scenarios are not intended to offer a realistic example of the transportation routes used but instead show the least and most difficult options. By averaging the man-power results of these two hypothetical situations, the aim is to offer a discussion of the requirements of material transportation. However, it is only by extensive future research, such as identifying material provenance and logistics of construction, that any further can be said about material transportation for the water supply and long wall.

Table 7.11 - Number of ox-cart and cargo ship trips for each contract section of the Water Supply of Constantinople and Anastasian Wall. For the calculations of the total distances travelled for each material, see Section A5.2 of the Appendix.

Material	Material (Tonnes) per Contract Section	Ox-cart Trips per Contract Section	Cargo Ship Trips per Contract Section
Water Supply – 4th Century			
Facing Stone	3.24	7,900	--
Rough Structural Stone	60.15	147,000	--
Lime	4.76	12,000	--
Bricks	11.11	27,000	1,000
Iron Clamps	0.035	85	3
Sand	2.70	6,600	--
Wood Fuel for Lime	18.51	45,000	--
Water Supply – 5th Century			
Facing Stone	9.51	23,000	--
Rough Structural Stone	184.99	453,000	--
Lime	14.18	35,000	--
Bricks	33.06	81,000	2,000
Iron Clamps	0.120	250	6
Sand	8.02	20,000	--
Wood Fuel for Lime	55.10	135,000	--
Anastasian Wall			
Facing Stone	88.27	216,000	--
Rough Structural Stone	165.62	406,000	--
Lime	9.51	23,000	--
Bricks	31.01	76,000	540
Sand	9.84	24,000	--
Wood Fuel for Lime	36.98	91,000	--

Table 7.12 - Labour requirements for transporting construction materials to the building sites of the Water Supply of Constantinople and Anastasian Wall.

Material	Ox-cart-days (in thousands)	Cargo ship-Days (in thousands)
Water Supply – 4th Century		
Facing Stone	187	--
Rough Structural Stone	3,032	--
Lime	240	--
Bricks	1,095	1
Iron Clamps	3	Negligible
Sand	136	--
Wood Fuel for Lime	359	--
Total	*5,052*	*1*
Water Supply – 5th Century		
Facing Stone	256	--
Rough Structural Stone	4,349	--
Lime	333	--
Bricks	1,678	3
Iron Clamps	5	Negligible
Sand	178	--
Wood Fuel for Lime	720	--
Total	*7,519*	*3*
Anastasian Wall		
Facing Stone	330	--
Rough Structural Stone	620	--
Lime	36	--
Bricks	116	1
Sand	37	--
Wood Fuel for Lime	39	--
Total	*1,178*	*1*

7.3.3 – Man-power for Planning, Site Management, and Construction

Up to this point, the labour requirements for obtaining, producing, and transporting the construction materials have been estimated. The last phase of the construction process takes these materials and melds them into functional units, ultimately forming the entirety of these systems. However, before the first stone was placed, the construction site needed to be readied.

SITE PREPARATIONS

While the first steps of producing these structures would be the survey of the landscape and the design of the structure, due to the limited evidence for the labour requirements, these processes are not involved in the study of the water supply or long wall. It should be noted that survey and design would have been a significant aspect of the overall building process as well as the associated man-power requirements.

When the courses of the water supply and long wall had been surveyed, the prospected path of the structure would need to be cleared of all vegetation. Because of the limited data for the current and historic biodensity of the Thracian forests, a conservative average yield of 4 kg of wood per m^2 (Wall, 2009: 20), based on an average New England oak forest, was chosen. Since the forests along modern Turkish Black Sea coasts have long been known to be thriving and resilient systems (see discussion of forests of the Black Sea coasts in Meiggs, 1982: 393), it is safe to assume that the modern density of the Thracian forests are analogous.

To calculate an estimate for the area to be cleared, textual evidence offers a good foundation. The Codex Theodosianus (15.2.1) states that no trees should be within 15 Roman feet of an aqueduct structure, probably to ensure the root systems do not compromise the structural integrity. This converts to roughly 4.44 meters from both sides of the structure. Over the distance of the fifth-century water supply, assuming that the majority of the system was through forested land, the total area to be cleared for construction is estimated at 1.83 million m^3. Applying the figure for the total yield, this equates to 7,200 tonnes. Similarly the fourth-century phase of the water supply would have required almost 11,000 tonnes of wood to be cleared. However, assuming that the Anastasian Wall would require clearing twice the area of for construction of the structures and ditch system, as well as assuming that the southern half of the wall was not heavily forested based on the modern landscape, only an estimated 2,100 tonnes of wood forest needed to be cleared.

According to the study of charcoal production in the Peruvian Amazon by Coomes and Burt (2001: 42), it takes one person, using non-mechanised tools, roughly seven days to obtain 7.182 tonnes of wood. This translates to 0.975 man-days per tonne. While these figures are useful, it should be stated that neither the figures for tonnage of wood per unit of area or the man-power estimates for clearing the forests used in this labour analysis take the root systems of the trees into account. It is assumed that the estimates for digging the foundations for these structures and the ditch for the wall would might make up for this.

Digging and shoring the foundations for above ground structures as well as the cut and cover method of channel construction are the next preparatory steps for the construction site. The total volume of removed earth for the foundations of the fourth and fifth-century phases of the water supply were estimated to be 1.78 million m^3 and 3.76 million m^3 respectively using methods discussed in Chapter 5 (pages 108-132). The same figure was estimated for the Anastasian Wall at 427,000 m^3 of removed earth (this does not include the ditch which is addressed in the construction phase below). The two long phases of the water supply would have required the extraction of far more earth in order to set the channel below the surface of the ground, producing a much larger volumetric figure than the much shorter length of the long wall. DeLaine (1997: 268), in her table of labour constants from Pegoretti (1897), indicated that this process would involve 0.150 unskilled man-days per m^3 to dig a foundation of over 1.6 m depth. In addition the foundation walls would have needed to be shored, with the requirements of 0.015 skilled man-days per m^3, and 0.018 unskilled man-days to raise the excavated earth from a foundation trench with a height greater than 16 m. In total, digging the foundations for these systems would have required 0.183 man-days per m^3.

Before construction began, the wood scaffolding and formwork could be prepared using the already-felled timber. Again applying the figure for stripping and sawing the wood from table of labour constants (DeLaine, 1997: 268), it would take a combination of skilled and unskilled labourers 0.075 man-days per m^2 of the surface area of the faces of the final structures.

With the addition of supervision and administration, the estimated man-power needed for readying the site totalled 376,000 man-days for the fourth-century phase of the Water Supply of Constantinople. Significantly greater due to the new broad channel width as well having many more and larger bridges, the estimated figure for the fifth-century phase was almost 1.41 million man-days. Having the lowest labour requirements of the three systems, the Anastasian Wall was estimated to require 243,000 man-days to prepare the sites.

MORTAR PREPARATIONS

Once the materials for the mortar arrived at the site, they would need to be mixed together and loaded in baskets for application. First the components would need to be brought to the mixing area. By averaging the labour requirements for crying the individual components from the material production phase, 0.261 unskilled man-days per m^3 was estimated for carrying these materials 10 m within the site.

Adding the components and mixing them into a mortar would have most likely required a combination of skilled and unskilled labourers. DeLaine (1997: 268) table of labour constants lists the figures of 0.550 man-days per m^3 for mixing mortar for the foundation and 0.700 for the wall mortars. Because of differences in mortar types of the Baths of Caracalla and the mortars of the systems examined in this study, an average of these figures (0.640 man-days per m^3) was chosen as a reasonable figure here. Once the mortar was mixed, the estimated labour requirements for loading it into baskets was figured to be 0.060 man-days per m^3 according to DeLaine's table of labour constants.

Considering the amount of mortars used in the construction of the Water Supply of Constantinople and Long Wall, the total man-power requirements for preparing the mortars can be calculated. The fourth and fifth-century phases of the water supply were estimated to require 402,000 and 806,000 man-days respectively. The Anastasian Wall was estimated to require 753,000 man-days.

BUILDING PREPARATIONS

The categories included in building preparation refer to a myriad of activities that are necessary to ensure a constant flow of materials and enable access, as the structures grow higher. The first process to be examined here is stone dressing. Once rough-cut stone blocks reached the construction site, they were cut and sculpted to precisely fit a specific location and maintain continuity of the courses. It is assumed that this was to be done at the construction site rather than the quarry due to the time consuming nature of the process that would be wasted if a stone block were broken while being transported. Additionally, this would allow for precise control of the size and shape of the blocks as they were hoisted into place. According to Perogetti's (1869) analysis, DeLaine (1997: 121) indicates that it would take one person seven and a half days to dress one cubic meter of marble. For the sake of estimating, all of the facing stones used in these systems are said to be some form of crystalline marble, meaning the estimate of 1.406 man-days per 0.1 m^3 block would be satisfactory for the labour required to dress a single stone. It should be kept in mind that parts of the wall and some aqueduct bridges are made of non-metamorphosed limestone. However, the time constraints of this project and the need for further data on proportion from surviving structures. This analysis will be saved for future research.

Going back to DeLaine's (1997: 268) table of labour constants (page 137), it is possible to estimate the man-power requirements for erecting the scaffolding. Her formula for erecting scaffolding requires an additional estimation for the number of upright posts (standards) spaced out to support the platforms. For the sake of estimating, it is assumed that the scaffolding for the Anastasian Wall and Water Supply of Constantinople used only engaged scaffolding (see Crow, Bardill, and Bayliss, 2008: 66; Crow et al., forthcoming). The uprights of the scaffolding are estimated to have been spaced at an average of 3 m apart since there is not enough evidence to calculate this figure. Her estimated man-power for placing the uprights and constructing the scaffolding 0.063 man-days per m^2 of facing plus 1.250 man-days per upright. This figure has been used for the water supply because of the greater average height of the bridges but the since the Anastasian Wall rarely exceeds 12 meters, it calculated to only take 0.075 man-days to place the shorter uprights. The workforce for such an important, yet labour-intensive activity has been assumed to be a combination of skilled and unskilled labourers.

The next labour requirement is carrying materials to the area of construction. Here, Pegoretti's (1869 from DeLaine, 1997: 268) constant of 0.0047 man-days per trip within the site plus 0.075 man-days per m^3 of material seems to be a thorough method of estimation. The number of trips for each material used in the construction of these systems was estimated dividing the total number of material units by the average weight that can be carried by human.

Including supervision and administration, the fourth-century phase of the water supply was estimated to require a little over 614,000 man-days to initiate and facilitate construction through carrying materials, constructing the scaffolding, and dressing facing stones. The fifth-century construction phase almost doubles the fourth-century estimate at 1.22 million man-days. However, the Anastasian Wall more than triples the total of the fifth-century total at 3.67 million man-days. This can be attributed to the much larger quantities of facing stones needing to be dressed, as well as the significantly higher quantity of above ground structure requiring scaffolding.

CONSTRUCTION

Through the actions of the phase of labour requirements, the structures of these systems would finally take shape. Starting in no particular order since the point of this study is not about detailing the processes but instead intends to show the magnitude of the overall workforce requirements, the preparation and construction of the vaults will be considered first. DeLaine's (1997: 268) table of labour constants (see Table 5.2 on page 137) splits the man-power figures into two sizes of vaults with values of 0.100 man-days per m^2 of a small vault's surface area and 0.200 man-days for a large vault. The small vault figure will be used in the water supply since the entirety of the channel systems are vaulted. In addition, the aqueduct bridges' arches would be categorised as large vaults. For the Anastasian Wall, entrances to the towers are considered small, while the gates of the forts have been classified as large vaults (although this classification does not affect the calculations).

Laying the foundation of the above-ground aqueduct bridge and wall structures depends on the depth (DeLaine, 1997: 268). This equation is 0.350 + 0.010 (d-1) man-days per m^3, where 'd' is the depth of the foundation. Assuming that the average depths of the foundations are roughly similar between the two systems at 2.5 m, this equates to 0.365 man-days per m^3.

Much of the time, construction materials had to be lifted above the height of an average human, increasing the labour requirements. DeLaine (1997: 268) takes this into consideration by using the equation 0.012 (h-1) man-days per m^2 wall surface area, where 'h' is the height of the structure. This constant should be no different for the type of faced structures dealt with in this study and thus, the average height of the bridges from each the fourth and fifth-century were used with this formula.

Building the base and walls of the water supply channels, as well as laying the channel mortar lining were calculated using two figures from the work of DeLaine. The figure for constructing the channel (0.365 man-days per m^3 of structure) was chosen to be the same figure for laying the foundations based on the assumption that this process applied similar care and masonry techniques as well as the consideration of depth of the structure. The estimate for labour requirements for laying the channel lining mortar was based of DeLaine's figure for wall plastering. Her figure of 0.500 man-days per m^2 for a thickness of 7.5 cm has been adjusted to 0.250 man-days for the channel mortar used in the water supply channels. This was done to compensate for the lining mortar's average thickness of only 1.5 cm but also taking into consideration the skill and precision required to produce continuously smooth and level surface for the water to flow.

For the modern and historical observers, the most accessible step of the building process of both the Water Supply of Constantinople and the Anastasian Wall was the above-ground construction. This involved placing the blockwork facing, laying the mortared rubble core, and constructing the vaults. Since the vaults have already been addressed, only the figures for labour requirements of the facing and core construction will be addressed. DeLaine (1997: 268) used a calculation for laying brick and core for walls based on the estimates of Pegortetti (1869). This is 4.180 + 0.130 (h-1) skilled man-days per m^3, where 'h' is the height of the wall, plus half this total for unskilled labour. While the water supply and long wall primarily used stone facing, this figure may underrepresent the total manpower requirements of lifting and placing the stone, as well as inserting the iron clamps and lead fittings into the sockets. However, as the only available formula for calculating this construction process, it was chosen as an acceptable, albeit conservative formula for calculating the labour requirements for the water supply and long wall.

The final construction process was digging the ditch for the Anastasian Wall. The total volume of excavated earth for the maximum 3.5 m deep, 12.5 m wide ditch was 1.15 million m^3. The same figure as digging the foundations of 0.150 man-days per m^3 of removed earth was used for this calculation. Crow (2007: 208) had calculated the man-power requirement for digging this ditch, using Squatriti's (2002: 41) study of work in 1930s Romania, stating that it would require "approximately 1000 men working for two years, taking in to consideration holy days and poor winter weather." In comparison, 0.150 man-days is a very conservative figure.

Ultimately, using these figures, the total labour requirements for constructing the Water Supply of Constantinople and Anastasian wall can be estimated. The fourth-century phase of the water supply has been estimated to require 1.27 million man-days to erect the system's 36 bridges and 271-km length of channels. More than doubling this figure based almost solely on the quantity and monumentality of the bridges, the fifth-century phase was estimated to require 2.83 million man-days. However constructing the forts, towers, and curtains of the Anastasian Wall would have required an estimated 15.14 million man-days— five times the total of the two phases of the water supply system combined.

Table 7.13 - Man-power requirements of preparing and constructing the Water Supply of Constantinople and Anastasian Wall.

Action	Man-days (in thousands)
Water Supply – 4th Century	
Site Planning and Preparations	376
Mortar Preparations	402
Building Preparation	614
Construction	1,271
Total	***2,663***
Water Supply – 5th Century	
Site Planning and Preparations	1,407
Mortar Preparations	806
Building Preparation	1,220
Construction	2,826
Total	***6,259***
Anastasian Wall	
Site Planning and Preparations	243
Mortar Preparations	753
Building Preparation	3,673
Construction	15,138
Total	***19,807***

7.3.4 – Total Man-power Requirements

The estimated total labour requirements for the Water Supply of Constantinople and Anastasian Wall are staggering. For instance, the man-power required to produce the material quantities necessary to build the fifth-century phase of the water supply was calculated to be 7.22 million man-days. In the hypothetical and extremely unlikely scenario that 10,000 labourers worked twelve-hour shifts every day of the year, it would take almost two years to produce the materials alone. Using the same scenario for the Anastasian Wall, the massive figure of 19.81 million man-days required for construction would take almost five and a half years.

Table 7.14 - Total labour requirements per construction phase for the Water Supply of Constantinople and Anastasian Wall.

Construction Phase	Total Man-days (in millions)
Water Supply – 4th Century	
Material Production	7.2
Material Transport	7.5
Construction	6.3
Water Supply – 5th Century	
Material Production	3.6
Material Transport	5.1
Construction	2.7
Anastasian Wall	
Material Production	5.3
Material Transport	1.2
Construction	19.8

Unfortunately without extending the discussion much further and also due to the limitations of the known evidence, little more can be said about these systems regarding work scheduling, cost, total workforce, or the timeframe of construction at this time. However, the figures for the total labour required (Table 7.15) do offer a rare insight into the magnitude of the long-distance Water Supply of Constantinople and Anastasian Wall.

Table 7.15 - Total required labour for the Water Supply of Constantinople and Anastasian Wall.

Total Required Labour (man-days)	
4th c. Water Supply	21.0 million
5th c. Water Supply	11.4 million
Anastasian Wall	26.3 million

Having these manpower figures does allow for a comparative discussion of other construction projects throughout history. Hill (2010: 126) calculated the man-power requirements for digging the Vallum of Hadrian's Wall at almost 400,000 man-days for 1.46 million m^3 of excavated material. The ditch of the Anastasian Wall was calculated to require 172,000 man-days to excavate 1.15 million m^3. This indicates two things: first, the estimate from the man-power calculations for the Anastasian

Wall are quite conservative and second, the quantity of excavated materials are quite similar between the 112 km- long Vallum of Hadrian's Wall and the 46 km-long ditch of the Anastasian Wall.

It is also interesting to compare the total man-power requirements of the Baths of Caracalla since much of the calculations are based on DeLaine's (1997) work. While these projects are completely different in terms of both function and structural form, they both had many of the same building requirements (i.e. - material production, transportation, and construction techniques). DeLaine's estimates (1997: 175-182) show that the main structure would have required 5.22 million man-days from material procurement to finished bath complex. With the addition of the precinct at a later period (DeLaine, 1997: 193), the total figure for the construction of the Baths of Caracalla are a little over 6.65 million man-days. This means that the man-power required for the 4th- and 5th-century phases of the water supply could have been used to build almost five Baths of Caracallas. Similarly, the Anastasian Wall would have required four times the man-power.

Chapter 8 - CONCLUSIONS AND FUTURE STUDIES

All men shall contribute their work and shall zealously urge forward the restoration of the port and the aqueduct, and no person shall be exempt from such common duty by any privileges of rank.

Codex Theodosianus, 15.1.23

While the remaining structures of the Water Supply of Constantinople and Anastasian Wall are impressive representations of the success of Late Antique construction, they offer only a small glimpse of the building technology, material quantities and required workforce. The work of Crow, Bardill, and Bayliss (2008) provided the most comprehensive study of the water supply, clearly showing that it was, without a doubt, the longest Roman water supply system. In addition, the work carried out by the Anastasian Wall Project and the forthcoming monograph by Professor James Crow show that the "the Anastasian Wall was the last and most monumental of the late Roman barrier walls constructed within the frontiers of the eastern empire" (Crow, forthcoming). The attention to the archaeological and historical Constantinopolitan framework of these projects, paired with the application of modern remote sensing techniques, serve as a prime example of the benefits of a multidisciplinary approach.

The objective of this study was to build onto these works in order to gain a better understanding of large-scale infrastructural construction in the Late Antiquity. By applying material sciences and structural evidence, mortars from various locations along the water supply and long wall were investigated. Through the qualitative macroscopic and microscopic observations of these samples, it was evident that the mortar recipes varied little between construction phases and structural type. This is not surprising considering these systems' heavy reliance on mortar for their longevity and success. Set against other studies of mortars from late antique structures reviewed in Chapter 4, the mortars of the water supply and long wall fit in with a ‘standard’ set of ingredients. Sand, broken and crushed brick aggregate, and lime seem to be found in almost every structure studied, regardless of the construction method or application. In only one sample from the water supply and long wall— the fifth century bridge of Kurşunlugerme— river pebbles were found used as aggregate. According to Mark and Çakmak (1992: 94), this fits in perfectly with evidence from the mortars of Hagia Sophia, where they claim that these pebbles are likely inclusions from the addition of sand.

Mortar analysis also indicated a reliance on local raw material resources, especially in regards to small sand aggregate. This is based on the variation of sand aggregate size and shape, most evident between samples from the middle sections of the Anastasian Wall and the northernmost point situated on sandstone cliffs overlooking the Black Sea at Evçik (see page 166). While this study did not incorporate a local geological study, which would have been used to identify precise locations of sand and stone quarries (see studies in section 4.1.2), all materials used in the construction of the water supply and long wall were available from raw material deposits on the Thracian Peninsula (Map 5.2; see discussion of brick clay in section 6.5 of Chapter 6).

With so much of the architecture of Constantinople using structural brick (see sections 3.2 and 3.3 of Chapter 3), the brick industry of the city must have been enormous. The study of brick aggregate materials indicated that raw clays all came from the same source, likely the same source as bricks used in structures within late-antique Constantinople (see brick tests in section 6.5 of Chapter 6). Despite the lack of evidence of production centres, the combination of this scientific analysis and the quantification of brick material needed for the construction of the Water Supply of Constantinople and Anastasian Wall (see section 7.2.2 of Chapter 7) show that Constantinople must have had a well-organised brick industry as big, or bigger, than that of Rome.

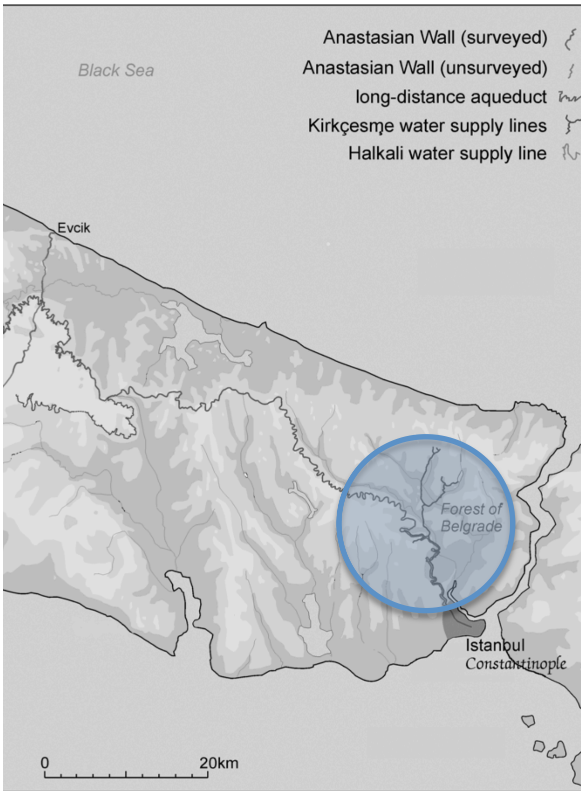
The mortars from the Water Supply of Constantinople and Anastasian Wall are shown to be good indicators of the technological abilities of the builders of the 4th, 5th, and 6th centuries. While these samples varied in friability, aggregate size, and weight, the cause was rarely linked to poor quality control. For example, the channel lining mortar sample from Karatepe was surprisingly poor quality but the evidence of rebuilding in the area and the unique nature of unburned fossiliferous limestone inclusions indicate that it was most likely a hasty repair in the centuries following the initial construction phase. Similarly, the likelihood that the sample from Belgrat Tower was a brick joint in an arch was evidenced by its light weight and tapering shape, indicating that mortar technology was adaptable to the desired function (Figure 8.1). As mentioned in section 3.3 of Chapter 3, the reliance on mortar in the water supply and long wall show how important the material was to builders.

Figure 8.1 - Sample TT-AW 5 from Büyük Bedesten. Notice the slight taper from right to left and the large size and quantity of brick aggregate

Large-scale construction would have required more than a proficiency in material production and application. It was obvious that these structures would have required extremely large quantities of materials but without knowing the overall scales of water supply and long wall, it would be impossible to estimate. Using the survey data from the Anastasian Wall Project's years of surveys, the overall volume of these systems were estimated. It was clear from this analysis that total material requirements were not tied to the length of the structures. For instance, the fourth-century water supply lines were almost 90 km longer than the fifth century but, due to the differing channel widths and average bridge size, the fifth-century phase was over twice the size. More impressively, while the fifth-century water supply line was over five times longer, the Anastasian Wall was volumetrically larger due to its pronounced height and width.

Architectural analysis was then used to ‘deconstruct’ the water supply and long wall into the individual construction materials: facing stones and iron clamps, rubble stone, structural mortar, and channel lining mortar. With the ultimate intent of this project being to gain a better understanding of the material and manpower requirements, materials requiring a process of production were broken down even further. Iron clamps were broken down into ore, bloom, and associated fuel. Mortar was broken down according to the previously calculated percentages of lime, brick, and sand. Lime required its own production process so raw limestone and wood fuel were estimated. Similarly, brick production required clay, sand temper, and fuel.

One of the most surprising findings was sheer volume of materials needed. All of the stone needed for the fourth and fifth century water supply, including facing stones, rubble stone, and raw limestone for mortar production has been estimated to be almost exactly the same. In comparison, the volume of the Great Pyramid of Giza, made almost exclusively of stone, has an estimated volume of 2.5 million m^3 (Levy, 2005). Even more impressive is that this estimate does not include the almost 700,000 m^3 of sand and brick material. Using the general figure for forest density as Wall (2009) for a dense oak forest, the area needed to yield enough wood fuel for brick, lime, and iron production was estimated to be 318 km^2 for the fifth-century phase of the water supply alone. This would cover almost the entirety of the Forest of Belgrade (Figure 8.2).



Map 8.1 - Estimated area of forest needed to meet the fuel requirements of the fifth-century phase of the Water Supply of Constantinople (after Crow, 2007: 269).

Total material volumes offer a rare insight into the necessary planning that was involved in large-scale construction. Unfortunately, there is little known evidence from Late Antiquity about construction organisation and logistics, let alone descriptions of raw material sources. This, along with the lack of archaeological evidence for production sites and quarries for Constantinople, was one of the most difficult aspects of the man-power analysis. However, the results of this study show some major differences in requirements. What is most intriguing is the vast amount of man-power required for the site preparation and construction of the Anastasian Wall while the transport requirements were estimated to be very low (Figure 8.3).

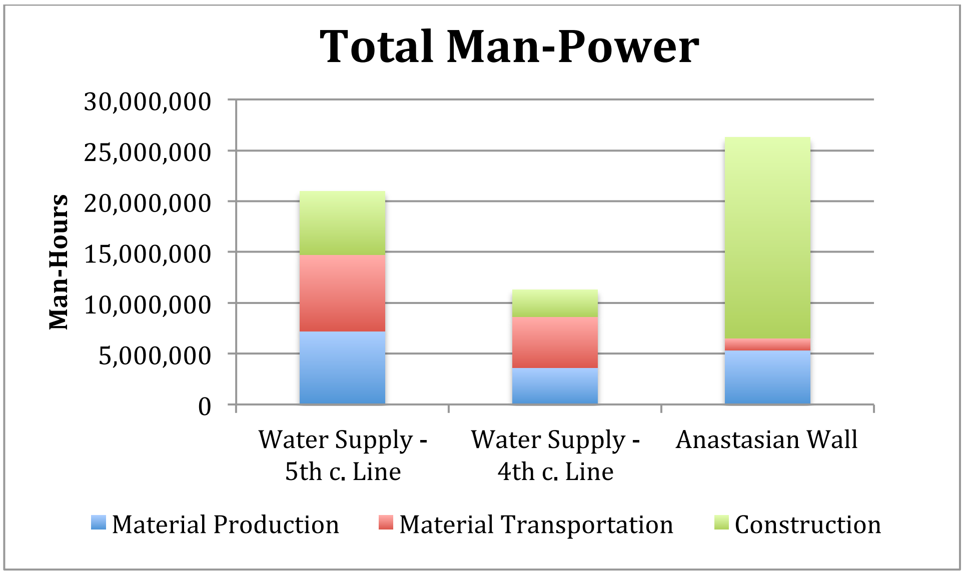


Chart 8.1 - Total man-power required for the construction of the Water Supply of Constantinople and Anastasian Wall.

Unlike Rome, New Rome had neither Frontinus to discuss the city's water supply network nor Vitruvius to share some insight into material technologies in late antiquity. As shown in Chapter 3, there has always been a heavy reliance on classical texts in the discussion of late antique construction by archaeologists and classicists. Chapter 4 reveals that scientific material studies can be used to greatly expand what we know about construction technology and organisation. Some of these methods have been used to analyse the scale and building technology of the water supply and long wall, yielding important results. We know from architectural evidence that construction within late-antique Constantinople from the 4th to 7th century was as intense as any period of Imperial Rome. This research shows that extensive large-scale construction stretched far beyond the confines of New Rome's city walls, with no indication of major stress or strain on resources or architectural ability.

However, this is not a stopping point. It is hoped that this study serves as the basis for a robust extension of material sourcing and technology through future geological comparisons specifically relating to brick, limestone, and sand. More important to the understanding of the true impact of large-scale construction in the Late Antique and early Byzantine world, this project could be used for a thorough examination of the economic implications of constructing the water supply and long wall. As this project evolved, new avenues of research were presented. From the microscopic to the macroscopic, the Water Supply of Constantinople and Anastasian Wall show the ingenuity and unprecedented dedication to New Rome in Late Antiquity.

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APPENDIX 1

A1.1 – Further Details of Laboratory Methods

The drill bit used was a diamond-coated coring bit, measuring 22 mm in diameter. This bit cut the perfect size cores whereas smaller diameter bits caused the sample to break apart and larger bits produced cores with a diameter too large to fit in the resin moulds. While the bit was cutting into the sample, a squeeze bottle was used to lubricate and flush out the cutting surface to remove large particles that could cause the sample to shatter if it caused the drill to jam. Once the coring bit had cut far enough into the sample, the drill and bit were pulled away. In a few instances, this dislodged the core from the sample, causing the core to be stuck in the bit. The bit has two vents on the side, which made it possible to push the core out using a small hex key. Most of the time, however, cored will still be attached to the sample at the bottom of the cutting surface. This was also had an easy remedy by which a small flat file was fed into the cutting hole and pressure was applied to the bottom of the core. This always caused the core to break at the lowest surface, creating an intact, full-length core.

Because the samples varied in degree of friability, it was of extreme importance to determine the proper steps to take during preparation. The possibility of breakage during the numerous processes required to make a thin section influenced the methods used to ensure the final result was as intact as possible. This was the most important factor to keep in mind during core drilling because of the nature and dimension of the abrasive cutting surface compared to the mortars' varying grain size. On initial tests, it was found that samples with higher friability would only produce a solid core when the speed of the drill was high and the least amount of pressure was applied. The high speed showed to significantly reduce the possibility of snagging, which causes the bit to catch briefly on larger, harder aggregates and increase the likelihood of breaking the core. This also considerably reduced the amount of turbulence between the cutting surface and the coring bit, creating a cleaner, more uniform core. While drilling at higher speeds, it was beneficial to have short bursts of water to keep the cutting surface lubricated, minimising friction. While water was needed to flush out the by-product, in samples of a highly friable nature, a constant jet of water proved to inundate the pores causing the mortar to disintegrate around the Inner and outer surfaces of the coring bit. Samples that were harder or made of extremely fine aggregate particles did not require as much care while cutting. It was found that a medium to high speed worked equally well on harder samples and that a small addition of pressure could be applied to expedite the cutting time. In this case, a constant jet of water was required for lubrication and cooling, as well as to flush out the core. For samples of fine aggregate, the drill speed seemed to play little role in the quality of the sample but, depending on the friability, the amount of water lubricant varied.

Samples were sliced to size using the Buehler Isomet 1000 Precision Saw. This piece of equipment houses a diamond coated cutting wheel with variable speed motor, adjustable sample arm with load and counterbalance weight, lubricant tank, and sample positioning knob. The positioning arm's position is linked to the LCD panel and can be zeroed after any adjustment is made. Below this is another LCD panel that indicates the speed setting for the saw and can be adjusted with arrow buttons to the side. A feature available but not needed for this process was the 'End of Cut' adjustment knob, which can be used to alter the point at which the blade is stopped during the cutting process. Seeing that the objective of this stage of the project was to cut clear through the sample, this feature was not needed.

Higher speed between 250 and 350 rpms and the least amount of pressure were used for samples that were more prone to fracture or crumble. To ensure the pressure was at its lowest, the lever was held in hand and lowered manually. Harder cores required less attention where rpms were kept between 150 and 300 and the sample arm was lowered automatically onto the blade.

When these hard quartz granules became dislodged from the sample, they occasionally became stuck in the abrasive paper. This was the most detrimental problem during the grinding process, as the quartz formed jagged bump that would tear through the sample when the grinding wheel would make a revolution. As a preventative method, it was thought that increasing the amount of water on the wheel for lubrication would clear off these quartz pieces. However, on closer inspection, these pieces would adhere to the paper at the point at which they became dislodged from the sample. It was found that changing the abrasive paper was the only way to ensure this did not continue.

While this machine has the option for an automatic, hands-free run on the polishing wheel for up to four samples, it was determined to only be used in the very early stages of grinding. During an automatic run, sample slides were placed in holders and attached to Vector head. Because of the variety in samples, it was decided that only slides of the same sample site could be run at the same time. This was to ensure that all samples were being ground down at the same rate. Automatic grinding was carried out under intense supervision and progress was checked regularly to ensure that no samples were damaged or ground too thin. This method was only used on samples that had considered sturdy during previous steps of preparation.

The camera used to take micrographs was a Sony Alpha a300 DSLR equipped with a remote control shutter release switch. This was attached to the Olympus BH2 Microscope's extension tube via the camera's lens attachment using a t-mount adapter. The a300 was chosen specifically for its 'Live View' feature and its ability to tilt the LCD screen 90 degrees. 'Live View' shows a live picture of the subject area, which was extremely useful for adjusting the focus. Because the extension tube and the eyepiece were slightly different focal lengths, it was only possible to set the proper focus based on the image on the LCD screen. The position of the camera's viewfinder was at the top of the microscope due to microscope's vertical extension tube, making it at an inconvenient angle and height. However, this particular camera was chosen because of its tilting LCD screen and 'Live View' feature, giving an easy view of the sample while having full access to the focusing knobs.

The camera had to be set to manual focus since there was no electrical connection between it and the microscope. It was impossible to use adjust the focus on the camera but because the microscope was acting as the lens, its controls were used for manual focusing. The camera's ISO settings were left unchanged but the microscope's brightness was adjusted for each new sample area. The brightness of the transmitted light depended on the type of material making up a majority of the sample. For instance, if a large portion of the viewable area were made up of brick, more light would be needed to go through the sample. The camera's exposure indicator gave a good indication of the amount of light being let in. However, it was found that better photographs resulted from being a little underexposed

A1.2 - 3D Modelling

Long before it was realised that this project would deal primarily with economic impact of the construction of the fifth century phase of the aqueduct system of Constantinople, it was thought that the application of hypothetical reconstruction using three-dimensional modelling would be a beneficial trial. At this time, before collecting samples from the Anastasian Wall, the hope was to create models of all of the structures from which samples were taken. This would include all six bridges from the Water Supply of Constantinople and individual sites from Thessaloniki and Ravenna. The original purpose for the three-dimensional models was to show how each of these structures utilised mortars comparatively. Whether mortars were taken from between brick joints, within the core of the structures, or as a facing, these models could be used to show the possible contrast between the make-up of the mortars and their intended function within the structure. In addition, and more influential to the goals of this project, these models could be used to quantify the total volume of material components with the structure. However, because of the change in project focus and the decrease in useful obtainable data, it was decided to use this approach as a case study for comparative data techniques.

A1.2.1 - Site Selection

Because of the water system's wide extent across a large geographic area, not to mention its varying phases and features, it was decided that a small portion would be a good starting place. One of the most interesting sites visited on the 2008 field survey was the monumental bridge called Kumarlıdere. Not only was this particular bridge a perfect representation of the archetypal colossal bridges of the fifth century building phase, it also had a unique feature that showed the ingenuity and ability of the architects. This feature, which will be discussed in much more detail further in this thesis, was what looked to be an artificial mound running along the western portion of the bridge. A possible change in landscape of this magnitude raised interest in this particular bridge and since no reconstruction or 3D computer modelling had been done, it seemed the perfect choice for this case study.

The most vital factor for reconstructing something like Kumarlıdere was obtaining as much information as possible. Like the methods used to determine the volume of the entire system, many different sources were used such as photographs, topographical maps, survey data, satellite images, and AutoCAD drawings. When used together, all of these resources helped paint a clearer picture of Kumarlıdere and the surrounding area. For example, even with the best photographs, much of the bridge would remain disguised by the surrounding landscape and dense forest. Even with the addition satellite images and topographical information, it would be impossible to determine proper dimensions and other key features of the bridge. Data collected from field surveys, along with the corresponding AutoCAD drawings, produced the clearest view of the structure in its entirety. This would be the foundation for the development of a 3D reconstruction model. However, it should be stated that, despite the most sophisticated methods, it would be impossible to come up with an exact replica of the original structure due to its deterioration over the centuries. Like the information compiled for the system's volumetric calculations, the final result of this 3D computer visualisation is still hypothetical.

A1.2.2 - Software

Very similar to the issues surrounding software for petrographic analysis, 3D modelling software has very specific objectives, not to mention a considerably wide price range. With experience using both the very expensive and considerably cheap pieces of software, it was evident that both served their specific purposes. Considering the free price, ease of use, and previous experience, it was an easy decision to choose Google SketchUp to create this model. Even more impressive was the large community of user forums with the help Google's own online help and tutorials. This software does not have the most comprehensive set of tools, especially compared to those used in engineering and architecture firms, but met and in most cases exceeded the requirements for this reconstruction.

A1.2.3 - Design

For the purposes of keeping this model organised and clean, it was decided to initially create two separate models: the first being the surrounding landscape and the bridge second. The first step was to obtain an adequate plot from the 1942 military topographic maps. 3D models from Satellite image data were available and considered but the accuracy of the small area selected was not as defined as needed. Instead, a selected area from the topographic map of the area was imported into Google SketchUp and all of the topographic lines were traced over and raised to their corresponding height. At this point, it was necessary to convert these 3D topographic lines into a landscape by draping over a solid surface. Once this was completed, the surface could be designated a style and surface. While the file size for this model would ultimately be very large, it was decided to use a full 1:1 scale for future analytical purposes.

The second half of the model was considerably more time consuming because of the intricacy of the bridge and its hypothetical reconstruction. This is the stage at which all of the collected data would be combined to form the model, whereas the information for the landscape was based on a single comprehensive map. The first step was to draw a two-dimensional outline of the bridge based off of an AutoCAD drawing of its current state. In addition, information on the size of the channels in reference to the total height of the bridge was used to reconstruct the upper-most portion of the bridge, the majority of which has since fallen away from the structure.

After a two-dimensional drawing of the south face was made, adding width was the beginning the second step. Even though width had been added to create a volume, it was necessary to remove the volume of each arch and add in the more intricate three-dimensional details of the bridge, such as the channel cover and string courses. This task also included the design of the narrow and wide channels that ran across the bridge. This level was the most difficult portion of the bridge to design due to its current state. Based on evidence from field surveys of other bridges and portions of channel, combined with comparative analysis from other Roman aqueduct systems, a hypothetical design was created. Once this was complete, colour and textures could be added to the face of the structure.

A1.2.4 – Model Images

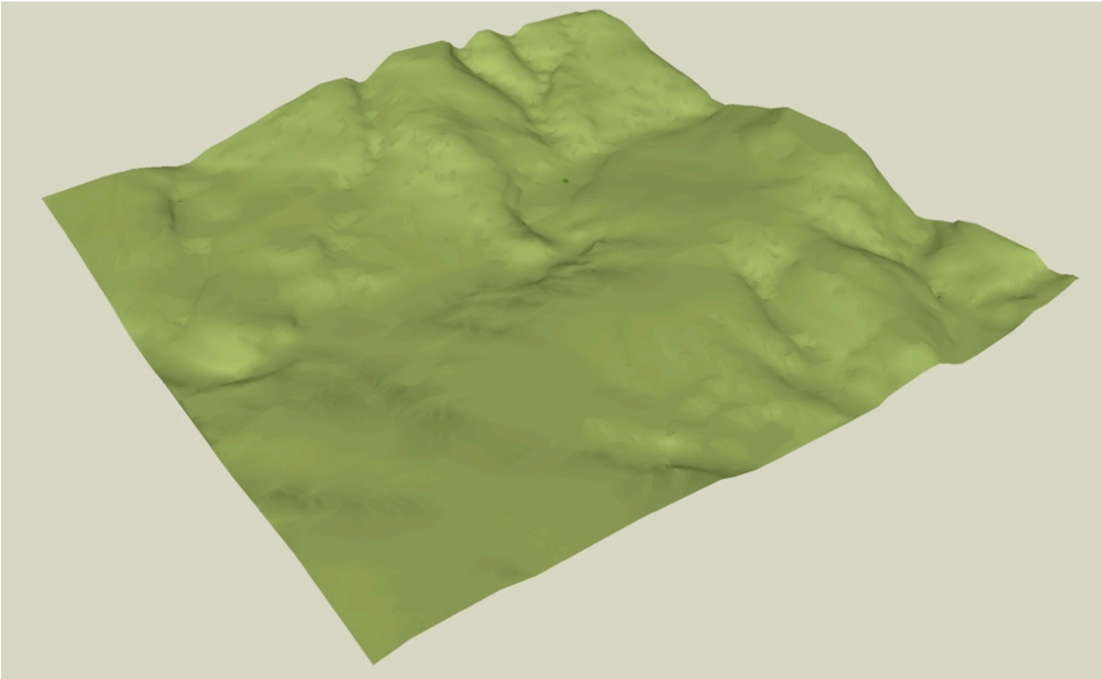


Figure A1.3:1 – An extended view of the terrain from the 3D digital reconstruction of Kumarlıdere bridge (K31).

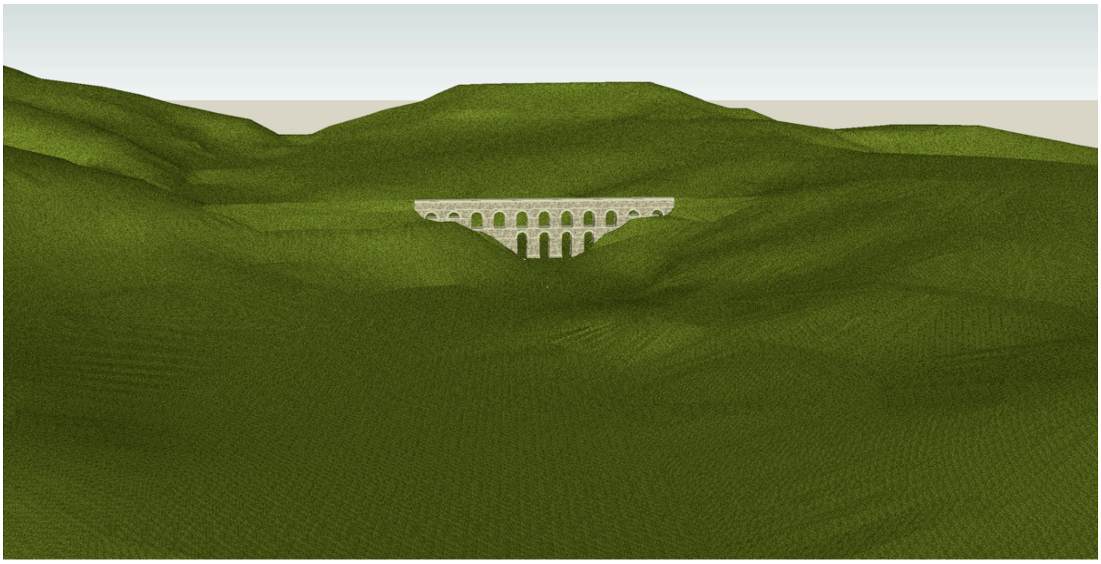


Figure A1.3:2 – A view from the east of the 3D digital reconstruction of Kumarlıdere bridge (K31).

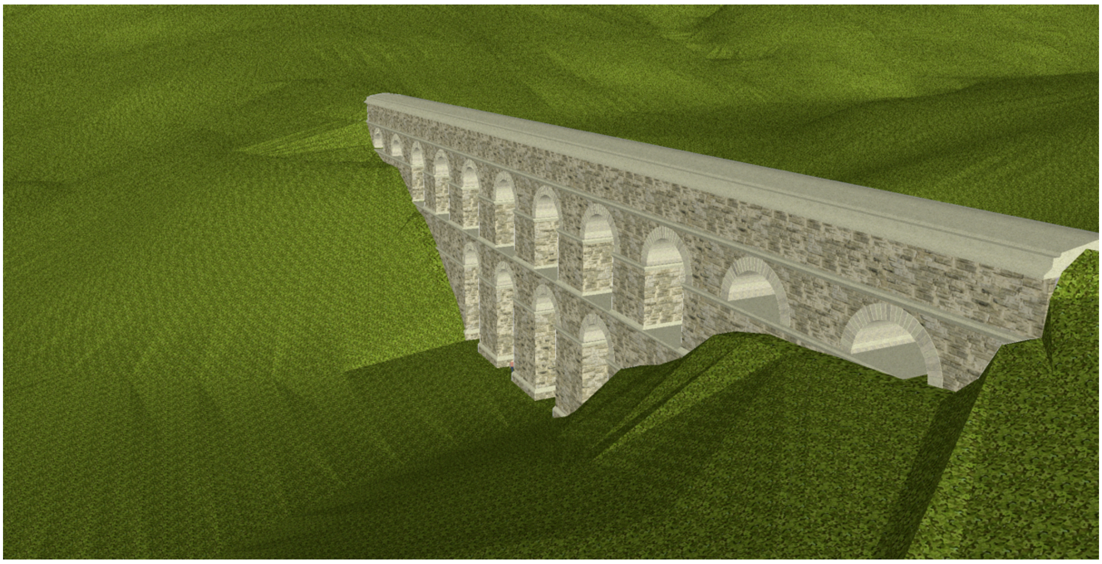


Figure A1.3:3 – A view from the northeast of the 3D digital reconstruction of Kumarlıdere bridge (K31).

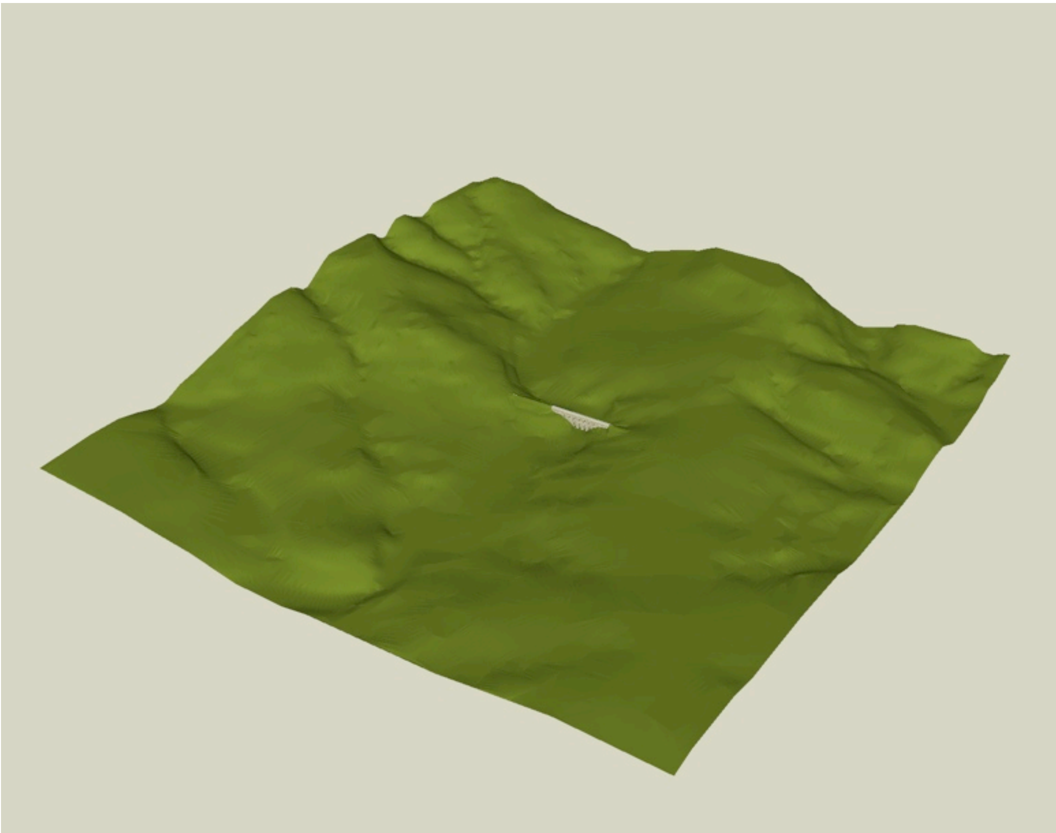


Figure A1.3:4 – Extended view of the 3D digital reconstruction of Kumarlıdere bridge (K31).

APPENDIX 2 – MATERIAL AND MAN-POWER DATA

A2.1 – Structural Measurements and Material Quantity Estimates

A2.1.1 – Individual Aqueduct Bridge Measurement Data

Aqueduct Bridge Name	Bridge Number	IV Phase	V Phase	VI Phase	Narrow	Broad	Width	Height	Length (Top)	Length (Base)	Arch Height (Base)	Arch Height (Middle)	Arch Height (Top)	Arch Width (Base)	Arch Width (Middle)	Arch Width (Top)	Number of Arches (Base)	Number of Arches (Middle)	Number of Arches (Top)
Kemer Dere	K1		X		X		5.30	15.00	60.00	25.00	9.00	0.00	0.00	4.00	0.00	0.00	2	0	0
In Dere	K2		X		X		6.90	15.00	65.00	20.00	9.00	0.00	0.00	4.00	0.00	0.00	2	0	0
Kucukkemer	K3		X		X		5.50	10.00	7.00	5.00	6.00	0.00	0.00	3.00	0.00	0.00	1	0	0
Akpinar Dere	K4		X		X		7.22	14.00	60.00	30.00	9.00	0.00	0.00	4.00	0.00	0.00	2	0	0
Ergene Dere	K4.1		X		X		3.00	8.00	25.00	15.00	5.50	0.00	0.00	3.50	0.00	0.00	1	0	0
Gokcesu	K5		X		X		6.00	15.00	130.00	85.00	5.70	0.00	0.00	4.50	0.00	0.00	5	0	0
Southeast Gokcesu	K5.1		X		X		5.00	8.00	25.00	12.00	5.00	0.00	0.00	4.00	0.00	0.00	1	0	0
Gelin Dere	K6		X		X		4.70	10.00	35.00	18.00	5.50	0.00	0.00	4.00	0.00	0.00	2	0	0
Ayvacik Dere	K7		X		X		4.44	14.00	85.00	40.00	7.50	0.00	0.00	4.40	0.00	0.00	3	0	0
East Yanosman Tepe	K7.1		X		X		4.50	8.00	20.00	10.00	5.00	0.00	0.00	4.00	0.00	0.00	1	0	0
Cingene Dere	K7.2		X		X		4.40	4.00	15.00	12.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0
Galata Dere	K8		X		X		6.00	25.00	130.00	75.00	7.00	0.00	5.00	5.00	0.00	4.00	3	0	3
Manganez Dere	K9		X		X		5.00	10.00	80.00	40.00	6.00	0.00	0.00	4.00	0.00	0.00	2	0	0
Ayle Dere	K10		X			X	5.50	12.00	40.00	20.00	7.00	0.00	0.00	5.00	0.00	0.00	1	0	0
Gineviz Dere (Alaton Dere)	K11		X			X	6.10	10.00	20.00	16.00	6.50	0.00	0.00	10.60	0.00	0.00	1	0	0
Babadar Dere	K11.1		X			X	5.25	9.00	15.00	7.00	5.50	0.00	0.00	4.00	0.00	0.00	1	0	0
Elmali Dere	K12		X			X	5.32	8.00	32.00	12.00	4.70	0.00	0.00	5.30	0.00	0.00	1	0	0
Karamanoglu	K13		X			X	5.00	8.00	95.00	80.00	6.00	0.00	0.00	5.35	0.00	0.00	4	0	0
Testiler Germesi	K13.1		X			X	8.00	8.00	20.00	12.00	5.00	0.00	0.00	4.00	0.00	0.00	1	0	0
Baliksirti	K14		X			X	7.00	16.00	18.00	10.00	6.00	0.00	0.00	4.00	0.00	0.00	1	0	0

Table A2.1.1 – Individual Aqueduct Bridge Measurement Data (units in meters unless otherwise indicated) – page 1 of 5

Aqueduct Bridge Name	Bridge Number	IV Phase	V Phase	VI Phase	Narrow	Broad	Width	Height	Length (Top)	Length (Base)	Arch Height (Base)	Arch Height (Middle)	Arch Height (Top)	Arch Width (Base)	Arch Width (Middle)	Arch Width (Top)	Number of Arches (Base)	Number of Arches (Middle)	Number of Arches (Top)
Cangevrek	K15		X			X	5.60	8.00	30.00	10.00	5.00	0.00	0.00	4.00	0.00	0.00	1	0	0
North Kurt Dere	K16		X			X	4.80	5.00	10.00	8.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0
Kurt Dere	K17		X			X	7.50	25.00	40.00	20.00	7.00	0.00	5.00	5.00	0.00	4.00	1	0	3
Luka Dere	K17.1		X	X		X	7.25	10.40	50.00	30.00	5.70	0.00	0.00	3.70	0.00	0.00	1	0	0
East Luka Dere	K17.2		X			X	4.40	6.00	40.00	28.00	3.00	0.00	0.00	3.00	0.00	0.00	1	0	0
Balligerme	K18		X			X	8.50	37.00	90.00	58.00	16.00	0.00	10.25	7.50	0.00	6.80	1	0	4
Hasan Dede	K18a	X			X		4.00	4.00	11.00	5.00	2.00	0.00	0.00	3.50	0.00	0.00	1	0	0
Gumuspinar Dere	K19	X	X			X	7.00	15.00	70.00	40.00	8.00	0.00	0.00	5.00	0.00	0.00	3	0	0
Dervis Kapi Dere	K19.1	X	X	X		X	6.50	13.00	50.00	22.00	7.00	0.00	0.00	5.00	0.00	0.00	2	0	0
Kursunlugerme Minor	B20.0.0.1	X			X		7.00	12.00	80.00	40.00	7.00	0.00	0.00	5.00	0.00	0.00	2	0	0
Kursunlugerme Major	K20		X		X	X	12.50	33.00	175.00	75.00	15.00	12.50	7.50	6.50	7.50	5.00	3	6	11
Ceviz Dere Minor	B20.1.1	X			X		4.50	3.50	6.00	4.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0
Ceviz Dere Major	K20.1		X			X	4.50	3.50	6.70	3.00	1.50	0.00	0.00	1.00	0.00	0.00	1	0	0
North Elkafdere	K20.2	X	X			X	3.00	3.00	8.30	7.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0
South Elkafdere	K20.3		X	X		X	5.00	7.00	9.00	4.50	3.30	0.00	0.00	2.70	0.00	0.00	1	0	0
Nikol Dere (Upper)	K20.4	X	X	X		X	5.20	7.00	15.00	6.00	3.50	0.00	0.00	4.00	0.00	0.00	1	0	0
Nikol Dere (Middle)	K20.4.1		X			X	5.00	5.50	11.00	5.00	3.00	0.00	0.00	3.00	0.00	0.00	1	0	0
Nikol Dere (Lower)	K20.4.2	X		X	X		5.00	3.50	7.00	4.00	2.00	0.00	0.00	2.00	0.00	0.00	1	0	0
Macka Dere Minor	B20.5.1	X			X		5.00	3.00	15.00	12.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0
Macka Dere Major	K20.5		X			X	5.20	3.00	30.00	25.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0

Table A2.1.1 – Individual Aqueduct Bridge Measurement Data (units in meters unless otherwise indicated) – page 2 of 5

Aqueduct Bridge Name	Bridge Number	IV Phase	V Phase	VI Phase	Narrow	Broad	Width	Height	Length (Top)	Length (Base)	Arch Height (Base)	Arch Height (Middle)	Arch Height (Top)	Arch Width (Base)	Arch Width (Middle)	Arch Width (Top)	Number of Arches (Base)	Number of Arches (Middle)	Number of Arches (Top)
Ortabel Minor	B20.6.1	X			X		5.00	7.00	8.00	4.00	3.30	0.00	0.00	2.70	0.00	0.00	1	0	0
Ortabel Major	K20.6		X			X	8.60	8.00	12.00	8.00	3.50	0.00	0.00	4.50	0.00	0.00	1	0	0
Kayinlik Tarla Germesi	K20.11	X	X	X		X	4.70	11.50	20.00	10.00	9.20	0.00	0.00	4.70	0.00	0.00	1	0	0
Cucurudere	K20.12					X	5.00	10.00	12.00	7.00	8.00	0.00	0.00	4.50	0.00	0.00	1	0	0
Koserelik Germesi (Cevizlik Dere main)	B20.0.1		X	X		X	8.90	14.00	40.00	25.00	12.00	0.00	0.00	6.50	0.00	0.00	1	0	0
Tatlidere Germesi (Gungormez Dere)	B20.0.2		X			X	7.50	16.00	40.00	20.00	12.00	0.00	0.00	6.50	0.00	0.00	1	0	0
Turcine Germe (Turcinecatak Germesi)	B20.0.3		X			X	7.50	20.00	60.00	30.00	12.00	0.00	6.00	6.40	0.00	3.60	1	0	2
Vadi	B20.0.4		X			X	7.50	22.00	55.00	22.00	12.00	0.00	6.00	6.00	0.00	3.60	1	0	2
South Talas	K21	X			X		5.20	15.00	15.35	8.00	8.00	0.00	0.00	4.95	0.00	0.00	1	0	0
Talas	K22		X	X		X	11.20	25.00	60.00	30.00	7.50	0.00	0.00	4.00	0.00	0.00	1	0	0
Leylek Kale	K23		X	X		X	8.80	12.00	30.00	12.00	7.00	0.00	0.00	3.00	0.00	0.00	1	0	0
Unkown - Only Documented on Maps	K24		X			X	7.00	10.00	25.00	14.00	6.50	0.00	0.00	3.50	0.00	0.00	1	0	0
Cevizlik Kale	K25		X	X		X	7.00	8.00	14.00	10.00	6.00	0.00	0.00	5.54	0.00	0.00	1	0	0
Kayinlik Dere	K26	X	X		X		5.00	14.00	20.00	10.00	8.00	0.00	0.00	5.00	0.00	0.00	1	0	0
Cesmekoru	K27	X	X		X		4.00	5.00	8.00	6.00	3.00	0.00	0.00	3.00	0.00	0.00	1	0	0
Kilise Tepe Minor	B28.1	X	X		X		5.00	8.00	12.00	7.00	5.00	0.00	0.00	3.00	0.00	0.00	1	0	0
Kilise Tepe Major	K28	X	X			X	7.00	10.00	18.00	9.00	6.50	0.00	0.00	3.50	0.00	0.00	1	0	0
Germe Dere	K28.1	X	X			X	7.00	8.00	8.56	6.00	4.00	0.00	0.00	3.00	0.00	0.00	1	0	0
Buyukgerme	K29		X		X	X	8.00	37.50	140.00	90.00	17.00	0.00	12.50	5.75	0.00	5.50	3	0	9
Merdiven Dere	K29.1	X			X		5.25	15.00	25.00	14.00	8.00	0.00	0.00	5.00	0.00	0.00	1	0	0

Table A2.1.1 – Individual Aqueduct Bridge Measurement Data (units in meters unless otherwise indicated) – page 3 of 5

Aqueduct Bridge Name	Bridge Number	IV Phase	V Phase	VI Phase	Narrow	Broad	Width	Height	Length (Top)	Length (Base)	Arch Height (Base)	Arch Height (Middle)	Arch Height (Top)	Arch Width (Base)	Arch Width (Middle)	Arch Width (Top)	Number of Arches (Base)	Number of Arches (Middle)	Number of Arches (Top)
West Merdiven Dere	K29.2	X			X		5.50	15.00	45.00	22.00	8.00	0.00	0.00	5.00	0.00	0.00	2	0	0
Kerezle Dere	K29.3	X			X		5.50	15.00	30.00	14.00	8.00	0.00	0.00	5.00	0.00	0.00	1	0	0
Karatepe A	K29.4		X		X	X	8.00	4.00	80.00	70.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0
Karatepe B	K29.5		X		X	X	7.00	15.00	30.00	10.00	8.00	0.00	0.00	5.00	0.00	0.00	1	0	0
Kecigerme	K30		X			X	6.35	33.00	80.00	40.00	12.00	0.00	10.00	6.40	0.00	6.40	1	0	5
Southwest Kecigerme	K30.1	X			X		5.20	12.00	30.00	16.00	7.00	0.00	0.00	5.00	0.00	0.00	1	0	0
Kumarlidere	K31		X		X	X	8.10	33.00	130.00	75.00	15.00	0.00	8.00	5.30	0.00	5.00	4	0	11
Sarap Dere	K31.1	X			X		5.20	8.00	15.00	8.00	6.00	0.00	0.00	4.00	0.00	0.00	1	0	0
East Sarap Dere	K31.2	X			X		5.00	8.00	15.00	8.00	6.00	0.00	0.00	4.00	0.00	0.00	1	0	0
Karlipinar	K32		X		X	X	7.00	8.00	20.00	10.00	6.00	0.00	0.00	4.00	0.00	0.00	1	0	0
Kasikci Dere	K33		X		X	X	7.00	5.00	8.00	6.50	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0
Ayazma Dere	K34		X		X	X	7.00	15.00	20.00	8.00	8.00	0.00	0.00	5.00	0.00	0.00	1	0	0
Yazlakoy	G25		X		X		6.00	22.00	30.00	14.00	12.00	0.00	0.00	6.00	0.00	0.00	1	0	0
Sazlidere	K34.1		X		X		5.00	8.00	20.00	12.00	4.00	0.00	0.00	3.00	0.00	0.00	1	0	0
Buyukkemer	K35		X		X		5.00	8.00	18.00	9.00	3.50	0.00	0.00	3.00	0.00	0.00	1	0	0
Raised Channel (2008 trip)	K35.1		X		X		6.00	3.00	50.00	42.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0
Kucukkemer	K36	X	X		X		5.00	8.00	12.00	5.00	6.00	0.00	0.00	4.00	0.00	0.00	1	0	0
Ortancakemer	K37	X	X		X		5.00	10.00	18.00	9.00	7.00	0.00	0.00	4.00	0.00	0.00	1	0	0
Kemiktepe	K38	X	X		X		5.00	8.00	12.00	6.00	6.00	0.00	0.00	4.00	0.00	0.00	1	0	0
Tilkiciftligi	k39	X	X		X		5.00	12.00	25.00	13.00	7.00	0.00	0.00	4.00	0.00	0.00	1	0	0

Table A2.1.1 – Individual Aqueduct Bridge Measurement Data (units in meters unless otherwise indicated) – page 4 of 5

Aqueduct Bridge Name	Bridge Number	IV Phase	V Phase	VI Phase	Narrow	Broad	Width	Height	Length (Top)	Length (Base)	Arch Height (Base)	Arch Height (Middle)	Arch Height (Top)	Arch Width (Base)	Arch Width (Middle)	Arch Width (Top)	Number of Arches (Base)	Number of Arches (Middle)	Number of Arches (Top)
Yikikkemer	K40	X	X		X		7.50	25.00	30.00	10.00	7.00	0.00	5.00	5.00	0.00	4.00	1	0	2
Kuru Dere	R1	X		X	X		3.00	12.00	25.00	14.00	7.00	0.00	0.00	4.50	0.00	0.00	1	0	0
Kale Dere A	R2	X		X	X		3.50	22.00	40.00	22.00	7.00	0.00	5.00	5.00	0.00	4.00	1	0	2
Kale Dere B	R3	X		X	X		3.25	18.00	20.00	8.00	8.00	0.00	0.00	5.00	0.00	0.00	1	0	0
Buyuk Kamara Dere	R4	X		X	X		3.25	8.00	10.00	5.00	4.00	0.00	0.00	3.00	0.00	0.00	1	0	0
Kucuk Kamara Dere	R5	X		X	X		3.25	6.00	12.00	6.00	3.25	0.00	0.00	3.00	0.00	0.00	1	0	0
Kucuk Kemer	B41	X	X		X		5.00	8.00	20.00	12.00	6.00	0.00	0.00	4.00	0.00	0.00	1	0	0
Buyuk Kemer	B42	X	X		X		5.00	10.00	15.00	8.00	6.00	0.00	0.00	4.00	0.00	0.00	1	0	0
Bozodagan Kemeri	AoV	X					4.60	22.50	971.00	535.00	8.40	0.00	6.80	4.40	0.00	4.40	88	0	54

Table A2.1.1 – Individual Aqueduct Bridge Measurement Data (units in meters unless otherwise indicated) – page 5 of 5

A2.1.2 – Individual Aqueduct Bridge Material Estimates

Aqueduct Bridge Name	Bridge Number	Surface Area	Surface Area of Arches	Total Volume	Volume of Facing Stone	Number of Facing Stones	Core Volume	Volume of Core Mortar	Volume of Core Stone Rubble	Total Volume of Structural Stone
Kemer Dere	K1	2127.63	140.77	3533.72	851.05	8510.54	2682.66	973.81	1708.86	2559.91
In Dere	K2	2382.49	183.26	4621.72	952.99	9529.95	3668.72	1331.75	2336.98	3289.97
Kucukkemer	K3	373.60	75.41	342.97	149.44	1494.40	193.53	70.25	123.28	272.72
Akpinar Dere	K4	2445.12	191.76	4803.22	978.05	9780.47	3825.17	1388.54	2436.63	3414.68
Ergene Dere	K4.1	541.37	38.99	518.56	216.55	2165.49	302.02	109.63	192.38	408.93
Gokcesu	K5	5242.96	253.35	10211.92	2097.18	20971.83	8114.74	2945.65	5169.09	7266.27
Southeast Gokcesu	K5.1	644.85	61.40	810.22	257.94	2579.40	552.28	200.48	351.80	609.74
Gelin Dere	K6	1019.86	91.93	1327.77	407.95	4079.46	919.82	333.90	585.93	993.87
Ayvacik Dere	K7	2720.38	139.08	4071.74	1088.15	10881.51	2983.59	1083.04	1900.54	2988.70
East Yanosman Tepe	K7.1	514.71	55.26	585.22	205.88	2058.83	379.33	137.70	241.64	447.52
Cingene Dere	K7.2	297.80	0.00	297.00	119.12	1191.20	177.88	64.57	113.31	232.43
Galata Dere	K8	7652.62	344.34	15855.40	3061.05	30610.48	12794.35	4644.35	8150.00	11211.05
Manganez Dere	K9	2128.85	102.80	3253.72	851.54	8515.40	2402.18	871.99	1530.19	2381.73
Ayle Dere	K10	1295.81	92.68	2107.68	518.32	5183.25	1589.36	576.94	1012.42	1530.75
Gineviz Dere (Alaton Dere)	K11	775.65	116.16	1140.36	310.26	3102.60	830.10	301.33	528.77	839.03
Babadar Dere	K11.1	482.67	69.72	553.22	193.07	1930.68	360.15	130.73	229.41	422.48
Elmali Dere	K12	762.29	66.08	1026.16	304.92	3049.15	721.25	261.81	459.44	764.35
Karamanoglu	K13	2739.76	201.24	3833.71	1095.90	10959.04	2737.80	993.82	1743.98	2839.88
Testiler Germesi	K13.1	773.70	98.24	1129.72	309.48	3094.79	820.24	297.75	522.49	831.97
Baliksirti	K14	985.42	99.96	1639.72	394.17	3941.66	1245.55	452.14	793.42	1187.58

Table A2.1.2 – Individual Aqueduct Bridge Material Estimates (units in cubic meters unless otherwise indicated) – page 1 of 5

Aqueduct Bridge Name	Bridge Number	Surface Area	Surface Area of Arches	Total Volume	Volume of Facing Stone	Number of Facing Stones	Core Volume	Volume of Core Mortar	Volume of Core Stone Rubble	Total Volume of Structural Stone
Cangevrek	K15	731.42	68.77	985.72	292.57	2925.68	693.15	251.61	441.54	734.10
North Kurt Dere	K16	252.00	0.00	259.20	100.80	1008.00	158.40	57.50	100.90	201.70
Kurt Dere	K17	3363.83	312.68	5770.40	1345.53	13455.30	4424.87	1606.23	2818.64	4164.17
Luka Dere	K17.1	1736.53	97.94	3282.68	694.61	6946.12	2588.07	939.47	1648.60	2343.21
East Luka Dere	K17.2	864.07	33.92	1036.17	345.63	3456.26	690.54	250.67	439.87	785.50
Balligerme	K18	10634.30	787.77	23576.06	4253.72	42537.19	19322.34	7014.01	12308.33	16562.05
Hasan Dede	K18a	204.62	23.98	150.81	81.85	818.48	68.97	25.03	43.93	125.78
Gumuspinar Dere	K19	3049.84	241.85	6052.68	1219.94	12199.37	4832.75	1754.29	3078.46	4298.40
Dervis Kapi Dere	K19.1	1809.92	160.55	3211.18	723.97	7239.66	2487.22	902.86	1584.36	2308.32
Kursunlugerme Minor	B20.0.0.1	2751.34	172.90	5395.18	1100.54	11005.37	4294.65	1558.96	2735.69	3836.23
Kursunlugerme Major	K20	27575.31	2982.69	52159.13	11030.12	110301.24	41129.00	14929.83	26199.18	37229.30
Ceviz Dere Minor	B20.1.1	130.50	0.00	101.25	52.20	522.00	49.05	17.81	31.24	83.44
Ceviz Dere Major	K20.1	150.33	16.07	95.82	60.13	601.33	35.69	12.95	22.73	82.87
North Elkafdere	K20.2	131.10	0.00	91.80	52.44	524.40	39.36	14.29	25.07	77.51
South Elkafdere	K20.3	291.30	40.70	259.17	116.52	1165.20	142.65	51.78	90.87	207.39
Nikol Dere (Upper)	K20.4	396.91	48.26	420.52	158.76	1587.62	261.75	95.02	166.74	325.50
Nikol Dere (Middle)	K20.4.1	282.99	38.55	248.97	113.20	1131.97	135.77	49.28	86.48	199.68
Nikol Dere (Lower)	K20.4.2	179.07	25.70	118.18	71.63	716.26	46.55	16.90	29.65	101.28
Macka Dere Minor	B20.5.1	283.00	0.00	270.00	113.20	1132.00	156.80	56.92	99.88	213.08
Macka Dere Major	K20.5	547.60	0.00	572.00	219.04	2190.40	352.96	128.12	224.84	443.88

Table A2.1.2 – Individual Aqueduct Bridge Material Estimates (units in cubic meters unless otherwise indicated) – page 2 of 5

Aqueduct Bridge Name	Bridge Number	Surface Area	Surface Area of Arches	Total Volume	Volume of Facing Stone	Number of Facing Stones	Core Volume	Volume of Core Mortar	Volume of Core Stone Rubble	Total Volume of Structural Stone
Ortabel Minor	B20.6.1	271.80	40.70	229.17	108.72	1087.20	120.45	43.72	76.73	185.45
Ortabel Major	K20.6	589.48	82.26	755.92	235.79	2357.94	520.13	188.81	331.32	567.12
Kayinlik Tarla Germesi	K20.11	661.89	99.07	835.68	264.76	2647.58	570.92	207.25	363.68	628.44
Cucurudere	K20.12	451.44	92.83	484.17	180.58	1805.75	303.60	110.21	193.39	373.97
Koserelik Germesi (Cevizlik Dere main)	B20.0.1	1953.91	246.57	4258.78	781.56	7815.64	3477.22	1262.23	2214.99	2996.55
Tatlidere Germesi (Gungormez Dere)	B20.0.2	1812.27	207.79	3745.03	724.91	7249.07	3020.13	1096.31	1923.82	2648.73
Turcine Germe (Turcinecatak Germesi)	B20.0.3	3666.18	355.14	6973.37	1466.47	14664.72	5506.89	1999.00	3507.89	4974.36
Vadi	B20.0.4	3485.80	353.43	6531.78	1394.32	13943.21	5137.46	1864.90	3272.56	4666.88
South Talas	K21	698.74	97.87	929.44	279.50	2794.96	649.94	235.93	414.01	693.51
Talas	K22	4104.20	193.54	13071.72	1641.68	16416.81	11430.04	4149.10	7280.93	8922.61
Leylek Kale	K23	1267.40	138.25	2379.37	506.96	5069.60	1872.41	679.68	1192.72	1699.68
Unkown - Only Documented on Maps	K24	937.36	104.97	1476.56	374.95	3749.45	1101.62	399.89	701.73	1076.68
Cevizlik Kale	K25	578.55	106.10	720.51	231.42	2314.20	489.09	177.54	311.55	542.97
Kayinlik Dere	K26	782.13	94.25	1082.68	312.85	3128.54	769.83	279.45	490.38	803.23
Cesmekoru	K27	210.78	30.84	156.97	84.31	843.12	72.65	26.37	46.28	130.59
Kilise Tepe Minor	B28.1	397.99	58.55	410.47	159.20	1591.97	251.27	91.21	160.06	319.26
Kilise Tepe Major	K28	721.36	104.97	1014.56	288.55	2885.45	726.02	263.55	462.47	751.02
Germe Dere	K28.1	423.38	67.97	444.61	169.35	1693.51	275.25	99.92	175.34	344.69
Buyukgerme	K29	19316.71	1220.38	34651.61	7726.68	77266.82	26924.92	9773.75	17151.18	24877.86
Merdiven Dere	K29.1	1034.72	98.96	1595.68	413.89	4138.89	1181.79	428.99	752.80	1166.69

Table A2.1.2 – Individual Aqueduct Bridge Material Estimates (units in cubic meters unless otherwise indicated) – page 3 of 5

Aqueduct Bridge Name	Bridge Number	Surface Area	Surface Area of Arches	Total Volume	Volume of Facing Stone	Number of Facing Stones	Core Volume	Volume of Core Mortar	Volume of Core Stone Rubble	Total Volume of Structural Stone
West Merdiven Dere	K29.2	1745.56	146.85	2873.18	698.22	6982.25	2174.96	789.51	1385.45	2083.67
Kerezle Dere	K29.3	1165.81	103.68	1893.68	466.32	4663.25	1427.36	518.13	909.23	1375.55
Karatepe A	K29.4	2030.00	0.00	3000.00	812.00	8120.00	2188.00	794.24	1393.76	2205.76
Karatepe B	K29.5	1222.84	131.95	2197.68	489.14	4891.37	1708.55	620.20	1088.34	1577.48
Kecigerme	K30	7369.56	580.95	12641.51	2947.82	29478.23	9693.69	3518.81	6174.88	9122.70
Southwest Kecigerme	K30.1	1008.81	87.62	1517.48	403.52	4035.22	1113.96	404.37	709.59	1113.12
Kumarlidere	K31	15947.26	1258.21	27622.13	6378.90	63789.05	21243.23	7711.29	13531.94	19910.84
Sarap Dere	K31.1	462.71	74.26	511.92	185.08	1850.82	326.83	118.64	208.19	393.28
East Sarap Dere	K31.2	450.85	71.40	491.22	180.34	1803.40	310.88	112.85	198.03	378.37
Karlipinar	K32	681.42	99.96	918.72	272.57	2725.66	646.15	234.55	411.60	684.16
Kasikci Dere	K33	272.50	0.00	304.50	109.00	1090.00	195.50	70.97	124.53	233.53
Ayazma Dere	K34	946.84	131.95	1525.68	378.74	3787.37	1146.95	416.34	730.60	1109.34
Yazlakoy	G25	1598.27	164.52	2961.86	639.31	6393.09	2322.55	843.09	1479.47	2118.78
Sazlidere	K34.1	575.99	48.55	705.97	230.40	2303.97	475.57	172.63	302.94	533.33
Buyukkemer	K35	503.99	43.55	594.97	201.60	2015.97	393.37	142.79	250.58	452.17
Raised Channel (2008 trip)	K35.1	968.00	0.00	1104.00	387.20	3872.00	716.80	260.20	456.60	843.80
Kucukkemer	K36	366.85	71.40	356.22	146.74	1467.40	209.48	76.04	133.44	280.18
Ortancakemer	K37	582.85	81.40	712.22	233.14	2331.40	479.08	173.91	305.17	538.31
Kemiktepe	K38	380.85	71.40	378.72	152.34	1523.40	226.38	82.17	144.20	296.54
Tilkiciftligi	k39	854.85	81.40	1204.72	341.94	3419.40	862.78	313.19	549.59	891.53

Table A2.1.2 – Individual Aqueduct Bridge Material Estimates (units in cubic meters unless otherwise indicated) – page 4 of 5

Aqueduct Bridge Name	Bridge Number	Surface Area	Surface Area of Arches	Total Volume	Volume of Facing Stone	Number of Facing Stones	Core Volume	Volume of Core Mortar	Volume of Core Stone Rubble	Total Volume of Structural Stone
Yikikkemer	K40	2404.58	265.58	3832.40	961.83	9618.30	2870.57	1042.02	1828.55	2790.38
Kuru Dere	R1	696.80	49.70	726.67	278.72	2787.21	447.95	162.61	285.35	564.07
Kale Dere A	R2	1928.03	123.94	2427.90	771.21	7712.11	1656.69	601.38	1055.31	1826.52
Kale Dere B	R3	737.77	61.26	822.18	295.11	2951.06	527.08	191.33	335.75	630.85
Buyuk Kamara Dere	R4	257.12	31.56	205.34	102.85	1028.49	102.49	37.20	65.29	168.14
Kucuk Kamara Dere	R5	244.50	26.68	192.97	97.80	977.99	95.17	34.55	60.62	158.42
Kucuk Kemer	B41	576.85	71.40	693.72	230.74	2307.40	462.98	168.06	294.92	525.66
Buyuk Kemer	B42	516.85	71.40	606.22	206.74	2067.40	399.48	145.01	254.47	461.21
Bozodagan Kemeri	AoV	57569.37	4611.67	77503.30	23027.75	230277.46	54475.55	19774.62	34700.92	57728.67

Table A2.1.2 – Individual Aqueduct Bridge Material Estimates (units in cubic meters unless otherwise indicated) – page 5 of 5

A2.1.3 – Total Aqueduct Bridge Material Estimates

Phase (Century)	Stretch of Supply Line	Number of Bridges	Total Length (m)	Total Volume (m^3)	Total Surface Area (m^2)	Surface Area of Arches (m^2)	Volume of Stone Facing (m^3)	Number of Facing Stones	Core Volume (m^3)	Volume of Core Mortar (m^3)	Volume of Core Stone Rubble (m^3)	Total Volume of Structural Stone	Average Height (m)	Volume of Foundation (m^3)
V	Pazarı to Manganez Dere (K9)	13	737.00	50,233.16	28,092.23	1,678.35	11,236.89	112,368.93	38,996.27	14,155.64	24,840.62	36,077.51		
	Manganez Dere (K9) to Balligerme (K18)	13	500.00	46,340.78	25,397.43	2,045.15	10,158.97	101,589.72	36,181.81	13,134.00	23,047.81	33,206.78		
	Balligerme (K18) to Kalfaköy	31	1,305.56	189,831.12	103,615.12	9,195.74	41,446.05	414,460.49	148,385.07	53,863.78	94,521.29	135,967.34		
	Danamandira to Constantinople	11	970.60	13,151.00	9,329.93	970.60	3,731.97	37,319.71	9,419.03	3,419.11	5,999.92	9,731.89		
	Total	**68**	**3,513.16**	**299,556.06**	**166,434.71**	**13,889.83**	**66,573.89**	**665,738.85**	**232,982.17**	**84,572.53**	**148,409.64**	**214,983.53**	**12.29**	**52,697.33**
IV	Land Walls to Binbirdirek Cistern	1	971.00	77,503.30	57,569.37	4,611.67	23,027.75	230,277.46	54,475.55	19,774.62	34,700.92	57,728.67		
	Danamandira to Constantinople	30	776.09	34,476.83	22,948.72	2,348.31	9,179.49	91,794.89	25,297.34	9,182.93	16,114.40	25,293.89		
	Pinarca to junction near Dagyenice	5	70.00	3,455.42	2,922.92	216.76	1,447.89	14,478.87	2,007.54	728.74	1,278.80	2,726.69		
	Total	**36**	**1,817.09**	**115,435.55**	**83,441.00**	**7,176.73**	**33,655.12**	**336,551.22**	**81,780.42**	**29,686.29**	**52,094.13**	**85,749.25**	**10.69**	**27,256.29**

Table A2.1.3 – Total Aqueduct Bridge Material Estimates – page 1 of 1

A2.1.4 – Channel Measurements and Material Estimates

Phase (Century)	Stretch of Channel	Channel Type	Total Legnth	Average Width	Average Height	Arch Thickness	Channel Wall Thickness	Channel Lining Thickness	Stone Block Dimensions	Cross-Sectional Area - Structure	Cross-Sectional Area - Mortat Lining
V	Pazarı to Manganez Dere (K9)	Narrow	51,190	0.68	1.4	0.3	0.65	0.015	.08 x .14	3.02	0.06
	Manganez Dere (K9) to Balligerme (K18)	Broad	80,264	1.6	2.1	0.7	1.5	0.015	.9 x .26	12.77	0.08
	Balligerme (K18) to Kalfakoy	Broad	51,258	1.5	2	0.7	1.5	0.015		12.32	0.07
	Total		**182,712**								
IV	Land Walls to Binbirdirek Cistern	Narrow	3,346	0.7	1.55	0.3	0.7	0.015		3.46	0.07
	Danamandira to Constantinople	Narrow	227,244	0.7	1.55	0.3	0.7	0.015		3.46	0.07
	Pinarca to junction near Dagyenice	Narrow	40,637	0.6	1.3	0.3	0.6	0.015		2.63	0.06
	Total		**271,227**								
II	Hadrianic System		46,688								
XVI	Ottoman Addition		30,027								

Table A2.1.4 – Channel Measurements and Material Estimates (units in meters unless otherwise indicated) – page 1 of 2

Phase (Century)	Stretch of Channel	Volume - Structure	Surface Area - Inside Channel Vaulting	Surface Area - Channel Lining Mortar	Volume - Mortar Lining	Total Volume	Volume of Removed Earth	Volume - Structural Mortar	Volume - Structural Stone	Total Volume - Mortar
V	Pazarı to Manganez Dere (K9)	154,386.99	163,199.35	143,332.00	3,255.68	157,642.68	304,068.60	56,660.03	97,726.97	59,915.71
	Manganez Dere (K9) to Balligerme (K18)	1,024,830.22	410,405.88	337,108.80	6,597.70	1,031,427.92	2,141,443.52	376,112.69	648,717.53	382,710.39
	Balligerme (K18) to Kalfakoy	631,408.47	248,915.26	205,032.00	3,752.09	635,160.56	1,314,767.70	231,726.91	399,681.56	235,479.00
	Total	**1,810,625.68**	**822,520.49**	**685,472.80**	**13,605.47**	**1,824,231.15**	**3,760,279.82**	**664,499.63**	**1,146,126.06**	**678,105.10**
IV	Land Walls to Binbirdirek Cistern	11,580.78	11,709.41	10,372.60	234.89	11,815.67	22,836.45	4,250.15	7,330.64	4,485.04
	Danamandira to Constantinople	786,510.23	795,246.06	704,456.40	15,952.53	802,462.76	1,550,940.30	288,649.26	497,860.98	304,601.78
	Pinarca to junction near Dagyenice	106,746.80	119,572.34	105,656.20	2,365.07	109,111.87	204,810.48	39,176.07	67,570.72	41,541.15
	Total	**904,837.81**	**926,527.81**	**820,485.20**	**18,552.49**	**923,390.30**	**1,778,587.23**	**332,075.48**	**572,762.33**	**350,627.97**
II	Hadrianic System									
XVI	Ottoman Addition									

Table A2.1.4 – Channel Measurements and Material Estimates (units in meters unless otherwise indicated) – page 2 of 2

A2.1.5 – Anastasian Wall Measurements and Material Estimates

	Variable	Variable Description	Minimum (m)	Maximum (m)	Estimated Average (m)*	Volume per Unit (m^3)	Surface Area per Unit (m^2)	Surface Area of Small Arches per Unit (m^2)	Surface Area of Large Arches per Unit (m^2)	Total Volume (m^3)	Total Surface Area (m^2)	Total Volume of Foundations (m^3)
	D_{Fdn}	Depth of Foundation	1.50	5.00	3.25							
	L_{TOTAL}	Total Length of Structure			52,346.00							
Forts	L_F	Length of Fort			64.00							
	W_F	Width of Fort			32.00							
	WT_F	Wall Thickness of Fort	1.80	3.20	2.50	11,884.63	7,114.00	30.85	53.56	178,269.43	106,710.00	23,400.00
	H_F	Height of Fort	11.50	12.50	12.00							
	$N_{T/F}$	Number of Towers per Fort			4							
	N_F	Number of Forts	14	16	15							
Towers	L_T	Length of Tower			11.00							
	W_T	Width of Tower			11.00							
	TW_T	Wall Thickness of Tower	1.80	3.20	2.50	1,233.70	819.00	16.71		419,456.40	278,460.00	121,550.00
	H_T	Height of Tower			11.50							
	N_T	Number of Tower			340							
Curtain Walls	L_{CW}	Length of Curtain Wall			47,646.00							
	W_{CW}	Width of Curtain Wall	1.80	3.20	2.50					1,578,273.75	1,500,849.00	387,123.75
	H_{CW}	Height of Curtain Wall			10.00							
Ditch	W_D	Width of Ditch	10.00	15.00	12.50							
	D_D	Depth of Ditch	3.00	4.00	3.50							
Total										**2,175,999.58**	**1,886,019.00**	**532,073.75**

Table A2.1.5 – Anastasian Wall Measurements and Material Estimates – page 1 of 2

	Total Surface Area of Small Arches (m^2)	Total Surface Area of Large Arches (m^2)	Volume of Removed Earth (Ditch)	Volume of Removed Earth (Foundation)	Volume of Facing Stone (m^3)	Number of Facing Stones	Core Volume (m^3)	Volume of Core Mortar (m^3)	Volume of Core Stone Rubble (m^3)	Total Volume of Structural Stone (m^3)
Forts	462.74	803.42		6,901.25	42,684.00	426,840.00	135,585.43	49,217.51	86,367.92	129,051.92
Towers	5,682.17			33,205.00	111,384.00	1,113,840.00	308,072.40	111,830.28	196,242.12	307,626.12
Curtain Walls				387,123.75	60,033.96	600,339.60	1,518,239.79	551,121.04	967,118.75	1,027,152.71
Ditch			1,145,068.75							
Total	**6,144.90**	**803.42**	**1,145,068.75**	**427,230.00**	**214,101.96**	**2,141,019.60**	**1,961,897.62**	**712,168.84**	**1,249,728.79**	**1,463,830.75**

Table A2.1.5 – Anastasian Wall Measurements and Material Estimates – page 2 of 2

A2.1.6 – Total Material Estimates for the Water Supply and Wall

	Phase (Century)	Entire Structure	Facing Stone	Rough Structural Stone	Limestone for Lime Production	Core Mortar	Channel Lining Mortar	Total Mortar	Lime in Mortar	Sand in Mortar	Brick in Mortar	Ore for Iron Clamps	Iron Clamps	Removed Earth (Foundation)	Removed Earth (Ditch)
		Volume (m^3)													
Water Supply of Constantinople	V	2,123,787.21	66,573.89	1,294,535.70	335,611.72	749,072.15	13,605.47	762,677.62	305,071.05	91,521.31	366,085.26	2,635.98	439.33	3,760,279.82	n/a
	IV	1,038,825.85	33,655.12	624,856.46	167,355.01	361,761.77	18,552.49	380,314.26	152,125.70	45,637.71	182,550.85	1,317.85	219.64	1,778,587.23	n/a
Anastasian Wall	VI	2,175,999.58	214,101.96	1,249,728.79	242,873.86	712,168.84	n/a	712,168.84	220,772.34	121,068.70	370,327.80	n/a	n/a	427,230.00	1,145,068.75

Table A2.1.6 – Total Material Estimates for the Water Supply and Wall – page 1 of 3

	Phase (Century)	Facing Stones	Rough Structural Stone	Sand for Mortar	Brick for Mortar	Wood for Lime Production	Lime for Mortar	Wood for Charcoal (Iron Clamps)	Iron Ore	Iron	Carcoal for Iron Production	Wood Fuel for Brick Production	Total Wood Required
		Mass (Tonnes)											
Water Supply of Constantinople	V	173,824.41	3,380,032.71	146,617.15	604,040.68	838,945.39	259,005.32	107,905.43	6,589.94	3,417.01	41,004.06	326,861.84	1,273,712.66
	IV	87,873.52	1,631,500.22	73,111.61	301,208.89	418,345.69	129,154.72	53,946.94	3,294.62	1,708.32	20,499.84	162,991.83	635,284.45
Anastasian Wall	VI	559,020.22	3,263,041.86	193,952.06	611,040.86	607,123.93	187,435.72	n/a	n/a	n/a	n/a	330,649.82	937,773.75

Table A2.1.6 – Total Material Estimates for the Water Supply and Wall – page 2 of 3

	Phase (Century)	Bricks for Mortar	Facing Stones	Number of Iron Clamps	Brick Kiln Firings	Lime Kiln Firings	Iron Furnace Firings	Entire Structure	All Arches
		Number of Units						Surface Area (m^2)	
Water Supply of Constantinople	V	57,200,821.81	665,738.85	610,179.54	8,171.55	5,084.52	113,900.18	166,434.71	836,410.32
	IV	28,523,569.58	336,551.22	305,057.10	4,074.80	2,535.43	56,943.99	83,441.00	933,704.54
Anastasian Wall	VI	57,863,717.98	2,141,019.60	n/a	8,266.25	3,679.54	n/a	1,886,019.00	6,948.32

Table A2.1.6 – Total Material Estimates for the Water Supply and Wall – page 3 of 3

A2.2 – Man-power Estimates

A2.2.1 – Material Collection and Production

Material	Phase (Century)	Facing Stone Quarrying	Carrying Stone 25m and Load Cart	Supervision and Administration	TOTAL MAN-DAYS
Material		Facing Stone			
Units Labour (Skilled, Unskilled, Combined)		Man-days/*.1m^3 Combined 0.750	Man-days*/.1m^3 Unskilled 0.200	Skilled 10% of Man-days	
Water Supply of Constantinople	V	499,037.84	133,147.77	63,218.56	**695,404.18**
	IV	252,278.79	67,310.24	31,958.90	**351,547.94**
Anastasian Wall	VI	1,604,908.29	428,203.92	203,311.22	**2,236,423.43**

Table A2.2.1 – Material Collection and Production – page 1 of 4

	Phase (Century)	Quarrying	Transport Clay 250m	Processing and Placing Clay in Forms	Loading Kiln	Firing 1m^3 using .252 tonnes of Wood	Unloading Bricks and Loading Cart	Crushing Bricks	Supervision and Administration	TOTAL MAN-DAYS
Material		Brick								
Units Labour (Skilled, Unskilled, Combined)		Man-days/m^3 Unskilled 0.151	Man-days/m^3 Unskilled 0.634	Man-days/m^3 Skilled 1.118	Man-days/m^3 Combined 0.118	Man-days/m^3 Combined 0.108	Man-days/m^3 Unskilled 0.065	Man-days/m^3 Unskilled 0.220	Skilled 10% of Man-days	
Water Supply of Constantinople	V	55,109.61	232,247.64	409,385.67	43,300.41	39,364.01	23,618.40	80,538.76	88,356.45	**971,920.94**
	IV	27,480.77	115,811.83	204,142.88	21,592.04	19,629.12	11,777.47	40,161.19	44,059.53	**484,654.83**
Anastasian Wall	VI	55,748.27	234,939.14	414,130.01	43,802.21	39,820.19	23,892.12	81,472.11	89,380.41	**983,184.46**

Table A2.2.1 – Material Collection and Production – page 2 of 4

	Phase (Century)	Ore Mining	Carrying Ore 25m	Cutting Wood and Producing Charcoal	Roasting and Smelting	Preparing Bloom and Casting	Loading Cart	Supervision and Administration	TOTAL MAN-DAYS
Material		Iron Clamps							
Units Labour (Skilled, Unskilled, Combined)		Man-days/Tonne Unskilled 2.333	Man-days/Tonne Unskilled 0.180	Man-days/Tonne Combined 5.830	Man-days/Tonne Skilled 180.000	Man-days/Tonne Skilled 570.000	Man-days/Tonne Unskilled 0.070	Skilled 10% of Man-days	
Water Supply of Constantinople	V	15,374.33	1,186.19	239,053.70	615,060.97	1,947,693.08	239.19	281,860.75	**3,100,468.21**
	IV	7,686.34	593.03	119,514.05	307,497.56	973,742.26	119.58	140,915.28	**1,550,068.10**
Anastasian Wall	VI	n/a							**n/a**

Table A2.2.1 – Material Collection and Production – page 3 of 4

	Phase (Century)	Quarrying Sand	Load and Carry 25m	Process and Sift	Loading Cart	Supervision and Adimistration	TOTAL MAN-DAYS
Material		Sand					
Units Labour (Skilled, Unskilled, Combined)		Man-days/m^3 Unskilled 0.090	Man-days/m^3 Unskilled 0.165	Man-days/m^3 Combined 0.120	Man-days/m^3 Unskilled 0.050	Skilled 10% of Man-days	
Water Supply of Constantinople	V	8,236.92	15,101.02	10,982.56	4,576.07	3,889.66	**42,786.21**
	IV	4,107.39	7,530.22	5,476.53	2,281.89	1,939.60	**21,335.63**
Anastasian Wall	VI	10,896.18	19,976.34	14,528.24	6,053.44	5,145.42	**56,599.62**

Table A2.2.1 – Material Collection and Production – page 4 of 4

A2.2.2 – Material Transportation

Water Supply of Constantinople								
Century	V							
Number of 'Contract' Sections	18							
Material	**Facing Stone**	**Rough Structural Stone**	**Lime**	**Brick**	**Iron Clamps**	**Sand**	**Wood Fuel - Lime**	**Totals**
Material (kg) per 'Contract' Section	9,513.57	184,992.38	14,175.61	33,059.72	102.02	8,024.49	55,099.53	
Ox-cart Trips per 'Contract' Section	23,318	453,413	34,744	81,029	250	19,668	135,048	
Cargo Ship Trips for Entire Material Mass				2,013	6			
Hypothetical Scenario 1								
Total Distance (km) Traveled (Land)	11,503,086.25	223,678,635.44	17,140,058.02	39,973,280.18	123,357.49	9,702,605.28	6,168,716.08	
Ox-cart-Days	383,436.21	7,455,954.51	571,335.27	1,332,442.67	4,111.92	323,420.18	205,623.87	**10,276,325**
Total Distance (km) Traveled (Water)				231,549	286			
Cargo Ship-Days				2,969	4			**2,972**
Hypothetical Scenario 1								
Total Distance (km) Traveled (Land)	3,834,362.08	37,279,772.57	2,856,676.34	60,700,166.20	187,320.64	970,260.53	37,012,296.47	
Ox-cart-Days	127,812.07	1,242,659.09	95,222.54	2,023,338.87	6,244.02	32,342.02	1,233,743.22	**4,761,362**
Total Distance (km) Traveled (Water)				162,084	500			
Cargo Ship-Days				2,078	6			**2,084**
Average of Scenarios (Land)	*255,624*	*4,349,307*	*333,279*	*1,677,891*	*5,178*	*177,881*	*719,684*	***7,518,843***
Average of Scenarios (Water)				*2,523*	*5*			***2,528***

Table A2.2.2 – Material Transportation – page 1 of 3

Water Supply of Constantinople

Century	IV							
Number of 'Contract' Sections	**27**							
Material	**Facing Stone**	**Rough Structural Stone**	**Lime**	**Brick**	**Iron Clamps**	**Sand**	**Wood Fuel - Lime**	**Totals**
Material (kg) per 'Contract' Section	3,239.85	60,152.57	4,761.87	11,105.42	34.74	2,695.59	18,509.03	
Ox-cart Trips per 'Contract' Section	7,941	147,433	11,671	27,219	85	6,607	45,365	
Cargo Ship Trips for Entire Material Mass				1,004	3			
Hypothetical Scenario 1								
Total Distance (km) Traveled (Land)	8,399,674.97	155,952,227.38	12,345,672.06	28,792,026.71	90,076.94	6,988,610.12	3,076,071.23	
Ox-cart-Days	279,989.17	5,198,407.58	411,522.40	959,734.22	3,002.56	232,953.67	102,535.71	**7,188,145**
Total Distance (km) Traveled (Water)				46,185	361			
Cargo Ship-Days				592	5			**597**
Hypothetical Scenario 1								
Total Distance (km) Traveled (Land)	2,799,891.66	25,992,037.90	2,057,612.01	36,912,854.76	115,483.26	1,164,768.35	18,456,427.38	
Ox-cart-Days	93,329.72	866,401.26	68,587.07	1,230,428.49	3,849.44	38,825.61	615,214.25	**2,916,636**
Total Distance (km) Traveled (Water)				36,145	113			
Cargo Ship-Days				463	1			**465**
Average of Scenarios (Land)	*186,659*	*3,032,404*	*240,055*	*1,095,081*	*3,426*	*135,890*	*358,875*	***5,052,391***
Average of Scenarios (Water)				*528*	*3*			***531***

Table A2.2.2 – Material Transportation – page 2 of 3

Century	VI							
Number of 'Contract' Sections	**5**							
Material	**Facing Stone**	**Rough Structural Stone**	**Lime**	**Brick**	**Iron Clamps**	**Sand**	**Wood Fuel - Lime**	**Totals**
Material (kg) per 'Contract' Section	88,270	165,617	9,513	31,014		9,844	36,978	
Ox-cart Trips per 'Contract' Section	216,349	405,923	23,317	76,014	n/a	24,128	90,632	
Cargo Ship Trips for Entire Material Mass				541				
Hypothetical Scenario 1								
Total Distance (km) Traveled (Land)	16,987,473	31,872,684	1,830,831	5,968,515		1,894,482	1,186,051	
Ox-cart-Days	566,249	1,062,423	61,028	198,950	n/a	63,149	39,535	**1,991,335**
Total Distance (km) Traveled (Water)				34,092				
Cargo Ship-Days				437				**437**
Hypothetical Scenario 1								
Total Distance (km) Traveled (Land)	2,831,246	5,312,114	305,139	994,752		315,747	1,186,051	
Ox-cart-Days	94,375	177,070	10,171	33,158	n/a	10,525	39,535	**364,835**
Total Distance (km) Traveled (Water)				45,456				
Cargo Ship-Days				583				**583**
Average of Scenarios (Land)	*330,312*	*619,747*	*35,600*	*116,054*		*36,837*	*39,535*	***1,178,085***
					n/a			
Average of Scenarios (Water)				*510*				***510***

Table A2.2.2 – Material Transportation – page 3 of 3

A2.2.3 - Construction

Grouping	Phase (Century)	Clearing Path	Digging Foundation	Sawying Wood for Scaffold/Formwork	Supervision and Administration	TOTAL MAN-DAYS
		Site Preparations				
Units Labour		Man-days/Tonne Unskilled 0.970	Man-days/m^3 Unskilled 0.183	Man-days/m^2 Combined 0.075	Skilled 10% of Total Man-hours	
Water Supply of Constantinople	V	7,006.31	688,131.21	11,440.87	700,272.70	**1,406,851**
	IV	10,514.80	325,481.46	5,719.82	34,171.61	**375,888**
Anastasian Wall	VI	2,017.60	78,183.09	140,930.30	21,911.34	**243,042**

Table A2.2.3 - Construction – page 1 of 5

Grouping	Phase (Century)	Carrying Ingredients 10m to Mixing Site	Adding and Mixing	Load Baskets	Supervision and Administration	TOTAL MAN-DAYS
		Mortar Preparation				
Units Labour		Man-days/m^3 Unskilled 0.261	Man-days/m^3 Combined 0.640	Man-days/m^3 Unskilled 0.060	Skilled 10% of Total Man-hours	
Water Supply of Constantinople	V	198,758.71	488,113.68	45,760.66	73,263.30	**805,896**
	IV	99,112.35	243,401.13	22,818.86	36,533.23	**401,866**
Anastasian Wall	VI	185,595.79	455,788.06	42,730.13	68,411.40	**752,525**

Table A2.2.3 - Construction – page 2 of 5

	Phase (Century)	Facing Stone Dressing	Erecting Scaffolding	Moving Building Materials 100m	Supervision and Administration	TOTAL MAN-DAYS
Grouping		Building Preparations				
Units Labour		Man-days*/.1m^3 Skilled 1.406	Man-days/m^2 + Man-days/Upright Combined .063 + 1.25(Water Supply)/.75(Wall)	Man-days/Trip + Man-days/m^3 Unskilled .0047 + .075	Skilled 10% of Total Man-hours	
Water Supply of Constantinople	V	936,028.83	11,366.91	162,097.56	110,949.33	**1,220,443**
	IV	473,191.01	5,713.19	79,320.61	55,822.48	**614,047**
Anastasian Wall	VI	3,010,273.56	161,005.95	167,389.26	333,866.88	**3,672,536**

Table A2.2.3 - Construction – page 3 of 5

	Phase (Century)	Prepairing and Erecting Small Vaults	Prepairing and Erecting Large Vaults	Laying Foundations	Raising Materials	Building Channel Walls and Base	Laying Channel Lining Mortar	Laying Facing Stones and Core Walls	Digging Ditch (Wall Only)
Grouping		Construction							
Units Labour		Man-days/m^2 Skilled 0.100	Man-days/m^2 Skilled 0.200	Man-days/m^3 Unskilled 0.365	Man-days/m^2 Unskilled .012(h-1)	Man-days/m^3 Combined 0.365	Man-days/m^3 Skilled 0.250	Man-days/m^3 Combined 6.27 + .195(h-1)	Man-days/m^3 Unskilled 0.150
Water Supply of Constantinople	V	13,704.77	2,777.97	19,234.52	20,661.88	250,197.57	171,368.20	2,091,147.27	n/a
	IV	10,604.26	1,435.35	9,948.55	8,872.08	199,751.22	205,121.30	719,579.46	n/a
Anastasian Wall	VI	614.49	92.55	194,206.92	202,939.63	n/a	n/a	13,192,504.80	171,760.31

Table A2.2.3 - Construction – page 4 of 5

Grouping	Phase (Century)	**Supervision and Administration**	**TOTAL MAN-DAYS**
Units Labour		Skilled 10% of Total Man-hours	
Water Supply of Constantinople	V	256,909.22	**2,826,001**
	IV	115,531.22	**1,270,843**
Anastasian Wall	VI	1,376,211.87	**15,138,331**

Table A2.2.3 - Construction – page 5 of 5

APPENDIX 3 – MORTAR ANALYSIS DATA

A3.1 – Point Counting: Water Supply

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm^2)	Image	Brick	Sand in Binder	Lime Binder	No Material	Sand in Brick	Unburnt Lime	Brick Sand Ø (mm)	Binder Sand Ø (mm)
1	**A**	TT-WS	Kurşunlugerme	Core	NW	68.33	4125	23.83%	22.39%	47.76%	5.97%	0.50%	0.00%	0.058	0.624
							4134	26.37%	22.39%	48.26%	0.00%	2.99%	0.00%	0.114	0.712
					NE	68.33	4137	38.25%	17.50%	37.25%	4.75%	2.25%	0.00%	0.209	0.408
							4145	74.50%	3.00%	12.00%	0.50%	10.00%	0.00%	0.191	0.303
					SW	68.33	4153	55.61%	7.23%	34.16%	0.00%	2.99%	0.00%	0.167	0.315
							4164	19.27%	24.58%	55.15%	0.00%	1.00%	0.00%	0.181	0.742
					SE	68.33	4167	83.33%	0.00%	0.00%	0.00%	16.67%	0.00%	0.249	
							4175	21.89%	21.89%	56.22%	0.00%	0.00%	0.00%		0.452
						273.33		42.88%	14.87%	36.35%	1.40%	4.55%	0.00%	0.167	0.508
1	**B**	TT-WS	Kurşunlugerme	Core	NW	66.23	4198	18.91%	13.93%	66.67%	0.00%	0.50%	0.00%	0.131	0.581
							4205	13.43%	55.22%	29.35%	0.00%	1.99%	0.00%	0.218	0.509
					NE	66.59	4211	21.08%	26.47%	51.47%	0.00%	0.98%	0.00%	0.087	0.510
							4216	57.71%	0.00%	0.00%	1.99%	40.30%	0.00%	0.223	
					SW	66.88	4223	55.72%	11.44%	22.89%	0.00%	9.95%	0.00%	0.384	0.591
							4233	12.95%	47.26%	39.30%	0.00%	0.50%	0.00%	0.215	0.938
					SE	66.88	4238	44.78%	8.46%	45.77%	0.00%	1.00%	0.00%	0.199	0.311
							4243	17.41%	19.90%	61.19%	0.00%	1.49%	0.00%	0.350	0.608
						266.58		30.25%	22.84%	39.58%	0.25%	7.09%	0.00%	0.226	0.578
1	**C**	TT-WS	Kurşunlugerme	Core	NW	51.03	4323	34.83%	12.44%	45.77%	0.00%	6.97%	0.00%	0.284	0.499
							4329	22.28%	23.27%	52.97%	0.00%	1.49%	0.00%	0.077	0.763
					NE	59.09	4335	47.02%	8.28%	35.76%	0.00%	8.94%	0.00%	0.478	0.369
							4338	77.29%	2.90%	11.59%	0.00%	8.21%	0.00%	0.208	0.313
					SW	59.09	4344	35.82%	20.90%	41.29%	0.00%	1.99%	0.00%	0.084	0.733
							4349	18.41%	37.81%	42.79%	0.00%	1.00%	0.00%	0.183	1.109
					SE	59.09	4361	16.42%	33.83%	48.26%	0.00%	1.49%	0.00%	0.101	0.482
							4369	9.95%	56.22%	33.83%	0.00%	0.00%	0.00%	0.093	1.430
						228.29		32.75%	24.46%	39.03%	0.00%	3.76%	0.00%	0.189	0.712
1	**D**	TT-WS	Kurşunlugerme	Core	NW	63.10	4423	19.12%	39.22%	41.67%	0.00%	0.00%	0.00%	0.057	0.689
							4429	10.45%	21.89%	57.71%	9.95%	0.00%	0.00%		0.425
					NE	77.07	4411	27.36%	20.28%	49.06%	0.00%	3.30%	0.00%	0.177	0.946
							4418	78.54%	0.49%	4.39%	7.32%	9.27%	0.00%	0.372	0.246
					SW	72.78	4403	20.90%	19.40%	59.20%	0.00%	0.50%	0.00%	0.193	0.470
							4408	22.39%	29.85%	39.30%	8.46%	0.00%	0.00%	0.142	0.650
					SE	77.07	4392	17.81%	19.63%	62.10%	0.00%	0.46%	0.00%		0.356
							4399	83.66%	0.00%	0.00%	0.00%	16.34%	0.00%	0.295	
						290.02		35.03%	18.85%	39.18%	3.22%	3.73%	0.00%	0.206	0.540

Table A3.1 – Point Counting: Water Supply – page 1 of 7

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm²)	Image	Brick	Sand in Binder	Lime Binder	No Material	Sand in Brick	Unburnt Lime	Brick Sand Ø (mm)	Binder Sand Ø (mm)
1	E	TT-WS	Kurşunlugerme	Core	NW	43.41	4451	15.84%	24.26%	59.41%	0.00%	0.50%	0.00%	0.088	0.525
							4454	25.25%	24.58%	49.83%	0.00%	0.33%	0.00%	0.143	0.697
					NE	43.48	4459	14.43%	16.42%	32.84%	0.00%	1.49%	34.83%	0.121	0.489
							4462	5.61%	5.94%	19.41%	6.60%	0.66%	62.05%	0.119	0.663
					SW	50.38	4465	20.40%	23.88%	55.22%	0.00%	0.50%	0.00%	0.106	0.906
							4471	25.62%	24.14%	50.25%	0.00%	0.00%	0.00%	0.123	0.725
					SE	47.64	4474	26.09%	29.47%	44.44%	0.00%	0.00%	0.00%	0.106	1.034
							4483	15.64%	47.87%	36.49%	0.00%	0.00%	0.00%	0.149	0.634
						184.90		18.61%	24.57%	43.49%	0.83%	0.44%	12.11%	0.119	0.709
1	F	TT-WS	Kurşunlugerme	Core	NW	63.59	4500	87.06%	0.00%	0.00%	0.00%	12.94%	0.00%	0.251	
							4508	58.42%	6.93%	24.75%	0.00%	9.90%	0.00%	0.184	0.328
					NE	63.59	4511	36.79%	25.00%	35.85%	0.00%	2.36%	0.00%	0.202	0.557
							4519	11.44%	43.28%	45.27%	0.00%	0.00%	0.00%		1.980
					SW	59.84	4525	16.42%	16.42%	42.79%	24.38%	0.00%	0.00%	0.086	0.532
							4533	31.19%	17.82%	48.51%	0.00%	2.48%	0.00%	0.143	0.594
					SE	62.17	4536	21.78%	16.34%	60.40%	0.00%	1.49%	0.00%	0.533	0.689
							4541	20.90%	17.91%	60.20%	0.00%	1.00%	0.00%	0.234	0.415
						249.17		35.50%	17.96%	39.72%	3.05%	3.77%	0.00%	0.233	0.728
1	H	TT-WS	Kurşunlugerme	Core	NW	76.13	4545	71.64%	0.00%	0.00%	0.00%	28.36%	0.00%	0.473	
							4557	9.45%	31.34%	41.79%	17.41%	0.00%	0.00%	0.223	0.449
					NE	80.35	4580	26.27%	12.29%	57.63%	0.00%	3.81%	0.00%	0.197	0.389
							4587	16.92%	24.88%	51.74%	2.49%	3.98%	0.00%	0.131	0.573
					SW	74.01	4592	17.41%	18.41%	43.28%	18.91%	1.99%	0.00%	0.208	0.596
							4596	19.90%	22.39%	52.74%	1.49%	3.48%	0.00%	0.059	0.396
					SE	77.58	4605	18.41%	32.84%	48.26%	0.00%	0.50%	0.00%	0.190	0.898
							4604	16.34%	33.66%	50.00%	0.00%	0.00%	0.00%	0.140	1.083
						308.07		24.54%	21.98%	43.18%	5.04%	5.27%	0.00%	0.203	0.626
1	I	TT-WS	Kurşunlugerme	Core	NW	72.35	100% Metamorphosed Limestone								
					NE	72.35									
					SW	72.35									
					SE	72.35									
						289.40									
								31.37%	20.79%	40.08%	1.97%	4.09%	1.73%	0.192	0.629

Table A3.1 – Point Counting: Water Supply – page 2 of 7

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm²)	Image	Brick	Sand in Binder	Lime Binder	No Material	Sand in Brick	Unburnt Lime	Brick Sand Ø (mm)	Binder Sand Ø (mm)
2	A	TT-WS	Kumarlıdere	Core	NW	69.51	4637	35.32%	22.89%	38.31%	0.00%	3.48%	0.00%	0.111	0.349
							4643	31.84%	5.97%	50.25%	4.98%	6.97%	0.00%	0.094	0.300
					NE	69.51	4649	54.23%	6.47%	28.86%	0.00%	10.45%	0.00%	0.137	0.291
							4655	37.31%	27.36%	31.84%	0.00%	3.48%	0.00%	0.123	0.625
					SW	59.14	4660	85.45%	0.00%	0.00%	0.00%	14.55%	0.00%	0.240	
							4668	45.27%	5.47%	38.81%	3.48%	6.97%	0.00%	0.274	0.203
					SE	58.21	4672	67.66%	1.00%	4.48%	0.00%	26.87%	0.00%	0.427	0.117
							4678	27.36%	3.98%	53.73%	9.95%	4.98%	0.00%	0.385	0.242
						256.37		48.06%	9.14%	30.79%	2.30%	9.72%	0.00%	0.224	0.304
2	B	TT-WS	Kumarlıdere	Core	NW	52.70	4691	25.37%	12.94%	35.32%	22.89%	3.48%	0.00%		0.450
							4694	20.30%	7.92%	29.70%	40.10%	1.98%	0.00%	0.215	0.347
					NE	56.21	4699	37.31%	16.42%	40.30%	0.00%	5.97%	0.00%	0.105	0.634
							4703	42.79%	14.93%	33.83%	0.00%	8.46%	0.00%	0.240	0.356
					SW	70.25	4706	26.37%	12.94%	49.25%	7.46%	3.98%	0.00%	0.350	0.423
							4712	31.68%	7.92%	37.62%	21.78%	0.99%	0.00%	0.103	0.280
					SE	70.25	4715	66.17%	2.49%	14.93%	0.00%	16.42%	0.00%	0.939	0.213
							4721	42.36%	14.78%	34.48%	3.45%	4.93%	0.00%	0.230	0.309
						249.41		36.54%	11.29%	34.43%	11.96%	5.78%	0.00%	0.312	0.377
2	C	TT-WS	Kumarlıdere	Core	NW	69.85	4731	33.33%	13.43%	37.31%	10.95%	4.98%	0.00%	0.131	0.265
							4735	35.47%	13.30%	48.28%	0.00%	1.97%	0.99%	0.285	0.208
					NE	69.75	4744	59.70%	1.49%	13.43%	18.91%	6.47%	0.00%	0.282	0.244
							4751	18.05%	3.41%	17.07%	20.98%	1.46%	39.02%	0.108	0.376
					SW	71.59	4754	36.32%	4.98%	29.85%	22.39%	5.47%	1.00%	0.090	0.238
							4760	49.75%	4.98%	28.36%	8.96%	7.96%	0.00%	0.240	0.388
					SE	71.59	4763	35.32%	10.95%	39.30%	5.97%	8.46%	0.00%	0.197	0.322
							4769	38.81%	14.43%	41.79%	0.00%	4.98%	0.00%	0.144	0.330
						282.79		38.34%	8.37%	31.92%	11.02%	5.22%	5.13%	0.185	0.296
								40.98%	9.60%	32.38%	8.43%	6.90%	1.71%	0.240	0.326

Table A3.1 – Point Counting: Water Supply – page 3 of 7

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm^2)	Image	Brick	Sand in Binder	Lime Binder	No Material	Sand in Brick	Unburnt Lime	Brick Sand Ø (mm)	Binder Sand Ø (mm)
3	A	TT-WS	Kecigerme	Core	NW	68.55	4788	48.26%	6.97%	36.82%	0.00%	7.96%	0.00%	0.147	0.175
							4795	36.32%	14.93%	37.31%	6.97%	4.48%	0.00%	0.160	0.503
					NE	72.35	4798	51.24%	4.98%	25.37%	6.97%	11.44%	0.00%	0.165	0.218
							4803	42.79%	8.46%	36.82%	2.49%	9.45%	0.00%	0.306	0.404
					SW	72.35	4808	20.69%	6.40%	50.74%	15.27%	2.46%	4.43%	0.179	0.535
							4813	26.87%	9.45%	52.74%	1.00%	1.00%	8.96%	0.111	0.213
					SE	72.35	4816	30.35%	6.47%	57.21%	2.29%	3.48%	0.00%	0.131	0.252
							4821	28.22%	14.36%	31.68%	1.49%	4.46%	19.80%	0.207	0.323
						285.60		35.59%	9.00%	41.09%	4.56%	5.59%	4.15%	0.176	0.328
3	B	TT-WS	Kecigerme	Core	NW	62.45	4850	41.67%	3.29%	27.94%	14.22%	12.25%	0.00%	0.200	0.323
							4856	67.66%	0.00%	0.00%	1.99%	30.35%	0.00%	0.589	
					NE	70.25	4859	27.36%	4.98%	42.29%	15.42%	9.98%	0.00%	0.402	0.201
							4866	26.37%	11.94%	51.24%	0.00%	2.99%	7.46%	0.316	1.030
					SW	63.20	4869	35.82%	2.49%	48.26%	6.47%	6.97%	0.00%	0.393	0.301
							4874	21.89%	9.46%	62.69%	0.00%	5.97%	0.00%	0.292	0.258
					SE	69.28	4877	25.25%	10.40%	62.87%	0.00%	1.49%	0.00%	0.121	0.306
							4887	50.00%	9.41%	29.70%	0.00%	10.89%	0.00%	0.265	0.329
						265.18		37.00%	6.50%	40.62%	4.76%	10.11%	0.93%	0.322	0.393
3	C	TT-WS	Kecigerme	Core	NW	70.85	4905	28.36%	7.46%	53.73%	4.98%	5.47%	0.00%	0.217	0.254
							4913	29.90%	4.90%	57.84%	0.49%	6.37%	0.49%	0.179	0.209
					NE	67.87	4916	26.87%	9.95%	58.71%	1.99%	2.49%	0.00%	0.100	0.340
							4920	13.93%	3.98%	16.92%	4.98%	0.00%	60.20%		0.283
					SW	70.85	4928	27.71%	10.84%	57.83%	0.00%	1.20%	2.41%	0.107	0.152
							4935	42.72%	10.68%	39.81%	0.00%	3.88%	2.91%	0.243	0.468
					SE	70.85	4938	32.17%	6.96%	58.26%	0.00%	2.61%	0.00%	0.159	0.242
							4945	45.71%	9.52%	41.90%	0.00%	2.86%	0.00%	0.248	0.376
						280.41		30.92%	8.04%	48.13%	1.56%	3.11%	8.25%	0.179	0.291
								34.51%	7.85%	43.28%	3.63%	6.27%	4.44%	0.226	0.337

Table A3.1 – Point Counting: Water Supply – page 4 of 7

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm²)	Image	Brick	Sand in Binder	Lime Binder	No Material	Sand in Brick	Unburnt Lime	Brick Sand Ø (mm)	Binder Sand Ø (mm)
4	**A**	TT-WS	Büyükgerme	Core	NW	71.64	4966	50.98%	5.88%	30.39%	0.00%	11.76%	0.98%	0.158	0.330
							4973	52.69%	10.75%	32.26%	0.00%	4.30%	0.00%	0.125	0.259
					NE	72.35	4977	43.14%	10.78%	36.27%	0.00%	9.80%	0.00%	0.294	0.306
							4981	55.77%	11.54%	25.96%	0.00%	5.77%	0.96%	0.202	0.256
					SW	71.01	4984	51.46%	5.83%	28.16%	0.00%	14.56%	0.00%	0.185	0.290
							4990	44.23%	12.50%	33.65%	0.00%	9.62%	0.00%	0.178	0.152
					SE	71.10	4994	49.51%	6.80%	30.10%	0.00%	13.59%	0.00%	0.334	0.440
							5001	57.28%	7.77%	23.30%	0.00%	11.65%	0.00%	0.294	0.267
						286.09		50.63%	8.98%	30.01%	0.00%	10.13%	0.24%	0.221	0.288
4	**B**	TT-WS	Büyükgerme	Core	NW	72.50	5020	45.19%	12.50%	33.65%	0.00%	8.65%	0.00%	0.178	0.415
							5026	44.12%	18.63%	31.37%	0.00%	5.88%	0.00%	0.565	0.609
					NE	72.50	5030	49.06%	7.55%	37.74%	0.00%	5.66%	0.00%	0.129	0.592
							5037	45.63%	7.77%	38.83%	2.91%	4.85%	0.00%	0.849	0.329
					SW	70.57	5040	43.69%	16.50%	35.92%	0.00%	3.88%	0.00%	0.166	0.222
							5044	46.30%	11.11%	31.48%	0.00%	11.11%	0.00%	0.281	0.326
					SE	72.50	5047	43.69%	10.68%	29.13%	5.83%	7.77%	2.91%	0.151	0.405
							5054	41.18%	5.88%	37.25%	0.00%	15.69%	0.00%	0.218	0.491
						288.06		44.86%	11.33%	34.42%	1.09%	7.94%	0.36%	0.317	0.424
4	**C**	TT-WS	Büyükgerme	Core	NW	61.90	5068	47.83%	11.30%	31.30%	0.00%	9.57%	0.00%	0.336	0.286
							5073	48.54%	4.85%	25.24%	10.68%	10.68%	0.00%	0.595	0.226
					NE	67.58	5077	49.51%	5.83%	28.16%	0.00%	16.50%	0.00%	0.406	0.275
							5082	50.49%	5.83%	30.10%	0.97%	5.83%	6.80%	0.308	0.466
					SW	69.51	5087	51.46%	3.88%	31.07%	6.80%	6.80%	0.00%	0.193	0.425
							5097	66.99%	0.00%	3.88%	0.00%	29.13%	0.00%	0.409	
					SE	60.75	5101	45.91%	11.11%	35.56%	0.00%	8.15%	0.00%	0.097	0.248
							5107	32.38%	11.43%	31.48%	14.29%	10.48%	0.00%	0.338	1.017
						259.75		49.14%	6.78%	27.10%	4.09%	12.14%	0.85%	0.335	0.420
								48.21%	9.03%	30.51%	1.73%	10.07%	0.49%	0.291	0.377

Table A3.1 – Point Counting: Water Supply – page 5 of 7

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm²)	Image	Brick	Sand in Binder	Lime Binder	No Material	Sand in Brick	Unburnt Lime	Brick Sand Ø (mm)	Binder Sand Ø (mm)
5	A	TT-WS	Karatepe	Lining	NW	71.13	5129	38.24%	13.73%	37.25%	0.00%	8.82%	1.96%	0.113	0.677
							5136	36.37%	12.75%	28.43%	0.00%	18.63%	3.92%	0.703	0.447
					NE	68.58	5139	40.54%	11.71%	37.84%	0.00%	9.91%	0.00%	0.719	0.684
							5145	42.31%	6.73%	33.65%	1.92%	11.54%	3.85%	0.215	0.297
					SW	72.35	5150	53.33%	12.50%	29.17%	0.00%	5.00%	0.00%	0.319	0.457
							5158	52.99%	9.50%	31.62%	0.00%	5.98%	0.00%	0.335	0.424
					SE	70.26	5161	30.39%	6.86%	34.31%	22.55%	3.92%	1.96%	0.270	0.221
							5166	40.57%	6.60%	37.74%	0.00%	9.43%	5.66%	0.157	0.366
						282.31		41.84%	10.05%	33.75%	3.06%	9.15%	2.17%	0.354	0.447
5	B	TT-WS	Karatepe	Lining	NW	50.09	5182	41.18%	14.29%	30.25%	0.00%	14.29%	0.00%	0.271	0.563
							5193	52.25%	11.71%	19.82%	0.00%	16.22%	0.00%	0.285	0.317
					NE	50.09	5197	38.78%	8.16%	43.54%	0.00%	8.16%	1.36%	0.221	0.289
							5205	33.04%	10.71%	32.14%	0.89%	9.82%	13.39%	0.255	0.357
					SW	50.09	5209	35.92%	4.85%	33.01%	17.48%	1.94%	6.80%	0.314	0.308
							5216	34.31%	9.80%	22.55%	22.55%	10.78%	0.00%	0.184	0.274
					SE	50.09	5222	42.72%	7.77%	15.53%	3.88%	11.65%	18.45%	0.532	0.247
							5224	24.53%	5.66%	35.85%	30.19%	3.77%	0.00%	0.184	0.382
						200.38		37.84%	9.12%	29.09%	9.37%	9.58%	5.00%	0.281	0.342
5	C	TT-WS	Karatepe	Lining	NW	66.78	5264	34.31%	14.71%	45.10%	0.00%	1.96%	3.92%	0.091	0.396
							5270	36.27%	8.82%	46.08%	1.96%	4.90%	1.96%	0.150	0.270
					NE	60.59	5274	25.00%	3.85%	12.50%	50.96%	7.69%	0.00%	0.301	0.130
							5280	46.67%	5.83%	40.83%	0.00%	6.67%	0.00%	0.227	0.215
					SW	56.97	5283	28.30%	13.21%	46.23%	3.77%	5.66%	2.83%	0.257	0.812
							5286	48.04%	0.98%	24.51%	0.00%	26.47%	0.00%	0.388	0.329
					SE	54.35	5289	28.57%	4.76%	18.10%	43.81%	3.81%	0.95%	0.199	0.382
							5298	62.50%	0.00%	0.00%	2.88%	34.62%	0.00%	0.312	
						238.69		38.71%	6.52%	29.17%	12.92%	11.47%	1.21%	0.241	0.362
5	D^1	TT-WS	Karatepe	Lining	NW	94.19	5312	22.64%	8.49%	21.70%	10.35%	0.00%	36.79%	0.139	0.448
							5326	40.78%	12.62%	31.07%	0.00%	13.59%	1.94%	0.308	0.196
					NE	96.67	5329	70.29%	0.90%	8.11%	0.00%	20.72%	0.00%	0.259	0.130
							5341	33.65%	6.73%	46.15%	0.00%	4.81%	8.65%	0.265	0.167
					SW	96.67	5346	46.67%	1.90%	29.52%	13.33%	8.57%	0.00%	0.165	0.257
							5360	44.44%	6.48%	34.26%	0.00%	14.81%	0.00%	0.392	0.302
					SE	90.36	5363	33.65%	2.88%	33.65%	4.81%	6.73%	18.27%	0.144	0.234
							5373	32.69%	9.62%	25.96%	20.19%	7.69%	3.85%	0.200	0.316
						377.89		40.60%	6.20%	28.80%	6.09%	9.62%	8.69%	0.234	0.256
5	D^2	TT-WS	Karatepe	Lining	NW	69.66	5436	30.10%	13.59%	42.72%	0.00%	10.68%	2.91%	1.017	0.342
							5444	30.10%	14.56%	47.57%	0.97%	5.83%	0.97%	0.182	0.336
					NE	69.66	5447	37.74%	6.60%	51.89%	0.00%	2.83%	0.94%	0.127	0.324
							5454	41.75%	11.65%	40.78%	0.97%	4.85%	0.00%	0.205	0.203
					SW	66.27	5458	28.70%	11.11%	39.81%	7.41%	2.78%	10.19%	0.237	0.892
							5462	30.77%	10.58%	41.35%	10.58%	6.73%	0.00%	0.219	0.194
					SE	69.66	5468	44.26%	13.11%	35.25%	0.00%	3.28%	4.10%	0.245	0.868
							5475	23.42%	7.21%	28.83%	0.00%	2.70%	37.84%	0.312	0.355
						275.25		33.36%	11.05%	41.03%	2.49%	4.96%	7.12%	0.318	0.439

Table A3.1 – Point Counting: Water Supply – page 6 of 7

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm²)	Image	Brick	Sand in Binder	Lime Binder	No Material	Sand in Brick	Unburnt Lime	Brick Sand Ø (mm)	Binder Sand Ø (mm)
5	**E[1]**	TT-WS	Karatepe	Lining	NW	75.13	5503	32.73%	11.82%	34.55%	15.45%	5.45%	0.00%	0.244	0.216
							5514	71.84%	2.19%	7.77%	0.00%	17.48%	0.00%	0.285	0.387
					NE	70.52	5521	25.96%	2.88%	25.00%	31.73%	6.73%	7.69%	0.422	0.208
							5532	32.35%	8.82%	38.24%	12.75%	7.84%	0.00%	0.177	0.274
					SW	70.53	5539	34.31%	11.67%	39.22%	9.80%	4.90%	0.00%	0.194	0.345
							5549	47.06%	2.94%	24.51%	2.94%	14.71%	7.84%	0.396	0.208
					SE	77.25	5554	44.66%	2.91%	33.98%	2.91%	11.65%	3.88%	0.355	0.347
							5563	33.98%	4.85%	40.78%	5.83%	14.56%	0.00%	0.292	0.289
						293.43		40.36%	6.01%	30.51%	10.18%	10.42%	2.43%	0.296	0.284
5	**E[2]**	TT-WS	Karatepe	Lining	NW	70.95	5606	1.94%	0.97%	2.91%	6.80%	0.00%	87.38%	0.204	
							5612	11.65%	0.00%	12.62%	0.00%	0.00%	75.73%	0.155	0.163
					NE	69.93	5616	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%		
							5623	4.63%	0.93%	3.70%	15.74%	0.00%	75.00%	0.084	0.205
					SW	71.59	5627	56.45%	11.29%	24.19%	0.00%	8.06%	0.00%	0.378	0.841
							5634	63.46%	0.96%	10.58%	0.00%	25.00%	0.00%	0.534	0.220
					SE	68.52	5637	28.57%	9.82%	39.29%	16.07%	1.79%	4.46%	0.147	0.579
							5645	46.60%	7.77%	39.81%	0.00%	2.91%	2.91%	0.197	0.397
						281.01		26.66%	3.97%	16.64%	4.83%	4.72%	43.19%	0.243	0.401
								37.05%	7.56%	29.85%	6.99%	8.56%	9.97%	0.281	0.362
6	**A**	TT-WS	Karatepe	Core	NW	79.77	5667	42.50%	8.33%	35.00%	9.17%	1.67%	3.33%	0.196	0.164
							5677	41.51%	2.83%	24.53%	21.70%	8.49%	0.94%	0.325	0.152
					NE	97.97	5684	61.54%	4.81%	23.08%	0.00%	10.58%	0.00%	0.267	0.412
							5690	33.03%	10.09%	46.79%	0.00%	5.50%	4.59%	0.285	0.358
					SW	89.15	5694	66.02%	0.00%	13.59%	0.00%	19.42%	0.97%	0.691	0.204
							5702	48.62%	16.51%	23.85%	0.00%	11.01%	0.00%	0.541	0.961
					SE	97.97	5708	57.28%	2.91%	24.27%	0.00%	15.53%	0.00%	0.588	0.385
							5715	19.23%	48.08%	29.81%	0.00%	1.92%	0.96%	0.273	0.410
						364.87		46.22%	11.70%	27.62%	3.86%	9.27%	1.35%	0.396	0.381
6	**B**	TT-WS	Karatepe	Core	NW	68.63	5754	26.21%	20.39%	46.60%	2.91%	3.88%	0.00%	0.192	0.555
							5764	20.00%	4.00%	22.67%	44.00%	9.33%	0.00%		
					NE	65.74	5767	18.45%	10.68%	59.22%	11.65%	0.00%	0.00%	0.246	0.641
							5776	31.73%	19.23%	39.42%	3.85%	5.77%	0.00%	0.416	0.842
					SW	68.63	5779	66.99%	0.00%	0.00%	3.88%	29.13%	0.00%	0.410	
							5787	13.46%	14.42%	62.50%	0.96%	6.73%	1.92%	0.335	0.414
					SE	62.04	5791	27.03%	25.23%	43.24%	0.00%	1.80%	2.70%	0.174	0.258
							5797	35.92%	13.59%	39.81%	0.00%	6.80%	3.88%	0.284	0.695
						265.03		29.97%	13.44%	39.18%	8.41%	7.93%	1.06%	0.294	0.568
								38.10%	12.57%	33.40%	6.13%	8.60%	1.21%	0.345	0.474

Table A3.1 – Point Counting: Water Supply – page 7 of 7

A3.2 – Final Percentages of Mortar Constituents: Water Supply

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm²)	Image	Totals								
								% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
1	A	TT-WS	Kurşunlugerme	Core	NW	68.33	4125 4134								
					NE	68.33	4137 4145								
					SW	68.33	4153 4164								
					SE	68.33	4167 4175								
						273.33		37%	15%	48%	0.3	3	2	0	8.79
								% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
1	B	TT-WS	Kurşunlugerme	Core	NW	66.23	4198 4205								
					NE	66.59	4211 4216								
					SW	66.88	4223 4233								
					SE	66.88	4238 4243								
						266.58		40%	23%	37%	0.4	4	1	1	3.44
								% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
1	C	TT-WS	Kurşunlugerme	Core	NW	51.03	4323 4329								
					NE	59.09	4335 4338								
					SW	59.09	4344 4349								
					SE	59.09	4361 4369								
						228.29		39%	24%	37%	0.5	3	0	2	6.46
								% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
1	D	TT-WS	Kurşunlugerme	Core	NW	63.10	4423 4429								
					NE	77.07	4411 4418								
					SW	72.78	4403 4408								
					SE	77.07	4392 4399								
						290.02		40%	19%	40%	0.3	0	2	1	7.13

Table A3.2 – Final Percentages of Mortar Constituents: Water Supply – page 1 of 7

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm^2)	Image	Totals							
1	**E**	TT-WS	Kurşunlugerme	Core	NW	43.41	4451 4454	**% Lime**	**% Sand**	**% Brick**	**Brick/Binder Sand Ø Difference (mm)**	**Occurrence of Olivine Granules**	**Occurrence of Organic Material in Binder**	**Occurrence of Organic Material in Brick Aggregate**	**Maximum Ø of Brick Aggregate (mm)**
					NE	43.48	4459 4462								
					SW	50.38	4465 4471								
					SE	47.64	4474 4483								
						184.90		56%	25%	19%	0.6	3	2	0	4.49
1	**F**	TT-WS	Kurşunlugerme	Core	NW	63.59	4500 4508	**% Lime**	**% Sand**	**% Brick**	**Brick/Binder Sand Ø Difference (mm)**	**Occurrence of Olivine Granules**	**Occurrence of Organic Material in Binder**	**Occurrence of Organic Material in Brick Aggregate**	**Maximum Ø of Brick Aggregate (mm)**
					NE	63.59	4511 4519								
					SW	59.84	4525 4533								
					SE	62.17	4536 4541								
						249.17		41%	19%	41%	0.5	2	1	2	9.39
1	**H**	TT-WS	Kurşunlugerme	Core	NW	76.13	4545 4557	**% Lime**	**% Sand**	**% Brick**	**Brick/Binder Sand Ø Difference (mm)**	**Occurrence of Olivine Granules**	**Occurrence of Organic Material in Binder**	**Occurrence of Organic Material in Brick Aggregate**	**Maximum Ø of Brick Aggregate (mm)**
					NE	80.35	4580 4587								
					SW	74.01	4592 4596								
					SE	77.58	4605 4604								
						308.07		45%	23%	31%	0.4	7	1	0	10.84
1	**I**	TT-WS	Kurşunlugerme	Core	NW	72.35	100% Metamorphosed Limestone								
					NE	72.35									
					SW	72.35									
					SE	72.35									
						289.40									
								43%	***21%***	***36%***	***0.4***	***3.1***	***1.3***	***0.9***	***7.2***

Table A3.2 – Final Percentages of Mortar Constituents: Water Supply – page 2 of 7

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm^2)	Image	Totals							
2	**A**	TT-WS	Kumarlıdere	Core	NW	69.51	4637 4643	**% Lime**	**% Sand**	**% Brick**	**Brick/Binder Sand Ø Difference (mm)**	**Occurrence of Olivine Granules**	**Occurrence of Organic Material in Binder**	**Occurrence of Organic Material in Brick Aggregate**	**Maximum Ø of Brick Aggregate (mm)**
					NE	69.51	4649 4655								
					SW	59.14	4660 4668								
					SE	58.21	4672 4678								
						256.37		32%	9%	59%	0.1	0	2	0	9.44
2	**B**	TT-WS	Kumarlıdere	Core	NW	52.70	4691 4694	**% Lime**	**% Sand**	**% Brick**	**Brick/Binder Sand Ø Difference (mm)**	**Occurrence of Olivine Granules**	**Occurrence of Organic Material in Binder**	**Occurrence of Organic Material in Brick Aggregate**	**Maximum Ø of Brick Aggregate (mm)**
					NE	56.21	4699 4703								
					SW	70.25	4706 4712								
					SE	70.25	4715 4721								
						249.41		39%	13%	48%	0.1	4	0	0	4.19
2	**C**	TT-WS	Kumarlıdere	Core	NW	69.85	4731 4735	**% Lime**	**% Sand**	**% Brick**	**Brick/Binder Sand Ø Difference (mm)**	**Occurrence of Olivine Granules**	**Occurrence of Organic Material in Binder**	**Occurrence of Organic Material in Brick Aggregate**	**Maximum Ø of Brick Aggregate (mm)**
					NE	69.75	4744 4751								
					SW	71.59	4754 4760								
					SE	71.59	4763 4769								
						282.79		42%	9%	49%	0.1	6	2	0	3.79
								37%	***11%***	***52%***	***0.1***	***3.3***	***1.3***	***0.0***	***5.8***

Table A3.2 – Final Percentages of Mortar Constituents: Water Supply – page 3 of 7

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm²)	Image	Totals							
								% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
3	**A**	TT-WS	Kecigerme	Core	NW	68.55	4788 4795								
					NE	72.35	4798 4803								
					SW	72.35	4808 4813								
					SE	72.35	4816 4821								
						285.60		47%	9%	43%	0.2	1	2	0	6.22
3	**B**	TT-WS	Kecigerme	Core	NW	62.45	4850 4856	% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
					NE	70.25	4859 4866								
					SW	63.20	4869 4874								
					SE	69.28	4877 4887								
						265.18		44%	7%	49%	0.1	0	2	0	6.55
3	**C**	TT-WS	Kecigerme	Core	NW	70.85	4905 4913	% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
					NE	67.87	4916 4920								
					SW	70.85	4928 4935								
					SE	70.85	4938 4945								
						280.41		57%	8%	35%	0.1	0	3	1	3.51
								49%	***8%***	***42%***	***0.1***	***0.3***	***2.3***	***0.3***	***5.4***

Table A3.2 – Final Percentages of Mortar Constituents: Water Supply – page 4 of 7

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm²)	Image	Totals							
								% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
4	**A**	TT-WS	Büyükgerme	Core	NW	71.64	4966 4973								
					NE	72.35	4977 4981								
					SW	71.01	4984 4990								
					SE	71.10	4994 5001								
						286.09		30%	9%	61%	0.1	0	4	5	3.98
4	**B**	TT-WS	Büyükgerme	Core	NW	72.50	5020 5026								
					NE	72.50	5030 5037								
					SW	70.57	5040 5044								
					SE	72.50	5047 5054								
						288.06		35%	11%	53%	0.1	0	6	2	6.61
4	**C**	TT-WS	Büyükgerme	Core	NW	61.90	5068 5073								
					NE	67.58	5077 5082								
					SW	69.51	5087 5097								
					SE	60.75	5101 5107								
						259.75		29%	7%	64%	0.1	1	6	3	5.02
								32%	***9%***	***59%***	***0.1***	***0.3***	***5.3***	***3.3***	***5.2***

Table A3.2 – Final Percentages of Mortar Constituents: Water Supply – page 5 of 7

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm^2)	Image	Totals							
								% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
5	**A**	TT-WS	Karatepe	Lining	NW	71.13	5129, 5136								
					NE	68.58	5139, 5145								
					SW	72.35	5150, 5158								
					SE	70.26	5161, 5166								
						282.31		37%	10%	53%	0.1	0	7	0	2.71
								% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
5	**B**	TT-WS	Karatepe	Lining	NW	50.09	5182, 5193								
					NE	50.09	5197, 5205								
					SW	50.09	5209, 5216								
					SE	50.09	5222, 5224								
						200.38		38%	10%	52%	0.1	1	4	0	2.39
								% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
5	**C**	TT-WS	Karatepe	Lining	NW	66.78	5264, 5270								
					NE	60.59	5274, 5280								
					SW	56.97	5283, 5286								
					SE	54.35	5289, 5298								
						238.69		35%	7%	58%	0.1	0	7	2	6.13
								% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
5	**D[1]**	TT-WS	Karatepe	Lining	NW	94.19	5312, 5326								
					NE	96.67	5329, 5341								
					SW	96.67	5346, 5360								
					SE	90.36	5363, 5373								
						377.89		40%	7%	53%	0.0	1	6	0	3.12
								% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
5	**D[2]**	TT-WS	Karatepe	Lining	NW	69.66	5436, 5444								
					NE	69.66	5447, 5454								
					SW	66.27	5458, 5462								
					SE	69.66	5468, 5475								
						275.25		49%	11%	39%	0.1	1	7	3	4.24

Table A3.2 – Final Percentages of Mortar Constituents: Water Supply – page 6 of 7

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm²)	Image	Totals							
5	E[1]	TT-WS	Karatepe	Lining	NW	75.13	5503 5514	% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
					NE	70.52	5521 5532								
					SW	70.53	5539 5549								
					SE	77.25	5554 5563								
						293.43		37%	7%	57%	0.0	0	8	5	8.65
5	E[2]	TT-WS	Karatepe	Lining	NW	70.95	5606 5612	% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
					NE	69.93	5616 5623								
					SW	71.59	5627 5634								
					SE	68.52	5637 5645								
						281.01		63%	4%	33%	0.2	1	4	2	7.79
								43%	***8%***	***49%***	***0.1***	***0.6***	***6.1***	***1.7***	***5.0***
6	A	TT-WS	Karatepe	Core	NW	79.77	5667 5677	% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
					NE	97.97	5684 5690								
					SW	89.15	5694 5702								
					SE	97.97	5708 5715								
						364.87		30%	12%	58%	0.0	3	7	1	9.31
6	B	TT-WS	Karatepe	Core	NW	68.63	5754 5764	% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
					NE	65.74	5767 5776								
					SW	68.63	5779 5787								
					SE	62.04	5791 5797								
						265.03		44%	15%	41%	0.3	3	2	2	9.86
								37%	***13%***	***50%***	***0.1***	***3.0***	***4.5***	***1.5***	***9.6***

Table A3.2 – Final Percentages of Mortar Constituents: Water Supply – page 7 of 7

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm^2)	Image	Brick	Sand in Binder	Lime Binder	No Material	Sand in Brick	Unburnt Lime	Brick Sand Ø (mm)	Binder Sand Ø (mm)
1	A	TT-AW	Karanlik Ayazma Sirti	Core	NW	71.44	5885	66.88%	6.88%	16.25%	3.75%	5.00%	1.25%	0.118	0.394
							5893	15.89%	1.32%	15.89%	58.28%	5.96%	2.65%	0.235	0.366
					NE	71.44	5896	49.01%	7.28%	32.45%	7.95%	1.32%	1.99%	0.223	0.353
							5903	53.21%	5.77%	37.18%	1.28%	2.56%	0.00%	0.218	0.462
					SW	71.44	5906	59.21%	7.24%	25.66%	3.95%	3.95%	0.00%	0.256	0.618
							5912	48.75%	8.12%	30.00%	0.62%	12.50%	0.00%	0.571	0.822
					SE	71.44	5916	35.67%	5.73%	42.68%	1.27%	8.28%	6.37%	0.396	0.605
							5924	20.31%	17.19%	23.44%	1.56%	4.69%	32.81%	0.202	0.599
						285.76		43.62%	7.44%	27.94%	9.83%	5.53%	5.63%	0.277	0.527
1	B	TT-AW	Karanlik Ayazma Sirti	Core	NW	64.45	5821	46.05%	14.47%	32.89%	0.00%	4.61%	1.97%	0.355	0.389
							5828	26.88%	28.12%	36.88%	1.88%	1.88%	4.38%	0.244	0.873
					NE	71.14	5832	31.41%	16.67%	44.87%	0.00%	3.85%	3.21%	0.242	0.672
							5841	35.19%	12.96%	20.37%	22.22%	5.56%	3.70%	0.323	0.732
					SW	71.14	5844	48.05%	12.34%	38.31%	0.00%	1.30%	0.00%	0.155	0.652
							5852	47.44%	11.54%	34.62%	3.85%	2.56%	0.00%	0.230	0.450
					SE	70.36	5857	37.09%	14.57%	45.03%	0.66%	1.32%	1.32%	0.248	0.647
							5865	50.65%	9.74%	36.36%	0.00%	3.25%	0.00%	0.209	0.326
						277.09		40.35%	15.05%	36.17%	3.58%	3.04%	1.82%	0.251	0.593
1	C	TT-AW	Karanlik Ayazma Sirti	Core	NW	72.19	5942	32.09%	7.55%	33.96%	0.00%	3.77%	22.64%	0.346	0.690
							5949	48.94%	19.15%	21.28%	6.38%	0.00%	4.26%	0.316	1.459
					NE	72.19	5952	41.18%	25.49%	23.53%	0.00%	5.88%	3.92%	0.336	0.708
							5959	30.36%	46.43%	19.64%	0.00%	3.57%	0.00%	0.288	0.574
					SW	72.19	5965	50.31%	9.32%	36.65%	0.00%	3.73%	0.00%	0.378	0.464
							5973	40.40%	5.30%	44.37%	1.32%	5.96%	2.65%	0.391	0.303
					SE	72.19	5978	52.00%	6.00%	32.00%	6.67%	1.33%	2.00%	0.204	0.528
							5985	43.04%	7.59%	39.24%	1.90%	8.23%	0.00%	0.458	0.407
						288.76		42.29%	15.85%	31.33%	2.03%	4.06%	4.43%	0.340	0.642
								42.08%	12.78%	31.81%	5.15%	4.21%	3.96%	0.289	0.587

A3.3 – Point Counting: Anastasian Wall

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm^2)	Image	Brick	Sand in Binder	Lime Binder	No Material	Sand in Brick	Unburnt Lime	Brick Sand Ø (mm)	Binder Sand Ø (mm)
1	**A**	TT-AW	Karanlik Ayazma Sirti	Core	NW	71.44	5885	66.88%	6.88%	16.25%	3.75%	5.00%	1.25%	0.118	0.394
							5893	15.89%	1.32%	15.89%	58.28%	5.96%	2.65%	0.235	0.366
					NE	71.44	5896	49.01%	7.28%	32.45%	7.95%	1.32%	1.99%	0.223	0.353
							5903	53.21%	5.77%	37.18%	1.28%	2.56%	0.00%	0.218	0.462
					SW	71.44	5906	59.21%	7.24%	25.66%	3.95%	3.95%	0.00%	0.256	0.618
							5912	48.75%	8.12%	30.00%	0.62%	12.50%	0.00%	0.571	0.822
					SE	71.44	5916	35.67%	5.73%	42.68%	1.27%	8.28%	6.37%	0.396	0.605
							5924	20.31%	17.19%	23.44%	1.56%	4.69%	32.81%	0.202	0.599
						285.76		43.62%	7.44%	27.94%	9.83%	5.53%	5.63%	0.277	0.527
1	**B**	TT-AW	Karanlik Ayazma Sirti	Core	NW	64.45	5821	46.05%	14.47%	32.89%	0.00%	4.61%	1.97%	0.355	0.389
							5828	26.88%	28.12%	36.88%	1.88%	1.88%	4.38%	0.244	0.873
					NE	71.14	5832	31.41%	16.67%	44.87%	0.00%	3.85%	3.21%	0.242	0.672
							5841	35.19%	12.96%	20.37%	22.22%	5.56%	3.70%	0.323	0.732
					SW	71.14	5844	48.05%	12.34%	38.31%	0.00%	1.30%	0.00%	0.155	0.652
							5852	47.44%	11.54%	34.62%	3.85%	2.56%	0.00%	0.230	0.450
					SE	70.36	5857	37.09%	14.57%	45.03%	0.66%	1.32%	1.32%	0.248	0.647
							5865	50.65%	9.74%	36.36%	0.00%	3.25%	0.00%	0.209	0.326
						277.09		40.35%	15.05%	36.17%	3.58%	3.04%	1.82%	0.251	0.593
1	**C**	TT-AW	Karanlik Ayazma Sirti	Core	NW	72.19	5942	32.09%	7.55%	33.96%	0.00%	3.77%	22.64%	0.346	0.690
							5949	48.94%	19.15%	21.28%	6.38%	0.00%	4.26%	0.316	1.459
					NE	72.19	5952	41.18%	25.49%	23.53%	0.00%	5.88%	3.92%	0.336	0.708
							5959	30.36%	46.43%	19.64%	0.00%	3.57%	0.00%	0.288	0.574
					SW	72.19	5965	50.31%	9.32%	36.65%	0.00%	3.73%	0.00%	0.378	0.464
							5973	40.40%	5.30%	44.37%	1.32%	5.96%	2.65%	0.391	0.303
					SE	72.19	5978	52.00%	6.00%	32.00%	6.67%	1.33%	2.00%	0.204	0.528
							5985	43.04%	7.59%	39.24%	1.90%	8.23%	0.00%	0.458	0.407
						288.76		42.29%	15.85%	31.33%	2.03%	4.06%	4.43%	0.340	0.642
								42.08%	12.78%	31.81%	5.15%	4.21%	3.96%	0.289	0.587

Table A3.3 – Point Counting: Anastasian Wall – page 1 of 8

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm^2)	Image	Brick	Sand in Binder	Lime Binder	No Material	Sand in Brick	Unburnt Lime	Brick Sand Ø (mm)	Binder Sand Ø (mm)
2	**A**	TT-AW	Belgrat Tower	Core	NW	82.51	6005	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%		
							6013	14.04%	30.99%	17.54%	35.67%	0.58%	1.17%	0.221	0.949
					NE	27.98	6015	11.63%	30.23%	25.51%	27.91%	0.00%	4.65%		1.116
							6022	9.43%	69.81%	13.21%	7.55%	0.00%	0.00%		1.039
					SW	70.91	6024	12.24%	26.53%	30.61%	22.45%	0.00%	8.16%	0.182	0.618
							6033	42.65%	19.12%	23.53%	10.29%	2.94%	1.47%	0.137	0.929
					SE	80.65	6036	28.95%	11.84%	32.89%	25.00%	1.32%	0.00%	0.185	0.978
							6047	59.17%	11.25%	25.42%	0.00%	2.50%	1.67%	0.124	0.759
						262.05		22.26%	37.47%	21.09%	16.11%	0.92%	2.14%	0.170	0.913
2	**B**	TT-AW	Belgrat Tower	Core	NW	55.18	6073	19.61%	37.25%	35.29%	0.00%	1.96%	5.88%	0.107	0.900
							6081	67.35%	0.00%	0.00%	0.00%	22.45%	10.20%	0.325	
					NE	69.54	6084	80.30%	0.00%	0.00%	1.52%	18.18%	0.00%	0.515	
							6088	71.93%	0.00%	0.00%	0.00%	28.07%	0.00%	1.017	
					SW	53.34	6093	15.91%	27.27%	22.73%	20.45%	0.00%	13.64%	0.131	1.039
							6097	81.63%	1.02%	2.04%	0.00%	15.31%	0.00%	0.508	0.360
					SE	77.48	6101	74.51%	0.00%	0.00%	0.00%	24.59%	0.00%	0.308	
							6107	83.05%	0.00%	0.00%	0.00%	16.95%	0.00%	0.408	
						255.54		61.79%	8.19%	7.51%	2.75%	15.94%	3.72%	0.415	0.766
2	**C**	TT-AW	Belgrat Tower	Core	NW	76.56	6135	53.49%	13.95%	23.26%	0.00%	9.30%	0.00%	0.408	0.523
							6145	25.42%	47.46%	11.86%	13.56%	0.00%	1.69%	0.125	2.471
					NE	93.69	6150	21.57%	23.53%	11.67%	39.22%	0.00%	3.92%	0.101	0.726
							6160	12.50%	10.71%	14.29%	55.36%	0.00%	7.14%		0.713
					SW	67.49	6166	11.84%	4.61%	69.08%	5.26%	0.00%	9.21%		0.274
							6169	30.51%	22.03%	37.29%	0.00%	6.78%	3.39%	0.201	0.770
					SE	67.62	6174	10.20%	40.82%	26.53%	20.41%	0.00%	2.04%		0.604
							6183	27.27%	29.09%	40.00%	0.00%	0.00%	3.64%		0.728
						305.36		24.10%	24.03%	29.25%	16.73%	2.01%	3.88%	0.209	0.851
								36.05%	23.23%	19.28%	11.86%	6.29%	3.24%	0.264	0.843

Table A3.3 – Point Counting: Anastasian Wall – page 2 of 8

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm²)	Image	Brick	Sand in Binder	Lime Binder	No Material	Sand in Brick	Unburnt Lime	Brick Sand Ø (mm)	Binder Sand Ø (mm)
3	A	TT-AW	Belgrat Tower	Core	NW	53.56	6229	69.29%	0.00%	0.00%	0.00%	31.71%	0.00%	2.124	
							6232	29.09%	38.18%	23.64%	3.64%	5.45%	0.00%	0.466	1.134
					NE	79.47	6240	7.69%	26.92%	13.46%	11.54%	0.00%	40.38%		1.037
							6245	33.93%	17.86%	12.50%	16.07%	3.57%	16.07%	0.176	0.838
					SW	72.94	6255	86.31%	0.00%	0.00%	0.00%	13.69%	0.00%	0.348	
							6262	26.79%	19.64%	30.36%	17.86%	3.57%	1.79%	0.114	0.874
					SE	69.60	6265	87.14%	0.00%	0.00%	0.00%	12.86%	0.00%	0.424	
							6270	21.28%	17.02%	23.40%	31.91%	6.38%	0.00%	0.311	0.694
						275.57		45.19%	14.95%	12.92%	10.13%	9.65%	7.28%	0.566	0.915
3	B	TT-AW	Belgrat Tower	Core	NW	80.56	6308	26.67%	33.33%	35.56%	0.00%	4.44%	0.00%	0.191	0.653
							6312	48.84%	16.28%	23.26%	0.00%	6.98%	4.65%	0.369	0.495
					NE	66.50	6314	28.57%	35.71%	26.19%	7.14%	0.00%	2.38%		1.516
							6320	23.40%	31.91%	38.30%	2.13%	0.00%	4.26%	0.166	0.897
					SW	59.43	6324	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%		
							6326	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%		
					SE	59.43	6329	16.67%	38.10%	42.86%	0.00%	2.38%	0.00%	0.103	0.816
							6331	19.57%	36.96%	26.09%	10.87%	0.00%	6.52%		0.849
						265.92		20.47%	49.04%	24.03%	2.52%	1.73%	2.23%	0.207	0.871
3	C	TT-AW	Belgrat Tower	Core	NW	65.60	6366	9.76%	34.15%	39.02%	17.07%	0.00%	0.00%		1.883
							6371	16.28%	51.16%	30.23%	0.00%	0.00%	2.33%		1.089
					NE	57.17	6372	21.57%	19.61%	50.98%	3.92%	0.00%	3.92%	0.174	0.437
							6383	37.25%	21.57%	27.45%	7.84%	5.88%	0.00%	0.176	0.521
					SW	34.94	6390	38.64%	36.36%	18.18%	0.00%	6.82%	0.00%	0.338	0.663
							6396	23.26%	20.93%	36.01%	18.60%	1.20%	0.00%	0.156	0.860
					SE	50.13	6397	21.43%	28.57%	42.86%	4.76%	2.38%	0.00%	0.294	0.782
							6404	23.26%	20.93%	51.16%	2.33%	0.00%	2.33%	0.282	1.292
						207.84		23.93%	29.16%	36.99%	6.82%	2.04%	1.07%	0.237	0.941
								29.86%	31.05%	24.65%	6.49%	4.47%	3.53%	0.337	0.909

Table A3.3 – Point Counting: Anastasian Wall – page 3 of 8

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm²)	Image	Brick	Sand in Binder	Lime Binder	No Material	Sand in Brick	Unburnt Lime	Brick Sand Ø (mm)	Binder Sand Ø (mm)
4	**A**	TT-AW	Çilingir	Core	NW	68.65	6435	86.36%	0.00%	0.00%	0.00%	13.64%	0.00%	0.325	
							6436	81.40%	0.00%	0.00%	0.00%	18.60%	0.00%	0.435	
					NE	69.46	6446	71.79%	0.00%	0.00%	0.00%	28.21%	0.00%	0.420	
							6451	64.15%	0.00%	0.00%	0.00%	35.85%	0.00%	0.616	
					SW	70.85	6453	30.61%	24.49%	42.86%	0.00%	2.04%	0.00%	0.359	0.893
							6460	39.29%	8.93%	30.36%	7.14%	5.36%	8.93%	0.327	0.639
					SE	64.61	6468	27.66%	14.89%	44.68%	6.38%	2.13%	4.26%	0.243	0.588
							6471	17.39%	15.22%	54.35%	6.52%	2.17%	4.35%		0.541
						273.57		52.33%	7.94%	21.53%	2.51%	13.50%	2.19%	0.389	0.665
4	**B**	TT-AW	Çilingir	Core	NW	41.57	6511	48.84%	4.65%	25.58%	0.00%	11.63%	9.30%	0.275	0.330
							6512	29.17%	16.67%	37.50%	10.42%	4.17%	2.08%	0.346	0.795
					NE	44.58	6518	15.91%	2.27%	6.82%	13.64%	4.55%	56.82%	0.503	0.183
							6521	50.94%	11.32%	28.30%	1.89%	0.00%	7.55%	0.255	0.406
					SW	34.05	6527	30.95%	9.52%	35.71%	21.43%	2.38%	0.00%	0.306	0.303
							6530	73.17%	0.00%	7.32%	0.00%	19.51%	0.00%	0.561	
					SE	35.70	6536	52.94%	10.29%	35.29%	0.00%	1.47%	0.00%	0.382	0.559
							6539	27.91%	13.95%	30.23%	23.26%	4.65%	0.00%		0.343
						155.90		41.23%	8.58%	25.84%	8.83%	6.05%	9.47%	0.375	0.417
4	**C**	TT-AW	Çilingir	Core	NW	72.65	6566	10.87%	0.00%	4.35%	2.17%	0.00%	82.61%	0.373	
							6576	50.00%	3.70%	35.19%	3.70%	5.56%	1.85%	0.195	0.280
					NE	72.65	6579	48.78%	17.07%	19.51%	9.76%	4.88%	0.00%	0.383	0.506
							6584	46.55%	10.34%	24.14%	6.90%	8.62%	3.45%	0.377	0.459
					SW	23.60	6589	44.19%	2.33%	27.91%	16.28%	9.30%	0.00%	0.486	0.202
							6591	0.86%	0.00%	1.72%	38.79%	0.00%	58.62%	0.231	
					SE	72.65	6595	45.24%	11.90%	35.71%	0.00%	0.00%	7.14%	0.354	0.472
							6605	52.94%	11.76%	26.47%	1.47%	4.41%	2.94%	0.253	0.309
						241.55		37.43%	7.14%	21.88%	9.88%	4.10%	19.58%	0.332	0.371
								43.66%	7.89%	23.08%	7.07%	7.88%	10.41%	0.365	0.485

Table A3.3 – Point Counting: Anastasian Wall – page 4 of 8

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm²)	Image	Brick	Sand in Binder	Lime Binder	No Material	Sand in Brick	Unburnt Lime	Brick Sand Ø (mm)	Binder Sand Ø (mm)
5	A	TT-AW	Büyük Bedesten	Joint	NW	38.79	6646	60.42%	4.17%	25.00%	8.33%	2.08%	0.00%	0.164	0.279
							6650	69.77%	1.10%	12.85%	0.00%	16.28%	0.00%	0.309	0.119
					NE	76.56	6651	58.33%	6.25%	14.58%	6.25%	10.42%	4.17%	0.212	0.272
							6656	69.77%	0.00%	0.00%	16.29%	13.94%	0.00%	0.363	
					SW	57.61	6669	52.17%	2.17%	26.09%	4.35%	8.70%	6.52%	0.260	0.145
							6674	84.09%	0.00%	0.00%	0.00%	15.91%	0.00%	0.586	
					SE	48.57	6680	62.07%	1.72%	10.34%	5.17%	17.24%	3.45%	0.198	0.202
							6682	46.30%	5.56%	16.67%	20.37%	7.41%	3.70%	0.139	0.254
						221.53		62.87%	2.62%	13.19%	7.60%	11.50%	2.23%	0.279	0.212
5	B	TT-AW	Büyük Bedesten	Joint	NW	59.42	6701	52.38%	9.52%	26.19%	0.00%	11.90%	0.00%	0.217	0.284
							6709	39.02%	7.32%	43.90%	0.00%	9.76%	0.00%	0.644	0.418
					NE	70.40	6720	42.86%	4.76%	45.24%	2.38%	4.76%	0.00%	0.254	0.253
							6723	70.83%	6.25%	10.42%	8.33%	4.17%	0.00%	0.274	0.609
					SW	70.40	6734	74.36%	0.00%	0.00%	0.00%	25.64%	0.00%	0.215	
							6735	35.71%	4.67%	28.57%	21.43%	9.52%	0.00%	0.203	0.198
					SE	70.40	6744	48.94%	14.89%	31.91%	0.00%	4.26%	0.00%	0.180	0.216
							6759	34.15%	12.20%	26.83%	4.88%	7.32%	14.63%	0.196	0.364
						270.62		49.78%	7.45%	26.63%	4.63%	9.67%	1.83%	0.273	0.335
5	C	TT-AW	Büyük Bedesten	Joint	NW	70.85	6783	60.87%	13.04%	21.74%	0.00%	4.35%	0.00%	0.362	0.235
							6797	51.16%	6.98%	34.88%	0.00%	6.98%	0.00%	0.209	0.172
					NE	65.56	6799	53.66%	4.88%	21.95%	12.20%	7.32%	0.00%	0.387	0.581
							6805	51.06%	4.26%	34.04%	0.00%	10.64%	0.00%	0.281	0.264
					SW	49.64	6815	42.86%	2.38%	28.57%	11.90%	14.29%	0.00%	0.575	0.357
							6822	53.33%	8.89%	31.11%	0.00%	6.67%	0.00%	0.248	0.351
					SE	55.33	6828	51.16%	4.65%	27.91%	11.63%	4.65%	0.00%	0.166	0.270
							6837	68.89%	0.00%	0.00%	0.00%	31.11%	0.00%	1.170	
						241.38		54.12%	5.64%	25.03%	4.47%	10.75%	0.00%	0.425	0.319
5	D	TT-AW	Büyük Bedesten	Joint	NW	68.45	6862	42.86%	2.38%	40.48%	4.76%	9.52%	0.00%	0.445	0.112
							6864	60.98%	4.88%	21.95%	0.00%	12.20%	0.00%	0.420	0.208
					NE	67.04	6870	83.33%	0.00%	0.00%	0.00%	16.67%	0.00%	0.481	
							6873	43.14%	9.80%	39.22%	0.00%	7.84%	0.00%	0.216	0.408
					SW	69.36	6884	35.71%	9.52%	42.86%	0.00%	11.90%	0.00%	0.275	0.351
							6887	60.98%	0.00%	21.95%	0.00%	17.07%	0.00%	0.197	0.099
					SE	69.36	6890	45.65%	6.52%	26.09%	2.17%	15.22%	4.35%	0.173	0.412
							6898	53.66%	9.76%	24.39%	0.00%	12.20%	0.00%	0.170	0.281
						274.21		53.29%	5.36%	27.12%	0.87%	12.83%	0.54%	0.297	0.267
								55.01%	5.27%	22.99%	4.39%	11.19%	1.15%	0.318	0.283

Table A3.3 – Point Counting: Anastasian Wall – page 5 of 8

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm²)	Image	Brick	Sand in Binder	Lime Binder	No Material	Sand in Brick	Unburnt Lime	Brick Sand Ø (mm)	Binder Sand Ø (mm)
6	A	TT-AW	South Dervis Kapı	Core	NW	61.90	6914	78.05%	0.00%	4.88%	0.00%	17.07%	0.00%	0.362	
							6924	30.95%	11.90%	35.71%	4.76%	2.38%	14.29%	0.118	0.641
					NE	67.27	6928	54.76%	2.38%	19.05%	9.52%	14.29%	0.00%	0.352	0.169
							6938	41.46%	12.20%	14.63%	24.39%	4.88%	2.44%	0.332	0.157
					SW	60.64	6943	64.29%	2.38%	21.43%	0.00%	11.90%	0.00%	0.478	0.145
							6948	39.53%	6.98%	34.88%	11.63%	6.98%	0.00%	0.317	0.408
					SE	53.49	6958	47.62%	11.90%	38.10%	0.00%	2.38%	0.00%	0.316	0.268
							6960	48.98%	14.29%	30.61%	0.00%	6.12%	0.00%	0.389	0.156
						243.30		50.71%	7.75%	24.91%	6.29%	8.25%	2.09%	0.333	0.278
6	B	TT-AW	South Dervis Kapı	Core	NW	53.79	6984	28.57%	14.29%	38.10%	11.90%	7.14%	0.00%	0.474	0.290
							6987	47.06%	0.00%	0.00%	7.84%	45.10%	0.00%	0.247	
					NE	64.60	6989	35.71%	2.38%	16.67%	21.43%	23.81%	0.00%	0.361	0.275
							6997	20.93%	37.21%	20.19%	11.63%	10.10%	0.00%	0.356	1.220
					SW	53.02	6999	40.35%	7.02%	33.33%	10.53%	8.77%	0.00%	0.197	0.141
							7010	57.14%	8.16%	22.45%	2.04%	10.20%	0.00%	0.198	0.563
					SE	36.51	7018	43.90%	4.88%	24.39%	17.07%	9.67%	0.00%	0.309	0.362
							7021	30.23%	6.98%	27.91%	32.56%	2.33%	0.00%		0.202
						207.92		37.99%	10.12%	22.88%	14.38%	14.64%	0.00%	0.306	0.436
6	C	TT-AW	South Dervis Kapı	Core	NW	34.84	7036	51.22%	9.76%	19.51%	12.20%	7.32%	0.00%	0.600	0.344
							7039	39.02%	9.76%	26.83%	12.20%	12.20%	0.00%	0.235	0.455
					NE	62.36	7042	43.75%	12.50%	20.83%	16.67%	6.25%	0.00%	0.250	0.331
							7048	51.22%	0.00%	0.00%	9.76%	39.02%	0.00%	0.532	
					SW	57.81	7061	70.80%	0.00%	0.00%	9.69%	19.51%	0.00%	0.306	
							7063	29.27%	4.88%	34.32%	29.10%	2.44%	0.00%	0.149	0.354
					SE	63.39	7078	40.48%	9.52%	21.43%	16.67%	11.90%	0.00%	0.186	0.317
							7079	82.93%	0.00%	0.00%	2.44%	14.63%	0.00%	0.231	
						218.40		51.09%	5.80%	15.37%	13.59%	14.16%	0.00%	0.311	0.360
								46.59%	7.89%	21.05%	11.42%	12.35%	0.70%	0.317	0.358

Table A3.3 – Point Counting: Anastasian Wall – page 6 of 8

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm²)	Image	Brick	Sand in Binder	Lime Binder	No Material	Sand in Brick	Unburnt Lime	Brick Sand Ø (mm)	Binder Sand Ø (mm)
7	**A**	TT-AW	South Dervis Kapı	Core	NW	68.94	7107	39.53%	11.63%	20.93%	0.00%	0.00%	27.91%	0.124	0.194
							7109	47.62%	4.76%	26.19%	7.14%	2.38%	11.90%	0.183	0.136
					NE	68.69	7113	26.19%	14.29%	33.33%	21.43%	4.76%	0.00%	0.156	0.410
							7118	65.12%	0.00%	6.98%	0.00%	27.91%	0.00%	0.386	
					SW	71.00	7132	58.54%	7.32%	24.39%	5.65%	4.11%	0.00%	0.343	0.297
							7135	67.44%	0.00%	0.00%	0.00%	32.56%	0.00%	0.643	
					SE	71.00	7142	63.64%	0.00%	0.00%	11.36%	25.00%	0.00%	0.789	
							7145	41.30%	10.87%	34.78%	2.17%	6.52%	4.35%	0.433	0.230
						279.63		51.17%	6.11%	18.33%	5.97%	12.91%	5.52%	0.382	0.253
7	**B**	TT-AW	South Dervis Kapı	Core	NW	69.79	7171	40.48%	11.90%	42.86%	0.00%	4.76%	0.00%	0.445	0.401
							7178	24.39%	12.20%	41.46%	14.63%	7.32%	0.00%	0.121	0.347
					NE	67.56	7180	48.95%	6.38%	27.66%	14.89%	2.13%	0.00%	0.326	0.322
							7191	28.26%	4.35%	58.70%	0.00%	8.70%	0.00%	0.300	0.276
					SW	69.17	7195	65.85%	0.00%	0.00%	0.00%	34.15%	0.00%	0.466	
							7202	32.56%	9.30%	48.84%	6.98%	2.33%	0.00%	0.344	0.198
					SE	58.86	7203	35.56%	6.67%	33.33%	8.89%	8.89%	6.67%	0.444	0.213
							7214	34.15%	2.44%	24.39%	29.27%	9.67%	0.00%	0.281	0.151
						265.38		38.78%	6.66%	34.66%	9.33%	9.74%	0.83%	0.341	0.273
7	**C**	TT-AW	South Dervis Kapı	Core	NW	60.25	7241	20.93%	4.65%	13.95%	58.14%	2.33%	0.00%	0.180	
							7244	33.33%	4.76%	21.43%	23.81%	16.67%	0.00%	0.303	0.315
					NE	69.72	7254	23.91%	8.70%	39.13%	28.26%	0.00%	0.00%	0.129	0.781
							7261	20.93%	4.65%	11.63%	62.79%	0.00%	0.00%	0.219	
					SW	71.59	7264	39.02%	9.76%	26.83%	2.44%	21.95%	0.00%	0.343	0.222
							7274	31.71%	2.44%	21.95%	41.46%	2.44%	0.00%	0.159	
					SE	71.59	7278	25.58%	2.33%	27.91%	39.53%	4.65%	0.00%	0.501	0.239
							7286	31.71%	12.20%	21.95%	26.81%	7.32%	0.00%	0.168	0.482
						273.15		28.39%	6.19%	23.10%	35.41%	6.92%	0.00%	0.250	0.408
								39.45%	6.32%	25.36%	16.90%	9.86%	2.12%	0.324	0.311

Table A3.3 – Point Counting: Anastasian Wall – page 7 of 8

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm²)	Image	Brick	Sand in Binder	Lime Binder	No Material	Sand in Brick	Unburnt Lime	Brick Sand Ø (mm)	Binder Sand Ø (mm)
8	A	TT-AW	Evcik	Core	NW	70.40	7302	73.17%	0.00%	0.00%	0.00%	26.83%	0.00%	0.370	
							7308	69.77%	0.00%	0.00%	9.30%	20.93%	0.00%	0.344	
					NE	70.40	7312	76.09%	0.00%	0.00%	0.00%	23.91%	0.00%	0.290	
							7319	77.78%	0.00%	0.00%	2.22%	20.00%	0.00%	0.419	
					SW	67.69	7322	59.57%	4.26%	8.51%	17.02%	10.64%	0.00%	0.285	0.324
							7328	78.57%	0.00%	0.00%	0.00%	21.43%	0.00%	0.302	
					SE	62.15	7331	33.33%	11.90%	21.43%	23.81%	9.52%	0.00%	0.340	0.957
							7338	6.98%	41.86%	37.21%	13.95%	0.00%	0.00%	0.148	0.512
						270.64		59.41%	7.25%	8.39%	8.29%	16.66%	0.00%	0.312	0.598
8	B	TT-AW	Evcik	Core	NW	63.59	7353	6.98%	65.12%	27.91%	0.00%	0.00%	0.00%		0.889
							7363	13.95%	46.51%	27.91%	11.63%	0.00%	0.00%	0.156	0.989
					NE	61.10	7368	56.10%	17.07%	14.63%	0.00%	12.20%	0.00%	0.335	0.434
							7379	7.32%	43.90%	36.59%	12.20%	0.00%	0.00%	0.271	0.769
					SW	61.95	7385	2.44%	56.10%	36.59%	4.88%	0.00%	0.00%	0.145	0.477
							7394	9.76%	46.34%	43.90%	0.00%	0.00%	0.00%		0.678
					SE	57.15	7397	6.67%	57.78%	35.56%	0.00%	0.00%	0.00%		0.668
							7406	4.88%	34.15%	29.27%	31.71%	0.00%	0.00%		0.636
						243.79		13.51%	45.87%	31.55%	7.55%	1.53%	0.00%	0.227	0.693
8	C	TT-AW	Evcik	Core	NW	55.74	7450	7.32%	53.66%	19.51%	0.00%	4.88%	14.63%	0.173	0.675
							7454	7.32%	39.02%	34.15%	17.07%	0.00%	2.44%	0.322	0.507
					NE	51.53	7461	21.95%	34.15%	39.02%	0.00%	4.88%	0.00%	0.230	0.492
							7469	14.63%	36.59%	26.47%	22.31%	0.00%	0.00%	0.229	0.727
					SW	61.32	7472	46.34%	31.71%	21.95%	0.00%	0.00%	0.00%	0.151	0.471
							7478	85.37%	0.00%	0.00%	0.00%	14.73%	0.00%	0.592	
					SE	59.39	7481	7.32%	58.54%	34.15%	0.00%	0.00%	0.00%		0.726
							7488	2.44%	46.34%	39.02%	12.20%	0.00%	0.00%	0.158	0.489
						227.98		24.09%	37.50%	26.78%	6.45%	3.06%	2.13%	0.265	0.584
8	D	TT-AW	Evcik	Core	NW	56.91	7522	8.11%	64.86%	27.03%	0.00%	0.00%	0.00%	0.098	0.654
							7529	7.89%	52.63%	23.68%	13.16%	0.00%	0.00%		0.549
					NE	60.29	7533	8.70%	67.39%	23.91%	0.00%	0.00%	0.00%	0.141	0.586
							7540	72.97%	0.00%	0.00%	0.00%	27.03%	0.00%	1.153	
					SW	60.29	7545	12.20%	29.27%	51.22%	0.00%	0.00%	7.32%		0.999
							7551	7.55%	45.28%	22.64%	16.98%	0.00%	7.55%		0.612
					SE	50.75	7556	14.63%	41.46%	43.90%	0.00%	0.00%	0.00%	0.139	0.527
							7561	52.63%	0.00%	0.00%	13.16%	34.21%	0.00%	0.455	
						228.24		23.09%	37.61%	24.05%	5.41%	7.66%	1.86%	0.397	0.655
								30.02%	32.06%	22.69%	6.93%	7.22%	1.00%	0.300	0.632

Table A3.3 – Point Counting: Anastasian Wall – page 8 of 8

A3.4 – Final Percentages of Mortar Constituents: Anastasian Wall

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm^2)	Image	Totals							
								% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
1	A	TT-AW	Karanlik Ayazma Sirti	Core	NW	71.44	5885, 5893								
					NE	71.44	5896, 5903								
					SW	71.44	5906, 5912								
					SE	71.44	5916, 5924								
						285.76		37%	8%	55%	0.3	2.0	4.0	2.0	6.8
								% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
1	B	TT-AW	Karanlik Ayazma Sirti	Core	NW	64.45	5821, 5828								
					NE	71.14	5832, 5841								
					SW	71.14	5844, 5852								
					SE	70.36	5857, 5865								
						277.09		39%	16%	45%	0.3	1.0	1.0	1.0	4.7
								% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
1	C	TT-AW	Karanlik Ayazma Sirti	Core	NW	72.19	5942, 5949								
					NE	72.19	5952, 5959								
					SW	72.19	5965, 5973								
					SE	72.19	5978, 5985								
						288.76		37%	16%	47%	0.3	1.0	4.0	1.0	5.1
								38%	***13%***	***49%***	***0.3***	***1.3***	***3.0***	***1.3***	***5.5***

Table A3.4 – Final Percentages of Mortar Constituents: Anastasian Wall – page 1 of 8

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm²)	Image	Totals							
								% Lime	**% Sand**	**% Brick**	**Brick/Binder Sand Ø Difference (mm)**	**Occurrence of Olivine Granules**	**Occurrence of Organic Material in Binder**	**Occurrence of Organic Material in Brick Aggregate**	**Maximum Ø of Brick Aggregate (mm)**
2	**A**	TT-AW	Belgrat Tower	Core	NW	82.51	6005 6013								
					NE	27.98	6015 6022								
					SW	70.91	6024 6033								
					SE	80.65	6036 6047								
						262.05		28%	45%	28%	0.7	7.0	3.0	0.0	4.6
								% Lime	**% Sand**	**% Brick**	**Brick/Binder Sand Ø Difference (mm)**	**Occurrence of Olivine Granules**	**Occurrence of Organic Material in Binder**	**Occurrence of Organic Material in Brick Aggregate**	**Maximum Ø of Brick Aggregate (mm)**
2	**B**	TT-AW	Belgrat Tower	Core	NW	55.18	6073 6081								
					NE	69.54	6084 6088								
					SW	53.34	6093 6097								
					SE	77.48	6101 6107								
						255.54		12%	8%	80%	0.4	5.0	2.0	2.0	14.4
								% Lime	**% Sand**	**% Brick**	**Brick/Binder Sand Ø Difference (mm)**	**Occurrence of Olivine Granules**	**Occurrence of Organic Material in Binder**	**Occurrence of Organic Material in Brick Aggregate**	**Maximum Ø of Brick Aggregate (mm)**
2	**C**	TT-AW	Belgrat Tower	Core	NW	76.56	6135 6145								
					NE	93.69	6150 6160								
					SW	67.49	6166 6169								
					SE	67.62	6174 6183								
						305.36		40%	29%	31%	0.6	10.0	2.0	0.0	6.0
								26%	***27%***	***46%***	***0.6***	***7.3***	***2.3***	***0.7***	***8.3***

Table A3.4 – Final Percentages of Mortar Constituents: Anastasian Wall – page 2 of 8

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm²)	Image	Totals							
3	A	TT-AW	Belgrat Tower	Core	NW	53.56	6229 6232	% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
					NE	79.47	6240 6245								
					SW	72.94	6255 6262								
					SE	69.60	6265 6270								
						275.57		22%	17%	61%	0.3	8.0	2.0	5.0	20.1
3	B	TT-AW	Belgrat Tower	Core	NW	80.56	6308 6312	% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
					NE	66.50	6314 6320								
					SW	59.43	6324 6326								
					SE	59.43	6329 6331								
						265.92		27%	50%	23%	0.7	5.0	4.0	0.0	
3	C	TT-AW	Belgrat Tower	Core	NW	65.60	6366 6371	% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
					NE	57.17	6372 6383								
					SW	34.94	6390 6396								
					SE	50.13	6397 6404								
						207.84		41%	31%	28%	0.7	8.0	3.0	0.0	3.6
								30%	***33%***	***37%***	***0.6***	***7.0***	***3.0***	***1.7***	***11.8***

Table A3.4 – Final Percentages of Mortar Constituents: Anastasian Wall – page 3 of 8

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm^2)	Image	Totals							
								% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
4	A	TT-AW	Çilingir	Core	NW	68.65	6435 6436								
					NE	69.46	6446 6451								
					SW	70.85	6453 6460								
					SE	64.61	6468 6471								
						273.57		24%	8%	68%	0.3	8.0	1.0	6.0	22.0
								% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
4	B	TT-AW	Çilingir	Core	NW	41.57	6511 6512								
					NE	44.58	6518 6521								
					SW	34.05	6527 6530								
					SE	35.70	6536 6539								
						155.90		39%	9%	52%	0.0	2.0	2.0	0.0	2.4
								% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
4	C	TT-AW	Çilingir	Core	NW	72.65	6566 6576								
					NE	72.65	6579 6584								
					SW	23.60	6589 6591								
					SE	72.65	6595 6605								
						241.55		46%	8%	46%	0.0	5.0	6.0	2.0	4.6
								36%	***8%***	***55%***	***0.1***	***5.0***	***3.0***	***2.7***	***9.7***

Table A3.4 – Final Percentages of Mortar Constituents: Anastasian Wall – page 4 of 8

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm²)	Image	Totals							
								% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
5	**A**	TT-AW	Büyük Bedesten	Joint	NW	38.79	6646 6650								
					NE	76.56	6651 6656								
					SW	57.61	6669 6674								
					SE	48.57	6680 6682								
						221.53		17%	3%	80%	0.1	2.0	3.0	4.0	14.9
								% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
5	**B**	TT-AW	Büyük Bedesten	Joint	NW	59.42	6701 6709								
					NE	70.40	6720 6723								
					SW	70.40	6734 6735								
					SE	70.40	6744 6759								
						270.62		30%	8%	62%	0.1	0.0	2.0	3.0	11.3
								% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
5	**C**	TT-AW	Büyük Bedesten	Joint	NW	70.85	6783 6797								
					NE	65.56	6799 6805								
					SW	49.64	6815 6822								
					SE	55.33	6828 6837								
						241.38		26%	6%	68%	0.1	0.0	4.0	2.0	9.7
								% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
5	**D**	TT-AW	Büyük Bedesten	Joint	NW	68.45	6862 6864								
					NE	67.04	6870 6873								
					SW	69.36	6884 6887								
					SE	69.36	6890 6898								
						274.21		28%	5%	67%	0.0	0.0	2.0	0.0	11.1
								25%	***5%***	***69%***	***0.0***	***0.5***	***2.8***	***2.3***	***11.7***

Table A3.4 – Final Percentages of Mortar Constituents: Anastasian Wall – page 5 of 8

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm²)	Image	Totals							
								% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
6	**A**	TT-AW	South Dervis Kapı	Core	NW	61.90	6914, 6924								
					NE	67.27	6928, 6938								
					SW	60.64	6943, 6948								
					SE	53.49	6958, 6960								
						243.30		29%	8%	63%	0.1	0.0	1.0	0.0	14.2
6	**B**	TT-AW	South Dervis Kapı	Core	NW	53.79	6984, 6987								
					NE	64.60	6989, 6997								
					SW	53.02	6999, 7010								
					SE	36.51	7018, 7021								
						207.92		27%	12%	61%	0.1	0.0	0.0	4.0	5.9
6	**C**	TT-AW	South Dervis Kapı	Core	NW	34.84	7036, 7039								
					NE	62.36	7042, 7048								
					SW	57.81	7061, 7063								
					SE	63.39	7078, 7079								
						218.40		18%	7%	76%	0.0	0.0	2.0	4.0	9.8
								24%	***9%***	***67%***	***0.0***	***0.0***	***1.0***	***2.7***	***10.0***

Table A3.4 – Final Percentages of Mortar Constituents: Anastasian Wall – page 6 of 8

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm^2)	Image	Totals							
								% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
7	**A**	TT-AW	South Dervis Kapı	Core	NW	68.94	7107, 7109								
					NE	68.69	7113, 7118								
					SW	71.00	7132, 7135								
					SE	71.00	7142, 7145								
						279.63		25%	6%	68%	0.1	0.0	2.0	2.0	13.6
7	**B**	TT-AW	South Dervis Kapı	Core	NW	69.79	7171, 7178								
					NE	67.56	7180, 7191								
					SW	69.17	7195, 7202								
					SE	58.86	7203, 7214								
						265.38		39%	7%	54%	0.1	0.0	2.0	5.0	9.2
7	**C**	TT-AW	South Dervis Kapı	Core	NW	60.25	7241, 7244								
					NE	69.72	7254, 7261								
					SW	71.59	7264, 7274								
					SE	71.59	7278, 7286								
						273.15		36%	10%	55%	0.2	0.0	10.0	1.0	6.1
								33%	***8%***	***59%***	***0.0***	***0.0***	***4.7***	***2.7***	***9.7***

Table A3.4 – Final Percentages of Mortar Constituents: Anastasian Wall – page 7 of 8

Sample	Core	Site Code	Site Name	Mortar Type	Quadrant	Sample Area (mm²)	Image	Totals							
								% Lime	% Sand	% Brick	Brick/Binder Sand Ø Difference (mm)	Occurrence of Olivine Granules	Occurrence of Organic Material in Binder	Occurrence of Organic Material in Brick Aggregate	Maximum Ø of Brick Aggregate (mm)
8	**A**	TT-AW	Evcik	Core	NW	70.40	7302 7308								
					NE	70.40	7312 7319								
					SW	67.69	7322 7328								
					SE	62.15	7331 7338								
						270.64		9%	8%	83%	0.3	2.0	2.0	8.0	22.0
8	**B**	TT-AW	Evcik	Core	NW	63.59	7353 7363								
					NE	61.10	7368 7379								
					SW	61.95	7385 7394								
					SE	57.15	7397 7406								
						243.79		34%	50%	16%	0.5	3.0	1.0	1.0	7.8
8	**C**	TT-AW	Evcik	Core	NW	55.74	7450 7454								
					NE	51.53	7461 7469								
					SW	61.32	7472 7478								
					SE	59.39	7481 7488								
						227.98		31%	40%	29%	0.3	2.0	4.0	3.0	5.2
8	**D**	TT-AW	Evcik	Core	NW	56.91	7522 7529								
					NE	60.29	7533 7540								
					SW	60.29	7545 7551								
					SE	50.75	7556 7561								
						228.24		27%	40%	32%	0.3	6.0	3.0	1.0	
								25%	***34%***	***40%***	***33%***	***3.3***	***2.5***	***3.3***	***11.7***

Table A3.4 – Final Percentages of Mortar Constituents: Anastasian Wall – page 8 of 8

A3.5 –Aggregate Measurements: Water Supply

Sample	Core	Site Code	Site Name	Quadrant	Olivine	Organic in Lime	Organic in Brick	Max Size - Brick Aggregate (mm)	Min Size - Brick Aggregate (mm)
1	A	TT-WS	Kurşunlugerme	NW	1	1	0		
				NE	1	0	0		
				SW	1	1	0		
				SE	0	0	0		
					3	2	0	8.79	2.02
1	B	TT-WS	Kurşunlugerme	NW	0	1	1		
				NE	0	0	0		
				SW	1	0	0		
				SE	3	0	0		
					4	1	1	3.44	2.07
1	C	TT-WS	Kurşunlugerme	NW	1	0	0		
				NE	1	0	1		
				SW	1	0	1		
				SE	0	0	0		
					3	0	2	6.46	2.13
1	D	TT-WS	Kurşunlugerme	NW	0	0	0		
				NE	0	0	1		
				SW	0	1	0		
				SE	0	1	0		
					0	2	1	7.13	2.53
1	E	TT-WS	Kurşunlugerme	NW	0	0	0		
				NE	0	2	0		
				SW	2	0	0		
				SE	1	0	0		
					3	2	0	4.49	1.97
1	F	TT-WS	Kurşunlugerme	NW	1	0	2		
				NE	1	0	0		
				SW	0	0	0		
				SE	0	1	0		
					2	1	2	9.39	2.34
1	H	TT-WS	Kurşunlugerme	NW	0	1	0		
				NE	1	0	0		
				SW	3	0	0		
				SE	3	0	0		
					7	1	0	10.84	2.12
1	I	TT-WS	Kurşunlugerme	NW	100% Metamorphosed Limestone				
				NE					
				SW					
				SE					
					22	**9**	**6**		
					3.14	***1.29***	***0.86***	***7.22***	***2.17***

Table A3.5 –Aggregate Measurements: Water Supply – page 1 of 4

Sample	Core	Site Code	Site Name	Quadrant	Olivine	Organic in Lime	Organic in Brick	Max Size - Brick Aggregate (mm)	Min Size - Brick Aggregate (mm)
2	A	TT-WS	Kumalıdere	NW	0	0	0		
				NE	0	0	0		
				SW	0	1	0		
				SE	0	1	0		
					0	2	0	9.44	2.57
2	B	TT-WS	Kumalıdere	NW	0	0	0		
				NE	4	0	0		
				SW	0	0	0		
				SE	0	0	0		
					4	0	0	4.19	1.72
2	C	TT-WS	Kumalıdere	NW	0	1	0		
				NE	1	1	0		
				SW	1	0	0		
				SE	4	0	0		
					6	2	0	3.79	1.87
					10	**4**	**0**		
					3.33	***1.33***	***0.00***	***5.81***	***2.05***
3	A	TT-WS	Kecigerme	NW	1	2	0		
				NE	0	0	0		
				SW	0	0	0		
				SE	0	0	0		
					1	2	0	6.22	2.11
3	B	TT-WS	Kecigerme	NW	0	0	0		
				NE	0	0	0		
				SW	0	1	0		
				SE	0	1	0		
					0	2	0	6.55	2.18
3	C	TT-WS	Kecigerme	NW	0	0	1		
				NE	0	0	0		
				SW	0	2	0		
				SE	0	1	0		
					0	3	1	3.51	2.09
					1	**7**	**1**		
					0.33	***2.33***	***0.33***	***5.43***	***2.13***

Table A3.5 –Aggregate Measurements: Water Supply – page 2 of 4

Sample	Core	Site Code	Site Name	Quadrant	Olivine	Organic in Lime	Organic in Brick	Max Size - Brick Aggregate (mm)	Min Size - Brick Aggregate (mm)
4	A	TT-WS	Büyük Germe	NW	0	0	0		
				NE	0	1	2		
				SW	0	2	1		
				SE	0	1	2		
					0	4	5	3.98	1.61
4	B	TT-WS	Büyük Germe	NW	0	2	0		
				NE	0	2	0		
				SW	0	0	1		
				SE	0	2	1		
					0	6	2	6.61	2.03
4	C	TT-WS	Büyük Germe	NW	0	3	0		
				NE	1	2	2		
				SW	0	0	1		
				SE	0	1	0		
					1	6	3	5.02	2.13
					1	**16**	**10**		
					0.33	***5.33***	***3.33***	***5.20***	***1.92***
5	A	TT-WS	Karatepe	NW	0	5	0		
				NE	0	1	0		
				SW	0	0	0		
				SE	0	1	0		
					0	7	0	2.71	1.89
5	B	TT-WS	Karatepe	NW	1	1	0		
				NE	0	0	0		
				SW	0	1	0		
				SE	0	2	0		
					1	4	0	2.39	1.83
5	C	TT-WS	Karatepe	NW	0	4	0		
				NE	0	2	1		
				SW	0	1	1		
				SE	0	0	0		
					0	7	2	6.13	2.39

Table A3.5 –Aggregate Measurements: Water Supply – page 3 of 4

Sample	Core	Site Code	Site Name	Quadrant	Olivine	Organic in Lime	Organic in Brick	Max Size - Brick Aggregate (mm)	Min Size - Brick Aggregate (mm)
5	D^1	TT-WS	Karatepe	NW	0	0	0		
				NE	0	2	0		
				SW	0	3	0		
				SE	1	1	0		
					1	6	0	3.12	1.73
5	D^2	TT-WS	Karatepe	NW	0	2	0		
				NE	1	2	1		
				SW	0	0	1		
				SE	0	3	1		
					1	7	3	4.24	2.08
5	E^1	TT-WS	Karatepe	NW	0	0	4		
				NE	0	3	1		
				SW	0	2	0		
				SE	0	3	0		
					0	8	5	8.65	1.86
5	E^2	TT-WS	Karatepe	NW	0	1	0		
				NE	0	0	0		
				SW	0	1	2		
				SE	1	2	0		
					1	4	2	7.79	2.77
					4	**43**	**12**		
					0.43	***6.14***	***1.71***	***5.00***	***2.08***
6	A	TT-WS	Karatepe	NW	1	2	0		
				NE	1	1	1		
				SW	0	1	0		
				SE	1	3	0		
					3	7	1	9.31	1.69
6	B	TT-WS	Karatepe	NW	0	0	0		
				NE	1	0	0		
				SW	1	0	1		
				SE	1	2	1		
					3	2	2	9.86	2.29
					6	**9**	**3**		
					3.00	***4.50***	***1.50***	***9.59***	***1.99***

Table A3.5 –Aggregate Measurements: Water Supply – page 4 of 4

A3.6 – Aggregate Measurements: Anastasian Wall

Sample	Core	Site Code	Site Name	Quadrant	Olivine	Organic in Lime	Organic in Brick	Max Size - Brick Aggregate (mm)	Min Size - Brick Aggregate (mm)
1	A	TT-WS	Karanlik Ayazma Sirti	NW	1	2	0		
				NE	0	2	0		
				SW	1	0	0		
				SE	0	0	2		
					2	4	2	6.79	1.72
1	B	TT-WS	Karanlik Ayazma Sirti	NW	0	0	0		
				NE	0	0	0		
				SW	1	1	1		
				SE	0	0	0		
					1	1	1	4.72	1.96
1	C	TT-WS	Karanlik Ayazma Sirti	NW	0	0	0		
				NE	0	2	0		
				SW	0	2	0		
				SE	1	0	1		
					1	4	1	5.10	1.75
					4	**9**	**4**		
					1.33	***3.00***	***1.33***	***5.54***	***1.81***
2	A	TT-WS	Belgrat Tower	NW	1	0	0		
				NE	1	1	0		
				SW	1	0	0		
				SE	4	2	0		
					7	3	0	4.57	2.29
2	B	TT-WS	Belgrat Tower	NW	3	2	0		
				NE	0	0	1		
				SW	2	0	0		
				SE	0	0	1		
					5	2	2	14.35	
2	C	TT-WS	Belgrat Tower	NW	5	0	0		
				NE	3	1	0		
				SW	0	0	0		
				SE	2	1	0		
					10	2	0	5.98	2.16
					22	**7**	**2**		
					7.33	***2.33***	***0.67***	***8.30***	***2.23***

Table A3.6 – Aggregate Measurements: Anastasian Wall– page 1 of 4

Sample	Core	Site Code	Site Name	Quadrant	Olivine	Organic in Lime	Organic in Brick	Max Size - Brick Aggregate (mm)	Min Size - Brick Aggregate (mm)
3	A	TT-WS	Belgrat Tower	NW	2	1	2		
				NE	5	0	0		
				SW	0	1	3		
				SE	1	0	0		
					8	2	5	20.06	1.76
3	B	TT-WS	Belgrat Tower	NW	1	1	0		
				NE	3	2	0		
				SW	0	0	0		
				SE	1	1	0		
					5	4	0		2.06
3	C	TT-WS	Belgrat Tower	NW	3	1	0		
				NE	4	1	0		
				SW	1	1	0		
				SE	0	0	0		
					8	3	0	3.60	
					21	**9**	**5**		
					7.00	***3.00***	***1.67***	***11.83***	***1.91***
4	A	TT-WS	Çilingir	NW	0	0	3		
				NE	2	0	2		
				SW	0	0	0		
				SE	6	1	1		
					8	1	6	22.00	2.13
4	B	TT-WS	Çilingir	NW	0	0	0		
				NE	1	1	0		
				SW	0	1	0		
				SE	1	0	0		
					2	2	0	2.36	1.38
4	C	TT-WS	Çilingir	NW	1	0	0		
				NE	2	4	0		
				SW	0	2	0		
				SE	2	0	2		
					5	6	2	4.61	1.67
					15	**9**	**8**		
					5.00	***3.00***	***2.67***	***9.66***	***1.73***

Table A3.6 – Aggregate Measurements: Anastasian Wall– page 2 of 4

Sample	Core	Site Code	Site Name	Quadrant	Olivine	Organic in Lime	Organic in Brick	Max Size - Brick Aggregate (mm)	Min Size - Brick Aggregate (mm)
5	A	TT-WS	Büyük Bedesten	NW	0	2	1		
				NE	1	1	2		
				SW	0	0	1		
				SE	1	0	0		
					2	3	4	14.87	1.76
5	B	TT-WS	Büyük Bedesten	NW	0	1	0		
				NE	0	0	0		
				SW	0	0	0		
				SE	0	1	3		
					0	2	3	11.30	1.56
5	C	TT-WS	Büyük Bedesten	NW	0	1	0		
				NE	0	0	0		
				SW	0	0	0		
				SE	0	3	2		
					0	4	2	9.67	1.70
5	D	TT-AW	Büyük Bedesten	NW	0	1	0		
				NE	0	1	0		
				SW	0	0	0		
				SE	0	0	0		
					0	2	0	11.11	2.08
					2	**11**	**9**		
					0.50	***2.75***	***2.25***	***11.74***	***1.78***
6	A	TT-WS	South Dervis Kapı	NW	0	1	0		
				NE	0	0	0		
				SW	0	0	0		
				SE	0	0	0		
					0	1	0	14.16	2.19
6	B	TT-WS	South Dervis Kapı	NW	0	0	0		
				NE	0	0	1		
				SW	0	0	0		
				SE	0	0	3		
					0	0	4	5.91	2.09
6	C	TT-WS	South Dervis Kapı	NW	0	0	0		
				NE	0	1	3		
				SW	0	0	0		
				SE	0	1	1		
					0	2	4	9.84	2.06
					0	**3**	**8**		
					0.00	***1.00***	***2.67***	***9.97***	***2.11***

Table A3.6 – Aggregate Measurements: Anastasian Wall– page 3 of 4

Sample	Core	Site Code	Site Name	Quadrant	Olivine	Organic in Lime	Organic in Brick	Max Size - Brick Aggregate (mm)	Min Size - Brick Aggregate (mm)
7	A	TT-WS	South Dervis Kapı	NW	0	1	0		
				NE	0	0	0		
				SW	0	0	1		
				SE	0	1	1		
					0	2	2	13.60	2.04
7	B	TT-WS	South Dervis Kapı	NW	0	0	1		
				NE	0	0	3		
				SW	0	1	0		
				SE	0	1	1		
					0	2	5	9.24	1.54
7	C	TT-WS	South Dervis Kapı	NW	0	1	0		
				NE	0	4	0		
				SW	0	3	0		
				SE	0	2	1		
					0	10	1	6.13	2.02
					0	**14**	**8**		
					0.00	***4.67***	***2.67***	***9.66***	***1.87***
8	A	TT-WS	Evcik	NW	0	0	4		
				NE	1	1	1		
				SW	0	0	3		
				SE	1	1	0		
					2	2	8	22.00	2.56
8	B	TT-WS	Evcik	NW	1	0	1		
				NE	1	1	0		
				SW	1	0	0		
				SE	0	0	0		
					3	1	1	7.84	
8	C	TT-WS	Evcik	NW	0	3	0		
				NE	1	0	0		
				SW	0	1	3		
				SE	1	0	0		
					2	4	3	5.21	3.53
8	D	TT-AW	Evcik	NW	1	2	0		
				NE	2	0	1		
				SW	2	1	0		
				SE	1	0	0		
					6	3	1		3.42
					13	**10**	**13**		
					3.25	***2.50***	***3.25***	***11.68***	***3.05***

Table A3.6 – Aggregate Measurements: Anastasian Wall– page 4 of 4

APPENDIX 4 – SEM/EBSD and XRD Data

A4.1 – SEM Images

A4.1.1 – Water Supply of Constantinople

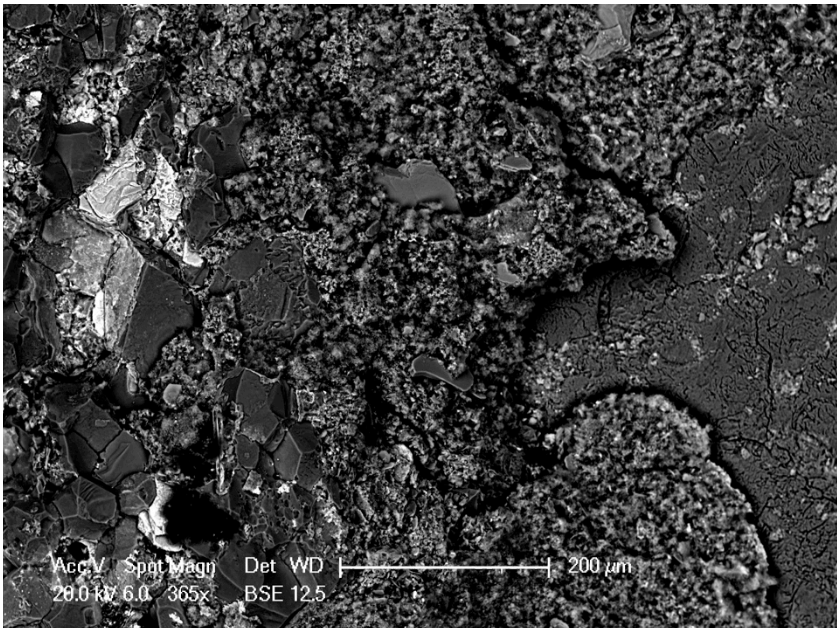


Figure A4 - TT-WS 1 - Image 1 of 3.

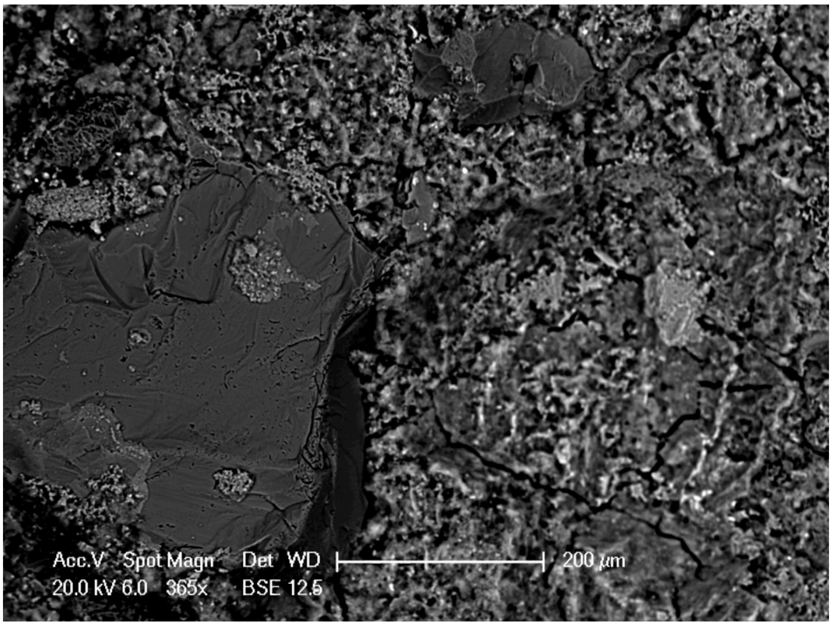


Figure A4 - TT-WS 1 - Image 2 of 3.

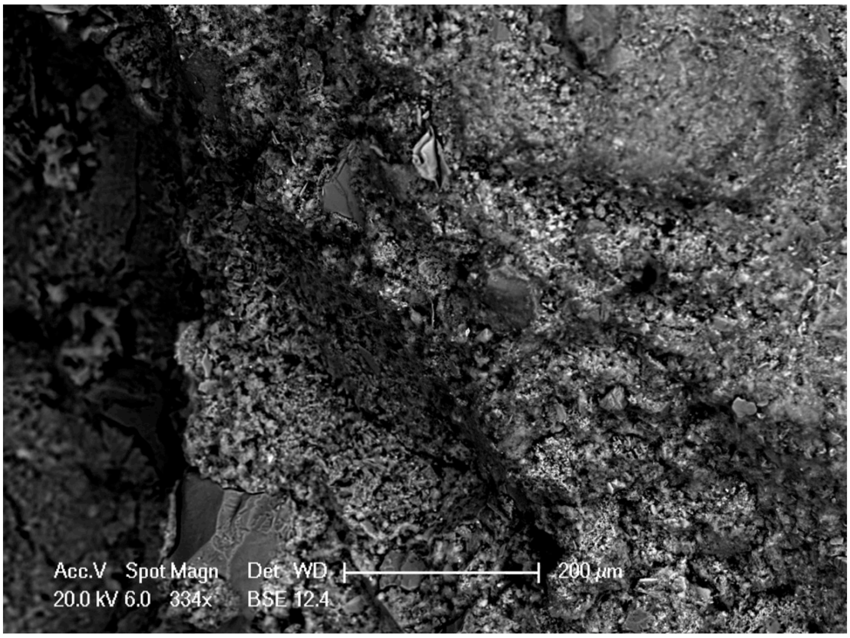


Figure A4 - TT-WS 1 - Image 3 of 3.

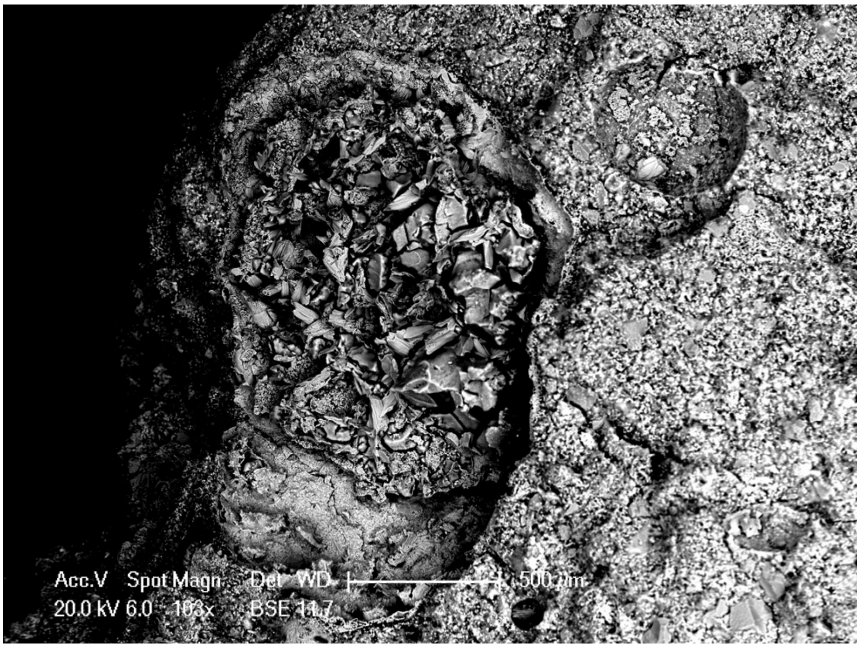


Figure A4 - TT-WS 4 - Image 1 of 3

Figure A4 - TT-WS 4 - Image 2 of 3.

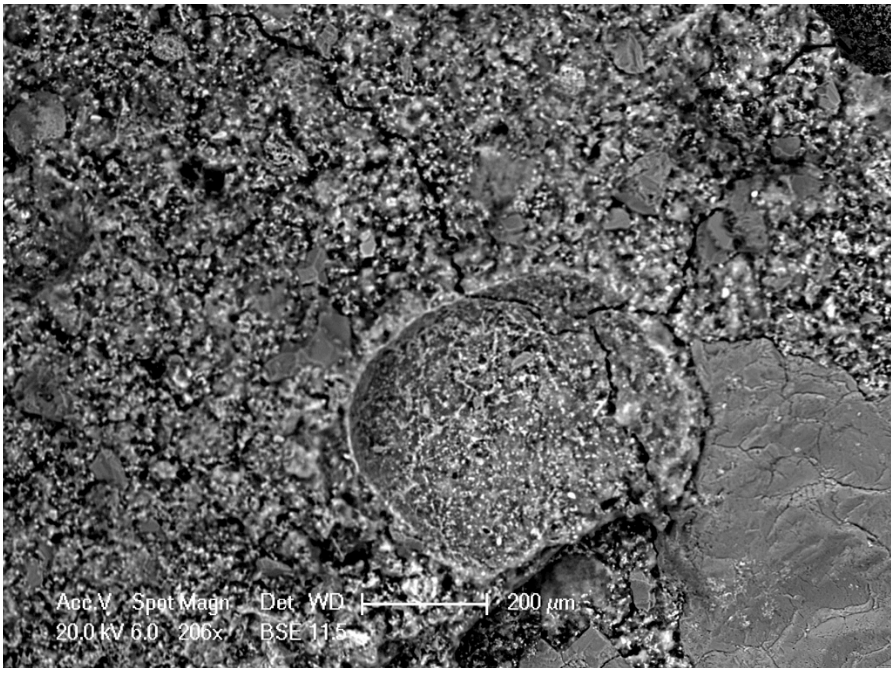


Figure A4 - TT-WS 4 - Image 3 of 3.

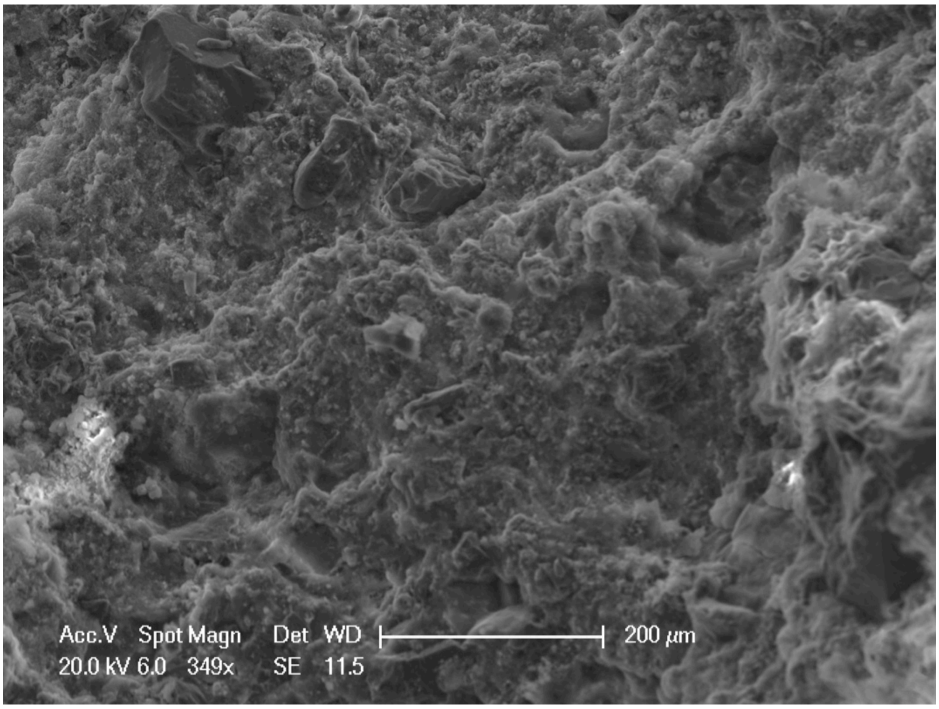


Figure A4 - TT-WS 5 - Image 1 of 1.

A4.1.2 – Anastasian Wall

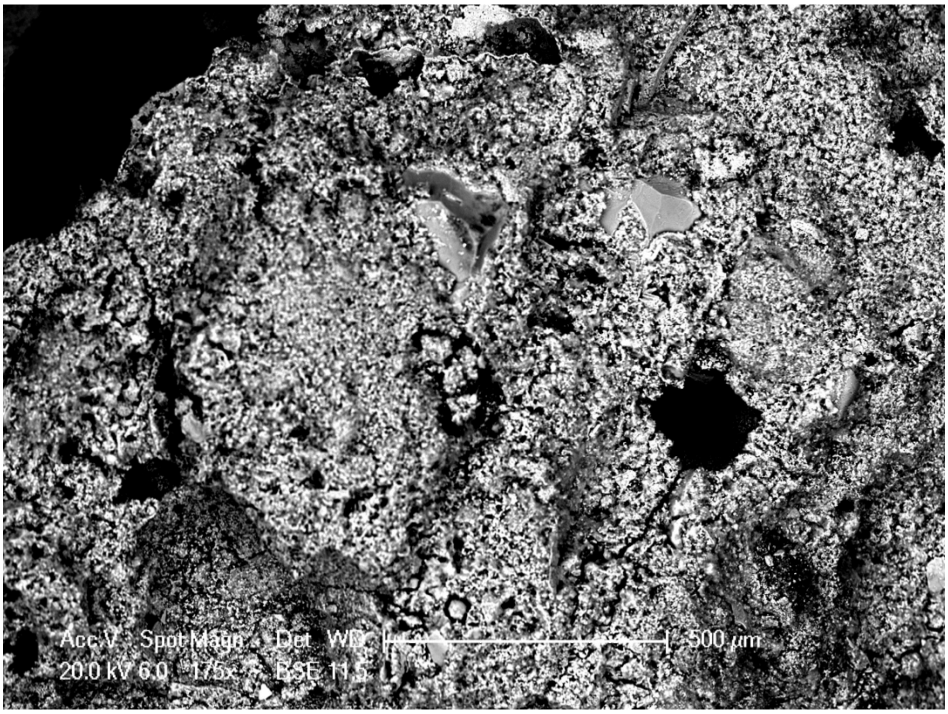


Figure A4 - TT-AW 1 – Image 1 of 1.

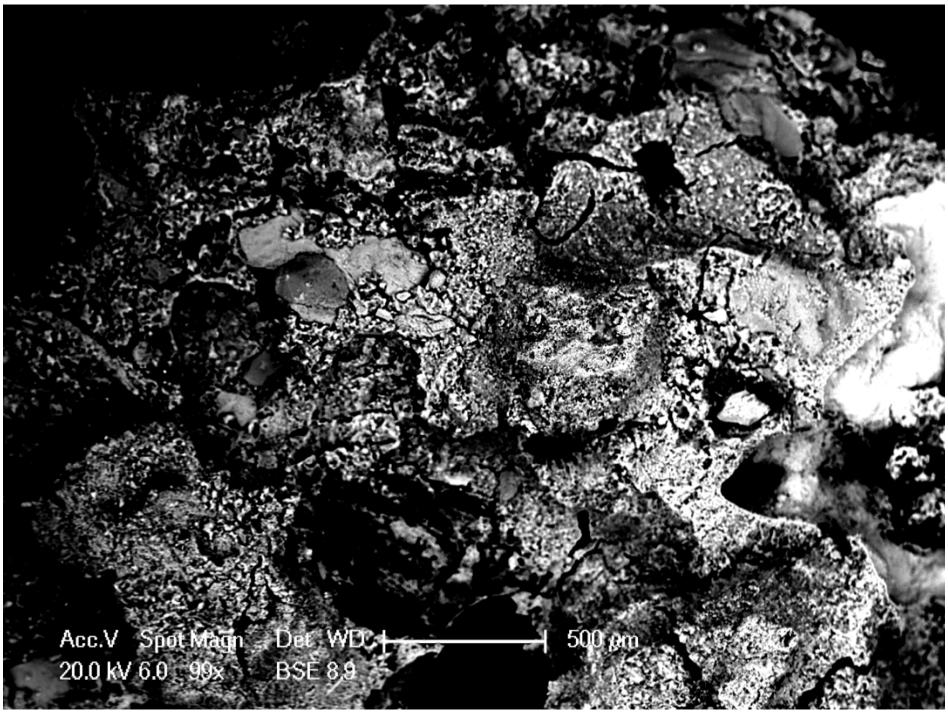


Figure A4 - TT-AW 3 – Image 1 of 1.

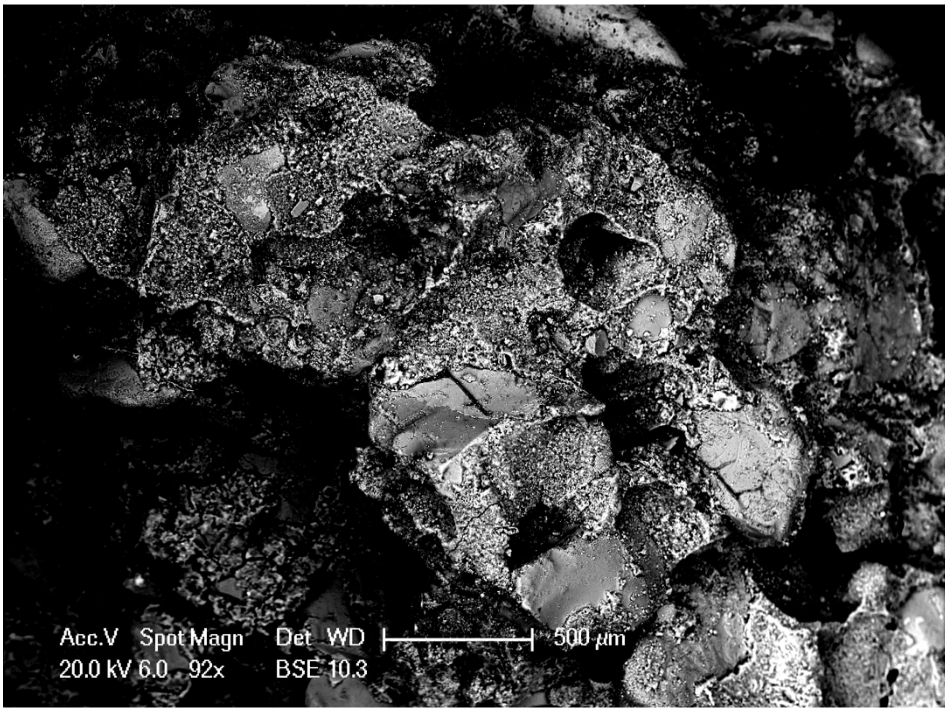
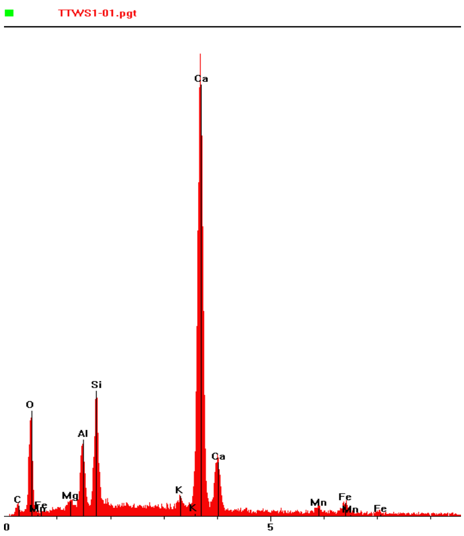
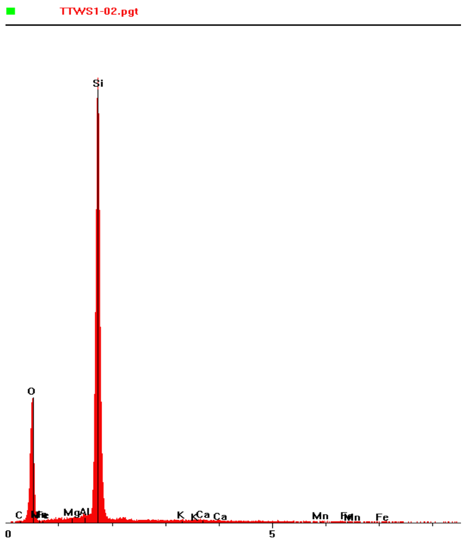


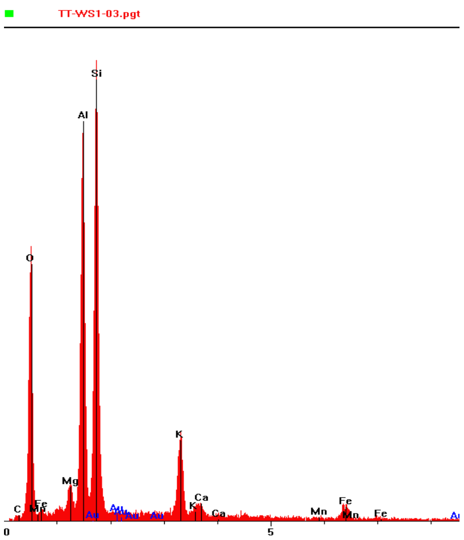
Figure A4 - TT-AW 8 (Evçik) – Image 1 or 1.

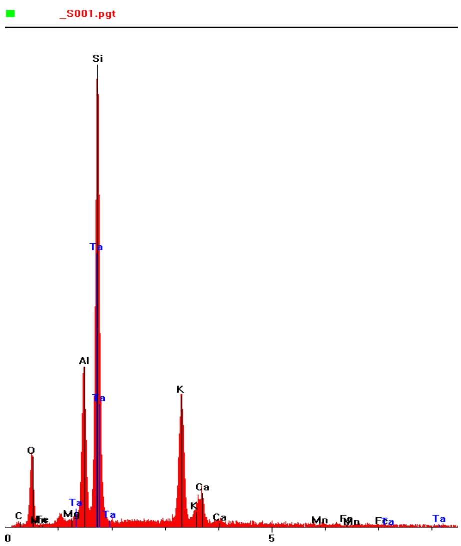
A4.2 – EBSD Charts

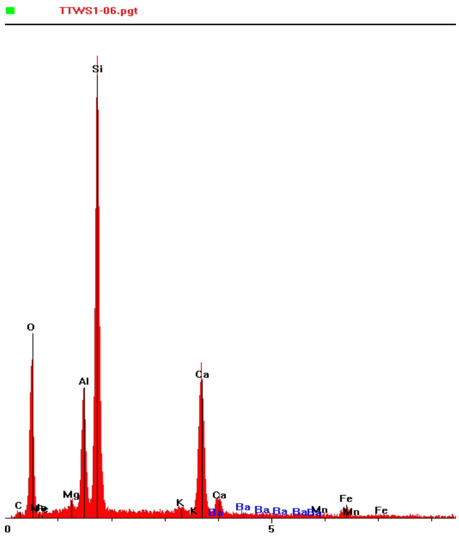
A4.2.1 – Water Supply of Constantinople







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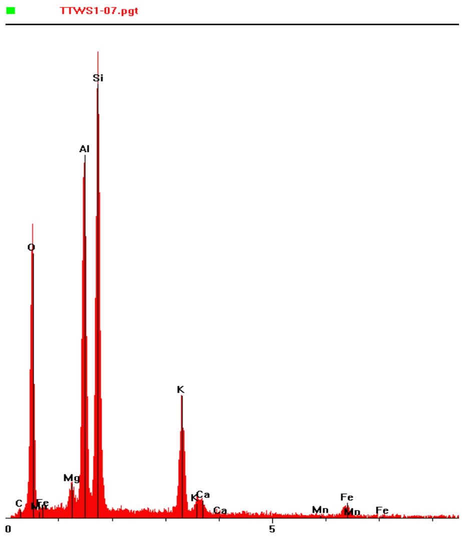
Al
Ca
C
Mg
K
Ba
Mn
Fe
0
5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Ca
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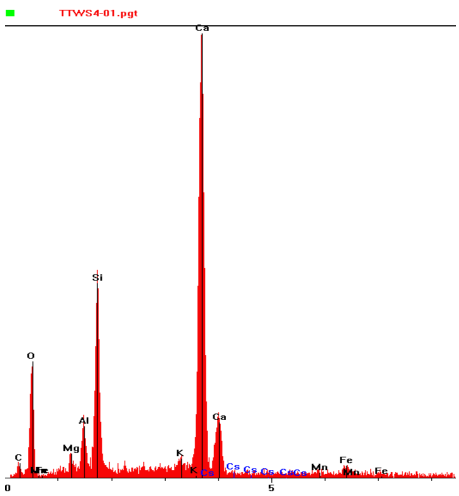
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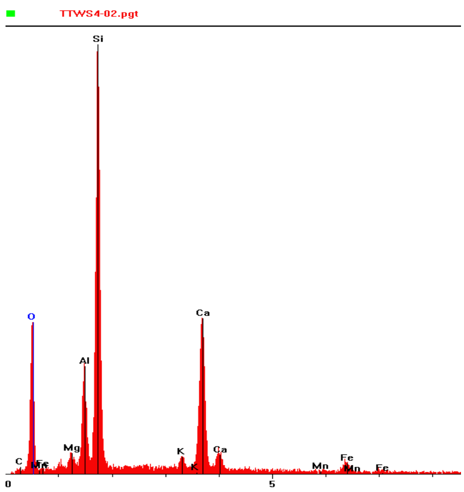
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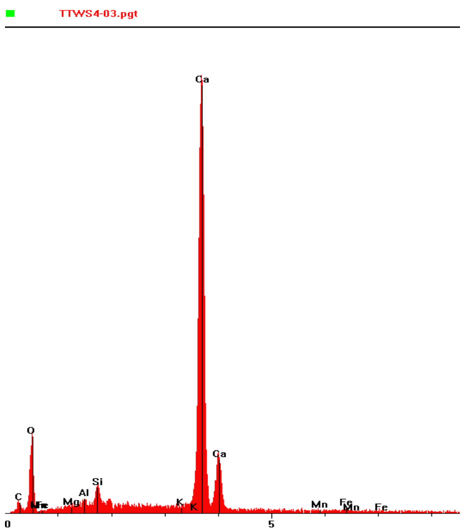
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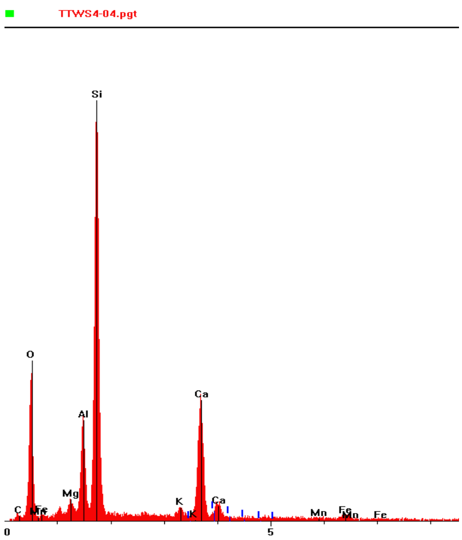
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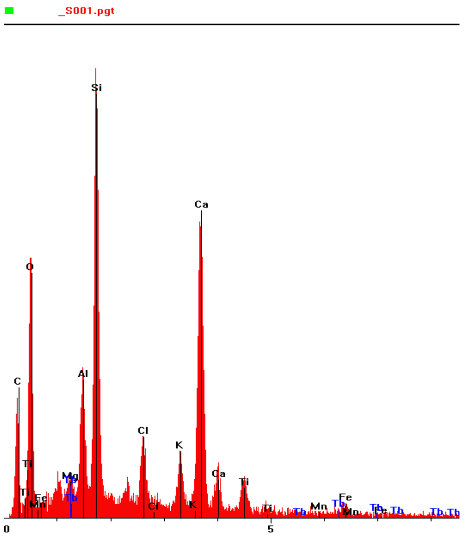
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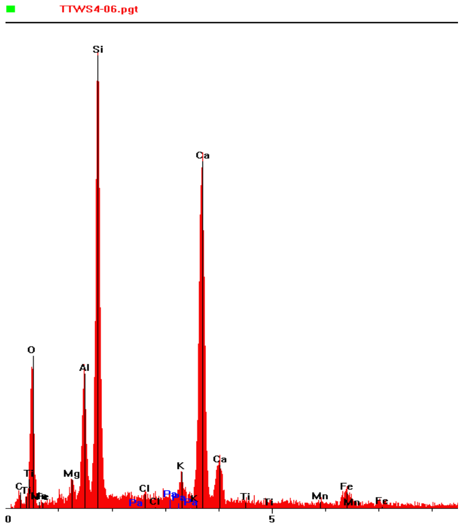
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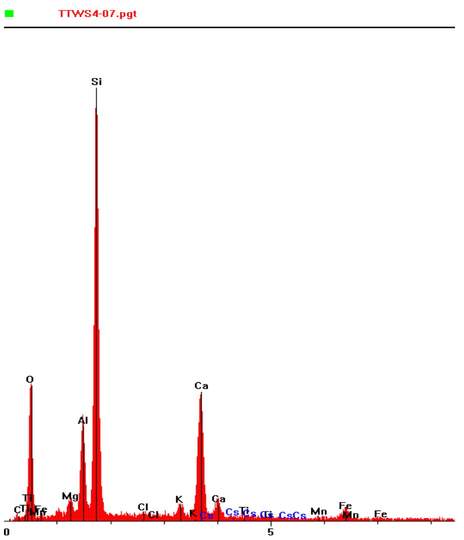
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Mn
Fe
0
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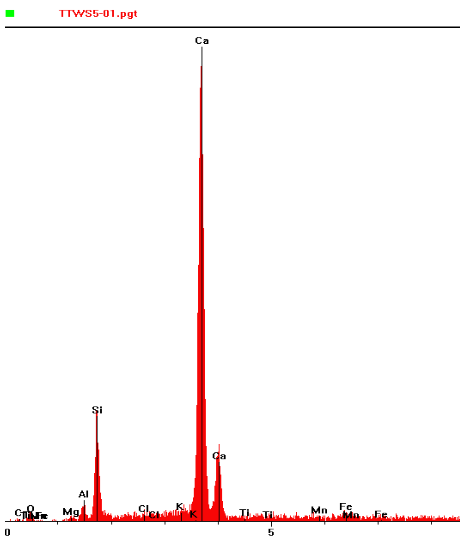
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Cl
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Ti
Mn
Fe
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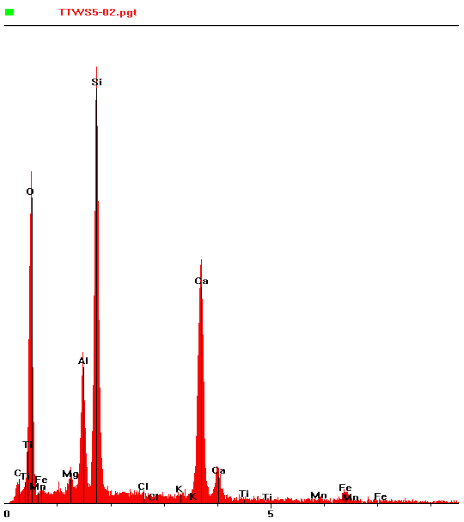
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K
Ti
Mn
Fe
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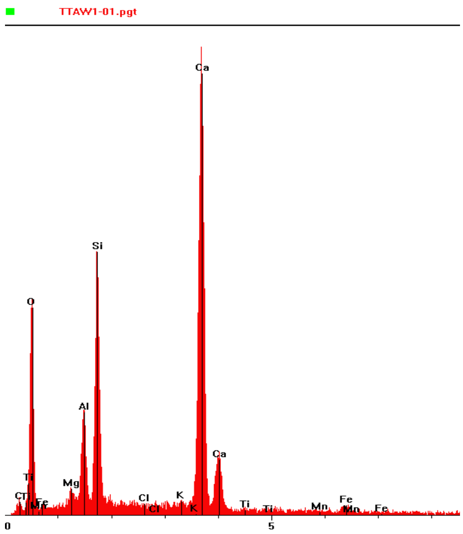
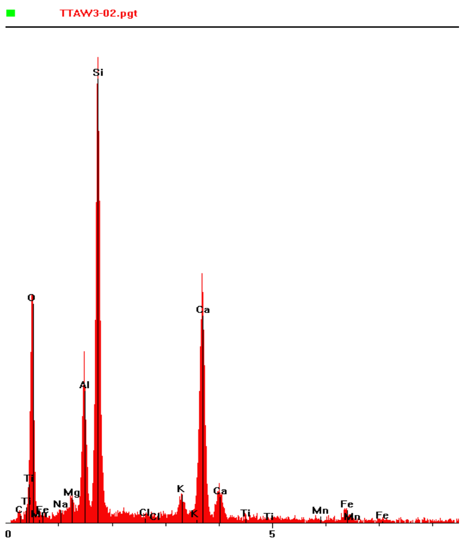
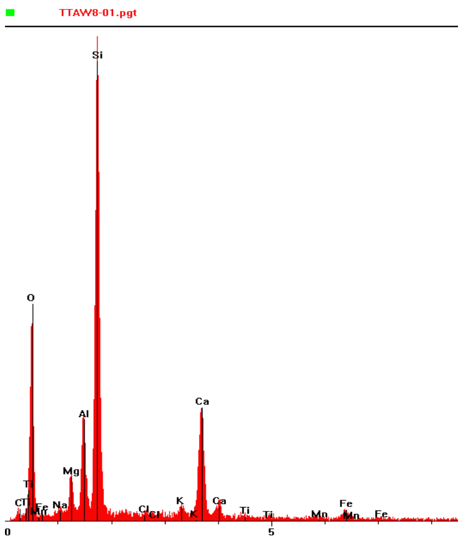
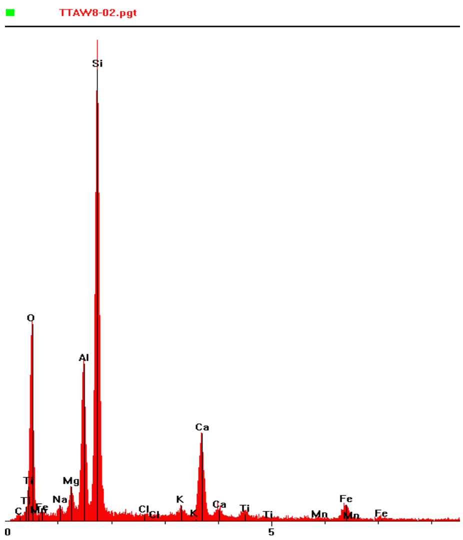
A4.2.2 – Anastasian Wall



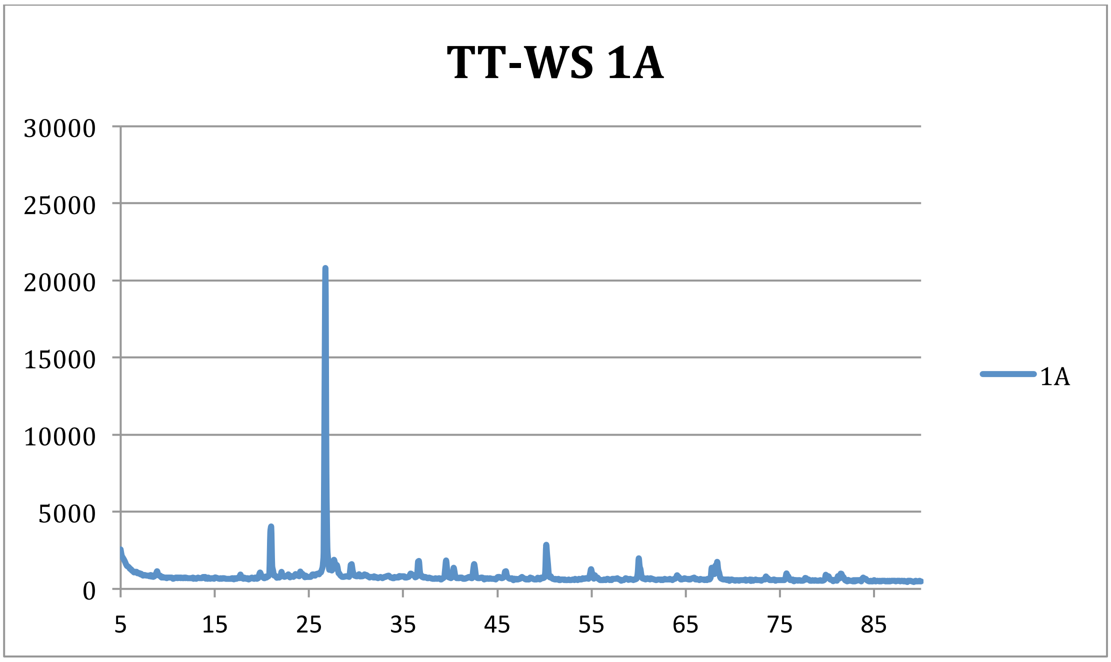


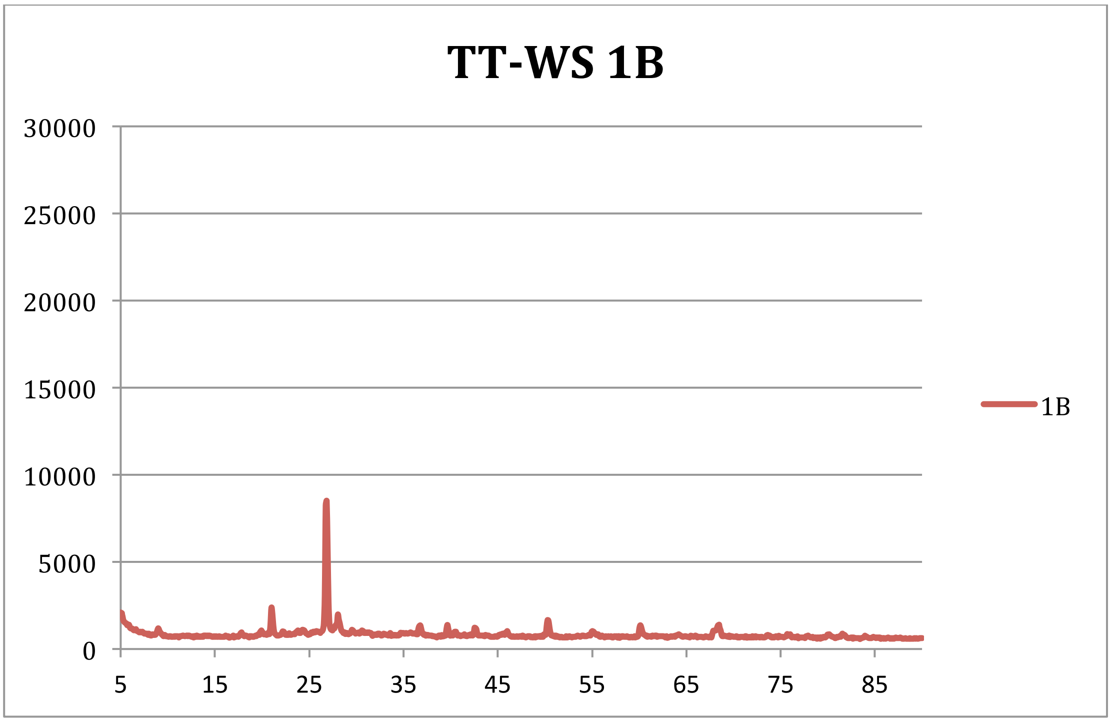


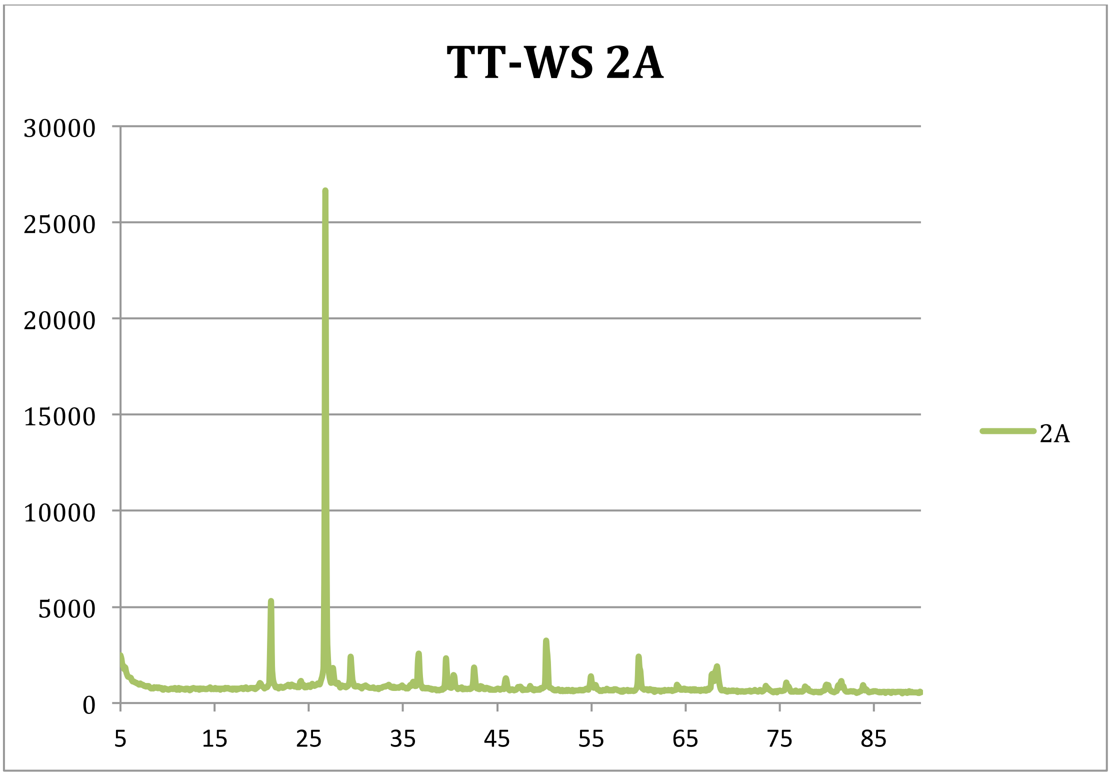


A4.3 – XRD Charts

A4.3.1 – Water Supply of Constantinople






TT-WS 2A
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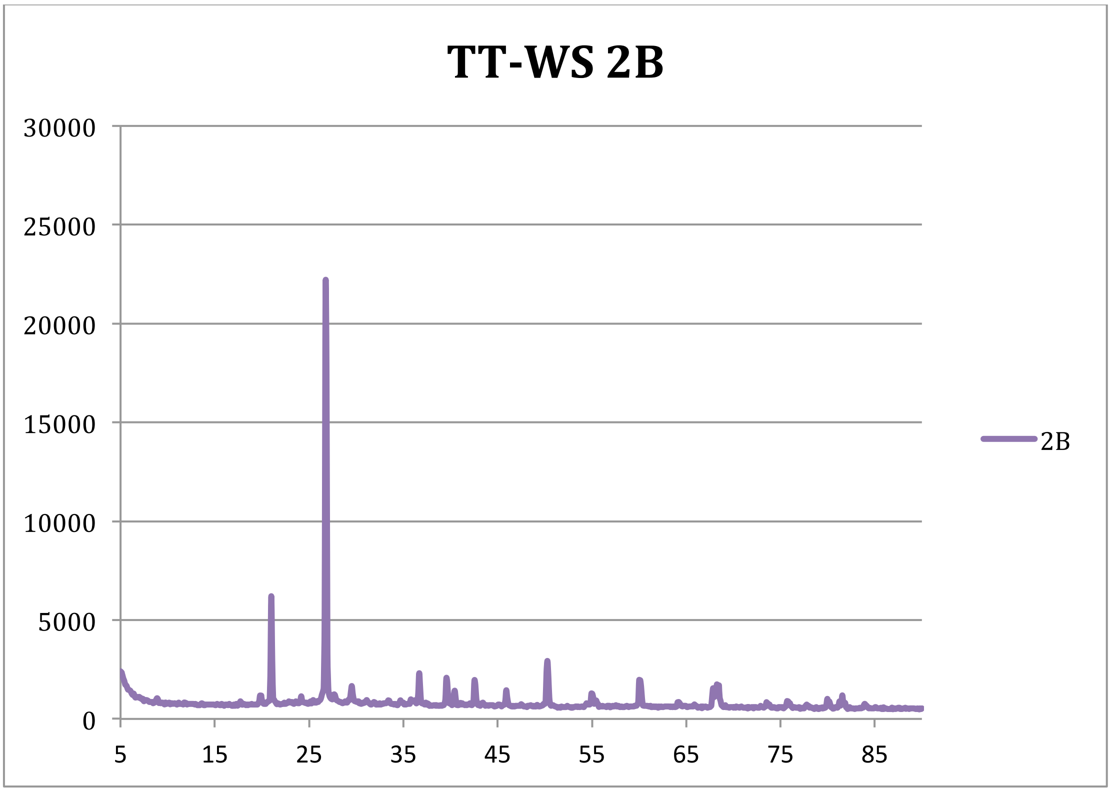
20000
15000
10000
5000
0
5
15
25
35
45
55
65
75
85
2A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20000
15000
10000
5000
0
5
15
25
35
45
55
65
75
85
2B

A4.3.2 – Anastasian Wall