

İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

**EVALUATION OF MASONRY WALL MATERIALS OF BYZANTINE AND
EARLY OTTOMAN PERIODS IN ISTANBUL**

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

**İSTANBUL'DAKİ BİZANS VE ERKEN OSMANLI DÖNEMİ
YIĞMA YAPI MALZEMELERİNİN DEĞERLENDİRİLMESİ**

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one geography, different cultures, same period....

FOREWORD

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June 2009

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LIST OF SYMBOLS

λ	: slenderness (for walls)
λ	: thermal conductivity (for materials)
Δ	: density
p	: porosity
B	: brick
S	: stone

EVALUATION OF MASONRY WALL MATERIALS OF BYZANTINE AND EARLY OTTOMAN PERIODS IN ISTANBUL

SUMMARY

As the studies about the conservation of architectural heritage increase, and the thought and attitude towards the subject improve, more detailed and more integrated perspectives must be developed to be able to succeed in the restoration works in the parts of building materials.

In the first phase of the study, the masonry wall techniques of the possible construction styles are investigated. This study is done both to be able to perceive the system as a whole and to be aware of the different parameters as a result of where and why the material is used.

The second phase is the research of the experiments done to the historical building materials to understand if the material succeeds in providing the requirements according to the place it is used. This is done to have right comments according to the certain values of the material investigations.

In the third phase, the information of the previous studies, on the Byzantine and early Ottoman periods in Istanbul in historic peninsula, are tried to be gathered. In this documentation phase, not just only the data about material qualifications and quantifications are studied. Also the information about the masonry wall techniques are worked on, as to be able to link the relationship between the materials and the system.

As the conclusion of the study, with the tables and visualisation of the information, it becomes possible to evaluate the masonry wall construction and masonry materials of Byzantine and early Ottoman periods. It is seen that there are differences, similarities and influences in both the cultures in the means of masonry wall construction and the materials used. By the tables, both the relationships between the system and the material are tried to be linked and with the information from the previous studies comparasions are able to be made between the physical, chemical and mechanical characteristics of the material. Due to the fact that the information about the periods are not sufficient enough and sometimes intensified on certain periods, it is only possible to investigate to a certain depth, but the subject may be further researched thoroughly with additional data of new material investigations.

İSTANBUL'DAKİ BİZANS VE ERKEN OSMANLI DÖNEMİ YIĞMA YAPI MALZEMELERİNİN DEĞERLENDİRİLMESİ

ÖZET

Mimari mirasın korunmasına yönelik çalışmalar hız kazandıkça, ve bu konudaki düşünme ve davranış stilleri geliştikçe, restorasyon çalışmalarında uygun malzemeler ile yardımcı olabilmek için, malzeme konusunda daha detaylı ve diğer sistem parametreleri ile (yapım teknikleri, v.b.) ilişkili bakış açıları geliştirilmesi gerektiği görülmektedir.

Çalışmanın ilk fazında öncelikle yığma yapım sistemleri olası kurgular üzerinden incelenmiştir. Bu çalışma, malzemenin farklı kullanım sebepleri ve alanları ile ilgili değişkenleri fark edebilmek ve sistemi bir bütün olarak algılayabilmek için yapılmıştır.

İkinci faz ise malzemenin kullanım yerine göre beklenenleri sağlayıp sağlayamadığını anlamak için yapılması gereken deneylerin araştırılmasıdır. Bu çalışma malzeme incelenmesi ile elde edilen değerlerini doğru yorumlayabilmek için yapılmıştır.

Üçüncü fazda ise İstanbul, tarihi yarımada ölçeğinde Bizans ve erken Osmanlı yapıları için daha önceki çalışmalardan elde edilen bilgiler derlenmeye çalışılmıştır. Bu çalışmada, sadece malzemeye yönelik bilgiler çalışılmamıştır. Aynı zamanda malzeme ve sistem arasındaki ilişkiyi kurabilmek için yığma yapım teknikleri ile ilgili bilgiler de derlenmiştir.

Çalışmanın sonucunda, elde edilen bilgilerin tablollaştırılması ve görselleştirilmesi ile, Bizans ve erken Osmanlı dönemlerinde yığma yapım sistemleri ve malzemelerinin gelişiminin değerlendirilmesi mümkün olmuştur. Her iki kültürde, yığma yapım teknikleri ve kullanılan malzemeler arasında benzerlikler, farklılıklar ve etkileşimler bulunduğu görülmektedir. Oluşturulan tablolarla, hem sistem ve malzeme özellikleri arasında bağlantılar kurulmaya çalışılmış, hem de daha önceki malzeme çalışmalarından elde edilen malzemenin fiziksel, kimyasal ve mekanik özellikleri kıyaslanabilmektedir. Konudaki çalışmaların azlığı ve kısmen çeşitli dönemlerde yoğunlaşması sebebi ile sadece belirli bir derinliğe kadar inceleme yapılabilmektedir, ancak ileride gerekli ve yeterli malzeme araştırmaları ile daha detaylı bir çalışma geliştirilebilir.

1. INTRODUCTION

The masonry walls of historic structures help to provide information of the building technology, together with the other information about the structure. Even sometimes, this information helps to date the building. Especially stone shaping techniques, brick and stone dimensions, the pattern of the wall, the mortar joint works, color and texture are important to identify the structural truly [1]. These building techniques usually correspond with material characteristics. As the building construction is related with the technique and the material, the parameters of wall techniques and the wall materials may carry the characteristics of the period.

There are still plenty Byzantine and Ottoman structures that must be conserved in Istanbul area. However, all the previous documents and records, and accepted criteria/codes must be regarded to make a deliberate work.

Understanding of "authenticity" is still much debated even after the Nara document on authenticity developed by ICOMOS in 1994 [2]. In the Nara document, the term "authenticity" was defined as a layered (or multifaceted) concept of values, meaning that it can be subdivided in different aspects:

"form and design, materials and substance, use and function, traditions and techniques, workmanship, location and setting, and spirit and feeling, and other internal and external factors." [2].

International centres, such as ICOMOS or ICCROM, have recommended the use of materials similar in composition and properties to the original ones for the restoration works [3].

The regarded parameters of the material production systematic are:

- reversibility
- compatibility
- retreatability
- reparability

1.1 Purpose of the Thesis

As the cultural sustainability develops by time, there are plenty of conservation works done by many different parties. Besides, the social awareness level about preventing and conserving objectives are raising in both micro and macro scales (in the local and global means) parallel to the development in cultural sustainability. The aim of the study is also to help the material production works for the protection of cultural heritage as both by trying to documentate the collected data of the material properties of the periods, and linking the relationships between the experiments and the properties found out. The construction techniques and materials of masonry walls in Byzantine and early Ottoman periods in Istanbul are researched from the previous studies. The hypothesis of the study is to see the differences and similarities between the periods and to see if it will be possible to link a relationship between mostly individual studies and if a generalization within the periods is possible to be done.

As with the influence of the difference cultures, possible similarities can be caused by the influence and possible differences can be caused by the cultures. There may be special construction techniques for different periods, and special materials and production processes.

1.2 Methods

A comparative analysis of material and technique of the same space, different centuries and related cultures is investigated. The thesis study is a literature research of past studies. The study relies on a literature research about the masonry wall techniques, and materials of Byzantine and early Ottoman periods in Istanbul. Also literature research about the experiments used to identify the material characteristics and the relationships between the experiments and the properties of the materials. All the quantitative values are results of previous researches. No quantitative analysis is done. The research is limited by Byzantine and early Ottoman buildings in Istanbul, as to see the influences, similarities and differences at the beginning of the Ottoman architecture in Istanbul, before developing the classical style of its own.

To be able to study chosen buildings, walls are the best component of the structure, as they resist time and environmental conditions better than other components. Hence, the material-technique systems are studied over the walls. Walls are thought

to be an integrated system of stone, brick and mortar. In detail, the characteristics of the elements are searched and summarized from the previous studies.

The investigation of masonry walls is based on two main topics:

- Masonry wall construction; including the wall pattern (the course patterns depending on the materials), material dimensions and mortar thicknesses.
- Masonry wall materials; including the materials used and the properties of the materials such as physical properties (colour, dimensions, porosity, etc.), mechanical properties (compressive strength, flexural strength) and chemical properties (efflorescence, effect of gases, etc.), thermal properties (thermal expansion, thermal conduction, etc.).

1.3 Historical Background of the Geography

1.3.1 Roman architecture

The Roman Architecture changed all the previous and advanced this by introducing new methods of architecture; The Columns and The Arches. With these methods the Romans were able to construct bigger temples and buildings than ever before [7].

The building process of the Roman Empire was largely derived from the nature of materials. In order to obtain secure and stable buildings construction had to proceed according to the rhythms of the work determined by the setting time of the mortar.

In essence, Roman wall making depended upon making and laying brick and upon shovelling and carrying. The walls of the Markets or the Pantheon are striking examples of Roman order as products of methodical construction and as visible forms.

Quarrying, transporting, and cutting stone compromised a major Roman industry. Also stone aggregate is a necessary part of concrete because mortar itself cannot sufficiently resist the crushing force of great weights. The Romans used several kinds of stones for aggregates, ranging in weight from selce, a very heavy lava stone used in foundation walls, to lightweight tufa (a local, granular stone) and pumice, both used in vaults. Other kinds of stone, as well as broken bricks and tiles were also used. All these materials were found in and near Rome. Architectural sculptures and other

stone members of demolished buildings were sometimes broken up and used as an aggregate.

The basic product of the baked-earth materials was the thin square brick or tile, made in many sizes. They were almost universally of excellent quality (very hard, fairly true, and sharply edged) and ranged in colour from magenta-brown through a deep reddish-brown to light yellow. The various colours of Roman bricks and decorative terra-cottas are important. By using different kinds of clay and by varying the length of the firing, colours were deliberately produced for visual purposes.

Vitruvius says that in making mortar, sea sand should be avoided. Good sands, he adds, crackle when rubbed and do not stain white cloth. Lime, after burning, should be set aside to age. By his day the Romans had mastered the use of pozzolana, which they added to the dry mix in lieu part of the sand. Pozzolan is a friable volcanic material, found in thick beds of chunks and gravel sized pieces in Latium and Campania and easily reduced to usable form. The importance of pozzolan is the mortar made with it will set readily underwater [8].

1.3.2 Persian architecture

Works of art and structures produced in the region of Asia traditionally known as Persia and now called Iran. Iran has seen the flow of many migrations and the development of many cultures, all of which have added distinctive features to the many styles of Persian art and architecture.

A unified style emerges in the Achaemenid period (c.550–330 B.C.). Influenced by the Greeks, the Egyptians, and those from other provinces of the Persian Empire, the Achaemenids evolved a monumental style in which relief sculpture is used as an adjunct to massive architectural complexes. Although there are marked analogies to Egyptian, Greek, and Assyrian architecture, the style as a whole and the feeling for space and scale are distinctive. The Persepolitan columns are slenderer and more closely fluted than those of Greece. Bases are high, often bell-shaped; capitals are composed of the foreparts of two bulls set back to back or of other animals above volutes with rosette ornament [4].

After the death of Alexander the Great (323 B.C.), there was turmoil in Iran until the rise of the Parthians (c.250 B.C.). Their art is essentially a crude art, synthesizing

Hellenistic motifs with Iranian forms. Buildings of dressed stone and rubble and brick were decorated with sculpted heads and mural paintings.

Of far greater artistic importance is the contribution of the Sassanids, who ruled Iran from A.D. 226 to the middle of the 7th century. Adapting and expanding previous styles and techniques, they rebuilt the Parthian capital at Ctesiphon. There a great palace with a huge barrel vault was constructed of rubble and brick. Sassanid architecture is decorated with carved stone or stucco reliefs and makes use of colourful stone mosaics.

Little remains from the early centuries of Islam in Iran, but the influence of Persia on Islamic art and architecture in Syria and Palestine is very strong. A significant innovation by the Persians is the raising of a dome over a square hall by means of squinches.

The earliest important Islamic monument extant in Iran is the mausoleum of Ismail the Samanid at Bukhara. Dated 907, it is a solid, square building in cut brick style, covered by a dome.

The Blue Mosque at Tabriz, named for its brilliant faience casing, is contemporary. Mosaic faience-covered architecture reached its height in 16th century Isfahan in the great building complex Maidan-i Shah [4].

1.3.3 Seljuk architecture

The exceptional period that flourished in Anatolia in the 12th and the 13th centuries, between the Crusades and the Mongol invasion, is marked by outstanding works of architecture and decorative arts [5].

The general characteristics of Anatolian Turkish architecture are cut stone material, decorations depending on the stonework and a simple space effect. Brick, glazed brick and mosaic tiles and sometimes plaster are mostly used as decorative materials. In a few number of examples, brick is considered as structural material apart from its decorative use [6].

With its wide inner court, brick also as a structural material and general design of Malatya Ulu Mosque stays as the only example and references Persian Seljuk mosques. As the architect of the mosque is local, the mosque proves that Anatolian Seljuk architects are aware of the developments in Persia during Seljuk Empire, but

also trying to develop a new style of their own. These efforts will be the basis for the Anatolian Emirates and Ottoman architecture. These observation places with a strong space affect, made of the cut stone architecture, with the decorative elements of stonework creates the basis for 14th century Anatolian Turkish architecture and so also for the universal Ottoman architecture. The architectural products of this era, called as Seljuk period, are the products of Turkish architectural work before Anatolia and stone as the structural material worked together with a research enthusiasm. Traditional plan and form designs developed attractive works with its new possibilities, and with the continuity of new, it had became the architectural style of the period [6].

Also, the caravanserais (or hans), used as stops, trading posts and defence for caravans, and of which about a hundred structures were built during the Anatolian Seljuk's period, are particularly remarkable. Their unequalled concentration in time and in Anatolian geography represent some of the most distinctive and impressive constructions in the entire history of Islamic architecture [5].

The largest caravanserai is Sultan Han, built in 1229, is on the road between the cities of Konya and Aksaray, enclosing 3,900 m². There are two caravanserais that carry the name "Sultan Han", the other one being between Kayseri and Sivas. Furthermore, apart from Sultanhanı, five other towns across Turkey owe their names to caravanserais built there. These are Alacahan in Kangal, Durağan, Hekimhan and Kadınhanı, as well as the township of Akkale/Akhan within Denizli metropolitan area. The caravanserai of Hekimhan is unique in having, underneath the usual inscription in Arabic with information relating to the edifice, two further inscriptions in Armenian and Syriac. There are other particular cases like the settlement in Kalehisar site (contiguous to an ancient Hittite site) near Alaca, founded by the Seljuk commander Hüsameddin Temurlu had founded a township comprising a castle, a madrasah, a habitation zone and a caravanserai, which were later abandoned apparently around the 16th century [5].

1.3.4 Western Anatolian Emirates architecture

The wall construction techniques and materials of the ancient periods developed by time and used in the Turkish periods of the Anatolia as well. In the monumental

structures, the external faces of cut-stone and internal filling as rubble wall techniques are used. For other structures, the Byzantine style of the region is applied.

During the architectural development of the Emirates, usually the western Anatolian techniques are used directly or indirectly (with the techniques of Persian and Anatolian Seljuk's) for the main structural elements of the building. The oriental influences are mostly about the architectural and decorative forms. However, besides the facts above, the architecture of the western Anatolia Emirates combines the architectural traditions of both the cultures and developed new styles and forms. Experimental forms are only used at the period and at the specific region. However, some of the elements are applied in the Ottoman architecture, and influenced the Classical Ottoman architecture [9].

2. MASONRY WALLS

Until the beginning of this century, most buildings were constructed with load bearing walls. The fundamental strength property of the masonry is its specified compressive strength [10].

Masonry structures today are made from stone or brick and block, which are called masonry units. Masonry structures predate written history. The earliest structures were huts made from unshaped native field stones piled upon one another without mortar or other materials in the joints. Sod or dried mud served the same purpose as the stone when the stone was not available. After a while, clay and silt were mixed with water and formed by hand into bricks. The spaces between these bricks were sometimes packed with mud to keep out the wind and rain and to make it easier to build level walls with irregular bricks. Later still, it was discovered that clay bricks placed in or adjacent to a fire became harder and more weather resistant. The Romans used this knowledge to build kilns to produce burned clay roofing tiles, and eventually burned clay bricks [11].

About 4000 B.C., the Mesopotamians built stone and sun dried brick buildings and 1000 years later, the Egyptians began building temples and pyramids of cut stone. The Egyptians made all pieces fit closely together by laboriously cutting the stone using bronze tools.

Early stone buildings were limited because of the limitations at the dimensions of the openings and column spacing. Roofs were made of wood. However the Babylonians built small arches over windows and other small openings.

When it became possible to make stone-working tools from iron, the art of stone building developed to a high order. The Greeks refined the process to produce fine details in stone. The Romans were able to build for the first time buildings with large open spaces. They were the first to build arches large enough to sustain bridges and large buildings.

The building of brick and stone structures without joint materials changed when the Etruscans developed a lime mortar that could be used to fill gaps between masonry units. Later, the Romans discovered how to make hydraulic cement by burning and grinding a type of volcanic rock, as this improvement led to stronger and more watertight stone and brick structures. This same discovery led to the expanded use of concrete.

The sun baked bricks used extensively by ancient peoples began to disappear after the Romans invented kilns. The production technique provided better baked clay which became hard enough so that its resistance to the elements expanded dramatically [11].

The fall of the Roman Empire was followed by the emergence Byzantine Empire, centred in Constantinople (Istanbul). The Byzantine Empire flourished for a thousand years until the Ottomans conquered it in 1453. Byzantine architecture combined Roman arch forms with other shapes and added detail and colour. The Romans developed the pendentive that makes the construction of a stone dome over a square space possible. Using this device, Byzantine architecture placed large stone domes over square buildings [11].

In the late 18th century the industrial revolution ushered in the modern era. Machines began to replace much of the handwork necessary to quarry and cut stone and to mould and fire bricks. Stone units became more uniform in shape and size. Bricks became more consistent in colour, strength, and size.

Until the development of the theory of elasticity in the 19th century, unit masonry and stone construction were based solely on experience. After that, masonry structures could be built using rational design based on calculated stresses.

Although they have been largely replaced by steel and concrete as primary load carrying elements in larger buildings, unit masonry and stone remain in great use today for cladding, partitions, and flooring. They are especially valuable where fire and weather resistance is required [11].

2.1 Masonry Wall Properties

Walls constructed of stone, brick, and adobes are in the classification of continuous, load-bearing walls generally. [10] Load bearing walls serve two main functional

roles: to form an envelope providing security and shelter from sight, wind, rain, and temperature, and to support the weight of the building superstructure.

The masonry walls, as a building element, can fulfil several functions including structure, fire protection, thermal and sound insulation, weather protection and subdivision of space [17].

According to their use in the construction, following physical and mechanical properties of masonry walls are required:

- Colour;
- Surface texture;
- Weight;
- Water absorption;
- Pore structure;
- Thermal conductivity;
- Thermal and moisture movement;
- Fire resistance;
- Compressive strength; and
- Flexural strength [17].

Over all of the mechanical properties of masonry units, the most important is compressive strength which, as well as being of direct relevance to the strength of a wall, serves as a general index to the characteristics of the unit [17]. The ultimate compressive strength is the strength at the point of failure. It is closely related to the compressive strength of the masonry units themselves and of the mortar. The quality of workmanship, thickness of mortar joints, regularity of the bearing surfaces of the units and workability of the mortar are also important [11]. The tensile strength of masonry units (both direct and flexural) has an influence on the resistance of masonry under various stress concentrations [17].

When composite walls or other structural masonry elements are composed of different kinds or types of units or mortars, the maximum compressive stress should not exceed the allowable stress for the weakest of the combinations of either the masonry unit(s) or the mortar type(s) of which the wall is composed [11].

Thermal conductivity of units is of great importance in satisfying building design requirements. Thermal and moisture movements in masonry walls must be taken into account in design of walls [17].

There are also other non-structural design factors which must not be regarded for the design of masonry walls [17]:

- Movement;
- Moisture exclusion;
- Durability;
- Thermal expansion;
- Acoustic properties;
- Fire resistance.

For the continuity of the structural system, openings for windows and doors need to be small in masonry walls [10].

2.2 Masonry Wall Construction

2.2.1 Brick walls

A brick is a masonry unit which is used in “wet” construction with mortar joints [12]. Bricks can only be used under compressive strength so it is important to work out the pressure forces first of all when working with masonry [13].

Appearance, strength, and weathering quality of brick masonry depend greatly on the quality of workmanship. Strength is generally the function of proper mortars, bond, and workmanship, rather than strength of the individual masonry units. Brickwork must be designed so that the individual units are bonded into a structure that will act as a whole. Different types of brickwork used commonly are shown below in Figure 2.1. Joints between individual units must be well formed and watertight. Each masonry unit must be set with full beds of mortar in both the horizontal and vertical joints [13].

The primary function of mortar is to develop a strong and durable bond with the brick masonry units. A good masonry mortar must remain workable long enough to permit the workmen to position the units. It must have relatively little shrinkage value, a high degree of resistance to moisture penetration, and the strength to resist

the forces that may be applied to it. Masonry units vary in the rate at which they absorb water. If they absorb the water in the mortar too quickly, the mortar may stiffen prematurely and lose its adhesive qualities. Thus masonry units with high rates of absorption, or suction, may have to be wetted previous to the application to provide a proper bond [13]. The traditional lime mortar had little strength, and its main function was to take up irregularities; the strength of brick walls depended mainly on their bond [12].

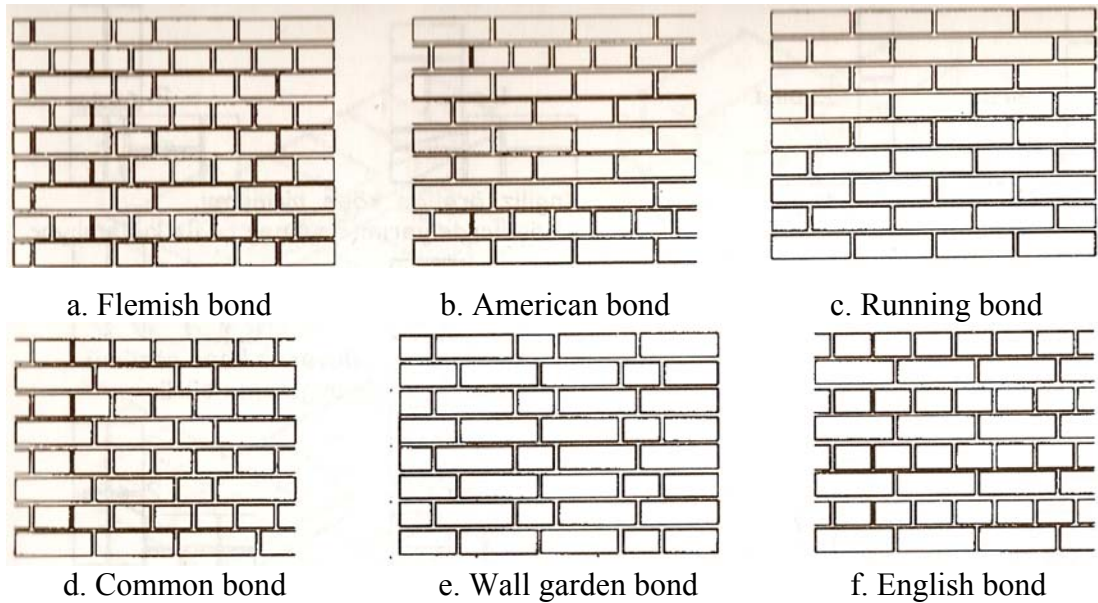


Fig 2.1 : Different types of common brickworks

2.2.2 Stone walls

Shaped stone was not used extensively until iron stone working tools were developed. Stone may be laid in mortar beds and supported by the stone below, or be supported by metal [11]. The mortar for stone masonry should be weaker than the stone selected. Jointing should generally be to a similar texture and colour to that of the dressed stone itself, and should be slightly recessed to emphasise the stones rather than the joints [14]. Before the Etruscans introduced lime mortar, cut stone buildings were made by accurately cutting and fitting stones together with no joint filler, which was time consuming and tedious work. The use of mortar joints reduced the need for extreme accuracy in stone cutting and speeded up the construction process. When the Romans developed hydraulic mortar, much stronger stone structures could be made and much longer spans built. It may also be adhered to

backing panels of concrete or metal. It may be used to build solid walls, arches, and vaults, as a facing over masonry, or as cladding. As cladding, it may be supported by the structure or mounted on a metal framework [11].

Stone was gradually replaced, to a large extent in smaller and residential buildings, by lighter and easier to handle brick and, later, concrete masonry units [11].

For the construction of the walls and foundations basic principles are [15]:

- Usually as the compressive strength of stones and mortar increase, bonds and workmanship develop the strength of the wall and as the slenderness ($\lambda = h/d$) increases strength decreases.
- Minimum wall section for the stone walls must be 50 cm. However this thickness can be reduced to 45 cm for roughly cut stones, and to 40 cm for cut stone walls.
- Slenderness must be 14 for cut stone walls, and 10 for other stone walls.
- Loads must not be eccentric and the wall must not have tensile strength forces.
- There must be a bond course at most for 1.5 metres.
- The bonds and mortar joints have an important role for a uniform behaviour of the wall. The thickness of the joints must not be over 4 cm for rubble walls, not more than 2-3 cm for stone walls corrected slightly with hammer, 1.5-2.5 cm for freestone walls, not more than 1-2 cm for cut stone walls.
- Stones must be placed with their largest surfaces and joint intersection must not be less than 10 cm. Concave stones smaller than 10 cm in height, 20 cm in length and width must not be used. Gaps in the bond must be filled with smaller connector stones.

Limestone and sandstone are the most frequently used for walling, but slate is also used where it is available locally [14].

Stone masonry walls are classified according to shape and surface finish of the stone as rubble, ashlar, and cut stone or dimension stone [17].

Rubble masonry: It is composed of stones as they are either collected, called fieldstone, or stone as it comes from the quarry. Thus the stones may have rounded natural faces or angular broken faces. Random rubble consists of fieldstones or quarry stones laid in an irregular pattern of sizes and shapes, with the large spaces

between them filled with spalls, or broken bits of stone. A special type of rubble masonry, called polygonal, mosaic, or mosaic web wall, is composed of random shaped stones fitted together to expose a web of more or less uniform mortar joints. Mosaic dry wall is similar, but is laid close together with no mortar showing. Coursed-rubble or strip-rubble walls are constructed of stone that has been quarried in layers of uniform thickness or of roughly shaped stones laid in approximately level beds. The stones are split to length by the mason on the job [16]. Rubble stonework examples can be seen in Figure 2.2 and Figure 2.3.

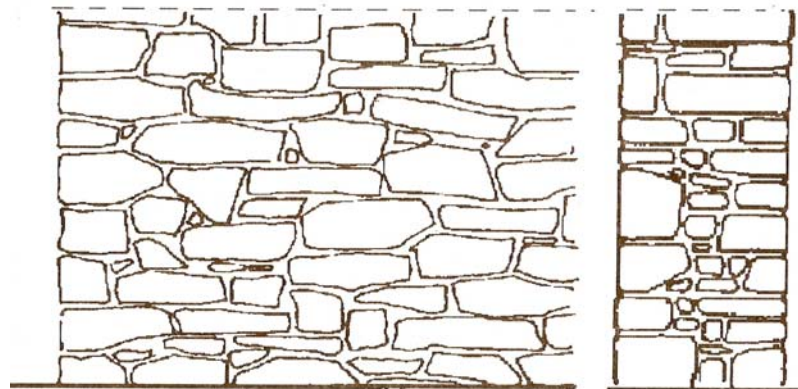


Fig 2.2 : The view and section of a rubble stone wall



Fig 2.3 : Photograph of a rubble stone wall

Ashlar masonry: It is constructed of squared stones set in random or uniform courses [16]. In ashlar masonry, the stones are carefully worked and finely jointed [14]. Walls of squared stones of different sizes set in random courses are classed as random or broken-range ashlar. A wall of squared stones that is not measured and cut according to shop drawings, but is set at the discretion of the mason, is considered an ashlar wall. The surface finish of ashlar walls may be quarry face, hand split, or a finish compatible to the stone used. Uniform continuous courses of the same height are called regular-course ashlar [16]. The drawing of ashlar masonry can be seen in Figure 2.4 and a photograph can be seen in Figure 2.5 below.

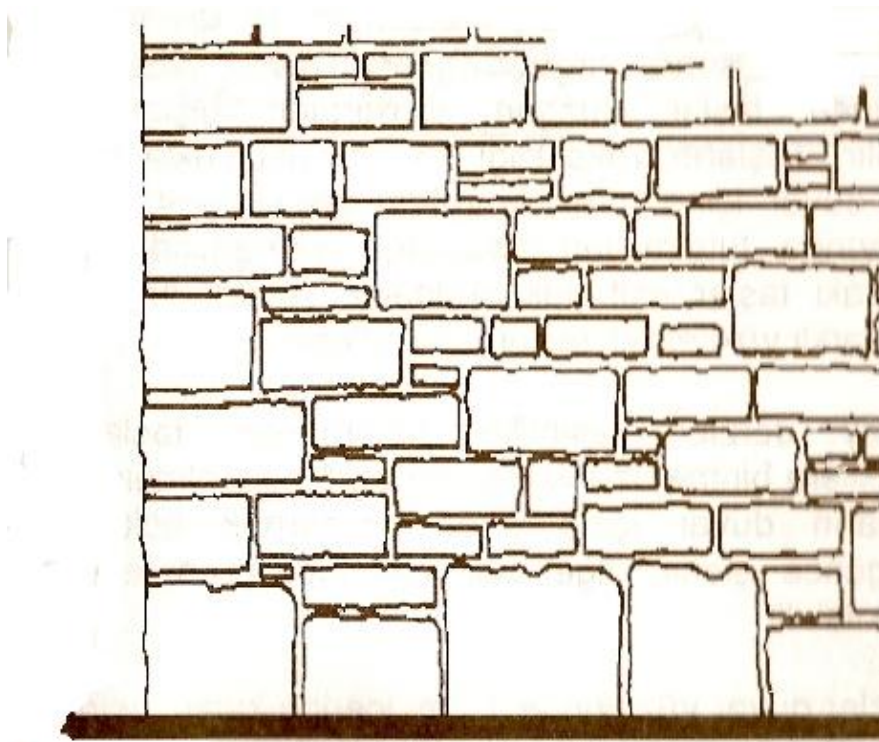


Fig 2.4 : An example of an ashlar masonry wall

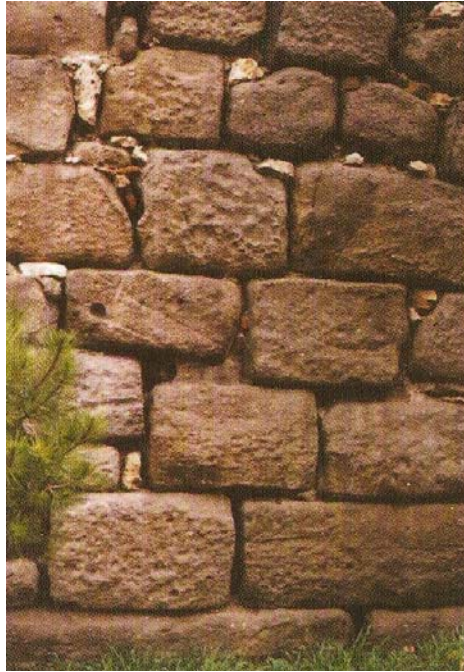


Fig 2.5: Photograph of the ashlar masonry

Cut stone masonry: It is sometimes called dimension stone, is defined here as stones which are wholly fabricated and finished at the mill ready to be set in the building in conformity to drawings and specifications. Each stone is numbered and located on shop drawings and setting diagrams [16]. A drawing and a photograph of cut stone examples are below in Figure 2.6 and Figure 2.7.

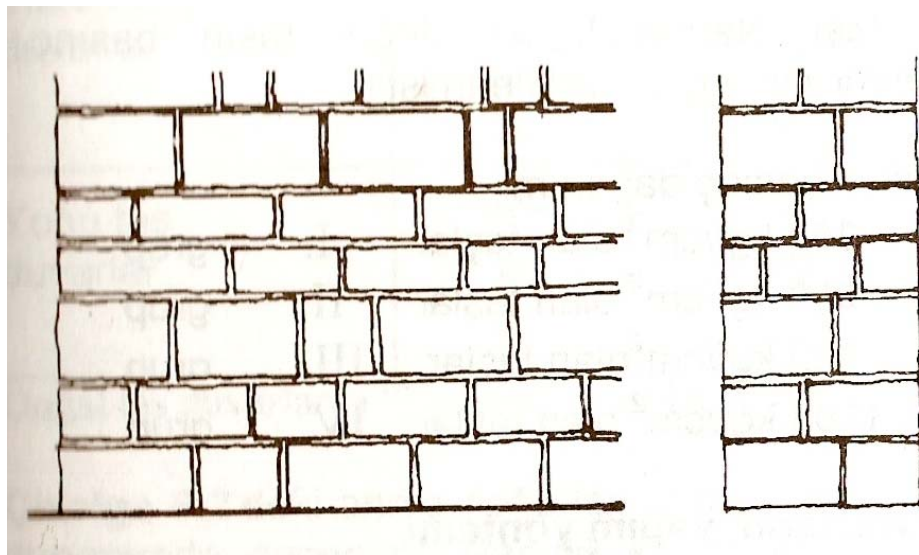


Fig 2.6 : Drawing of a cut stone wall



Fig 2.7 : Photograph of a cut stone wall

Traditional Stone Setting: Stone structures may be built in traditional mortar bed methods are placed either as rubble or as ashlar complete wall or as a facing for masonry. Finished joints may be either mortar or sealant filled. Traditional mortar bed setting methods are used today primarily to build stone retaining walls, planters, and the like; for installing stone copings and trim in masonry walls; and in restoration work on existing stone structures [11].

2.2.3 Alternating courses of brick and stone

Alternating courses of brick and stone is a wall construction technique used during both Byzantine and early Ottoman period. The system is not independent from both the brick and stone construction techniques. The repeating rates and joint techniques may change during periods, thus helping to date the building in some cases. According to the frequency of stone and brick courses, the rarely repeated material may behave as the bonding course. The technique will be further explained in detail, depending on the period it is used.

3. MASONRY WALL MATERIALS

Masonry materials must be able to satisfy the masonry system characteristics summarised before. Masonry materials may be used alone or in the system of more than one component. In case of a system, the system must be sufficient enough for the desired properties.

The main properties of masonry wall materials are [18]:

- Must be resistant to atmospheric effects, must not be affected and decayed by ultraviolet and infrared radiations;
- Must be resistant to freeze;
- Must not be affected by wetting and drying cycles;
- Must not exceed the acquired values of water absorption;
- There must not be capillary cracks, voids and surface deformations in the structure;
- Adhesion of structural materials with the mortar must be sufficient enough;
- Structural materials must have a convenient joint to supply an aesthetic look;
- The possibility of having moss, bacteria, mushroom and spore on the material and the joints must be prevented;
- There must be a harmony in colour, pattern and dimensions.

As the mechanical properties are functions of physical and chemical properties of the materials structure, there are certain experiments which are done to understand the mechanical behaviour. The analyses can be grouped as:

a. Macroscopic Analyses

- Texture
- Colour
- Dimensions

b. Microscopic Analyses

- Atomic Force Microscope (AFM)
- Optical Microscopy (OM)
- Scanning Electron Microscopy (SEM)
- SEM/EDS
- SEM/EDAX
- Fluorescent Light Microscopy
- X-Ray Diffraction (XRD)
- Polarizing Microscopy

c. Hygric Analyses

- Density
- Specific Gravity
- Water Behaviour Tests
- Freeze–Thaw Cycles
- Drying Index
- Water Absorption (by weight)
- Water Absorption (by volume)
- Water Absorption Rate and Capacity
- Capillarity and Capillarity Coefficient
- Saturation Degree and Saturation Coefficient
- Porosity
- Open Porosity
- Pore Size Distribution
- Porosimetry
- MIP
- Compactness
- Water Vapour Resistance Factor
- Moisture Amount Assessment
- Thermal Expansion Factor

d. Chemical Analyses

- Acid Dissolution / Wet Chemical Separation
- Sieve Analyses
- Aggregate Grading
- Binder/Aggregate Ratio
- Ignition Loss
- Carbonate Ratio
- Hydraulic Properties
- Determination of Moisture Content
- Water Soluble Components
- Detection of Organic Compounds Containing Proteins
- Detection of Oil
- pH
- Pozzolanic Activity
- Characterisation of Pigments
- Calcination
- Conductivity
- Salt Crystallisation Cycles
- Mineralogical Composition
- Salt Analysis
- Conductivity
- Protein Analyses
- Saponifiable Oil
- ICP
- Moisture Content

e. Thermal Analyses

- Infrared Spectrometry (FT) (FT-IR)
- Thermogravimetric Analyses (TGA) (TG-DTG) (TG)
- Differential Thermal Analysis (DTA)
- Differential Scanning Calorimetry (DSC)

f. Mechanical Analyses

- Compressive Strength
- Tensile Strength
- Flexural Strength
- E-modulus
- Hardness
- Crack Assessment

As a result of the experiments above, certain characteristics are observed. Mainly the behaviour of the material depends on the parameters below

Physical properties, such as unit weight, specific gravity, water absorption and saturation coefficient, are indicated by hygric tests. According to the physical properties, if unit weight and compactness increase, properties like strength and thermal conductivity increase. On the contrary if the porosity increases, strength and thermal conductivity decrease [19].

Saturation coefficient is important for frost resistance. When a material absorbs water and freezes, water expands 10% of its volume. If all the holes in the material are filled with water, then there stays no space for expansion and the ice pressure causes the material to explode. If less than 80% of the holes are fulfilled with water, then there remains enough space for the expansion. As a result, the frost resistance of the material depends either the saturation coefficient is less than 80% or not. In heavy stones, if the water absorption by weight is less than 1%, the material is resistant to frost [19]. In practice, open pores are important for frost resistance [20].

The materials can absorb and transfer the atmospheric gaseous and humidity, according to the percentage and continuity of the pores [19]. As explained before, the pore structure of the material is closely linked with the unit weight, water absorption, and permeability also [20]. Some of the pores are open and some are closed, open and capillary ones are important for water absorption and permeability [20]. The capillary water absorption of the material is proportioned with the surface area and time independent from the pressure [20]. Capillarity coefficient is related with the percentage and the types of voids of the material [19]. The amount of water absorbed at a unit time is related with water amount, pressure and surface area, inversely

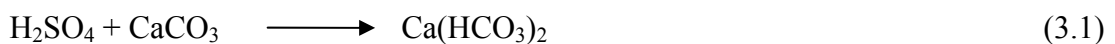
proportioned with thickness. There is also a coefficient related with the porosity of the material.

Thermal properties are results of thermal experiments. As the temperature rises, the atoms start to move more and more, and the distance between them increases, thus causing an increase in the length of the material. The most important factor of thermal expansion is the thermal stresses. If the material/element is fixed on both sides, as not letting it to change its length, then thermal stresses may cause the material/element to break [19]. Generally thermal conductivity is related with material type, structure of the material and the errors and the temperature [20]. Thermal conductivity (λ) is highly related with the unit weight of the material. Light weight and porous materials have smaller λ , causing these materials not conducting heat. Also the humidity of the material is an important factor. Humidity increases the thermal conductivity. If a material has a higher λ coefficient, then it is a good conductor, else, it is called an insulator [19].

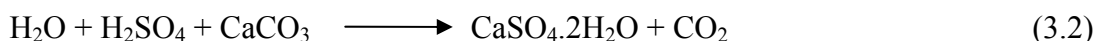
In some cases, the voids in the material structure transfer the water vapour from one side to the other. This is called the vapour permeability of the material. It is close to the water permeability but there are more complicated laws related with the subject. In certain cases, the percentage of the transfer of the gases or air can be important [19]. The pore structure of the material is also closely linked with noise and thermal insulation [20].

Chemical properties are results of chemical experiments.

The effect of the gases can be explained as; CO_2 and SO_3 in the air turn into H_2CO_3 and H_2SO_4 especially on rainy and foggy weathers. On the lime based materials [19]:



As a result, outer surfaces turn into a form that melts by water and so the material starts to rotten.



After the reaction, a volume expansion occurs and the material explodes.

The effect of water can occur different, depending the type of the water. One of the types of the water that harms the building material is pure water. As the CO_2 cannot find lime to neutralize itself in the water, then the reaction below happens;



H_2CO_3 occurs after the reaction, and then this turn limestone into $\text{Ca}(\text{HCO}_3)_2$ from equation (3.1) and material melts by the effect of the running water [19].

The second type of harmful water contains sulphates. Depending to the equation (3.2) it causes the expansion and explosions.

The third type is the sea water. It has also harmful effects on the material due to the NaCl and MgSO_4 having slight effects of sulphate [19].

The efflorescence effect damage can be seen especially on the walls, as a result of salts dissolved in water [19]. It is the result of capillary water absorption and evaporation from the material. The salts causing the efflorescence effects are mainly:

- a. KNO_3 or NaNO : can be cleaned with water.
- b. NaSO_4 : is the most common type on the brick walls, can be cleaned by water, depends on the sulphate in the coal smoke during firing meeting with the Na in the clay.
- c. $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$: the sodium sulphate in the brick and the lime in the mortar crystallises as gypsum.
- d. CaCO_3 : oily lime mortars, and cements with excess lime have this deterioration.

There are also the effect of chemical substances and the effect of organisms.

The effect of ultraviolet radiation from the sun also causes a chemical effect. The alpha particles of the ultra violet radiation hit the atoms of the material thus causing changes in the atomic structure [19].

3.1 Mortar

Mortars are organic or inorganic binder materials with aggregates filling the gaps between the building element or building materials and helping them to glue or cover. Although mortar accounts for as little as 7% of the total volume of masonry, it influences performance far more than this proportion indicates [11]. Mortar is a

structural material that keeps stone or brick together, which provides stability to the wall [24].

Mortar is placed in the joints between individual masonry or stone units in a wall or other building element to cushion the units and to provide a level setting bed for them. It also seals the spaces between the units, compensates for size variations in the units, and provides an aesthetic quality by creating shadow lines and colour effects [11].

There are different types according to the function they have in the structure:

Structural Mortar: It is used for construction of load bearing masonry walls.

Rendering Mortar: It is used to protect masonry facades or to make impervious walls that are exposed to humidity. Old mortars are characterized by their durability continue to play their role in the structure. They are generally of low strength in comparison with modern cement based mortars. They have been manufactured by using soft, low potential binders such as mud, lime and local pozzolan [22].

3.1.1 Production of mortar

Mortar is a combination of one or more cementitious materials (Portland cement, lime, or masonry cement); a clean, well-graded aggregate, such as sand; and enough water to give the mixture a plastic, workable quality [11]. They still have integrity, although they are composite materials consisting of binder and aggregate materials.

Mortars consist of binding materials, pozzolan, sand, water and additives as raw materials.

a. Binding Materials

The materials known as binders have the property of losing the plasticity that it had gained by adding water. In addition, the binding materials must have the property of gaining strength by time, after they form a paste by mixing with water. This gaining strength process is called setting. Setting is the mechanical strength gaining property of binding materials. Binding materials can be divided into two groups according to the environment they set:

- Air binders: They can only set in air because they need CO_2 to set. Fat lime, pure lime, dolomitic lime are examples. Non hydraulic materials will only harden slowly by absorption of CO_2 from the air [14].

- Hydraulic binders: They can set both in air or water. They do not need CO₂. Hydraulic lime is an example [21]. Hydraulic cements and limes set and harden by internal chemical reactions when mixed with water [14]. They are produced from lime stones with aluminium silica, and aluminium oxide and calcium silica produced after heating, binds with water and turns to aluminium hydroxide and calcium hydroxide [21].

Mortars can also be classified according to the main binder they contain:

- Gypsum mortar; gypsum is a natural substance, a compound of calcium sulphate (lime) and water. CaSO₄ additives and water/gypsum ratio influence the strength, workability and porosity of the hardened material. However, constant contact with water will dissolve gypsum, so unsuitable for external applications [21].
- Lime mortars; they have poor mechanical strength; but they provide good adhesion between stone and brick, and they have good workability.
- Cement mortars; they have high strength but are rigid and crack as the result of building forces [21]. Cement pointing is particularly detrimental if applied to soft stone or bricks. It is hard, no resilient and comparatively non absorbent. Nor it does not respond to the variations in the atmosphere to the same extent as the surrounding stone or brickwork. Hard pointing can cause rapid weathering of the softer stone or brick. Many causes of stone decay have been traced to the use of impervious mortar with a porous stone. In such cases saturation and evaporation are confined to the stone whereas the process should be distributed evenly over stone and pointing. Where a particularly soft stone is employed then the mortar should sacrifice itself for the stone [23].

The ratio of binder to aggregate ranges widely, but generally speaking it can be said that for the most structural mortars, it is 1/ 2.5 or 1/ 3, while for renderings and plasters richer in binder content, the ratio is mostly 1/ 1 or 1/ 1.5. The mechanical characteristics are mainly dependent on their binding system. However, in comparison with modern cement based mortars, it could be said that they possess low compressive strength, low modulus of elasticity and relatively greater deformability [22]. Some indicative values are given below:

- Low apparent specific density 1.5–1.8;
- High porosity 20–40%;

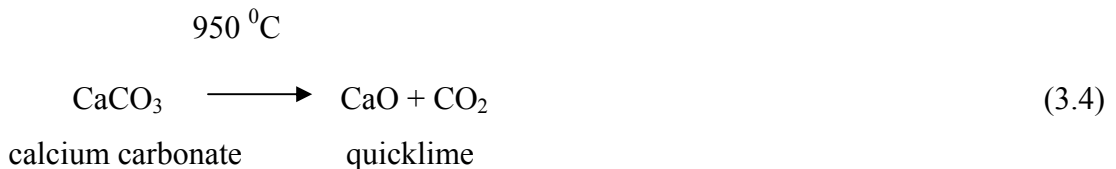
- Compressive strength ranges from 3 to 6 MPa;
- Modulus of elasticity ranges from 2 to 6 GPa.

The porosity of the mortars is high and usually ranges from 20 to 40%. In relation to the binder mixture, lime is usually present in excess. The most widely used ratio of lime to pozzolana is 1/ 1 [22].

Lime: Most pre 19th century buildings used lime mortars and plaster. Materials used to repair or replace original masonry should have similar properties so as not to disrupt the balance of interaction within the building. As gypsum mortars are not a part of masonry constructions, and as cement mortars are not used at the Byzantine and Ottoman buildings, lime will be the focused as the mortar material in this section [23].

Manufacture of Lime

Lime is manufactured by calcining natural carbonate, typically hard rock carboniferous stone. The mineral is quarried) crushed, washed and screened to the required size range [14]. Limestone (calcium carbonate), when burnt in a kiln, loses carbon dioxide and becomes quicklime (calcium oxide) [23]. Quicklime include calcium limes (CL) and dolomitic limes (DL) depending upon the composition of the starting mineral [14].



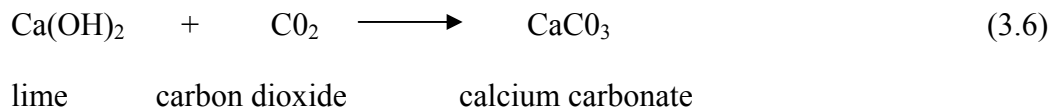
On contact with water, it combines with it, producing great heat, to form slaked lime (calcium hydroxide), also called lime putty [23].



Lime putty is produced by slaking quicklime with an excess of water for a period of several weeks until a creamy texture is produced. Alternatively, it can be made by stirring hydrated lime into water, followed by conditioning for at least 24 hours. However, the traditional direct slaking of quicklime produces finer particle sizes in the slurry; the best lime putty is produced by maturing it for at least six months [14].

Additionally, lime putty, often mixed with sand to form coarse stuff, is used directly as a pure lime mortar particularly in restoration and conservation work. It sets, not by reaction with sand and water, but only by carbonation and is therefore described as non hydraulic [14].

Lime hardens by the absorption of carbon dioxide from the air, which gradually reconverts the calcium oxide back to calcium carbonate.



This gradually takes up CO₂ (carbon dioxide) again from the air and changes back to calcium carbonate (CaCO₃). This ‘setting’ is called carbonation. Lime putty mixed with sand makes mortar. This then hardens into an artificial stone made up of grains of sand embedded in a mass of calcium carbonate [23].

The carbonation process is slow, being controlled by the diffusion of CO₂ into the bulk of the material. When sand or stone dust aggregate is added to the lime putty to form a mortar or render, the increased porosity allows greater access of CO₂ and a speedier carbonation process. Typical lime putty/ aggregate ratio for lime mortar mixes are within the range 1/ 2 ^{1/2} and 1/3 . Because of the slow carbonation process, masonry lifts are limited, and the mortar must be allowed some setting time to prevent its expulsion from the joints [14].

Lime wash, as a traditional surface coating, is made by the addition of sufficient water to lime putty to produce a thin creamy consistency [14].

The resulting lumps of quicklime are pulverized, and water is added in a hydrator to produce hydrated lime powder (which is calcium hydroxide, Ca (OH)₂. This may be packaged in large paper bags.

Hydraulic limes are manufactured from chalk or limestone containing various proportions of clay impurities. The materials produced partially harden through hydration processes, rather than solely through carbonation, as happens with non-hydraulic pure calcium oxide lime. Hydraulic limes rich in the clay impurities are more hydraulic and set more rapidly than those with only a low silica and alumina content. Hydraulic limes are categorised as feebly, moderately or eminently hydraulic depending upon their clay content, which is in the ranges 0-8%, 8-18% and

18-25% respectively. Eminently hydraulic lime mortar is used for masonry in exposed situations, moderately hydraulic lime mortar for most normal masonry applications and feebly hydraulic lime mortar is appropriate for conservation work and solid wall construction [14].

Hydraulic lime is gauged with sand only, giving a mix which develops an initial set within a few hours, but which hardens over an extended period of time. The workable mortar mixes adhere well and, because the material is flexible, the risks of cracking and poor adhesion are reduced.

Gypsum: Natural gypsum is crushed, ground and fired at kilns at temperatures between 300°C and 1000°C. This drives off the bound water with crystallization to produce different kinds of gypsum for building, according to the hydration stages of the calcium sulphate [21].

Cement: Cements are hydraulic binders for cement and concrete. They consist of compounds of calcium, silicon, aluminium and iron oxide. The composition of oxide depends on the type of the cement. The production of the Portland cement, the common one, involves firing a mixture of lime and clay at above the sintering limit, 1450°C. The cement clinker is grounded in ball mills to form a fine powder. Afterwards the addition of water enables cements to set in air and underwater by giving heat.

b. Pozzolan

Pozzolan does not have a binding property on its own. However it gains the property when mixed with a binder, like cement or lime. They contain a high percentage of colloidal elements, especially silica and lesser alumina [21]. There are two types according to their productions:

Natural Pozzolan: They are found at specific geographies, in Germany at Rennsteig region, in Italy Naples and Rome, and Santorin Islands of Greece. In Turkey, Kayseri region is rich [21].

Artificial Pozzolans may be grouped into two:

Baked Clay: Clay is heated to 600-900 °C. Then the material is grinded to the size of cement and mixed. The mixing of brick or tile powder with binder gives the same result. The binding property of pozzolan is explained by the free lime as the result of

hydration of active alumina. Horasan mortars are binders made with brick powder and lime. This material has better properties than lime. Before the use of cement, water durable materials were only produced by pozzolan [27].

Fly Ash: It is ash remaining from the coal powder burning at thermal stations' blast-furnace slag. Slag is the remaining material after the production of iron, when the iron is taken out of the furnace. It is consisted of alumina, silica and lime [27].

c. Sand

Sand is used in mortars as the filling material and as the skeleton of the mix. Mortars can be prepared for different workability situations. For a better workability of mortars, all the voids between the sand particles must be filled with binder paste and all the sand particles must be covered by a thin paste film helping them to slip over each other. The optimum granulometry of the sand (fine and coarse particles together) makes less binder paste used to fill the voids. To increase the compactness of the total, aggregates of different radiuses must be used, so that the smaller ones will fill the voids between the bigger ones [19].

d. Water

Water is used for better workability and for the viscosity for bonding property. If the water percentage of the mortar is more and the percentage binder is less; then mortar is weak and sand particles fall apart.

e. Additives

3.1.2 Mortar properties

Requirements expected from the mortar depend on the type of the mortar, due to its role and function in the structure.

Functional requirements derive from both the role and the function of the mortars in the masonry element and the role of the masonry element in the building [2]. The most important functional requirements are considered to be:

- To ensure the load bearing capacity of the wall and, when applicable, good earthquake behaviour;
- To prevent water penetration through a wall; the sequence of pore size distributions;

- To resist different kinds of environmental influences and processes acting on a wall and protect the user of the building against negative effects; in this respect the estimation of environmental conditions (macroclimate and microclimate);
- The diagnosis of the degradation mechanism should be determined to avoid any eventual detrimental effects;
- To contribute to the aesthetic appearance of a facade.

Technical requirements are defined starting from a systematic analysis (chemical, mineralogical and physical analysis, and also includes damage analysis). Also series of requirements (values / authenticity, concepts and functional requirements) must be refined and translated into technical requirements [2].

The most decisive technical characteristics for compatibility between new and old mortar are:

- Surface features (colour, texture, surface finish);
- Composition (type of binder, type of aggregates, grain size distribution);
- Strength (compressive, tensile and bond);
- Elasticity (modulus of elasticity, deformability);
- Porosity properties (total porosity, apparent specific gravity, pore size distribution, water absorption by capillarity and vapour transport);
- Coefficient of thermal dilation;
- Durability;
- Swelling by water.

As the mortars are placed while plastic and then harden, they must have two sets of properties: both the properties present when they are in their plastic state, and properties that result after they have hardened. Proper plastic properties and hardened properties are both necessary for a mortar to be suitable for use in building construction. Both sets of properties affect a finished wall's strength, durability, and water tightness [11].

The plastic properties are:

- Workability

A workable mortar is uniform, cohesive, and of a consistency that makes it usable. A mortar is workable when particles in the mix do not segregate and when it spreads

easily, holds the weight of the units, makes alignment easy, clings to the vertical surfaces of masonry units, and easily extrudes from the mortar joints without dropping or smearing.

Calcination and slaking are very important operations in the manufacture of building limes as they govern properties such as lime reactivity, shrinkage, density and water retention capacity, which in turn determine workability, plasticity and carbonation speed. It has been demonstrated that underwater storage following slaking of quicklime improves plasticity and workability of limes due to particle size reduction and morphology changes [27].

Water retention, flow, resistance to segregation, and other factors affect a mortar's workability. These in turn are affected by the properties of the mortar ingredients. This complex relationship makes quantitative estimates of workability difficult [11].

- Water retention

Water retention in a mortar prevents rapid loss of water and a resultant loss of plasticity when the mortar contacts a masonry unit with a high absorption rate. A high degree of water retention also prevents a mortar from bleeding when it comes into contact with a masonry unit that has a low absorption rate. Bleeding is a process in which water leaves the mortar and is deposited in a thin layer between the masonry unit and the mortar. When this happens, the unit is said to float. This floating materially reduces bond [11].

- Initial flow and flow after suction

The water retention of a mortar is the ratio of a plastic characteristic called flow immediately after mixing to the flow of the same mortar after suction [11].

The hardened properties are:

- Bond strength

It mainly depends on the power of the binder, the consistency of the mortar, the roughness of the surface, porosity, the area of the surface, the amount of water in the mix, the water retention characteristics of the mortar or the entrained air content, and the mortar's compressive strength [11, 22]. The amount of water in a mortar mix and its water retention affect its flow. As there is more water, the greater the flow is. A mortar's tensile bond strength is a mechanical function rather than a chemical one.

The mortar flows into pores in the masonry unit and interlocks with them. Therefore, bond strength always increases as the mortar's flow increases because wetter mortar flows more readily into these pores. When the air content of a mortar exceeds 12% there is an accompanying decrease in bond. The type of masonry unit in contact with a mortar can affect its bond strength. Masonry unit characteristics that can affect bonding include surface texture, the suction of clay masonry units. The air temperature and relative humidity during the curing period a mortar can also affect its bond strength [11].

- Compressive Strength

Strength depends on the type of the binder and the porosity. The compressive strength of a mortar rises when the cement content is increased. Conversely, a larger flow brought about by a rise in the water content of a mortar will decrease its compressive strength [11].

- Volume Change

Volume stability depends on the type of the binder. Also as volume stability is a function of shrinkage; it is related with binder amount and water amount [11].

- Water-Tightness

When a wall leaks significantly, and there are no major holes in it, fine cracks between the mortar and the masonry or stone units, especially in the vertical joints, are usually the culprit. The water tightness of the masonry units themselves, or of mortars commonly used today, is seldom a factor in wall leaks [11].

- Rate of Hardening

The rate of hardening of mortar is the speed at which it develops a resistance to indentation and crushing. Too rapid hardening may interfere with the use of the mortar by a mason. Hardening too slowly may impede the progress of the work or may subject mortar damage from frost action during winter. A well defined, consistent rate of hardening allows a mason to tool joints at the same degree of hardness and thus helping to obtain uniform joint color [11].

Table 3.1 below shows the colour and compressive strength values for building limes.

Table 3.1 : Properties of building limes

Lime Description	Color	Compressive Strength	
		at 28 days (MPa)	Proposed range (MPa)
Fat lime (pure lime)	white	No strength requirement	0.3-0.5
Slightly hydraulic lime	off-white	1.3	1.3-2.0
Feebly hydraulic lime			
Moderately hydraulic lime	Pale grey of buff-coloured	2.6	2.0-5.0
Eminently hydraulic lime	Darkest colour	6.0	5.0-10.0
Natural cement hydraulic lime		10.0	≥10
Pozzolanic lime			

3.1.3 Analysing mortar quality

The purpose of mortar and plaster analysis of historical buildings is not to make a quality control of the material used, but to determine the physical, chemical and mechanical properties [24]. The analysis has to provide answers of a cognitive nature so as to identify raw materials, their relationship to each other, the dimensions of the aggregates, and to furthermore define the microstructure, identify the extraneous compounds and, if possible, the quality of the existing adhesive bond with the support [28].

a. Macroscopic Analyses

The macroscopic analyses are done to investigate colour, dimensions, and the consistency of the aggregates [28].

b. Microscopic Analyses

With the microscopic analysis, which permits the identification and even quantification of proportions of components, a qualitative and quantitative distinction between binder and aggregate, is possible. The content and shape of air voids and cracks qualitatively indicate something about the mechanical properties of the mortar and about the moisture content at the time when it was applied [31].

- Petrographic microscope

Petrography (using polarising and fluorescence microscopy) applied to thin sections of the material is a proper method to gain understanding of the named compounds as well as of the composition of the mortar [30]. The petrographic microscope is also an essential tool in building material science in order to study, size and shape of mineral grains and matrices; their relationships and arrangement; their decay and the

presence of pores, cracks, cements and directional textures, the analysis of the structure and texture of the mortar (meaning the spatial distribution of components) [28, 32]. Also it can provide information about the current bonding, the kind of binder and aggregate, even partly about the hardening process, how the mortar was applied, preliminary information about the use of additives and admixtures in the mortar [31].

- Fluorescent Light Microscopy

When the samples are impregnated with a fluorescent resin, fluorescent light microscopy (using ultraviolet light) can be used to visualise in more detail the structure of pores and cracks [31].

- X-ray Diffraction Analysis (XRD)

If no information is available about the original materials then the determination of its composition is a primary aim. Following a qualitative assessment using visual analysis, the binder (lime, gypsum, cement and other hydraulic components etc.) and the aggregate (siliceous, calcareous and other natural or artificial aggregates), grain dimension, shape, location system, colour, tissue and crystal structure can be identified with X-ray diffraction analysis (XRD). X-ray diffraction (XRD) analysis is suitable for the identification and differentiation of binders and kinds of aggregate within a mortar, if they are crystalline. XRD can only clearly identify phases when they are present and have sufficient quantities for the equipment to detect, usually [25, 32].

- a. Investigation of binders
- b. Investigation of aggregates provides information on the mineralogy of the aggregate, but not necessarily about the lithologies of the grains present in the aggregate.
- c. Investigation of admixtures and additives generally, organic additives cannot be identified using X-ray diffraction.
- d. Evaluation of X-ray diffraction analysis helps the determination of the relationship between the binders, aggregates and admixtures, as well as hints at possible interaction with the environment (e.g. efflorescence) [31].

- Scanning Electron Microscope (SEM)

Other methods of analysis in determining the grain dimension, shape, location system, color, tissue and crystal structure, morphologies, microstructures and chemical compositions are scanning electron microscope (SEM) and elemental dispersive analysis (EDAX) [25, 26]. Characteristics of brick–lime interfaces and their composition are investigated using SEM-EDS [25].

FESEM secondary electron images of thin polished sections of mortar+brick and mortar+calcarene samples can be taken in order to analyse their texture and degree of porosity especially in the contact zone [29].

General microstructural observations are performed by both secondary electron image (SEI) and BSE (backscattered electron image) coupled with EDS to identify the microstructural features [26].

- Atomic Force Microscope (AFM)

Characteristics of brick–lime interfaces and their composition are also investigated using atomic force microscopy (AFM) on polished sample surfaces [25].

c. Hygric Analyses

Water absorption, desorption and capillarity tests are performed to determine the amount of water retained and evaporated, as well as the speed at which these processes took place. The following parameters can be obtained: free water absorption, drying index, capillarity, saturation coefficient, open porosity, apparent density and real density. The distribution of the pore access size and the pore volume enable us to study the relationship between the materials.

d. Chemical Analyses

- Acid Dissolution / Wet Chemical Separation

Wet chemical separation (acid dissolution) is done to determine the chemical composition of the acid-soluble binder and, after separation, information on the mortar's aggregate. It is limited, when aggregate is acid soluble [32].

Regarding the characterisation of the binder and the determination of its content in the mortar, it is assumed that the acid soluble parts of the examined building material sample result solely from the binder. As "leading oxides" for the determination of

binder or, if necessary, also of a two component mix, the contents of calcium oxide (CaO), magnesium oxide (MgO), silicon dioxide (SiO₂) and sulphate (SO₃), after ignition, can be used [32].

- determination of the soluble Fe₂O₃
- determination of the soluble Al₂O₃
- determination of soluble CaO
- titration and calculation of soluble CaO and MgO
- determination of the soluble SO₃
- determination of sulphides
- determination of soluble Na₂O and K₂O
- determination of ignition loss

The content of siliceous aggregate is related to the sample being free of ignition loss and thus gives the aggregate content within the original mortar [32].

- Sieve Analyses

Sieve analysis is made in order to determine the grain dimension dispersion of the material used as aggregates. If there are additional fibrous additives like hay, it is revealed during the analysis [24]. Raw materials of the mortars are determined by dissolving their binder in dilute hydrochloric acid and sieving the undissolved brick powder in a standard sieve set [25]. If the binder in the original mortar is lime, sieve analysis is made after solving the mortar in acid. If the binder is soil, the sieve analysis is made for the aggregate after it is dissolved in water. Particle size analyses is done to assess the granulometry of the mixtures and to obtain information about single component [28]. The size grading curve of the aggregate and the binder to aggregate ratio are interesting for the characterisation and "reproduction" of the mortar [32].

- Moisture Content
- Water Soluble Components

Owing to a building's position or the influences of environment, substances such as salt, can penetrate the mortar or can be developed there which result in a transition or change of physical and chemical properties [32]. Other experiments under the heading of chemical analyses are the analysis of salts dissolved in water. They are

chloride (Cl^-) analysis, sulphate (SO_4^{2-}) and carbonate (CO_3^{2-}) analysis, nitrate (NO_3^-) analysis, protein analysis and saponifiable oil analysis [24].

- Detection of Organic Compounds Containing Proteins

While ingredients such as hair, straw or charcoal can be seen macroscopically after binder dissolution, or with a microscope, substances containing proteins which hint at the use of casein, whey or blood serum can only be identified qualitatively with a specific kind of analysis [32].

- Characterisation of Pigments

Inorganic pigments can only be found with an analysis if they are materially and structurally different from the binder or aggregate. As the detection of pigment enrichment and also the characterisation of its spatial distribution in the mortar are required, the use of SEM is recommended, which combined with electron beam micro analysis can characterise the chemical composition of pigment particles or pigment agglomerates. In this way one can also visually present the distribution of pigments in the mortar [32].

- ICP

The material is expressed in terms of chemical formulas with the ICP analyses minerals [24].

- Calcination

Calcination, carbonate determination test is made by heating the sample mortar at high temperatures and calculating the amount of loss [33]. Calcination analyses are made in order to determine the type of the binder, presence of organic matter and their ratios of presence, determination of humidity, water content, loss through heating and the content of organic matter are revealed [24].

e. Thermal Analyses

- TGA

Hydraulic properties of the mortars can be predicted by determining the weight loss due to chemically bound water of hydraulic products between 200 °C and 600 °C, and the weight loss due to the CO_2 content of the carbonated lime between 600 °C and 900 °C by TGA [19]. Their utility for use in the moist environment may be

explained by their hydraulic characteristics due to the reaction products of lime binder with brick aggregates at the brick lime interface and the pores of the bricks [25].

- Infrared Spectrometry (IR)

Infrared spectroscopy (IR) is used for the qualitative identification of the various compounds that are present in the mixtures [28]. By using Infra-Red spectroscopy (IR), especially Fourier Transform Infra-Red spectroscopy (FTIR), in addition to the identification of the main mineral phases in a binder, small quantities of admixtures and additives can be identified [31].

- Thermogravimetric Analyses (TG)

Thermogravimetry (TG) measures the weight loss in a sample as it is heated. Weight loss during heating can be related to specific physical decompositions in the materials [31]. Thermogravimetric analysis (TG-DTG) help to determine quantitatively the various compounds in the total sample and in the corresponding finer sieved fraction, which is considered to mostly constitute the binder [28].

- Differential Thermal Analysis (DTA)

With DTA, a graph is continuously plotted during heating that shows the temperature difference between the sample and an inert standard, which is heated at the same rate and at the same time. Endothermic peaks are recorded usually the loss of chemically bound components, for example water from gypsum or CO₂ from calcite and dolomite. The endothermic or exothermic transitions are characteristic of particular minerals, which can be identified and quantified using DTA [31].

- Differential Scanning Calorimetry (DSC)

During heating using DSC, energy is added to maintain the sample and the reference material (Al₂O₃) at the same temperature. DTA and DSC pose another advantage over TG in the identification of minerals in mortars in that they are capable of resolving polymorphic transformations in compounds that do not involve weight loss [31].

e. Mechanical Analyses

- Compressive Strength

Compressive strength tests must be done to the samples to identify the strength.

- Flexural Strength

Flexural tests may be done by three-point flexural test method.

A summary of the experiments done to mortars to characterise them can be seen below in Figure 3.1.

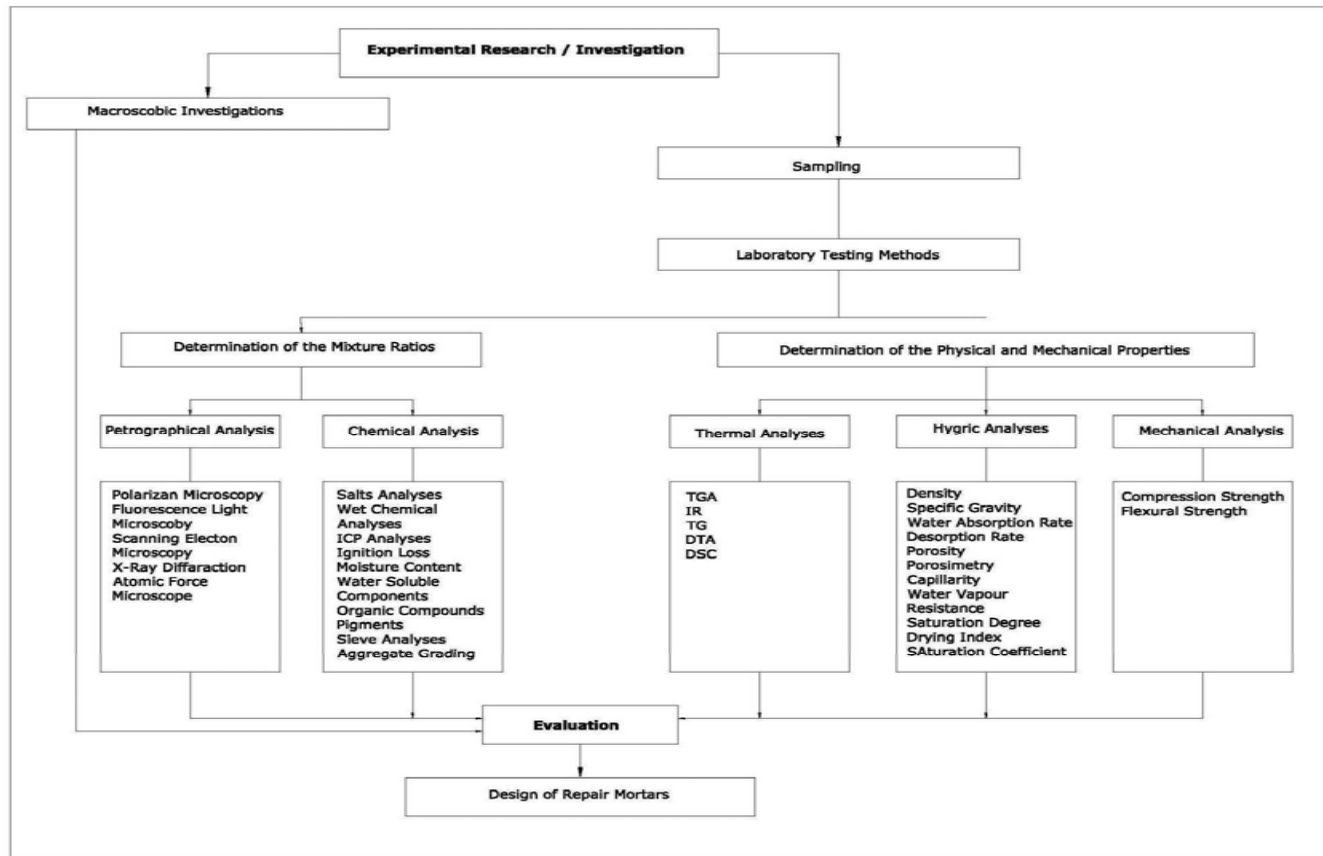


Figure 3.1 : Schematic flow diagram of the mortar experiments [24]

3.1.4 Factors affecting mortar durability

The main parameters affecting durability are:

- Composition

The natures of the raw materials also determine the properties of and durability of mortars. For example, the presence of magnesium lime and/or reactive aggregate can impart a hydraulic set and therefore determine the quality of a mortar [27]. The most durable old mortars contain substances with reactive silica from local deposits or brick dust incorporated into the lime in order to increase the strength and resistance of the mortar.

- Production

Long slaking has also been associated to an increase in the water retention capacity of lime thus facilitating carbonation therefore enabling development of an early strength and improving mortar durability [11].

- Hygric Properties

The durability of mortar is measured principally by its ability to resist water penetration. Repeated cycles of freeze and thaw, under natural weather conditions will cause the surface of the mortar or masonry unit to pop off (spall) [11]. The results of freeze and thaw resistance and wet and dry cycles may influence the drying behaviour of the whole masonry and therefore may be decisive for durability of the whole [2].

- Porosity

The response of the mortar to the environmental action (hydrothermal changes) is governed by its porosity and composition. Long-term deformations are also influenced by porosity and pore size distribution. Many processes influence the development of the pore morphology [2].

Higher porosities allow better portlandite carbonation. A relationship between mechanical properties and pore structure can be established. However, in case of binder excess, the increase in voids leads to a strength reduction. The use of calcareous aggregates improves strength more as compared to the use of siliceous aggregates. Factors as grain size distribution and grain shape of the aggregates must be considered [3]. The dimension of the ceramic fragments affects directly the

hydraulic reactivity, but also the physical-mechanical behaviour in terms of porosity, transportability, lightness and adhesion [27]. It is clearly determined that porosity influences the strength of cement-based mortars. As previously indicated, porosity reduction causes the strength to increase. However, in lime-based mortars, larger amounts of binder cause porosity increase because lime is a very porous material [3]. Also, as porosity ratio decreases, both compressive strength and durability increase.

- Salts

When even after thousands of years cracking is limited, it is due mainly to salt crystallization. The crack openings may be reduced by the formation of recrystallization products [22]. The content of soluble salts or impurities should be low in order to avoid efflorescence and crystallisation damage. Water entering a mortar will dissolve salts in the mortar. These salts will then leach out into or onto the surface of adjacent masonry. Upon drying, these salts will crystallize. Salts that crystallize on the exterior face of a wall (efflorescence) are unsightly but do little harm. However, when the crystallization occurs within a wall (subflorescence or cryptoflorescence) considerable damage can result. Subsequent wetting followed by drying causes larger and larger crystalline deposits forming, until the deposits grow large enough to cause the surface of the mortar or masonry units to spall [11].

- Compressive Strength

The strength of mortars is closely related with the durability of them. The strength characteristics depend on a couple of parameters:

Elasticity (modulus of elasticity, deformability): It can be estimated on the basis of the compressive strength [2]. The compressive strength is closely related to tensile strength and elasticity whose properties affect the deformability of masonry [2].

Binder/Aggregate Ratio: In general, binder decrease in the mortar reduces its strength. In spite of the fact that larger amounts of binder increase the total porosity, the strength can also be increased [3].

Curing Time: It takes a lime mortar many years to reach its total carbonation [3]. Obviously, because of binder hardening, the mechanical strengths increase with curing time. However, the age at which lime mortars exhibit their peak strength is unknown. It is also unknown how the mortar strength varies quantitatively with curing time, i.e., the degree of carbonation [3].

Aggregate Characteristics: For the strength results, it is observed that the grain size distribution of the aggregates is the most important attribute in relation to aggregate characteristics. An adequate grain size distribution allows the development of a high strength in the mortar [3].

3.2 Brick

Excavations in Egypt show that the ancient Egyptians used sun-dried and kiln-fired bricks for houses and palaces of nobility. In the Babylonian civilization (4000 B.C.), which developed in the valley of the Tigris and Euphrates Rivers, the thick mud and clay laid down by these rivers was well suited for brick, which thus became the usual building material of this civilization. Palaces and temples were constructed of sun-dried brick, faced with brilliant kiln-fired glazed brick [13].

The Romans also made wide use of brick, in conjunction with the very efficient mortar of volcanic tufa and lime. The Roman bricks were comparatively thin for their length. They were laid in thick beds of mortar in several patterns. After the fall of the Roman Empire the art of brick making was lost throughout Europe until the beginning of the 14th century.

Bricks are generally classified as adobe, made of natural sun dried clays or earth and a binder; fired clay, composed of clays or shales to which other materials may have been added and fired to achieve hardness; sand lime, mixtures of sand and lime hardened under steam pressure and heat; and concrete, solid or cored units composed of portland cement and aggregates [13]. The types of the bricks, possibly used, within the scope of the thesis are:

Kiln-fired Brick: The most widely used type of building brick is made of natural sand and clays or shale. These clays are composed of silicate (SiO_2) or alumina (Al_2O_3) and small percentages of other minerals. Clays with a large percentage of feldspar and iron oxide turn a salmon, red, or brown on firing. Clays with a large percentage of calcium carbonate (CaCO_3) burn to a yellowish color. Shale is a type of clay that has been solidified under pressure. It is not soluble in water in its solid form and must be ground or pulverized to be used in the manufacture of clay products [13].

Sand-Lime Brick: Sand-lime brick is a pearl-grey brick formed much like dry-pressed burned-clay brick. Lime, in the form of dolomite lime or a high calcium

lime, is mixed with clean, washed sand and allowed to stand for several hours before it is delivered to a press. The brick is then allowed to harden in closed vessels under steam pressure. The grading and use of sand-lime brick is similar to that of hard burned clay brick [13].

3.2.1 Brick production

In general, the manufacturing process consists of mining (winning), preparing, and storing the raw materials; and forming, drying, glazing, burning, cooling, drawing, and storing the finished units [34].

Raw Materials: To satisfy production requirements, the clays used in making clay masonry units must have enough plasticity so that they can be shaped or moulded when mixed with water. They must also have sufficient tensile strength to maintain their shape after they have been formed. The clay particles must fuse when they are subjected to high temperatures in a kiln. The types of clays used to manufacture clay masonry units take three principal forms having similar chemical compositions but different physical characteristics. All are compounds of silica and alumina with varying amounts of metallic oxides and other impurities. The metallic oxides act as fluxes, which promote fusion at lower temperatures than would be possible without them. They also influence the color of finished units [34].

Most natural clay contains impurities such as soda (Na_2O), potassium (K_2O), and lime (CaO), which act as fluxes when the clay is heated. Bricks are made by pressing or extruding moist clay, or mixture of clay and shale, into the desired shape. Dry pressed bricks are made from raw material ground with only a little moisture to a crumbly consistency, which is pressed into moulds with appreciable force. Semi dry pressed or stiff plastic bricks are made with a slightly moister mix [12].

Extruded or wire cut bricks are made from clay mixed a plastic consistency, which is extruded through a die. After extrusion bricks are cut to the required thickness with a taut wire. The bricks produced by any of these processes must be strong enough to be handled and stacked. To avoid distortion during firing, they are first dried gradually in warm air. They are then fired in a kiln and allowed to cool slowly. During firing the clay is partially vitrified, that is a glassy substance is formed by the clay and fluxes which binds the material. Depending on the type of brick, the visual vitrification may be considered a defect, or it may be a desirable feature which gives

a texture to face bricks. The temperature and the time of firing must be carefully adjusted for each particular type of clay, and for the type of brick to be produced. Too short firing produces a brick that lacks durability and strength. Too much firing causes the brick melt partially, so that it loses its shape and adheres to other bricks [12].

Firing : The product does not become water-resistant until it has been fired. The foliar clay structure fuses at a temperature of about 800 °C. The earthenware produced in this way has a high capillarity. From about 1200 °C the sintering process takes place: the aluminium compounds fuse to produce a vitreous structure. Cavities are surrounded, and the capillarity thus reduced to a minimum, giving a frost proof sintered product. Ceramics lose volume in the firing process. This cannot be predetermined, and means there are high dimension and product tolerances [13].

All but the hardest burnt bricks can absorb an appreciable amount of water, and they expand slightly as they do so, and contract again as they dry out. All bricks expand slightly in warm weather, and contract again as the temperature drops. A more important phenomenon is brickwork growth, which is an expansion that occurs after the bricks are removed from the kiln. For most bricks all the growth that is likely to occur will have taken place after six months, but for some the expansion continues at a reducing rate for many years [12].

3.2.2 Brick properties

The properties expected from bricks depend on the requirements that the masonry bricks must satisfy.

The functional requirements expected from masonry bricks are:

- To ensure the load bearing capacity of the wall;
- Preventing water penetration through a wall;
- Resisting different kinds of environmental influences;
- To contribute to the aesthetic appearance of a facade.

The technical requirements related with the functional requirements are:

- Surface features;
- Composition;

- Strength (compressive, tensile);
- Porosity properties;
- Coefficient of thermal dilation.

The properties of finished units depend on the characteristics of the raw materials and the effects of the manufacturing process [34].

As there are not any free electrons within the structure, ceramic materials are good insulators of electricity and heat. As the atomic bonds are stronger than the metals, they have higher strength to thermal and chemical effects. On the other hand, they are fragile and break under little stresses. They are hard materials. However, due to the crystal structure, ceramics cannot creep and do break easily. Theoretically, fracture strength of the ceramics is rather high, but according to the structural reasons, the tensile strength is practically low. They have a good compressive strength [15]. The resistance to radiation of ceramics is rather low. This is because the ceramics are ionic or covalent material without free electrons. Strength, brittleness, electrical conductivity increases, colour changes by the effects of radiation.

- Porosity

The durability of clay masonry units is affected by pore size within the units and by the amount and completeness of fusion during firing. In general, higher firing temperatures produce harder clay masonry units [34].

A major weathering action that affects fired clay masonry units is alternate freezing and thawing in the presence of moisture. Units produced from the same raw materials and by the same method of manufacture may have different resistances to damage by freeze-thaw cycles depending on their compressive strengths and absorption. Units with high compressive strength and units with low absorption are usually the more resistant to damage during freeze-thaw cycles.

- Compressive Strength

The clay, the method of manufacturing, and the degree of firing affect compressive strength. With some exceptions, the plastic clays used in the stiff mud process have higher compressive strengths when fired than do the clays used in the soft mud or dry

press process. For a given clay and method of manufacture, higher compressive strengths are associated with higher firing temperatures [34].

- Water Absorption

The degree of water absorption also depends on the clay, manufacturing method, and temperature of firing used. Plastic clays and higher firing temperatures generally produce units having lower absorption. Generally, the stiff mud process produces units with lower absorption than either the soft mud or dry press process. Suction, which is the initial rate of absorption of a brick, results from pores or small openings in the fired clay that act as capillaries to draw or suck water into the unit. Suction has little bearing on the transmission of free water through a brick, but it has an important effect on the bond between brick and mortar [34].

Table 3.2 below shows the properties of the bricks required in the building codes TS-EN 771-1, TS 704 and [15].

Table 3.2 : The required properties of solid bricks

Property	Value	Unit
Density	1,8	g/cm ³
Water Absorption (by weight)	10	%
Compressive Strength (average)	20	N/mm ²
Compressive Strength (minimum)	16	N/mm ²

3.2.3 Analysing brick quality

To date, only a limited number of non destructive techniques, such as thermography or ultrasonic testing, can be used to characterise historic bricks in situ. [35]

a. Macroscopic Analyses

The parameters like the dimensions, colour, and texture are documented by macroscopic investigations. The dimensions of the bricks may show characteristics of certain periods, or construction styles, the colour may help the determination of raw materials.

b. Microscopic Analyses

- X-Ray Diffraction (XRD)

The mineralogy and textural study of the bricks is determined by X-ray diffraction (XRD) [37, 38]. It must be known that the calculated values are not always in agreement with observations made using other analytical techniques such as SEM or OM [35].

- Scanning Electron Microscopy (SEM) and Optical Microscopy (OM)

The textural evolution of the bricks and the changes in the components of the prograde phases can be studied by scanning electron microscopy (SEM), as well as the vitrification evolution [37, 38]. SEM reveals how the shapes of the pores in the bricks as well as the brick texture undergo significant changes depending on the firing temperature and raw clay composition. Porosity and pore size distribution results can be obtained from digital image analysis (DIA) of scanning electron microscopy photomicrographs. DIA discloses the evolution of size, shape and connectivity of macro pores ($r > 1 \text{ mm}$) and evidences that MIP results underestimate the macro pore content [38].

c. Hygric Analyses

- Water Behaviour Tests

These are performed to determine the saturation coefficient and the drying index. Also, the evaporation curve can be established [35]. Porosity and pore size distribution results are obtained from hygric tests. Pore shape, spatial distribution, and connectivity can be found also [38]. The porosity accessible to water can be calculated from water absorption data according to recommendations. Both free and under pressure absorption of water and drying tests may be carried out [36, 37]. The differences in the hygric behaviour of bricks can be further confirmed by capillarity tests [38].

- Freeze–Thaw Cycles

In order to evaluate their decay behaviour, brick samples must be exposed freeze–thaw cycles. These help to evaluate the degree of durability of the bricks with time and to study how the texture and pore system is affected by the water change from liquid to solid state [37].

- Mercury Injection Porosimetry (MIP)

The analysis of the pore system of the bricks was carried out by studying its behaviour in different tests at the presence of water and in mercury injection porosimetry (MIP) [37]. Also MIP gives a good estimate of the open porosity and of the distribution of pores with $r < 1 \text{ mm}$ [38].

d. Chemical Analyses

- Salt Crystallisation Cycles

Salt crystallisation cycles can be applied also to evaluate their decay behaviour [35].

- ICP

ICP analyses help to determine the chemical formulas of the material [24].

e. Mechanical Analyses

- Compressive Strength

To analyse the mechanical behaviour of the bricks the velocity of propagation of ultrasonic waves and the compressive strength must be measured in the specimens using a ultrasound generator [37].

- Hardness

A table for the characterization of the bricks is visualised in Figure 3.2 below.

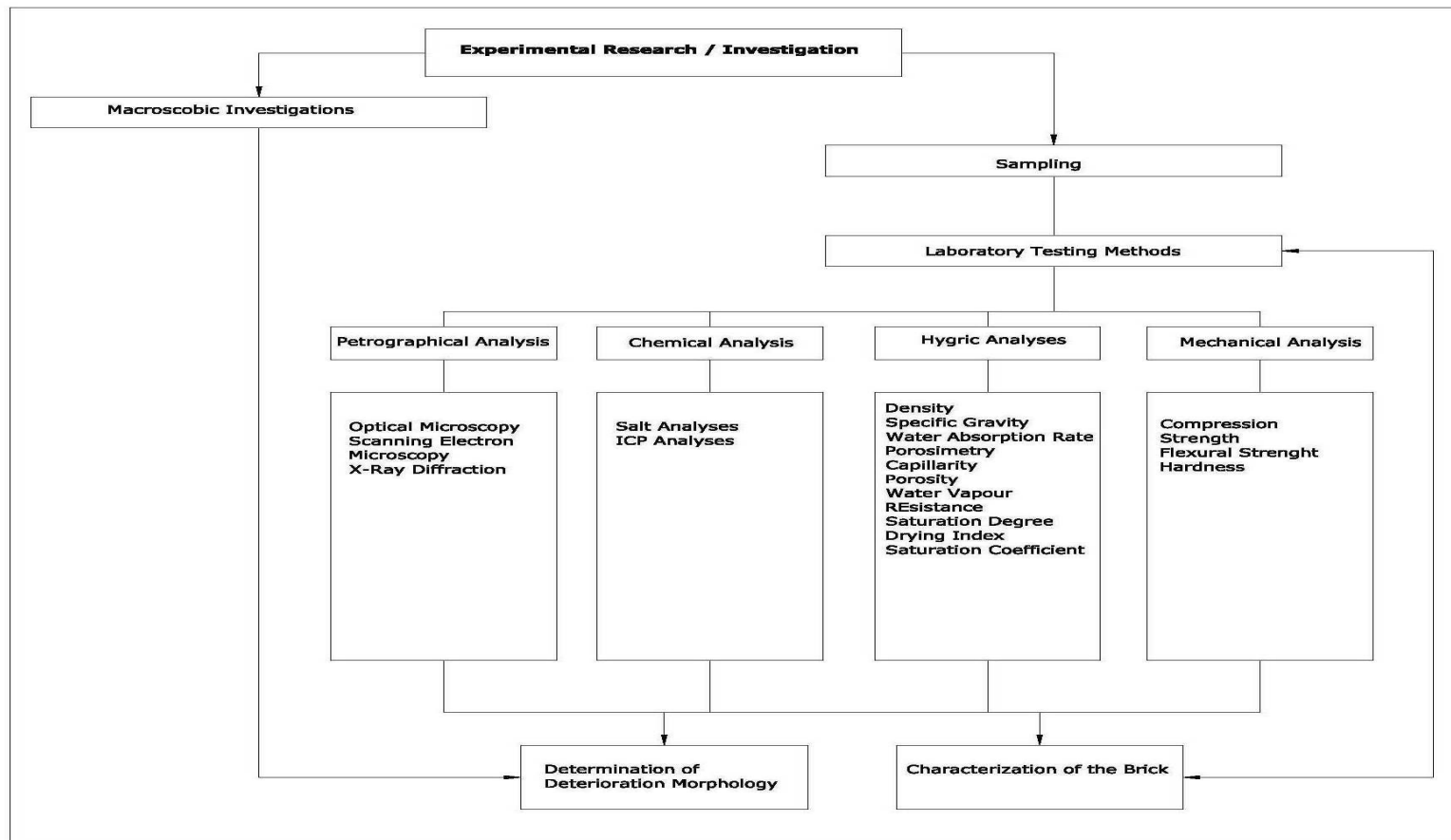


Fig 3.2 : Schematic flow diagram of the brick experiments

3.2.4 Factors affecting brick durability

In construction materials, particularly in those used for historic buildings, their resistance is the determining factor for the evaluation of their durability. The best results of hygric tests, ultrasound and accelerated ageing tests, must be used as a quality index for new brick production [37]. The parameters affecting durability are:

- Clay composition

Evolution of vitrification degree, porosity and pore size distribution depend mostly on raw clay composition and firing temperatures. The influence of raw material composition is important on hygric behaviour and durability upon weathering [35].

Salt crystallisation and freeze-thaw cycles cannot be notably improved easily because of unfavourable pore size distribution and crack development cannot be controlled. A volume increase problem, lime blowing, can be avoided by closely controlling grain size and content of carbonates in the raw clays [35].

The presence or absence of carbonates strongly influences the porosity development and, therefore, the brick texture and physical-mechanical properties. The carbonates in the raw clay promote the formation of fissures and of pores under 1 mm in size when the bricks are fired between 800 °C and 1000 °C. The absence of carbonates results in a continuous reduction in porosity and a significant increase in the pore fraction with a radius, $r > 1$ mm as the firing temperature rises and smaller pores coalesce [38].

- Firing Temperature

The behaviour of the bricks may be improved with increasing firing temperature. Samples fired at lower temperatures were found to be less resistant [35]. In fact, the increase of vitreous phase in the bricks tends to reduce decay [37]. The behaviour of the bricks may be improved with increasing firing temperature. Samples fired at lower temperatures were found to be less resistant [35].

Tite and Maniatis state that control of firing temperature would be less critical in the case of calcareous clays, since their morphology remains essentially unchanged over a wide range of temperatures. Furthermore, the oven atmosphere and the firing temperature have less of an effect on the final colour of calcareous than on non calcareous bricks [35].

Differences in mineralogical and textural evolution during firing of calcareous and non calcareous bricks are studied. Results reveal significant differences in the evolution of vitrification degree, porosity and pore size distribution. Such evolution depends also on firing temperatures. The improved durability appears to be due to a more favourable pore size distribution and a reduction in porosity. Results from textural and hygric studies of the brick samples indicate that these parameters can be controlled by varying raw clay composition and firing temperature, thus making it possible to fabricate replacement bricks for particular conservation purposes [35].

Firing of clay bricks produces a series of mineralogical, textural, and physical changes that depend on many factors and influence porosity. As an example, grain size is a significant parameter, since ceramics manufactured with a high sand fraction tend to be very porous and permeable. Significant variations in the composition and/or concentration of mineral phases also cause changes in the pore system. It is shown, that a high proportion of calcite produces more porous ceramics due to its high temperature decomposition and the release of CO₂. The physical–chemical changes that occur during firing are partly responsible for volume changes in ceramics. These changes comprise rapid, uneven expansion and contraction associated with chemical–structural changes that can show up as exothermic or endothermic reactions. Generally, products fired at high temperatures are more vitreous and undergo the greatest changes in size (contraction) and porosity [38].

Vitrification: Generally, brick durability is considered to be closely related to the vitrification degree. The vitrification degree alone has however been shown to be insufficient to predict weathering behaviour: in order to estimate brick durability, porosity and particularly pore size distribution must be considered as well [35]. The degree of vitrification increases with the increasing temperature and it reduces the connection between the pores. And regardless to temperature, the carbonates always have an influence on durability since they increase absorption and interconnection of the pores. It is thus advisable to use raw materials with low carbonate content to obtain resistant bricks [37].

Tite and Maniatis found a trend with respect to differences in the degree of vitrification induced by the presence or absence of carbonates. The behavioural differences between specimens with and without carbonates can be explained by the different evolution of texture and mineralogical composition developed during the

firing process. Carbonates are shown to result in bricks with different mineralogy, depending on firing, but with a stable microstructure within a wide range of temperatures (800°C–1000°C). This may be an advantage when manufacturing pottery but these pieces lack mechanical resistance to high temperatures. Salt partially modifies the mineralogy of the bricks, acting as a melting agent, especially at high firing temperatures, and giving rise to more resistant products which are suitable for restoration work [37].

- Hygric Properties

Textural and microstructural characteristics are correlated with the bricks' and their performance in hygric and weathering tests. The drying behaviour can be explained by considering the pore size distribution. The saturation coefficient also correlates well with porosity data [35]. A clear correlation between the water absorption and drying behaviour of the bricks and the porosity plus pore size distribution is observed. To evaluate the degree of pore interconnectivity and its modification with firing, the free water absorption may be compared with the forced water absorption values. The open porosity values drop indicating a significant increase in vitrification and densification of the ceramic bodies [38].

The results of other tests indicate that in the specimens without additives a progressive reduction in water absorption capacity clearly takes place with increasing firing temperature [37].

The results denote a better quality of the bricks when the absorption coefficients and drying index reduces the negative influence of water on the bricks.

- Porosity

The porosity and, particularly, the pore-size distribution have been considered as key parameters for predicting the durability of different building materials, and especially bricks, subjected to various types of weathering phenomena in aggressive environments (e.g., acid rain related attack and dissolution, salt crystallisation and freeze-thaw cycles) [38]. Brick behaviour shows good correlation with porosity measurements, revealing that lower porosity and a significant amount of large pores enhance durability [35]. Winslow et al. suggested that bricks with high porosity would be less durable when repeatedly exposed to freeze-thaw conditions unless a significant amount of pores had a pore diameter of $>3\ \mu\text{m}$. Bellanger et al. have

described the buffering action of large pores in partially saturated porous materials submitted to freezing conditions. The trapped air in large pores will be compressed and thus reduces the pressure induced damage generated [35].

The presence of carbonates clearly influences porosity evolution during firing. The reactions result in an increase in volume and cause the formation of fissures, a phenomenon often described as “lime blowing” in the literature, which produces further increases in porosity. The transformation of dolomite also contributes to the porosity increase.

With the observations of Tite and Maniatis, that revealed a smaller decrease in porosity of calcareous clays until temperatures of over 1080 °C are reached. In non calcareous clays, a significant reduction in porosity already occurs at 1020 °C [35].

In bricks, pore size distribution follows a similar trend towards larger pore sizes as firing temperatures increase. In general, smaller pores between clay particles disappear at higher firing temperatures as a result of melting and coalescence of particles, and larger pores form due to gas release caused by loss of OH⁻ groups in phyllosilicates [35].

Crack development is confirmed by higher pore connectivity. Thermal decomposition of carbonates also causes the development of a microporosity that affects the durability of the bricks [38].

Although the water absorption behaviour, density and porosity of different types of bricks have been studied and compared in the previous studies, there is still no detailed explanation of their relationship with the textural features of the ceramics after firing. Some relationships between clay mineralogy and porosity are known [38].

The improved weathering resistance appears to be related to a reduction in porosity and a more favourable pore size distribution. Brick samples with a high porosity (~40%) and a high percentage of pores with a diameter of < 2 µm undergo significant damage. Different damage patterns are observed, depending on clay type and firing temperature. Exposure to freeze–thaw cycles commonly results in fracturing, while salt crystallisation tests leads to sanding and edge rounding. However, in the latter test, severe fracturing is also observed in calcareous bricks, fired at between 800 °C and 1000 °C [35].

Since there are many difficulties associated with the determination of the degree of vitrification, it appears more appropriate to study porosity, pore size distribution and water behaviour (e.g., saturation coefficient and drying index).

It is confirmed that brick porosity and its evolution with firing temperature is a parameter directly associated to the mineralogical composition of the starting material [38]. The higher compressive strength and vitrification degree observed in samples also provide better resistance to the forces generated by freezing of water [35]. Bricks pore system include the reduction in both the mechanical resistance over time because of fluid circulation in the pore system of solid bricks, and the bonding strength between the bricks and mortars or cements and other building materials [38].

- Salts

Another factor that affects the durability of clay masonry units is their soluble salts content. Such salts will dissolve when water is present and crystallize either on the surface of the masonry units or within them. Surface deposits (efflorescence), although unsightly, are not damaging. Internal crystallization (cryptoflorescence), however, will build up until the surface of the masonry units spalls [34].

Differences regarding resistance to salt crystallisation are detectable between calcareous and non-calcareous bricks. All initially show an increase in weight due to salt accumulation, in most cases not exceeding 4%. The brick behaviour can be explained by considering textural features. Damage may be observed in all exhibiting both high porosity (~40%) and a large amount (>60%) of pores with a diameter of <2 μm . The high degree of porosity enhances resistance in the weathering tests [35]. Binda and Baronio observed deterioration patterns in bricks exposed to salt crystallisation tests, which coincide with other observations. Bricks fired at lower temperatures tend to powder, while extensive vitrification prevents alteration. The behaviour of the bricks may be improved with increasing firing temperature. Samples fired at lower temperatures were found to be less resistant [35]. In fact, the increase of vitreous phase in the bricks tends to reduce decay [37]. In general, salt accumulated in existing cracks and caused further damage upon crystallisation [35].

- **Compressive Strength**

Textural and microstructural characteristics are correlated to compressive strength. Carbonates have a positive influence on the textural evolution of bricks fired at lower temperatures, promoting a higher degree of vitrification and higher compressive strength. Several researchers studied the influence of clay composition on the quality of fired bricks, and generally reported positive effects of moderate amounts of carbonates, which act as a flux. It has been found that carbonates lead to a reduction in shrinkage and anisotropic behaviour and to an increase in compressive strength [35].

Examples show an increase in the ultrasonic wave's propagation with increasing firing temperature, thus relating with the compressive strength.

Compressive strength evolution correlates to textural and microstructural changes in the bricks, including increasing vitrification and reductions in porosity. Both result in an increase in the mechanical strength. However, measuring only compressive strength does not necessarily offer useful information regarding brick durability, and it may be necessary to apply accelerated weathering tests in order to identify bricks suitable for conservation purposes [35].

3.3 Natural Stones

The term stone refers to natural rocks after their removal from the earth's crust. The significance of stone as a building material is illustrated by widespread prehistoric evidence and its sophisticated use in the early civilisations of the world, including the Egyptians, the Incas of Peru, and the Mayans of Central America [14]. Natural stone is the principal raw material for concrete, and lime, gypsum, and cement. They are all made from various types of rocks [10]. Thus natural stone has today uses as:

- As a raw material for other ceramic materials;
- In the repair of old stone buildings, which are mostly of a type no longer built today;
- As a facing material in relatively thin slabs;
- As construction materials (foundations, walls) [15];
- As filling and isolation material;

- As aggregate material.

And stone is also used as sculpture and monument material as well [16].

All types of stone are used in building, but the most important ones in the construction industry are granite, sandstone, slate, limestone, and marble [11, 17]. Geologically, all stones can be classified into one of three groups: igneous, metamorphic or sedimentary, according to the natural processes by which they were produced within or on the earth's surface [14]. The characteristics of each type have a definite bearing on their durability and use [17].

Igneous Stones: The igneous stones used in building are not part of the original crust of the earth, but molten rock material that solidified subsequently [10]. Igneous stone is the product of heat and pressure, such as that caused by volcanic activity and pressure exerted by the shifting of the earth's surface [16]. They are particularly strong, hard and largely homogenous in structure [12].

Igneous stones are the oldest and they form about 95% of the earth's crust, which is up to 16 km thick. Depending whether solidification occurred slowly within the earth's crust or rapidly at the surface, the igneous stones are defined as plutonic or volcanic respectively. This defines the grain structure of the types.

Apart from crystal size, igneous stones also vary in composition according to the nature of the original magma, which is essentially a mixture of silicates. This property causes the stone to be either acidic or basic [14].

Granite is granular igneous stone consisting mostly of quartz or feldspar. Mostly granite is hard and dense, and thus form highly durable building materials, virtually impermeable. In water, resistant to impact damage and stable within industrial environments [14]. It is strong, frost resistant, largely resistant to weathering, and is available in a wide range of colours. Granite can be finished in any way required [12]. Granite is almost impervious to water [11].

Basalt is a fine grained stone nearly as hard as granite. It can be melted at 2400 °C and cast into tile units which are deep steel grey in colour [14].

Sedimentary Stones: It is made up of silt or the skeletal remains of marine life that have been deposited by ancient seas [16]. Sedimentary stones are produced by the weathering and erosion of older stones. Weathering action by water, ice and wind

breaks the stones down into small fragments which are then carried by rivers and sorted into size and nature by further water action. Sand and clay were produced in the first instance by the disintegration of igneous stones. Sand is mostly silica, and clay is produced by weathering from the feldspars, which are the chief minerals in granite stone [10]. Most deposits are laid down in the oceans as sedimentary beds of mud or sand, which build up in layers, become compressed and eventually are cemented together by minerals such as calcium carbonate (CaCO_3) (calcite), quartz (SiO_2) (silica), iron oxide or dolomite (magnesium and calcium carbonate) remaining in the groundwater. The natural bedding planes associated with the formation of the deposits may be thick or thin but are potentially weak; this is used to advantage in the quarrying process. In masonry, to obtain maximum strength and durability, stones should be laid to their natural bed except for cornices, cills and string courses which should be edge-bedded, stones which are face bedded will tend to delaminate [14]. Sedimentary stones are formed from particles. They can contain a number of cavities, horizontal layers or even animal or vegetable fossils, according to the way in which they were formed. They are less strong than igneous stones, but easier to work [12].

Sandstone is deposit of sand cemented together by calcium carbonate (CaCO_3), silica (SiO_2), iron oxide and dolomite. They are generally frost resistant [14]. Sandstone is not as strong as granite. It can absorb a great deal of water, so has only limited frost resistance, and is susceptible to airborne pollution, and so weather resistant to only a limited extent. It is considered very easy to work. Sandstone often has a slightly banded, open texture and is available in many colours. Calcareous sandstones are not durable in acid environments. Siliceous sandstones are predominantly grains of silica (sand) cemented with further natural silica, and are therefore durable even in acid environments [14]. Ferruginous sandstones are bound with oxides of iron which may be brown, ochre or red. They are generally durable. Dolomitic sandstones are bound with a mixture of magnesium and calcium carbonates, and therefore do not weather well in urban environments. They are generally off-white and buff in colour [14].

Limestone is sedimentary stone that is composed either of calcium carbonate (CaCO_3) (calcite) or dolomite, which is a mixture of calcium and magnesium, or of a mixture of calcite and dolomite..[11]. Limestone is the largest stone category used in

the building industry. Its composition makes it susceptible to chemical processes. Limestone occurs in pastel shades, often contains fossils, and some of its varieties can be polished. Many types of limestone, including marble, are transparent when cut very thin [12]. They are generally classified according to their mode of formation [14]. Oolitic limestones are formed by crystallisation of calcium carbonate in concentric layers around small fragments of shell or sand, producing spheroidal grains or oöoliths [14]. Oolitic limestones are very workable. Organic limestones are produced in bedded layers from the broken shells and skeletal remains of a wide variety of sea animals and corals. Frequently clay is incorporated into organic limestones and this adversely affects the polish which can otherwise be achieved on the cut stone. Crystallised limestone occurs when water containing calcium bicarbonate evaporates; it leaves a deposit of calcium carbonate. Dolomitic limestones have had the original calcium carbonate content partially replaced by magnesium carbonate. In general this produces a more durable limestone, although it is not resistant to heavily polluted atmospheres [14].

Metamorphic Stones: Metamorphic stones are sedimentary or igneous stones whose structure has been drastically altered by great heat and pressure or chemical processes [10]. They are usually cavity-free, and have a distinctive texture [12]. Clay is metamorphosed to slate, limestone to marble and sandstone to quartzite [14].

Slate is derived from fine-grained sand-free clay sediments [14]. Slate is a microcrystalline metamorphic stone formed originally from clay. It consists of thin plates that can be easily split into sheets [11]. Clay shale, or slate, is very densely structured, absorbs little moisture, splits well and is used as thin slabs. Even though it barely resists abrasion it can also be used as a floor covering. The material responds to surface damage by splitting off (individual layers of the material are worn away), and so remains homogeneous [12]. Slate is strong, acid and frost resistant, lasting up to 400 years as a roofing material. Roofing and external cladding slates satisfy the requirements for the Class A1 characteristic reaction to fire performance, without the need for testing [14].

Marble is metamorphic stone composed principally of calcite and dolomite (limestone) that has been recrystallized by heat and pressure. Marble is metamorphosed limestone in which the calcium carbonate has been recrystallised into a mosaic of approximately equal sized calcite crystals. The process, if complete,

will remove all traces of fossils, the size of the crystals being largely dependent on the duration of the process. Marble is classified into four categories: calcite, dolomite, serpentine and travertine [11]. Calcite itself is white, so a pure marble is white and translucent. The colours and veining characteristics of many marbles are associated with impurities within the original limestone; they range from red, pink, violet, brown, green, beige, cream and white to grey and black. Marble is attacked by acids; therefore honed, rather than highly polished surfaces, are recommended for external applications. Marbles are generally hard and dense, although fissures and veins sometimes require filling with epoxy resins. Reconstituted marble is manufactured from marble chippings and resin into tiles and slabs [14].

Quartzite is metamorphosed sandstone. The grains of quartz are recrystallised into a matrix of quartz, producing a durable and very hard wearing stone used mainly as a flooring material [14].

Alabaster is naturally occurring gypsum or calcium sulphate [14].

3.3.1 Stone properties

Properties and requirements expected from building stones are closely related with their types.

The most important functional requirements are considered to be:

- To ensure the load bearing capacity of the wall;
- To resist different kinds of environmental influences.

Technical requirements expected from building stones are:

- Strength (compression, flexural, abrasion resistance);
- Density;
- Porosity properties;
- Thermal conductivity;
- Thermal expansion;
- Durability;
- There must not be parts splitting away because of cracks or air
- If there are pyrites and magnesites in the chemical structure of the rock, there must not be yellowish, brown colour changes during the experiment, indicating that there might be rusting [16].

Natural stones show different characteristics due to the formation processes they passed [15]. The stones which will be used as a construction materials, must be homogenous, non porous, resistant to atmospheric effects, and have high compressive strength and sufficient physical properties. The types of igneous rocks and physical sedimentary rocks are suitable for the purpose [16].

They have a high gross density, great strength, great surface hardness and high thermal conductivity. Most stone resists natural processes such as weathering, frost and chemical processes, and is very durable [12]. One important mechanical characteristic of natural stone is its abrasion resistance, the extent to which it can resist mechanical friction. This correlates with high density and high compressive strength, again the basis for a low water absorption coefficient. This is a key feature for frost resistance, and is determined by the porosity and capillarity values of the stone. A high value, as for sandstone, for example, means that the stone has to be protected from water penetrating [12].

They must provide the values required in the codes, shown in Table 3.3 [15,71];

Table 3.3 : Required properties of building stones

Property	Value			Unit
	Igneous	Sedimentary	Metamorphic	
	Granite	Limestone	Marble	
Water Absorption (by volume)	0,75	4	0,4	%
Unit Volume Weight	2.56	2,16	2,55	g/cm ³
Compressive Strength	117,68	49	49	MPa
Flexural Strength	7,36	2,94	5,99	MPa
Abrasion Resistance	1	1	1	
Weight Loss for Freeze and Thaw Resistance		>5		%
Impact Test		<0.6-1.2		N/mm ²

3.3.2 Analysing stone quality

a. Microscopic Analyses

Microscopic analyses must be made to both preserved and deteriorated parts of the stone. These analyses are done to determine the mineral type and structure of the stone.

- Polarizing Microscopy

Prepared cross section samples are observed under polarising microscopes. Optical qualities of the minerals help to determine their types [36].

- Scanning Electron Microscope (SEM)

The sample is prepared for the SEM microscope and its photos are taken and its EDX diagram is drawn. The phases of the minerals and the matter of its composition are observed [36].

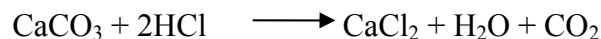
- X-Ray Diffraction (XRD)

This method is used to determine the composition of the minerals and also used to determine the minerals that compose the unresolved remainder that is unable to melt when the carbonated stones are placed in the acidic solution.

b. Chemical Analyses

- Mineralogical Composition

To identify the stone type, sections of the material is investigated and its chemical reaction with HCl is observed. If there are no changes in the structure, it is an igneous rock. Depending on the sedimentation type and colour, it may be said that whether it is sedimentary or metamorphic [16].



- Salt Analysis

The chemical analyses include chloride (Cl^-), sulphide (SO_4^{2-}), carbonate (CO_3^{2-}), and nitrate (NO_3^-) [36].

- Conductivity
- Protein Analyses
- Saponifiable Oil
- ICP

c. Hygric Analyses

These experiments must be done both on the deteriorated and the protected parts of the stone. The parameters which can be found after standard hygric tests are:

- Density
- Specific Gravity
- Water Absorption Rate and Capacity

With the help of experiment tube, the approximate water absorption capacity of the stone is measured in situ without causing any damage on the stone. The capacity of the stone also provides information about its deterioration morphology [36].

- Porosity
- Pore Size Distribution
- Porosimetry
- Capillarity Coefficient
- Water Vapour Resistance Factor
- Saturation Degree
- Thermal Expansion Factor
- Freeze-Thaw Resistance
- Moisture Amount Assessment

A neutron drill, measuring the concentration of hydrogen (H_2) atoms, is used. For the same purpose, tools that measure electrical resistance may also be used; two rods of opposite poles are placed on the stone and the level moisture is determined in accordance with the amount of resistance [36].

d. Mechanical Analyses

The mechanical experiments must be done both to wet and dry samples. The tests must also be applied to preserved and deteriorated stone samples.

- Compressive Strength

In situ compression resistance assessment is done with the help of a Schmidt hammer, the stiffness value of the stone (recoiling coefficient) can be measured. Depending on the recoiling coefficient, the pressure resistance value can be calculated. This experiment should be conducted both on the wet and dry sides of the stone [36].

- Tensile Strength
- Flexural Strength
- E-modulus
- Hardness

The hardness of the stones used within a building can be measured with the help of a needle. If the stone is scratched, then the hardness value is less than 6. Comparisons between different stone types can be made depending on the scratch types and the degree of the scratches. The deterioration starts when the hardness of the stone is less than the normal values [36].

- Cracks Assessment:

In order to determine cavities, breaks and cracks in a stone, an ultrasound device is used. By placing the two probes of an ultrasound device on the stone, the irregular cavities within a stone are designated within the sound transfer period. The scope of the visible cracks is measured with the help of a microscope. In order to measure active cracks on the building, stones are examined with the help of fissurometer. If the crack is active, reparation is required [36].

A schematic way to observe stone parameters is drawn below in Figure 3.3 below:

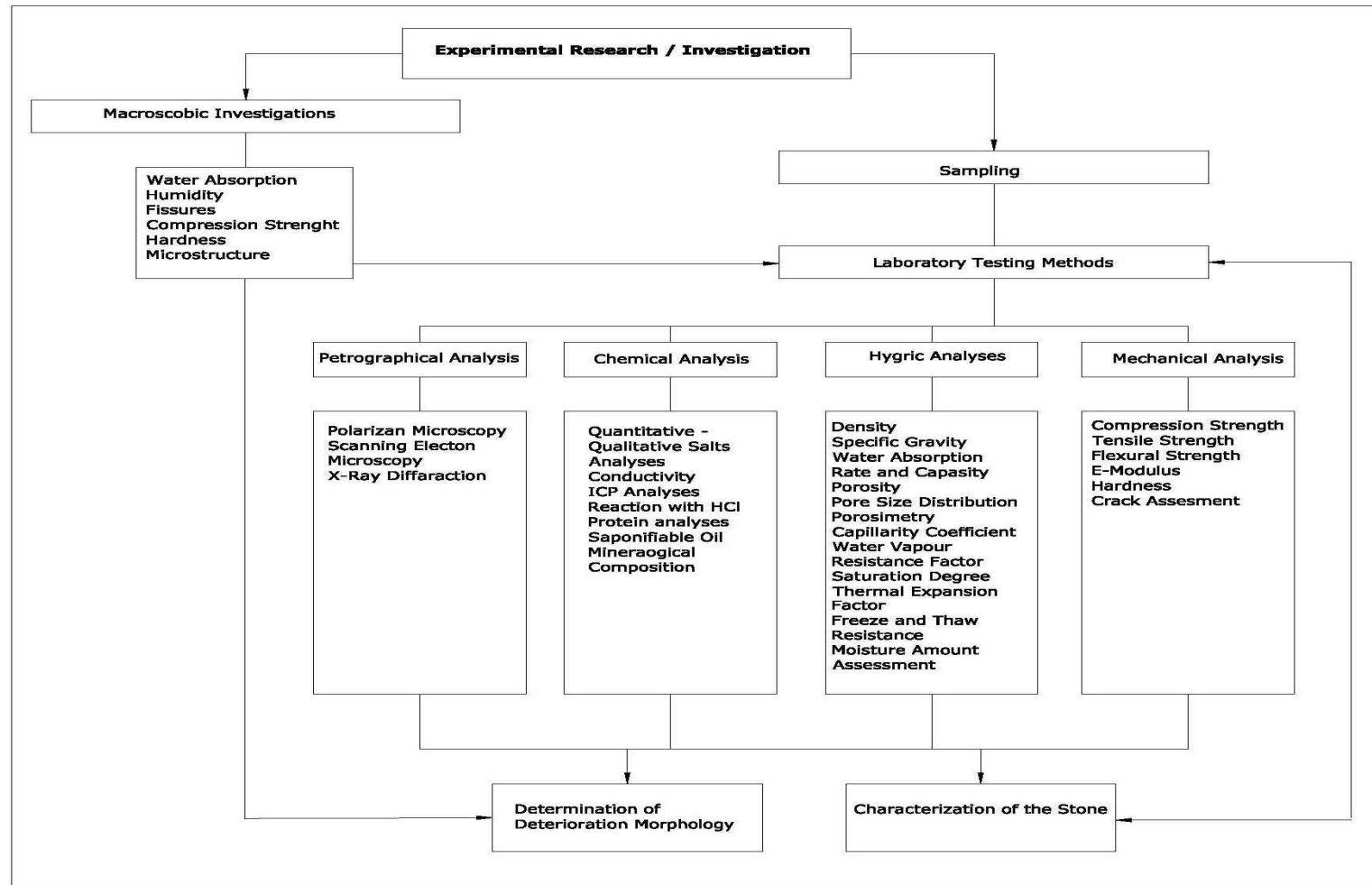


Fig 3.3 : A schematic table for the flow diagram of the stone experiments [36]

3.3.3 Factors affecting stone durability

The durability of the stone depends on its mechanical characteristics, which are results of physical and chemical values. The parameters affecting the durability are:

- Composition

The mineral composition of the stone is important for the durability values, due to the fact that many properties of the stone are very closely related with the composition and type of the stone. Every type of the stone has its own character derived from its grain properties and porosity.

- Hygric Properties

The physical properties, found as a result of hygric experiments, of the stone give information on the durability of the materials. For example, if the specific gravity is more than density, high absorption capacity can be expected. When the degree of saturation is above 80 %, it is possible to determine that the stone will be affected by wetting-drying or freeze-thaw circles.

- Porosity

Non porous stones are used as construction materials, due to better resistance. Water trapped in the pores and capillarity of the stone can cause damage when it freezes because its volume increases by about 9 % as it turns into ice. Although majority of igneous rocks are classed as frost resistance, numerous aspects must still be taken into account to avoid problems. Frost causes the separation of pieces of stone, but does not produce powder as in crystallisation attack. Generally, limestones and magnesian limestones are more vulnerable to frost damage than sandstones. Marble, slate and granite used in the buildings are normally unaffected by frost due to their low porosities [14].

- Salts

If moisture containing soluble salts evaporates from the surface of stonework, then the salts will be left either on the surface as white efflorescence or as crystals within the porous surface layer. If the wetting and drying cycles continue, the crystalline material builds up within the pores to the point at which the pressure produced may

exceed the tensile strength of the stone, causing it to crumble. The actual pore size significantly influences the durability of individual stones, but generally more porous stones, such as limestone and sandstone, are susceptible to soluble salt action [14].

- Compressive Strength

Compressive strength is closely related with the type and the porosity of the stone. Depending on their strong, hard and largely homogenous structure, the best compressive strength values are expected from igneous stones. Physically sedimentary rocks also provide sufficient compressive strength values as a building material.

- Atmospheric Pollution

Stones based on calcium carbonate (CaCO_3) are particularly vulnerable to attack by acid atmospheric pollutants. Sulphur dioxide (SO_2) in the presence of water and oxygen from air produces sulphuric acid (H_2SO_4) which attacks calcium carbonate (CaCO_3) to produce calcium sulphate (CaSO_4). Limestones and calcareous stone are vulnerable to attack. In the case of limestone, the gypsum (calcium sulphate) produced at the surface is slightly soluble and on exposed surfaces gradually washes away leaving the eroded limestone clean. In unwashed areas, the surface becomes blackened with soot producing a hard crust, which eventually blisters exposing powdered limestone. Magnesium limestones react similarly, except that in some cases the recrystallisation of magnesium sulphate under the blackened crust causes a more serious cavernous decay of the stone. Calcareous sandstones, when washed by rain, gradually decay to powder; however, in unwashed areas they produce a hard crust in which the pores are blocked with gypsum. The crust eventually fails due to different thermal expansion. Dolomitic sandstones are less vulnerable to attack, unless they contain a significant proportion of vulnerable calcite (CaCO_3). Siliceous sandstones, which are not attacked directly by atmospheric acids, can damage the calcium sulphate (CaSO_4) washings from limestone which then cause crystallisation damage to the sandstone surface. Marble, which is essentially calcium carbonate (CaCO_3), is also affected by atmospheric acids. Any polished surface is gradually eroded; however as marble is generally non porous, crystallization damage is unusual and limited [14].

4. EVALUATION OF MASONRY WALL MATERIALS OF BYZANTINE AND EARLY OTTOMAN PERIODS

4.1 Byzantine Architecture

The information about Byzantine masonry wall construction and masonry wall materials from 4th century till 15th century is found in 18 studies, about 33 buildings.

4.1.1 Masonry wall construction

The masonry wall construction system of Istanbul in the 5th century is the rubble stone with mortar filling, with stone courses and brick courses alternating [39]. Till the last periods of the empire, only brick structures and freestone walls with brick bond courses can be both seen. The alternative use of brick and stone together can be seen consistently approximately for a period of 1000 years [40]. Two types of masonry wall construction of Byzantine period in İstanbul are as follows;

4.1.1.1 Brick walls

The first example of only brick walls in Istanbul is a 5th century building, Chalkopteria Church. Bukolean Palace and Myreallion are examples of later formed brick structures [40].

There was plenty of different bonding techniques used during different civilization periods of Istanbul. As an addition to technique of rubble stone with mortar filling, outer shell made of roughly freestone or cut stone technique, the use of alternating courses of brick and stone together are examples of typologies of bonding techniques of Byzantine periods [40]. An example of brick wall technique is shown in Figure 4.1.



Fig 4.1 : Example of Byzantine brick wall construction, Myreallion Church

4.1.1.2 Alternative courses of brick and stone

The alternative courses of brick and stone walls of Byzantine depend on [41]:

- Color changes of stone and brick;
- Changes of material/color/dimension/direction;
- Changes of color of the stone (very few, in the central empire).

The alternative use of brick and stone together generating a colourful polychromatic wall also has a very strong visual effect, as a result of using two different materials of different colour and texture [40]. The first examples of wall construction of alternating materials, which can be seen from outside, are in Hypodrom especially in Sphendone, in Mumhane walls and in Karpos Paplyos Martyrion [40].

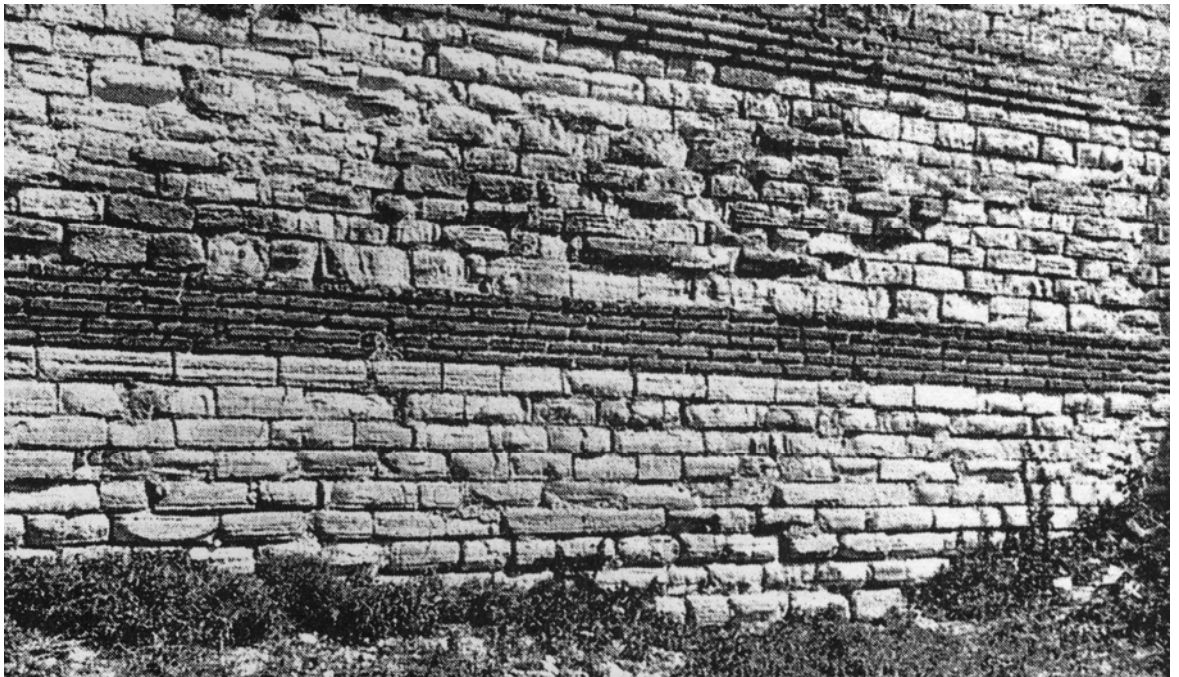
During the period, Justinian had the best engineers and the most advanced technology in the world [42]. A different type of wall technique during the time of Justinian can be seen as brick structures with stone bond courses. During the period, rubble stones with mortar filling is not used and brick is mainly used as building material. The masonry work resembles the alternating courses of brick and stone, and the stone courses are placed in the brick masonry often. The wall structure can be observed on the walls of Hagios Sergios and Bacchus, Hagios Polyeuctos, the

primary walls of Hagia Eirene dating 6th century, and on the walls of Hagia Sophia [40].

As Rodley explains, during the Dark Ages, churches were built smaller and were poor in terms of arts and architecture. Very few remained of badly constructed churches due to this reason [42].

During the period of Komneios, the bonding courses of brick are used in the superstructures and recessed brickwork is applied to the thick mortar joints [40].

There is a consistency of repeating rate and joint techniques in the late Byzantine period. The thicknesses of the joints are 4-6 cm for the middle period. The thickness of the mortar is always more than the thickness of the bricks used and the mortar thickness for the late Byzantine period changes between 4-7 cm. 4 courses of stone alternating with 4 courses of bricks becomes common and by the recessed brickwork technique, the thickness of the mortar becomes even thicker [41]. Examples of alternating courses of brick and stone are shown in Figure 4.2.



a. City Walls

Fig 4.2 : Examples of Byzantine alternating wall constructions



b. Hagia Euphemia Church



c. Studion Johannes Church

Fig 4.2 : Examples of Byzantine alternating wall constructions (continued)

Recessed Brickwork : Another brick technique used in the late periods of middle Byzantine period is recessed brickwork. This technique can be seen both on pure brick structures and on alternating courses of brick and stone systems. The brick course between the other two brick courses is replaced reared than the other courses. The recessed brick is covered with mortar, the joints of this wall system are differencing with their very thick mortars. The best examples can be seen in Istanbul, and it is executed since the middle 11th century till the 12nd century, especially being used in the 12th century.

If the recessed brickwork technique is not used, the mortar joints are likely at the same thickness as the bricks. The joint work is always grooved. The same grooved mortar system is used on the stone walls. However not so effective on rubble walls, due to fact that stone is not much neatly worked on the surface. [41] An example of recessed brickwork technique is shown in Figure 4.3.

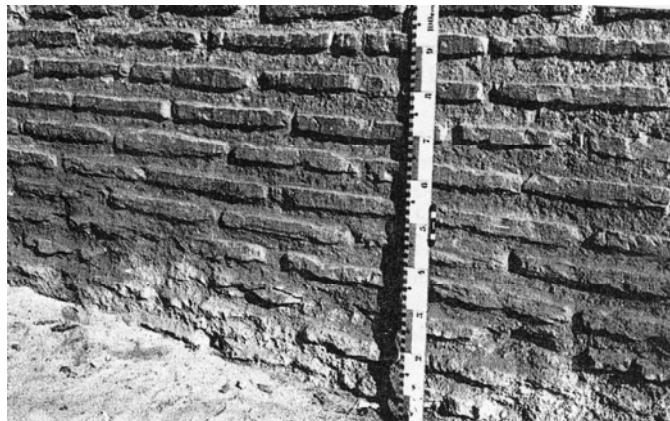


Fig 4.3 : Example of Byzantine recessed brickwork constructions

4.1.2 Masonry wall materials

The materials of the system in the beginning period of Byzantine are stone, brick and mortar.

4.1.2.1 Mortar

The transfer of the imperial capital from Rome to Constantinople in the 4th century meant that there were no nearby sources of pozzolan. Builders in the new capital were thus forced to adapt techniques of Roman pozzolan construction to local building materials. One example can be seen in the massive fortification walls of the city. Begun in the 5th century but rebuilt and enlarged periodically, they are

composed of a mortar and rubble core faced with alternating courses of brick and stone (a treatment that continued to be used well into the Renaissance era throughout much of the Mediterranean region) [44].

Walls of monumental Byzantine buildings were normally composed of alternating layers of brick and mortar, with the mortar consisting of brick fragments and dust, including bits of charcoal, that impart semi hydraulic properties (i.e., the ability to cure chemically and develop good strength but at a slower rate than mortars based on true hydraulic cements) to its limestone sand mortar base. Extremely thick mortar joints, often exceeding the thickness of the bricks themselves, today display a hard monolithic mass similar to Roman concrete. Such wide mortar beds would have allowed very rapid bricklaying, perhaps even approaching the speed possible with Roman concrete construction, but their uneven appearance, compared with tightly pointed brickwork, called for a covering with thin veneer. Almost all Byzantine walls displayed stucco, marble veneer, or decorative mosaics [44].

Mortar sample of 10th century appear to be intact, integral and durable presenting a granoblastic character. The ceramic fragments in the mortar are mainly reddish; some turn into yellow. An almost equal participation of sand and crushed brick is observed in the mortar. The binding material is exclusively calcitic. A hydraulic character is revealed due to significant participation of Ca, Al, and Si species. The brick fragments are substituted with caolinite rich clay [41].

4.1.2.2 Brick

Brick is a material, which is enrolled from Anatolian architecture tradition to Istanbul. After the start of the Byzantine style, brick is started to be used in alternating courses with stone. In this system, brick bond courses are used as a connective system between both external and internal surfaces and also arranging the wall material to have a horizontal design. Brick is the primary building material in the Byzantine structures in Istanbul, and along the fact that it provides the stability of the wall; it is also the one of the determinants of the wall thickness [43].

The information on the brick production areas in İstanbul during the Byzantine period is insufficient. The development of brick industry is obvious at the wall technique of the Constantine Lips Monastery. The bricks in the arches of the niches, and the bricks in other niches or bricks of different geometric decorations are

specially produced according to the place they were used [40]. The same can be said for the bricks of Theodokos Pammakaristos and Chora Monastery, as there are specially produced bricks according to the geometric shape where they were used [40].

Byzantine brick is square, flat and bigger in dimensions. The thin plate tradition of the brick is a result of Roman tradition. Ottomans also used the same brick. However, although the shapes are similar, the dimensions are differencing. Roman brick dimensions change from region to region, the dimensions of the central Rome is 25-29 x 3.0-3.5 cm. In the west Anatolia 27-34 x 4.5-5.0 cm bricks are used [43].

Although the Byzantine bricks are square shaped, rarely some rectangular shaped ones can be observed. However, this cannot be seen as a leading building material style. In Studios Monastery, the rectangular shaped bricks can be seen [43].

The use of brick as a building material reaches its intense use during the Palaigolos Period. The period of changing courses of the materials is very neat during the period [40].

Between the three dimensions of the bricks, the dimension which helps to compare is the length due to the fact that the height is shorter, and so the differences in the height may not be sufficient enough to make a detailed comparison [43].

In the early period, the lengths of the bricks change between 37-39 cm. The limits are 34 cm minimum and 40 cm maximum. The bigger sizes of the bricks show a characteristic of the earlier period [43]. The material quality does not develop much between the periods. According to Ersen, the bricks of the early period are likely (33.5-42)x(35-42)x(4-4.5), and they were produced as half bricks. The dimensions reduce in the middle period, as the thickness also reduces. The dimensions turn to (33-38)x(33-38)x(3.5-4). During the middle period, the dimensions are averagely 33-36 cm as the minimum length is 30 cm, and 38 cm for maximum. The dimensions decrease by the late period and changes averagely between 30-34 cm. There are few extreme examples ranging to 28.5 cm for minimum, and 36-37 cm maximum. The brick dimensions in the late period is (30-35)x(2.5-4) cm [43]. When the lengths of the bricks are compared, the dimensions of the Byzantine bricks decrease by time. It may be seen that the length of the early Byzantine bricks are much longer (maximum 52 cm, average 37 cm) than both the late Byzantine (maximum 39 cm, average 32

cm) .While comparing the height of the bricks used, the periods do not show such a significant difference as the brick height, however, the height also decreases by time, reaching 2 cm thickness for the late Byzantine period. Nevertheless, the average value is 3.5 cm and the maximum is also 6 cm for all the periods.

The bricks of the early Byzantine period are square bricks and are better fired compared to the Ottoman bricks and stamped also. These bricks are used with a thicker mortar joint on the masonry walls. Brick mixtures are mostly pinkish or greyish white. They were also consisting of coarser brick particles, and finer pebbles and external particles coming with the sand used. The joint mortars are much a better quality and a redder material. The joints are continuous and grooved and have a circular section [39].

There is an obvious decrease in the dimensions through the periods. There is also a construction technique used in the late period of middle Byzantine era. The brick layer between the other two is recessed and covered with the mortar. For some recessed brick constructions two types of bricks (smaller and bigger) are produced. This system makes the mortar joints seem thicker [43].

4.1.2.3 Stone

The stone used during Byzantine period is mainly kufeki, used as cut, roughly cut or rubble stone according to the place in the building and on the importance of the building [41]. Also, grey limestone and greenstones are used as cut stones as well. Greenstone is used in the constructions of the Byzantine period. Greenstone is a local stone, quarried, according to Van Milligen from Bakırköy quarries [39].

Kufeki is a building stone used in İstanbul through centuries. It is a calcareous stone sedimentated of shale, mostly of oysters. It is a compact stone, usually light beige, with fine particles, having a sandy shape, with a high resistance to shear and break. Due to the carbonate percentage, it is reactive to acids. It has a porous texture full of plenty fossils. Another important property is; after it is quarried, it is possible to work easily. Also after it contacts with air, with the CO₂, the stone passes through a second carbonation and gains strength, hardness and power. It does not change its properties when used under water.

However, the stone type was not differentiated according to the importance of the facade. The dimensions of the stones change between 11-56x16-22 depending on the

research of Ersen [41]. Besides; Hagia Sophia, Aspar Cistern and Studios Johannes Church have stones over 60 cm in length. The use of neatly worked stones in the beginning period, changed to roughly-cut stones or rubble stones during the middle era [41].

Stone constructed is done by even thicker mortar joints as a result of their shapes. The mortar joints in the rubble stone walls are irregular because of the shapes of the stones, and more regular in roughly cut stone walls [41].

4.1.3 Chronological evaluation of the Byzantine structures

As there are some information that cannot be classified in the tables, with the other data, the specific material and construction characteristics of some Byzantine buildings are explained below.

Mumhane Walls has the bonding technique of 5B/1S, 6B/1S [43].

The main parts of the Karpos Papylos Martyrdom are of alternating courses of brick and stone with brick bond-courses. There are 5 courses of brick and 3-4 courses of stone. Average brick length is 37 cm [39]. Only the circular shaped structure is of pure brickwork [43].

Aspar Cistern has alternating courses of 5B/6S [43].

The main walls of Lausos Antiochus Palace rises on a foundation flowing over 15-25 cm, is made of rubble stones with mortar filling. The lowest part of the walls is of 4 courses of cut-limestone. The 34-45 cm blocks are seamed to each other with masonry anchors. Over these, there is brickwork of 9 courses and 75 cm high. The dark red bricks are 36-37 cm in length and thickness of 5 cm. Over the brickwork of 4 courses, there is a 5 coursed bond course of brick. The uppest part of the building, still standing, is of 4 courses of rubble stone masonry. The mortar joints of the brick masonry are concave. The mortar on the upper rubble stone section is at the same level as the stone surface but is 2 parallel lines are drawn to make it clearer [45].

The section made of brick and crushed stone is at the same height as the cut stone section. The only cut stone rising up to 120 cm are on the edges of the hexagonal structure [45].

The lower part of the building of cut limestone has a distinguishing character. Bardill declares that the seamed cut stone technique does not belong to any period in particular but continues till the 4th century. However, when the similar techniques both for the construction and stone working are observed in the Myrelaion, Antiochus and Lausos, it might be said that these may point the 5th century [45].

The main walls of the Antiochus Palace are made of crushed stone and brick, and this is typical of 4th-5th centuries. However, when the 5th century buildings are examined, it might be said that the courses of the structures depend on a system. The alternating courses of brick and stone can be observed at; Hagios Karpos Papylos Martyrion 5B/3S, 5B/4S, Studios Ioannes Monastery 5B/3S. The alternating wall pattern of the hexagonal part of Antiochus Palace may seem close to the rhythm of the similar structures. However there is also a different bonding technique as the 9 courses of brick masonry on the stone courses. The structures on the sides of the main building show alternating courses of 5B/4S [45].

The walls of Christ Pantepoptes Church are constructed with alternating courses brick and stone course technique [52]. Christ Pantepoptes has a surface texture that is further developed by the use of the recessed brickwork technique, in which alternate layers of brick are inset and then covered with mortar, giving a coarsely stripped finish to the wall. In places, bricks are arranged in a meander and other patterns, but it is possible that these belong to the Palaiologan alteration [46].

The foundation walls of the Mangana Palace are made of recessed brickwork as Cyril Mango declares [52]. The first example of the recessed brickwork technique can be seen on the walls on St. Georg Church, in the Mangana Palace. Also, the technique helps to date the buildings in 100 years of period [40].

Chalkoprateia Church is also made of pure brickwork [43]. There are thick mortar beds of 5.5 cm and modulus of 10 course bricks is 91 cm in height [47].

The bonding technique of Studios Ioannes Church is alternating courses of 5B/3S [43]. The masonry type of the basilica, where it is not disturbed or repaired, is alternating courses of brick with bands of stone. That is exactly same masonry as the body of the church [47].

Hagios Sergios and Bacchus is constructed on alternating courses of 6B/3S [43]. Structurally the south wall of Hagios Sergios and Bacchus must belong to a different

building campaign from the rest of the church. The east, north, and west walls, with the exception of areas of repair such as the northeast corner, are constructed of uniform brick masonry with courses of stone occurring occasionally at intervals of about 20 courses; this is a Justinianic masonry observable at Hagia Sophia and Hagia Eirene as well [48]. The south wall, however, is of an entirely different construction. Much of the wall is made up of an irregular stone and brick patching, and most of this patching is modern. In other parts of the wall, however, a more regular kind of masonry can be observed, consisting of an alternating courses of brick (2-4 courses) and courses of stone (3-4 courses); this is a type of masonry common in 5th century Constantinople, although usually with 5 courses of brick. Hence may be assumed that the south wall belongs to a different and earlier period than the rest of Hagia Sergios and Bacchus [47].

With the exception of the principal piers of stone, the entire structure of Hagia Sophia is of brick and mortar in a volumetric relationship of about 1/1.6. This ratio implies a form of concrete with brick aggregate, a plastic material of that type that curving plans and roofs practicable in later Roman and Byzantine buildings. This material weighs 68 kg/0.03m³ roughly, and likely the same weight as the stone masonry. Due to the plasticity and ease of laying up brick and mortar can be used over greater distances than cut stone [49].

Hagia Sophia's slow hardening mortar was one of the causes of these tilts and deformations [48]. Historians have pointed to the construction speed of Hagia Sophia, as contributing to the great distortions, reasoning that lime mortar would not have had sufficient time to set in the massive piers before they were loaded laterally by the great arches. Yet the main piers are not of brick and mortar, but rather of cut stone, at least up to the level of the gallery floor [44].

Legends tell that the mortar used in Hagia Sophia was mixed with a broth of cooked barley and willow twigs. If such vegetable substances were every employed, Prof. Morris finds no traces of them; his analysis of a thin section made from a specimen of the earliest mortar shows it to consist of burnt lime, sand, occasional pieces of gravel and a considerable immixture of crushed brick. Of these ingredients a grain of sand and a chip of brick merit brief digressions. In the specimen of mortar Prof. Morris identified a grain of a special kind of granite which according to available geological information could only have come from exposures along the coast of the

Black Sea north of Istanbul, perhaps from as far as the Dobrudja. The addition to Byzantine mortar of a porous substance like crushed brick, which assists the absorption of excess water, afforded particles of lime a more intimate contact with the bricks and thus improved the density of the mortar [50].

Mineralogical components of a chip of brick in the earliest mortar (a chip from a brick older, of course, than the building itself) are identical with those of bricks employed in the initial construction and those manufactured by the Ottomans in the 15th century or later. This uniformity, which Prof. Morris identified by studying thin sections of specimens of bricks of the typical sizes mentioned above, indicates that they were made from the deposits of marine clays in which Istanbul is situated, for clays of marine origin are capable of producing homogeneous bricks over a long period of time. The minerals identified in a brick of the largest size are, in contrast, entirely foreign to the clays in the region of Istanbul, and these largest bricks must have been imported, possibly from Rome where similar sizes were commonly used in centuries prior to the Byzantine era [50].

Despite it is said that bricks were brought from Rhodes Island during the construction of Hagia Sophia, Salzenberg who had made an intense investigation over the bricks, declares that there was not any sufficient information on the subject.

The first notable point regarding materials is that the buttresses are not composed of homogeneous masonry but contain brickwork of three different kinds. That of the earliest period of construction consists of square bricks. The exposed edges of which average 4.5 x 37.5 cm; its horizontal joints have a slightly concave surface, and 10 courses measure 1.01m. The second type, also Byzantine and possibly of the 10th century, is distinguished by variety in sizes of bricks, edges of a few being 6x60 cm, by sloping, or "weathered" joints, and by a wider spacing of courses which increases the height of 10 courses to as much as 1.26m. The third type is Ottoman; it consists for the most part of 2 courses of bricks 30x28.5 cm alternating courses with one of faced rubble [50].

As to the capacities and behaviour of masonry composed of the bricks and mortar just described, there are significant clues. In the first place, the beds of mortar are thicker than the bricks themselves; the ratio of brick to mortar, by volume, is about 1 to 1.4, and there is consequently about half again as much mortar as brick in certain parts of the structure. This fact leads Prof. Voss to suggest two probabilities: it is

likely that brick laying, despite the speed with which the initial construction was prosecuted, had to proceed in a horizontal direction and rather slowly in order to prevent the weight of superimposed courses from pressing the uncured mortar out of such thick joints; and because considerable time is required for mortar in deep masses to dry out and attain its full strength it will flow if subjected prematurely to excessive pressure. What might be called an "acquired" characteristic of the brickwork may be due in part to this action [50].

Like the propylaeum and the Chalkoprateia church; like the propylaeum wall, the masonry of the skeuophylakion is pure brick rather than alternating brick and stone. The brick wall of propylaeum of Hagia Sophia may belong to 4th century church [47].

As the main body of Hagia Sophia is made of brick mostly, bands of greenstone run to tie the walls. Greenstone which is essentially an olasitic tuff from Karamursel is not a durable stone [51].

Hagios Polyeuktos Church has a bonding technique of alternating courses of 5B/4S [43].

Special bricks are produced for the masonry brickwork of Chora Mosque. The special production and the intense use of the brick at the period of Palaigolos show the importance of brick manufacture at the dates [40].

Addition chapel and all the supplemental buildings are made of brick and cut-stones. The alternating course technique is 4B/4S. Also, the colour harmonies of the façades are quite strong. The bricks used in the vaults are produced during the Byzantine Period [40]. The main building is on the lower left side. Depending on the brick and stone bonding techniques, it resembles the Byzantine style of the time [40].

In the atrium of Hagia Eirene, there is a Justinianic character of the masonry, fine brick masonry with occasional greenstone bands. The east end of the church is rough alternative courses of 5/6 courses of brick with 3/4 courses of stone [47].

Myrelaion Church is entirely of brick and the structure below is made of big cut stone blocks and brick [52,43].

Bukoleon Palace is a structure made of pure bricks [43].

Hagios Nikolaus Church is made with alternating courses of 4B/4S [52].

Hagia Theodosia is dated 11th-12th century because of the recessed brickwork is used in its construction. It is a building of the Palaiologan period. The period produced a distinctive final phase of Byzantine architecture that consisted in new combinations of several old architectural forms [46].

Theotokos Church of Constantine Lips has elaborate brickwork following the Byzantine tradition of interspersing courses of brick with stone in order to visually lighten the structure [48]. There are several courses of brick masonry alternating with several courses of brick (as in bema) [53]. All the walls except the east facade, after 6 courses of stone masonry, continue with 5 courses of brick masonry. The east wall stops after the stone courses. The masonry above and below is identical, except the treatment of mortar joints. Throughout the church the joints are flush pointed, with a finer mortar, then grooved with a tool about 2.5 cm. This was employed in brick masonry of the entire structure [53].

The structure of stone and brick was strengthened by tensile reinforcements at two levels and of two different materials. The lower bonding system was timber; the beams have entirely disappeared by time [53]. Also a layer of lime with crushed brick was found at the depth of 140 cm [53].

The construction technique of the Byzantine period phases tends to be sloppy, as if rapidly executed, incorporating much brick of different sizes [54]. Brick is the principal material of Monastery of St. Saviour Pantokrator. The three churches of the Pantokrator Monastery are masonry buildings made cut of brick, with occasional limestone courses on the walls. Recessed brick technique is employed in all the phases. Thin layers of brick were alternately applied with cut stone courses [42]. The bonding technique is the alternating courses of brick and stone. Also the bricks of the recessed brickwork are produced in two dimensions, and the technique of the recessed brickwork depends on using both these bricks. If the types of this special production are coded as b (bigger and thicker) and s (smaller and thinner) then the alternating brick courses for the recessed brickwork are: 5b/5s, 5b/6s, 6b/6s and 7b/7s [43]. The mortar beds of all the buildings were scored with similar incised lines along the edges of the brick courses [54].

Recessed brickwork Technique is observed on the walls of Anonymous Church (Ese Kapı Mesjid) by Ötüken, and this observation extends the time period of the technique till the 13rd-14th century.

The recessed brickwork of both the church and the cistern of Theotokos Pammakaristos argue for a late 12th century attribution [46].

4.2 Early Ottoman Architecture

The information about Byzantine masonry wall construction and masonry wall materials between 1453-1505 could be found in 12 studies, about 19 buildings.

4.2.1 Masonry wall construction

While the Seljuk buildings in Iran were built of brick, Ottoman buildings which followed the Anatolian Seljuk tradition were built of stone [48]. After the collapse of Anatolian Seljuk, the influence of local building traditions are observed in the architecture of the contemporary emirates of the Ottoman Emirate [55]. The Ottomans had access to Byzantine building methods for many years prior to the conquest of Constantinople [48]. The period since the foundation of the Ottoman dynasty till the end of the 15th century (II. Beyazıt Mosque, İstanbul, 1501-1505) is called the Early Ottoman period.

The first examples of the mosques with one dome can be seen in the Anatolian Seljuk mesjids. Ottomans improved the style and constructed monumental examples. The oldest Ottoman mosque is Hacı Özbek Mosque in İznik and can be dated to 1333 is a structure with one dome. The walls of brick and stone courses, dome covered with tiles are characteristics of the style [56].

Another important type of the early Ottoman period is a typical type called mosques with cells. One of the earliest examples of this style is Nilüfer Hatun Imaret in Iznik again. This structure cannot be exactly dated. However, as it is done by the order of I. Murat, the structure may be thought to be constructed in the third half of the 14th century. The wall construction of brick and stone masonry is also a characteristic for the period [56].

Kuban sees, Ottoman architecture as an organization of mass and a correspondence of upper and lower parts by means of mass, and not a relationship determined by the elements [48].

Ersen declares that that temporary material and Byzantine shape patterns are more intense and directly enrolled rather there is a development in the material quality in the second half and the shape patterns are interpreted and adapted and acquired a local attribute; and the last quarter of the century must be regarded as assimilation and creation period [55].

According to Akıncı, there are two types of wall construction system in the period;

- pure stone
- brick/stone alternating

Only brick wall is not characteristic in Ottoman architecture, and only brick structures are not observed within the period. According to the hierarchy of the walls, stone walls or alternating walls are used [55].

4.2.1.1 Stone walls

Cut-Stone Walls: In the monumental structures of the Ottoman architecture usually close jointed cut stone is used. In this construction pattern there is the use of rubble stone with mortar filling in the middle and the binder is Horasan mortar [55]. An example of cut stone wall technique is shown below in Figure 4.4.



Fig 4.4 : Example of Early Ottoman cut stone wall constructions, Firuzağa Mosque

Roughly cut stone walls : The stone surfaces are cut but not worked so neat in this type of the construction pattern. Stone dimensions are usually 15-35cm in width and 12-30 cm in height. This type of pattern is used usually in the secondary walls and on the construction of the walls that will be covered afterwards. As it is built, the height of the stones in the course is equalized by thick mortar joint heights. Pebbles and broken bricks are added to the mortar joints. The horizontal mortar joints are likely 2-4.5 cm, and the vertical mortar joints are likely 1-3 cm. Akdeniz Çifte Başkurşunlu Madrasah of Fatih Kulliye (the external walls), and Tahtakale Hamam (the internal walls) can be examples of the system [55]. The photograph and drawing of roughly cut stone wall is shown in Figure 4.5.



Fig 4.5 : Example of Early Ottoman roughly cut stone wall constructions

4.2.1.2 Alternating courses of brick and stone

The building element that influenced Ottoman architecture the most, is the alternative walls of brick and stone. During the first periods of the Ottoman architecture, the element is mostly directly used with the patterns of Byzantine wall systems. However the repeating rates, dimensional relations, mortar joint techniques, are developed by the second half of the 14th century [41].

The alternating wall system materials used in Istanbul are mainly cut stone and brick or roughly cut stone and brick. The most common patterns are 2B/1S and 3B/1S. There are also examples of bricks in the vertical mortar joints and B/2S or B/3S.

However this pattern is used rarely. The example of 2B/1S may be Murat Paşa Mosque (1471-72) [41,55].

An example of alternating courses of brick and stone wall technique used in early Ottoman period is shown in Figure 4.6.



Fig 4.6 : Example of Early Ottoman alternating walls, Murat Paşa Mosque

Bond Courses: Stone, brick, timber and Horasan mortar (as the binder) is used in the wall construction. As most of the building still stand, it is not possible to see the timber bonding element in the wall structure. However, from the ruins of some structures, the timber bond courses used as a grill (through the length and the width of the wall) can be seen. This system, as ancient as the Anatolian architecture, is also a characteristic of the Ottoman masonry [55].

4.2.2 Masonry wall materials

Brick, rubble, roughly cut stone and cut stone are used together in harmony in Ottoman structures [61].

4.2.2.1 Mortar

The structural wall mortar of the Byzantine and Ottoman monumental architecture is Horasan mortar. This mortar is a lime mortar where broken bricks are used as pozzolan materials. There are fibrous materials and materials containing proteins (organic materials) are used [55].

Closed mortar joints are used in cut-stone walls. The mortar joints height varies between 1-5 mm. The mortar joints of the rubble and roughly cut stone walls changes between 3-8 cm. There are brick pieces in the thicker ones. In the mortar joints of the alternating walls the mortar joint where the brick is put over the stone is thicker than the ones between the brick or when the stone is put n the brick. The joints are detailed as not to let water penetrate in [55].

4.2.2.2 Brick

The brick manufacture areas of Ottoman period are mainly located around the clay quarries or close to the locations [57]. As declared in the study of Kahya, the physical properties of the Ottoman bricks are likely the same as the Byzantine bricks. The water absorption and the porosity values of the early Ottoman bricks are over the values of the 14th century Byzantine bricks. There is a similarity between specific gravities and densities. On the contrary of the similarities in the physical properties, the compressive strengths of the Ottoman bricks are rather less than the Byzantine ones. According to the observations of Kahya, this is a result of the brick paste. The distribution of the grains is not homogenous in the brick paste and there are coarse particles. This may resemble the reason of the mechanical properties of the early Ottoman bricks [43].

4.2.2.3 Stone

Coarse sand stone is a type of limestone and is used in nearly all the mosques and kulliyye, and it was quarried from Bakırköy, Davutpaşa and Safraköy [58]. Stone is the main building material of the Ottoman architecture. Gathered stones are always used in the structures [55]. The most common stone material type in Istanbul during Ottoman period is kufeki stone, used since the Roman period. The stone channels are Neocene formations, starting from Davutpaşa, Bakırköy and Safraköy districts and continues along west till Küçükçekmece. This stone channels are present today, however became residential areas as the city grew. It became impossible to gather

the arterial for restoration works from these channels so the calcareous stones from Bakırköy and Haznedar are preferred as they are close to the city and workable. The stones used, except küfeki, are od stone and the marble of Marmara [55].

Use of Gathered Material on the Walls: The gathered material use is very common in the Ottoman structures as it was in the Anatolian Seljuk. The foundations of Beyazıt Hamam (1506-1507) can be an example. The od stone used in Fatih Kulliye, Akdeniz Çifte Başkurşunlu Madrasa (1462-71) may also be examples [55].

4.2.3 Chronological evaluation of early Ottoman structures

Like the Byzantine examples, there is also some unclassified information of the early Ottoman period. The specific material and construction characteristics of some early Ottoman buildings are explained below.

Tahtakale Hamam has some façades are cut stone and other facades are neatly cut rubble work [43]. The main walls are roughly cut stone and the entrance of the men's part is made of cut stone [59].

Mahmut Pasa Mosque is constructed by Mahmut Pasa, vizier of Fatih, is one of the late examples of mosques with cells. The structure dating 1463 has an untidy planning. There are very few decorations. However, Mahmut Pasa Tomb, just beside the mosque has a rather interesting decoration style of dark blue and turquaz tiles which are replaced inside the stone structure [56].

After the conquest of Istanbul, the first structure built by the Ottomans is Fatih Kulliye. The mosque in the centre of the kulliye is constructed in 1470-1471. The structure is badly damaged by the earthquake in 1765, and mostly reconstructed. Fatih period is the period of developing the style of the empire. To be successful new techniques and styles were tried [56]. Walls of Fatih Madrasa structures are mainly neatly constructed with roughly cut stone [60]. Karadeniz Madrasas of the Fatih Madrasa complex has external walls of both roughly cut stones and cut stones [61].

Murat Pasa Mosque has alternative courses of brick and stone courses of 2B/1S. The stone used in the structure is cut stone [57]. Murat Pasa Mosque, dating 1471, is also an example of mosques with cells. The structure is very plain in the design, and resembles the early mosques of Bursa [56].

Koca Mustafa Pasa Madrasa has different techniques on different façades. The west wall of the structure is built of roughly cut stones and rubbles and there are irregular brick bond courses. The north wall is covered with cut stones.

Firuzaga Mosque is a masonry structure of cut stone [62].

The main walls of Seyh Vefa Tomb are of brick and cut stone alternative courses of 3B/1S. The width of the wall is 80 cm [57].

Atik Ali Pasa Mosque is of cut stone masonry, without use of bricks [62].

One of the early Ottoman structures in Istanbul is Davut Pasa Mosque. The mosque has a very simple design. Davut Paşa Mosque, besides the architecture, is important about the colourful wall decorations [56]. Main walls of Davutpaşa Madrasa are examples of stone masonry construction of neatly built roughly cut stones [43, 62].

Main walls of Ishakpasa Hamam are constructed of stone masonry [43].

4.3 Evaluation and Discussion

4.3.1 Masonry wall construction

Analysing the Table A.1 in the Appendix, it is seen that Byzantine period buildings are either of pure brick or of alternating courses of brick and stone, as declared by Cyril Mango. Early Byzantine buildings mostly have the characteristics of 5-6 brick courses alternating with stone courses. There are also few examples (like Hagios Sergios and Bacchus, Hagia Eirene and Hagia Sophia) in the late 5th century and early 6th century, having alternating courses of 19- 20 bricks. In the late Byzantine period, usually 1-4 courses of bricks are observed. After the Byzantine period, the early Ottoman buildings have 1-3 courses of brick alternating with stone. Pure brick buildings cannot be seen during the early Ottoman period; on the contrary, there is a construction style of stone buildings. Table A.2 in the Appendix shows a schematic diagram of the patterns of alternating courses used during all the periods.

4.3.1.1 Brick walls

Table A.3 and graphic illustration in Table A.4 in the Appendix show the brick dimensions and the brick-mortar joint dimensions quantitatively and graphically. While comparing the thicknesses of the bricks used, the periods do not show a significant difference. The minimum value for all periods is 3.5 cm and the

maximum is also 6 cm, with the exception of 2 cm height for the late Byzantine period, as discussed earlier.

However when the lengths of the bricks are compared, as it was declared in the previous studies, the dimensions of the Byzantine bricks decrease by time. It may be seen that the length of the early Byzantine bricks are much longer (maximum 52 cm, average 37 cm) than both the late Byzantine (maximum 39 cm, average 32 cm) and early Ottoman periods (maximum 38.5 cm, average 28 cm). As the decrease in the brick length continues by time, the early Ottoman bricks (with the exception of Çinili Kiosk) have even shorter length.

Comparing the height of the brick mortar joints, the early Byzantine brick joints seem the thickest. There is not sufficient data of the late Byzantine period. The brick mortar joints of early Ottoman period are rather thinner (maximum 4.6 cm, minimum 1cm) compared with the early Byzantine period (maximum 9 cm, minimum 3.5 cm) and similar to the few data of the late Byzantine period.

4.3.1.2 Stone walls

The stone used in the building construction can be discussed according to the dimensions (thickness and length) and the height of the stone joints, the results can be seen in Table A.5 and the graphic can be seen in Table A.6 in Appendix. Although the minimum and maximum values for the heights of the stones used during all the periods are similar (for Byzantine period minimum 10 cm, maximum 33 cm; for early Ottoman period minimum 12 cm, maximum 52 cm), commonly used stone thicknesses are rather higher in the early Ottoman period than the Byzantine period. Despite the fact that there are few examples resembling the late Byzantine period, it may be seen that the stone thicknesses decreased in this period compared to early Byzantine and early Ottoman periods.

When the stone lengths are compared similar attitude as the thicknesses may be claimed. The longest stones are used in the early Ottoman period. As the lengths of the early Byzantine period (minimum 16 cm, maximum 69 cm) seem shorter compared to early Ottoman period (minimum 10 cm, maximum 150 cm), the lengths of the late Byzantine period (minimum 11.5 cm, maximum 45 cm) are even the shortest.

Only one research gives an example of stone mortar joints of the early Ottoman period (5-6.5 cm). Due to this fact, from the researches the minimum and maximum stone mortar joints are seemed to be applied during the Byzantine period (minimum 3.5 cm, maximum 9 cm). When the heights of the stone mortar joints are compared, the Byzantine periods show a contrast with the stone thickness. Thinner mortar joints are used in the early Byzantine period when thicker stones were used, and on the contrary thicker joints are used for thinner stones.

4.3.2 Masonry wall materials

4.3.2.1 Mortar

Lime mortar is actually composed of non-hydraulic lime, which is irrisistant to water. When combined with pozzolan, hydraulic lime is formed which is hard and resistant to water at the same time. Lime mortar made out of pozzolan and brick pieces have been named by the Romans as “opus cementicium” and they have continued to survive until today [24]. This type of mortars are called Horasan in Turkey, Surkhi in India, Homra in Arabic countries and Cocciopesto by Romans [26].

Brick fragments are not just inert filler in the mortars and plasters, but they contribute to strength development through reaction with lime. The brick powder mixed with lime must be fired at low temperature (less than 900 °C) to develop desired level of pozzolanacity that is derived from the amorphous structure obtained from the decomposition of clay minerals. This type of mortars and plasters were successfully used in historical constructions owing to their desirable characteristics as good cohesion, low porosity and high mechanical properties. Gypsum was often added into lime as an additive to provide early strength of historic mortars and plasters [26].

However, in some Roman, Byzantine and Ottoman period buildings, coarse brick aggregates which acquire less hydraulic character were used in thick joint mortars. The use of coarse brick aggregates in the thick joint mortars was, however, explained by their roles in influencing deformability and weight of the mortar as opposed to a pozzolanic contribution [25]. This type of mortar is as strong as concrete. Horasan mortar has been widely used in Ottoman buildings especially in those that belong to the 15th century and in the period that follows [24].

From Table A.7 in the Appendix, it may be said that density of the early Byzantine mortars (ranging between 1.23-1.77 g/cm³) are higher compared to the Ottoman mortars (with the result of only one study, 1.25g/cm³). The graphic of the density values are shown in below Figure 4.7.

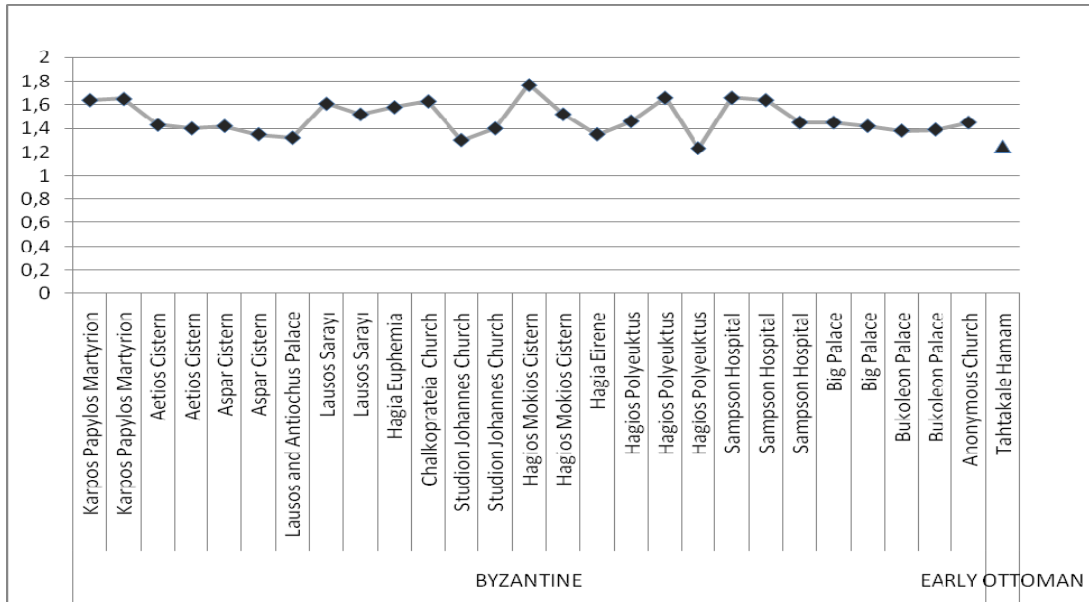


Fig 4.7 : Density -Timeline graphic of Byzantine and early Ottoman mortars

However, although the Byzantine mortars have higher values for specific gravity, there is not such a significant difference in the specific gravity values between the Byzantine mortars (between 2.41-2.72 g/cm³) and early Ottoman mortar (2.47g/cm³). These values can be seen in graphic in the Figure 4.8.

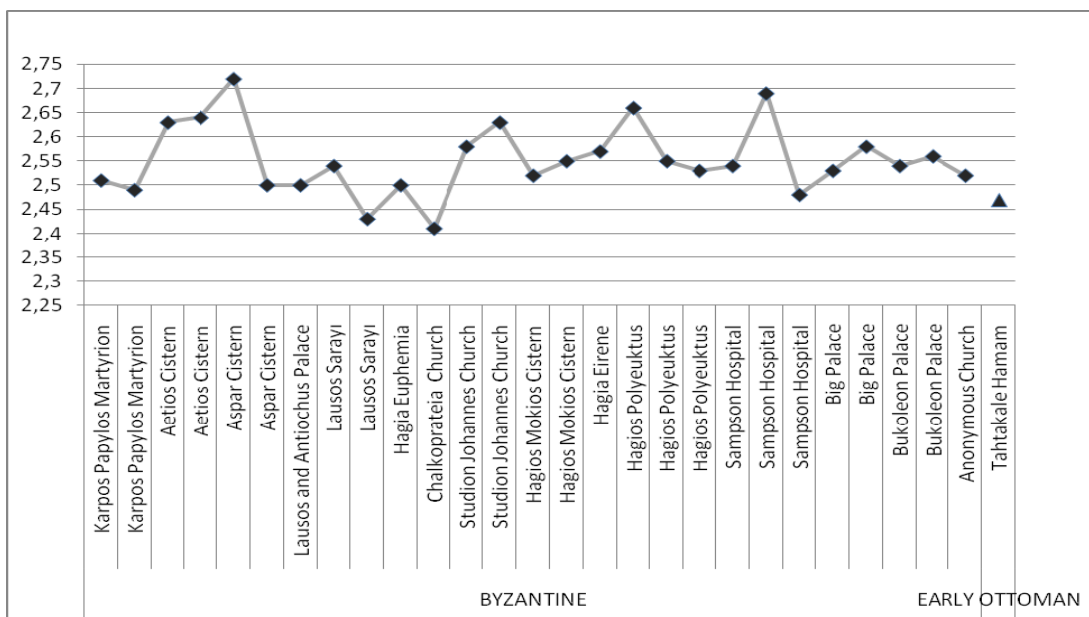


Fig 4.8 : Specific Gravity -Timeline graphic of Byzantine and early Ottoman mortars

The porosity value of the early Ottoman mortar (49 %) is in the range of porosity values of the Byzantine mortars (ranging between 30-52 %). However Byzantine mortars averagely have lower porosity values than the only example of early Ottoman mortar. Figure 4.9 below show the porosity values of the mortars from previous researches.

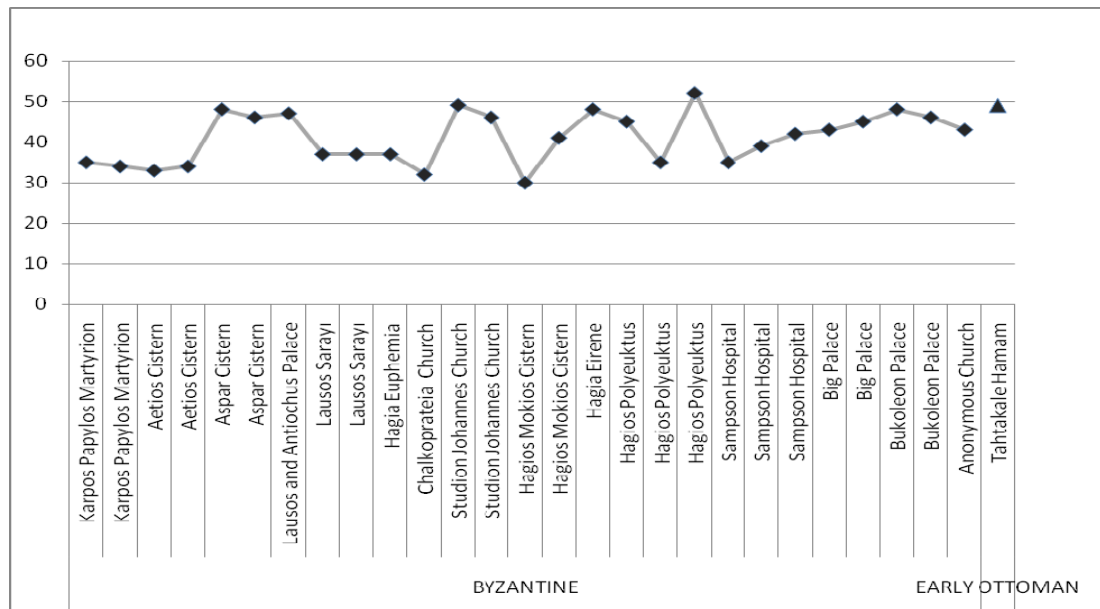


Fig 4.9 : Porosity -Timeline graphic of Byzantine and early Ottoman mortars

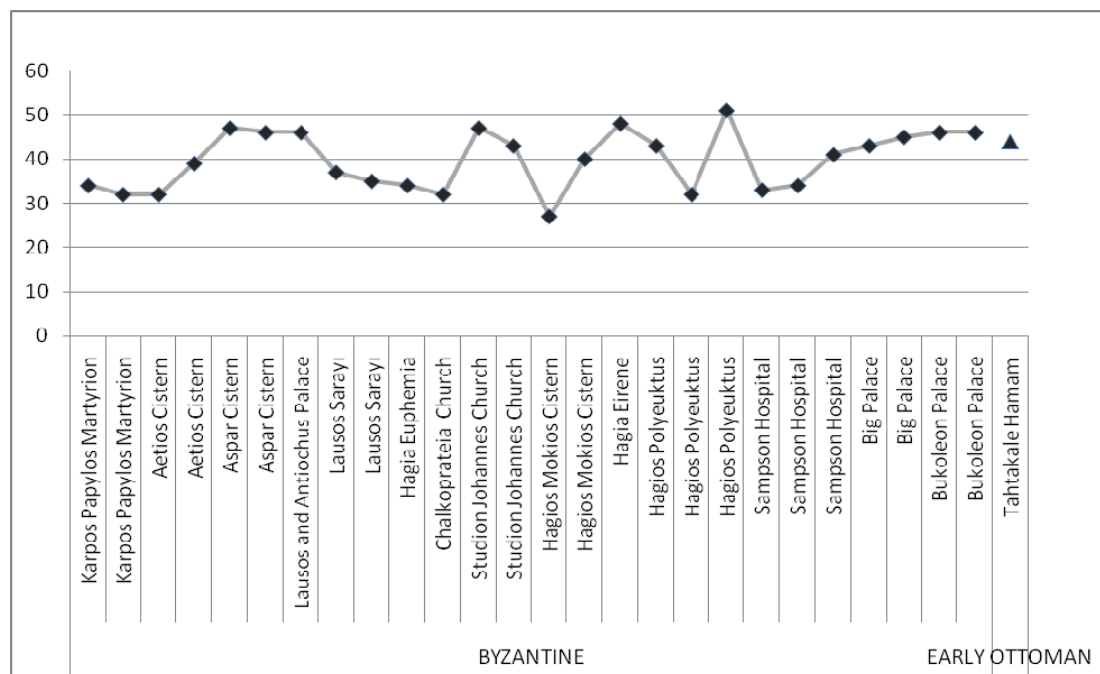


Fig 4.10 : Water Absorption (by volume) -Timeline graphic of Byzantine and early Ottoman mortars

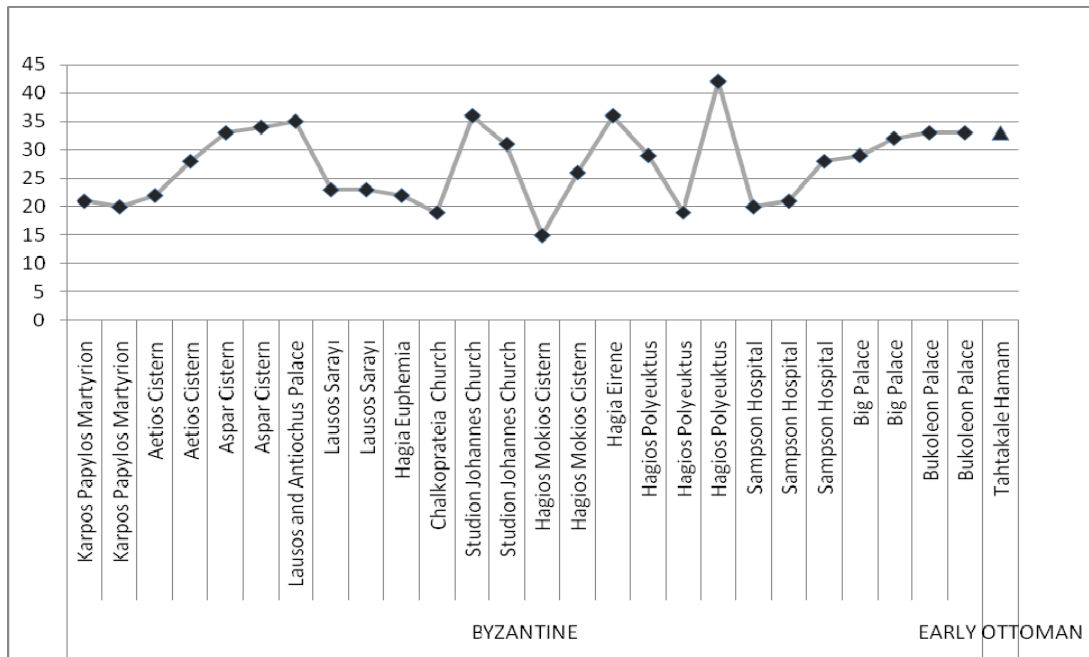


Fig 4.11 : Water Absorption (by weight) -Timeline graphic of Byzantine and early Ottoman mortars

As the porosity values increase by time, the average water absorption values increase parallel to the porosity. Figure 4.10 shows the water absorption (by volume) – timeline graphic, and Figure 4.11 shows the water absorption (by weight) values for the Byzantine and early Ottoman mortars.

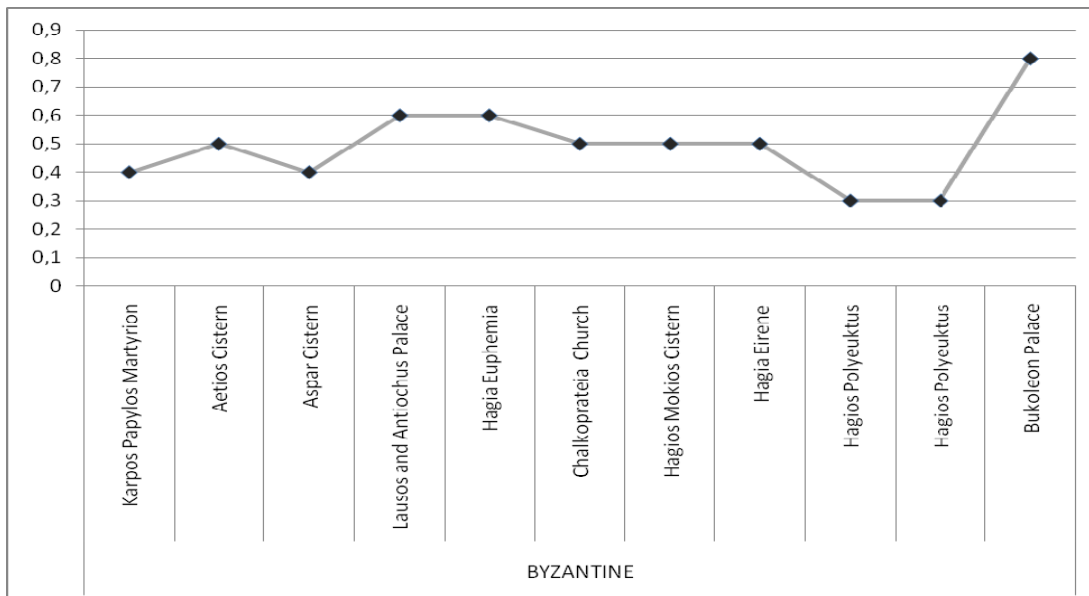


Fig 4.12 : Compressive Strength -Timeline graphic of Byzantine and early Ottoman mortars

There are not any data about the compressive strength values from previously studied early Ottoman mortars. The compressive strength values for Byzantine mortars seem to develop by time. There are 8 MPa values reached at the later Byzantine structures. Figure 4.12 is the graphic of the compressive strength values for the investigated mortars.

Other experimental studies such as, chemical separation, binder/aggregate ratio, pozzolanic activity, carbonate percentage, pH are investigated by Kahraman for early Byzantine mortars. However, there are not any data to compare them with early Ottoman mortars.

4.3.2.2 Brick

As the physical properties of bricks are compared according to the Table A.8 in the Appendix, at first the density of the early Ottoman bricks seem to be similar within the period and averagely have a denser character (ranging between 1.73-1.89 g/cm³) compared with previous periods (ranging between 1.61-1.85 g/cm³, with just one example of 2.02 g/cm³). The density values of Byzantine bricks change in a higher range. As there are less dense bricks or extreme density values, the average is similar. Comparing the bricks with the solid brick standards today, the density values are likely acceptable with the standard value of 1.8 g/cm³. The density-timeline graphic of the Byzantine and early Ottoman bricks can be seen in Figure 4.13 below.

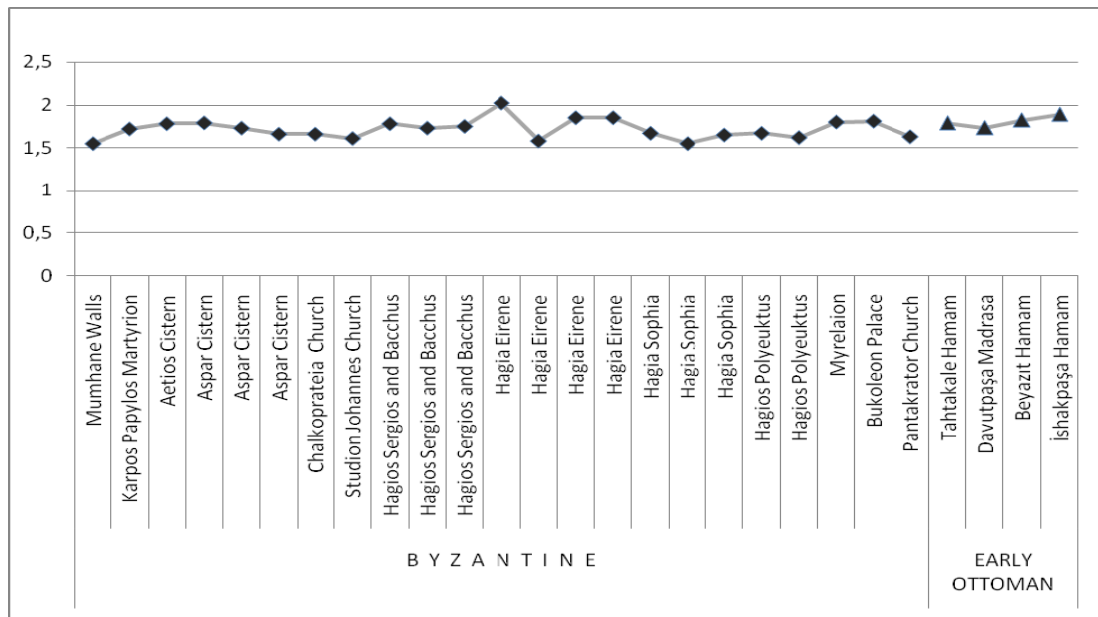


Fig 4.13 : Density (g/cm³) -Timeline graphic of Byzantine and early Ottoman bricks

Higher specific gravity values (maximum 2.84 g/cm³) may be seen in Byzantine bricks, especially in the ones produced during the early Byzantine period. The specific gravity values are lesser for early Ottoman bricks (between 2.71-2.78 g/cm³) compared to the Byzantine period. The graphic of the specific gravity-timeline graphic for the Byzantine and early Ottoman bricks is below in Figure 4.14

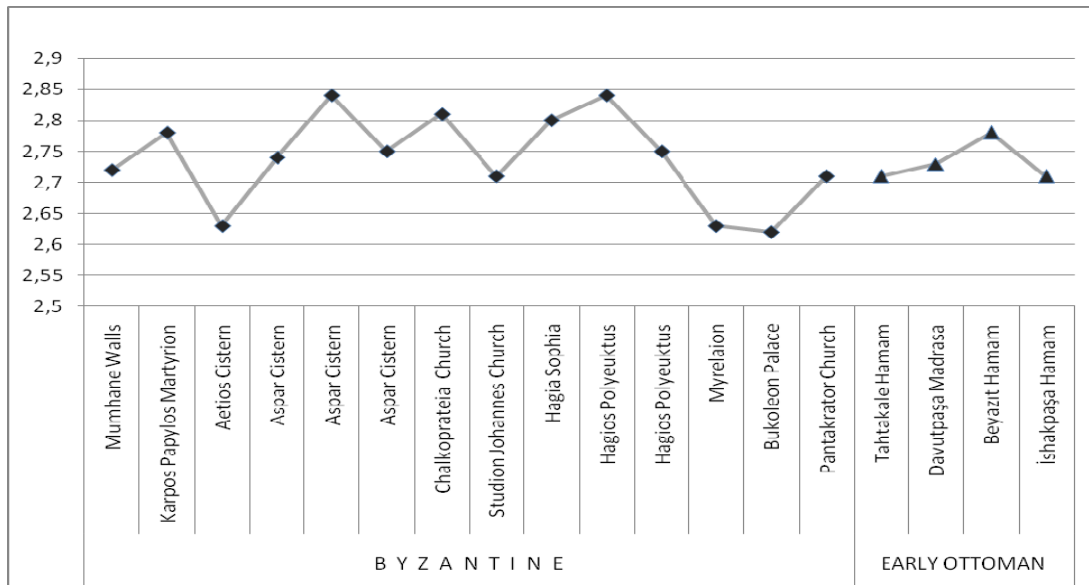


Fig 4.14 : Specific Gravity (g/cm³) -Timeline graphic of Byzantine and early Ottoman bricks

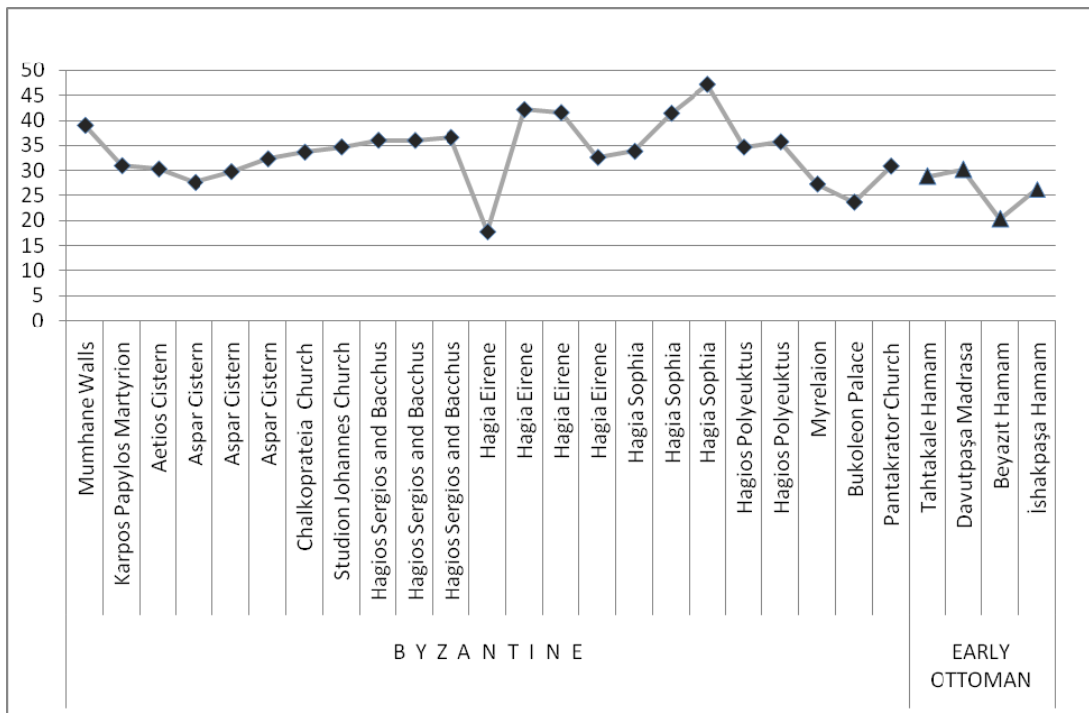


Fig 4.15 : Porosity (%) -Timeline graphic of Byzantine and early Ottoman bricks

As a result of the relationship of the density and specific gravity values, the porosities of the Byzantine bricks are much higher (maximum 47.21 %) compared to early Ottoman bricks (maximum 30.15 %). Figure 4.15 shows the porosity-timeline graphic for the Byzantine and early Ottoman bricks.

Historic bricks commonly show high porosity (30–40 %). High porosity may not always be an original feature of historic bricks, but rather happens due to decay processes related to physical weathering [35]. However, the selection of suitable materials for the restoration of historic buildings is not simple. The most durable material is not always the most suitable since it could divert the alteration agents towards the more sensitive original materials [37]. The selection of replacement bricks, which display lower porosity, absorb significantly less water and dry much faster than the historic bricks, could accelerate the deterioration of the historic structure. Thus, a replacement brick of similar porosity and hygric behaviour should be chosen [35]. When high salt concentrations are detected in the original masonry materials, bricks rich in carbonates may be chosen for restoration in order that their high porosity acts as a “sponge” (a sacrificial substrate, a salt trap) for the salts present in the medium, thus protecting the original bricks [36, 37]. It has been proven experimentally that salt induced deterioration occurs in the most porous material [35].

The values of water absorption (by volume) correspond with the porosity data, and the values for water absorption (by weight) shows the similar decrease (between 25.16-13.13 % for Byzantine period; and between 17.23-11.19 % for early Ottoman period), parallel to porosity or water absorption (by volume). The water absorption by weigh is higher compared to the related value in the codes today. As the water absorption by weight is 10 % (according to the codes), although there is a significant decrease by time, these values are always over the limits. For Byzantine bricks, the water absorption (by weight) values start with 25% for the bricks of Mumhane Walls. With the decrease during the periods, the water absorption (by weight) values are quite close to 10 % for the early Ottoman bricks. Figure 4.16 shows the water absorption (by volume) – timeline graphic, and Figure 4.17 shows the water absorption (by weight) – timeline graphic for byzantine and early Ottoman mortars.

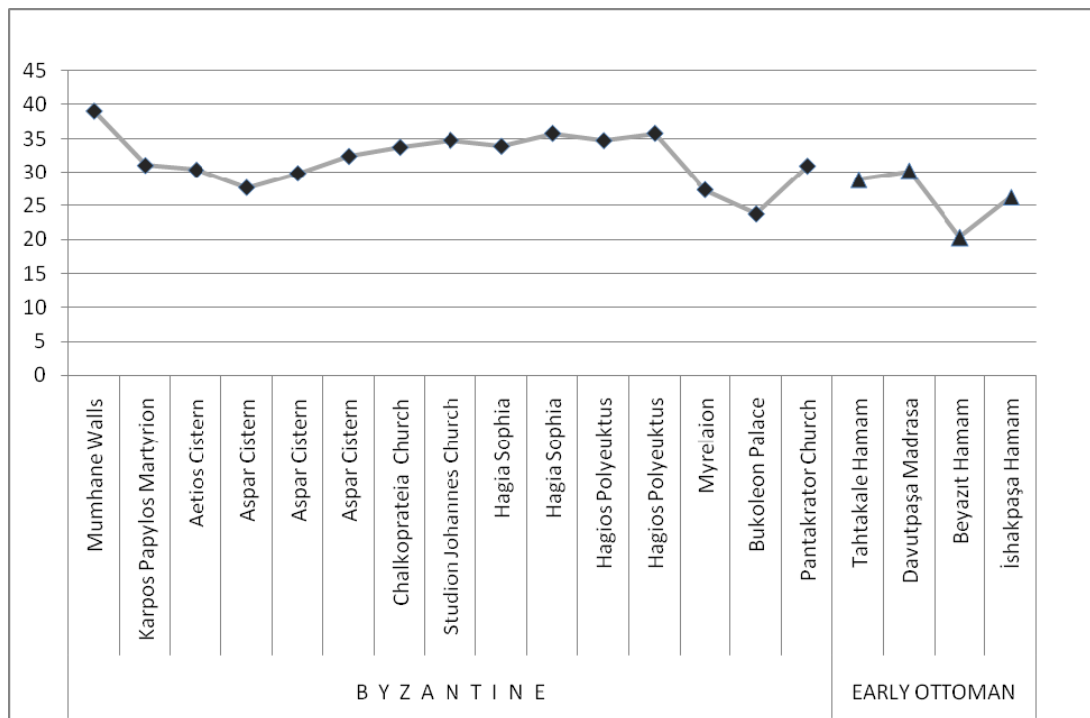


Fig 4.16 : Water Absorption (by volume) (%) -Timeline graphic of Byzantine and early Ottoman bricks

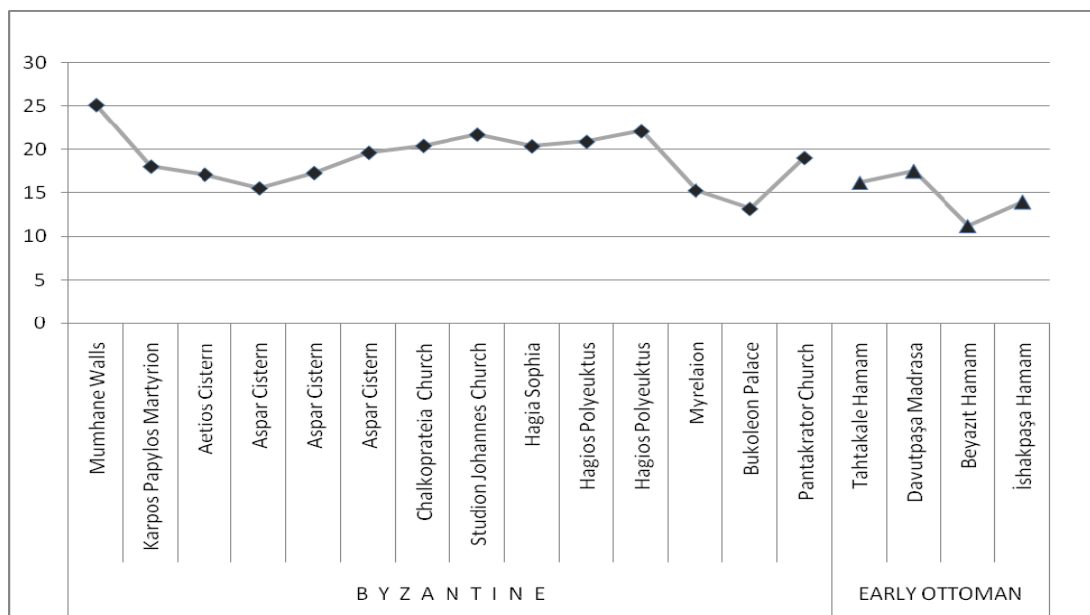


Fig 4.17 : Water Absorption (by weight) (%) -Timeline graphic of Byzantine and early Ottoman bricks

Hardness of the bricks decreases by time, mostly 3.0 and 4.0 according to Mohs scala for the Byzantine period; between 2.5-3.0 for early Ottoman period. The hardest bricks are produced during the early Byzantine period, and hardness keeps decreasing by time, ending with softest bricks in the early Ottoman period. Figure

4.18 below shows the hardness (Mohs) – timeline graphic for the byzantine and early Ottoman bricks. Also Figure 4.19 shows the hardness (Schmidt) – timeline graphic for the previously investigated brick samples.

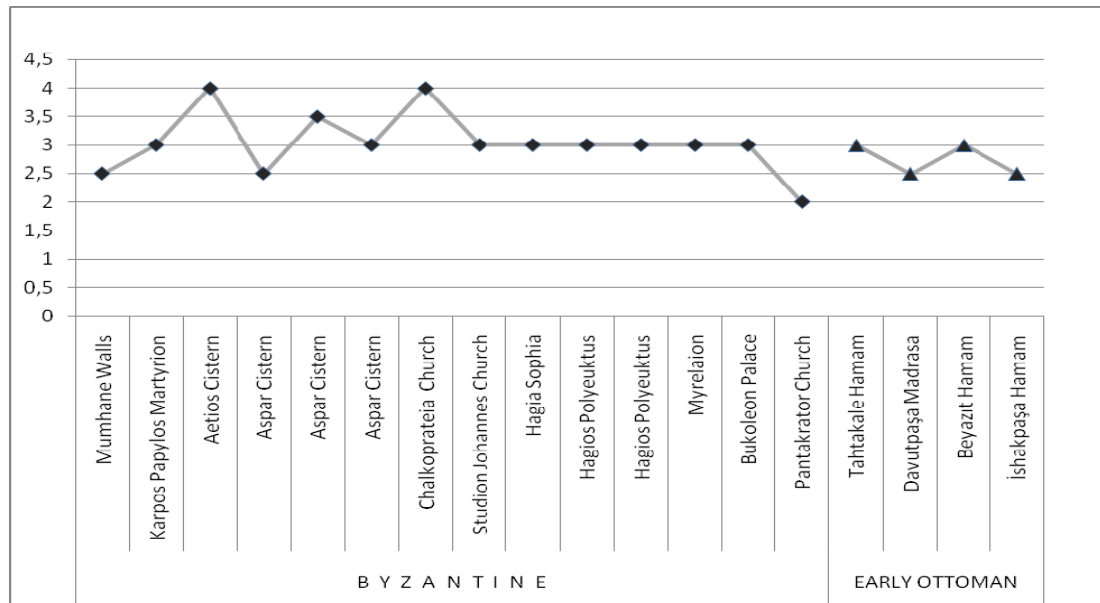


Fig 4.18: HArDness (Mohs)-Timeline graphic of Byzantine and early Ottoman bricks

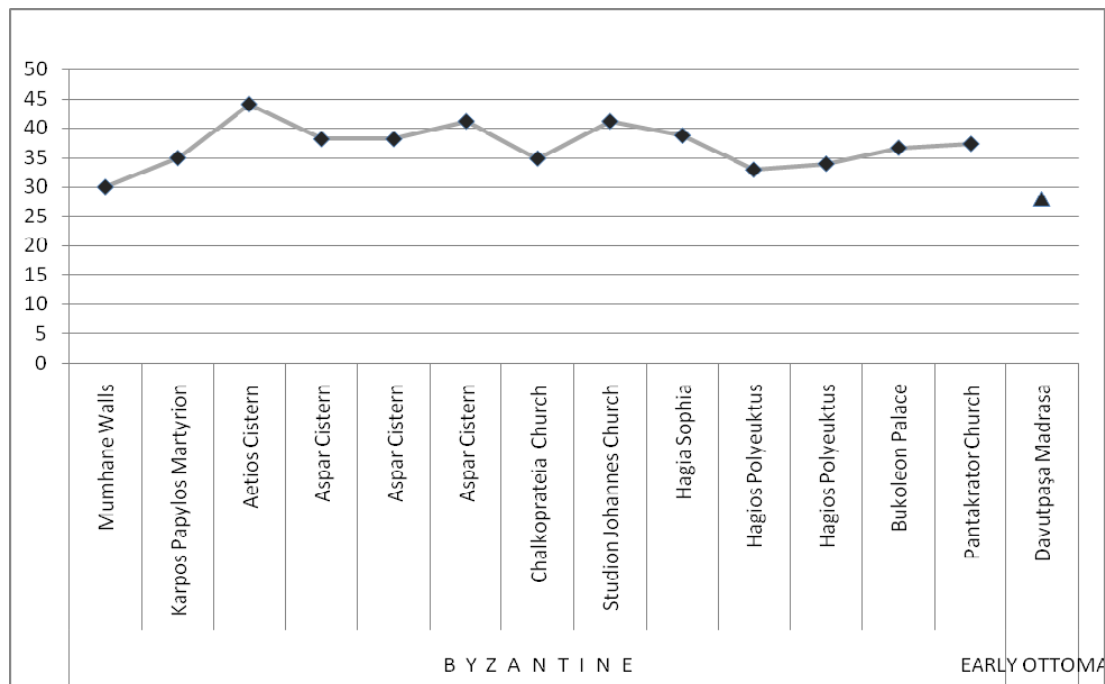


Fig 4.19 : Hardness (Schmidt)-Timeline graphic of Byzantine and early Ottoman bricks

The ultrasound test values of the Byzantine bricks (maximum 3.34 mm/μs) are higher compared with the early Ottoman bricks (maximum 2.29 mm/μs). The

ultrasound-timeline graphic for Byzantine and early Ottoman bricks is below in Figure 4.20.

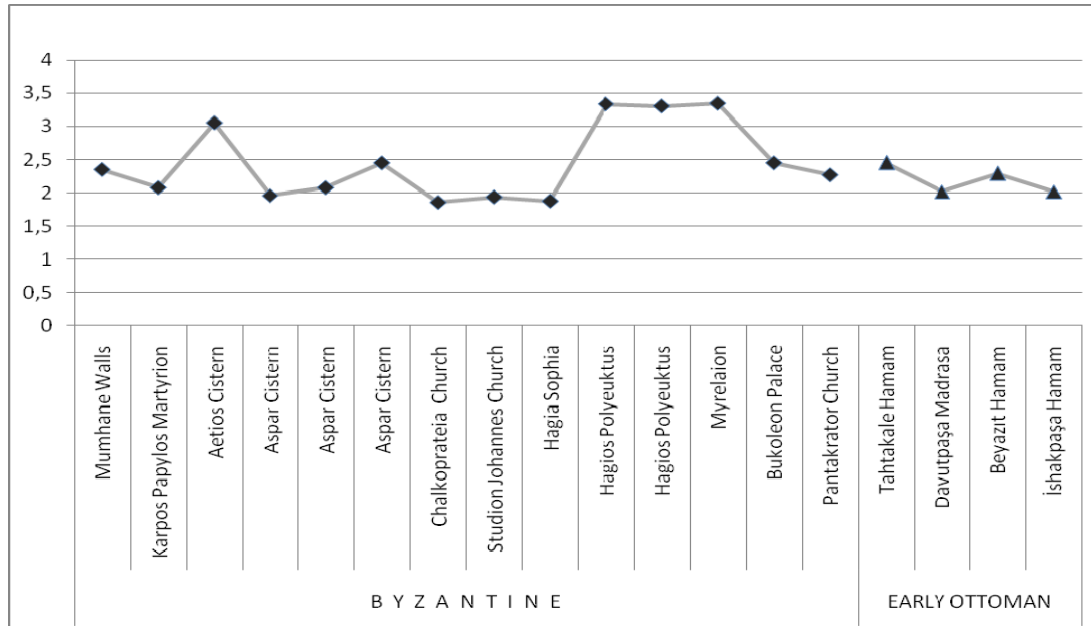


Fig 4.20 : Ultrasound (mm/μ) -Timeline graphic of Byzantine and early Ottoman bricks

Figure 4.21 below shows the compressive strength- timeline values for the Byzantine and early Ottoman bricks. When the compressive strengths are compared, there is a significant decrease in the early Ottoman bricks. The compressive strength values for 16.94-50.22 N/mm² for Byzantine bricks, and 8.27-13.99 N/mm² for early Ottoman bricks.

The compressive strength values are similar with the ultrasound test results, however rather unexpected compared to porosity data. As the porosity decreased by time, there is also a decrease in the compressive strength, on the contrary of what is expected. Kahya reasons this reduce to the paste of the bricks and its production properties. Compressive strength values are acceptable regarding today's standards for the Byzantine bricks, all over 16 N/mm² (minimum value of the codes), but all the bricks of the early Ottoman period fail to achieve 16 N/mm².

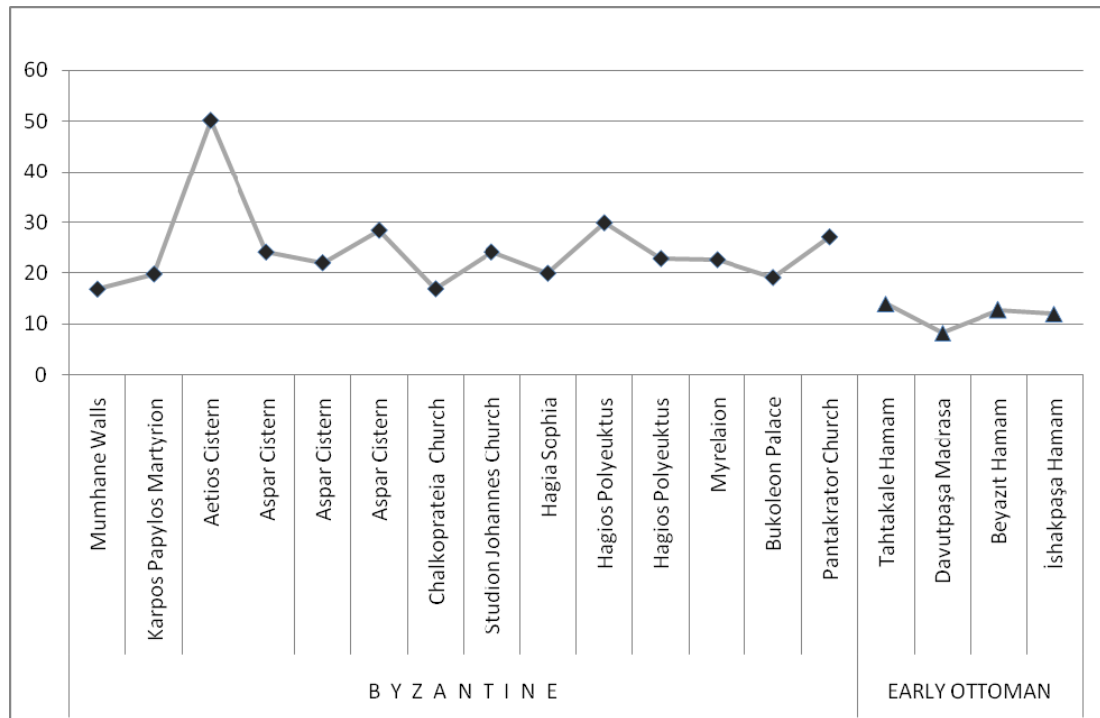


Fig 4.21 : Compressive Strength (N/mm²) -Timeline graphic of Byzantine and early Ottoman bricks

4.3.2.2 Stone

Also from Table A.5 in the Appendix, it is seen that, although there are few information about the stone used, Bakirkoy kufeki (a type of coarse sand stone of sedimentary stones) is used for both Byzantine and early Ottoman structures. Od stone (formerly applied name rather loosely to certain dark colored igneous rocks, including diorite, diabase, etc) is used mostly during Byzantine period and also in Early Ottoman period as well. Besides, it is known that green stone is also used for Byzantine structures.

Regarding that most of the stones, used for both Byzantine and early Ottoman buildings in İstanbul are kufeki, a type of limestone, the possible values from the codes can be given approximately in Table 4.1 as:

Table 4.1 : The properties of limestone

Property	Value	Unit
Water Absorption (by volume)	4	%
Specific Gravity	2.16	g/cm ³
Compressive Strength	49	MPa
Flexural Strength	2.94	MPa
Abrasion Resistance	1	
Weight Loss for Freeze and Thaw Resistance	>5	%
Impact Test	<0.6-1.2	N/mm ²

5. CONCLUSION

As the conclusion, it may be said that pure brick and alternating courses of brick and stone can be seen in the Byzantine periods, with the difference of alternating course styles between early and later Byzantine constructions. During the early Ottoman period, alternating courses of brick and stone are also used with a quite similar style to the later Byzantine structures. Besides, there are not any pure brick constructions in the early Ottoman period, but pure stone structures are constructed.

Comparing the use of stone, it may be said that there are differences between the periods, as higher stones (maximum 52 cm) used in early Ottoman periods than Byzantine period (maximum 33 cm). There is even a more significant difference in the length of the stones, but longer stones are used during the early Ottoman period (maximum 150 cm) rather than Byzantine period (maximum 64 cm). From the measurements of the stone mortar joints, it may be said that the height of the joints in the early Ottoman period are thinner (between 3.5-6.5 cm) than Byzantine period (between 3.5-8.5 cm). This may be a result of a more developed stone wall construction in the early Ottoman period compared to Byzantine period.

Though the results are not sufficient enough in the means of the numbers, it may be said that the dimensions of the brick mortar joints decrease by time. The early Byzantine brick-mortar joints commonly having height of 5-5.5 cm, with the maximum of 9 cm, the early Ottoman brick mortar joints are mostly 3.5 cm in height, with the maximum of 4.6 cm. As the fact that the brick thicknesses decrease (for Byzantine period bricks with a maximum of 6 cm, mostly of 4.5-5 cm; for early Ottoman period mostly 3.5 cm, with just one exception of 6 cm) parallel to the decrease in the mortar joints height, this may be a result of reduce in the thickness of the brick, however, the relationship between the brick and mortar properties must be studied further. A following study of the bricks and mortars from the same Byzantine and Ottoman structures may help to establish a true relationship with the material properties and the wall patterns of the periods.

As the conclusion of the physical properties, the lower results in porosity of the later period bricks (the early Byzantine bricks having porosity values up to 47 %; the early Ottoman bricks with a maximum of 30.15 %) may be thought as having better porosity values gained by the development of the technology. However, this technologic achievement is supposed to affect all the physical characteristics of the material used. Despite the reduce in the porosity of the bricks, the compressive strength values also decrease by time. As a result of the decrease during the periods, the water absorption (by weight) values are quite close to the value in the codes (10 %) for the early Ottoman bricks (17.23-11.19 %). However, the porosities of the early Ottoman bricks may be thought to be close to the values in the codes today (minimum 16 N/mm²)., the compressive strength values are very low (and 8.27-13.99 N/mm²). Besides, the compressive strength values for all Byzantine bricks satisfy the minimum value in the codes, but, all the Byzantine bricks fail to achieve the water absorption (by weight) values in the codes (25.16-13.13 % for Byzantine bricks).

On the contrary to the reduce in the porosity of the brick by time, the porosity of the mortar samples increase. The porosity values of the mortar samples of the Byzantine period ranges between 30-49 %, and the porosity values for the early Ottoman mortars (results of only two structures) are between 43-49 %. As a result of this, the closer porosity values for brick and mortar can be seen in the early Byzantine period structures, even two structures (Mumhane Walls and Chalcopteria Church) having higher porosity degrees for brick than mortar. However, the difference between the porosity of bricks and mortars increase by time.

The physical properties of stones are not studied specifically in the previous studies. The reason might be the physical properties do not change as the nature of the building stone is shaped during it is formation. However the use of the stone and the masonry system techniques must be investigated due to fact that the dimensions may play a role in the physical properties of the system.

As the fact that the quantitative values obtained from the previous studies are about individual buildings, and especially about one specific material used in the building, it is not possible to make a comparison between the system properties and material relationships within the system. Also, it is seen from the tables that these are not sufficient in number to make reliable estimations. Either to prove or to reach to more

statistical results; more structures, systems and materials must be studied and the relationships between the parameters and values must be established for better understanding of the historic structures, and for the following conservation studies.

In the future, different types of materials from the same structure may be examined and the wall pattern of the wall may be documented. Then with regard to the results of the basic physical and mechanical property experiments, relationships between the material properties and the wall pattern can be established. Further studies on especially early Ottoman bricks and mortars from later periods of Byzantine, and early Ottoman periods should be analysed.

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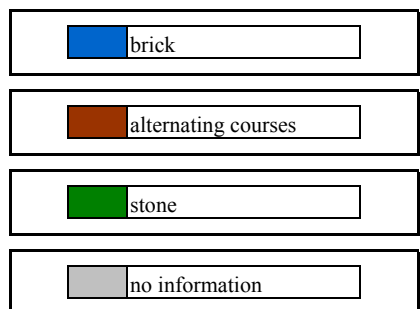
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APPENDICES

- APPENDIX A.1 :** Wall pattern schema of Byzantine and early Ottoman walls
- APPENDIX A.2 :** Schema of alternating brick/stone coursed wall patterns of Byzantine and early Ottoman periods
- APPENDIX A.3 :** Table of colour and dimensions of bricks and brick courses used
- APPENDIX A.4 :** Graphic illustration of dimensions of bricks and brick-mortar joints
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- APPENDIX A.8 :** Table of experimental results of bricks used during Byzantine and Early Ottoman Periods

A.1 : Wall pattern schema of Byzantine and early Ottoman walls
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A.2 : Schema of alternating brick/stone coursed wall patterns of Byzantine and early Ottoman periods

STONE

BRICK

1

2

3

4

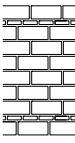
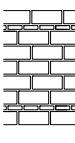
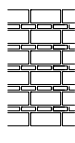
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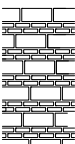
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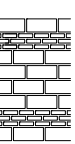
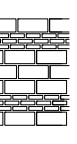
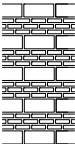
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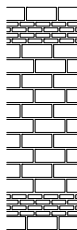
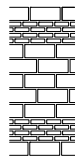
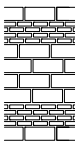
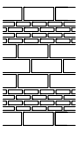
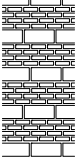
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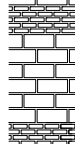
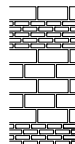
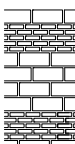
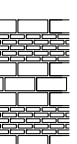
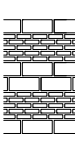
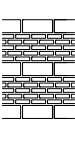
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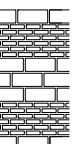
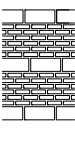
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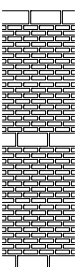
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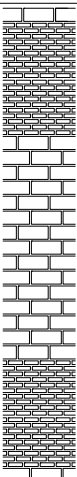
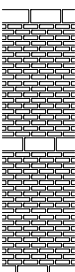
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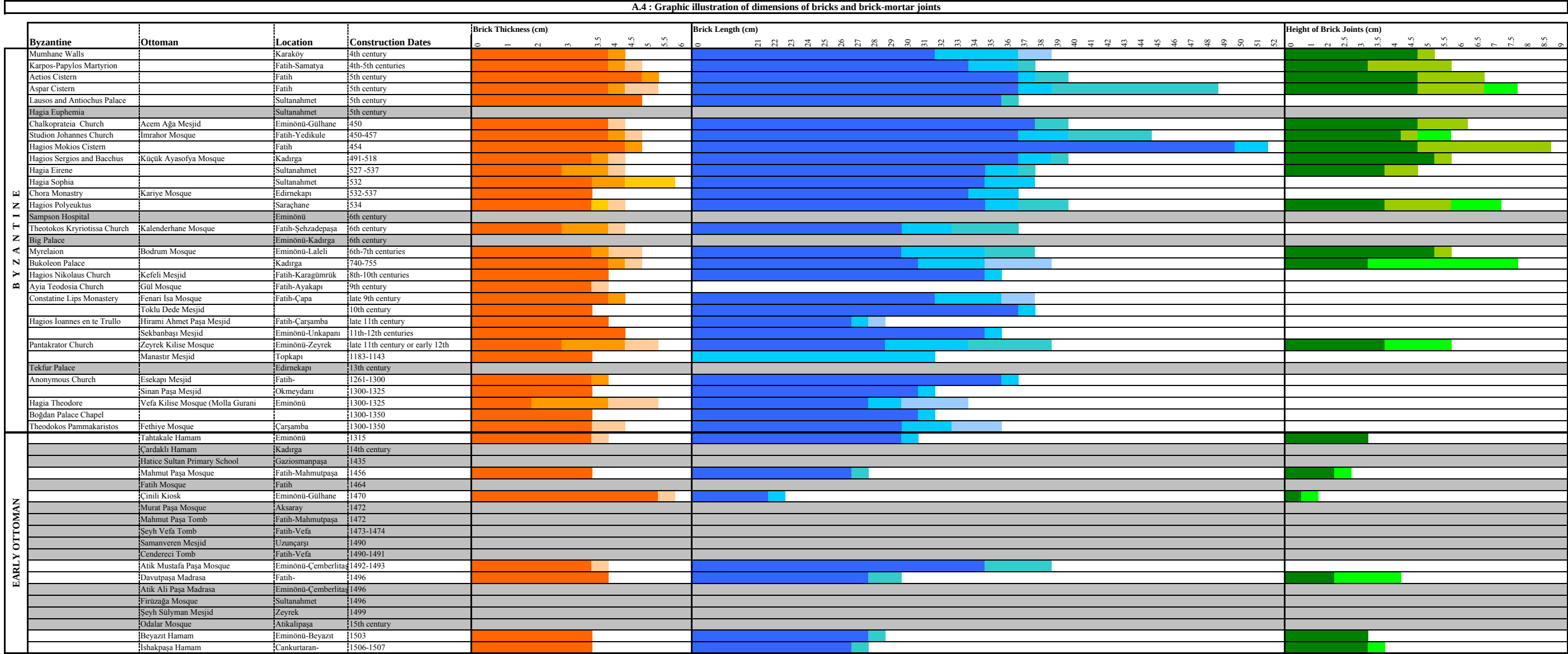


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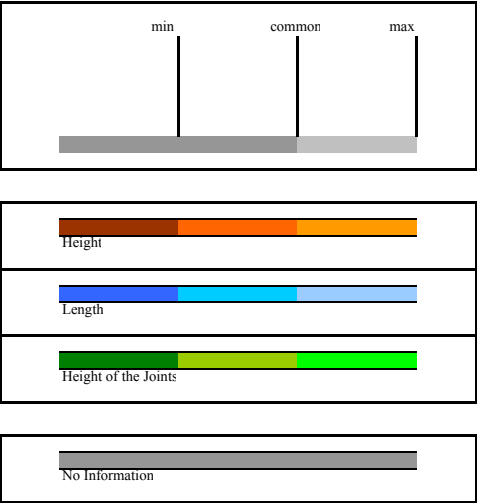


A.3 : Table of colour and dimensions of bricks and brick courses used

	Byzantine	Ottoman	Location	Construction Dates	Brick Colour	Course Pattern	Thickness cm	Length cm	Height of Brick Courses cm	Height of Brick Joints cm
B Y Z A N T I N E	Mumhane Walls		Karaköy	4th century	light reddish	5B/1S	4.5 min:3.9 max:4.7	37 min:32 max:39	5B:42-44 6B:63-65	5-5.5
	Karpos-Papylos Martyrion		Fatih-Samatya	4th-5th centuries	reddish brown	brick	4.6-5.0 min:4 max:5	37.0 min:34 max:38	10B:78-81	3.5-6
						5B/3S, 5B/4S, 5B/5S			5B:41-42	
					reddish brown	5B/3S, 5B/4S	4.5-5	34-38	5B:45	3.5-6
	Aetios Cistern		Fatih	5th century	reddish yellow, yellowish red	4B/10S	5.0 max:5.5	38 min:37.5 max:40	4B:37.5-43	5-7
					light orange	4B/10S	5.0	37-39	4B:43	5-7
	Aspar Cistern		Fatih	5th century	yellowish red	5B/6S	4.6-5.0 min:4 max:5.4	38 min:36.5 max:40	5B:45-50	6-7
					reddish yellow					
					pale red					
					light orange	5B/6S	4.5	48	5B:35-39	5-8
	Lausos and Antiochus Palace		Sultanahmet	5th century					9B:75	
					dark red		5	36-37		
					brick/crushed limestone					
						5B/4S				
	Chalkoprateia Church	Acem Ağa Mesjid	Eminönü-Gülhane	450-457	reddish yellow	brick	4-4.6	38-39.5	10B:87-92	5-6.5
						brick	4-4.5	39	10B:87-89	
						brick	4	38	10B:91	
				867-886		brick	4-4.5	39	10B:84	
	Studion Johannes Church	Imrahor Mosque	Fatih-Yedikule	454	reddish yellow	5B/3S	4.4-4.5 min:4.2 max:4.8	37-39.5	5B:42	4.5-5
							4-4.5	37.5	5B:40	
							4-4.5	37.5-39.5	10B:87	
					orange		4.5-5	45	36-38	5
					orange		4.5-5	45	36	5-6
					orange		4.5	42	38-39	5-6
	Hagios Mokios Cistern		Fatih	491-518	light orange	5B/S	4.5-5	50-52	35-39	5-9
	Hagios Sergios and Bacchus	Küçük Ayasofya Mosque		527 -537	reddish yellow	6B/3S	4.0 min:3.3 max:4.5	37.5-38 min:36 max:39	6B:49-51	5.5-6
						20B/1S				
						irregular repeating rates	4-4.5	37-38	10B:87	
	Hagia Eirene		Sultanahmet	532		recessed brick, grooved mortar	3-3.5	35-36		
							4	34	10B:62	4-5
				740		19B/1S, 20B/1S	4-4.5	35	10B:94.5	
						4/5, 5B/5S	4.5	38	5B:46.5-49	
	Hagia Sophia		Sultanahmet	532-537		5B/rubble	3.5-5	37.5	5B:49, 10B:101	
						5B/1S	3.5-4	36.5-38	3B:43.5-52	
						brick	4.5		10B:98	
						20B/1S, 20B/1S	4.5-6	35-38	10B:96-104	
						brick	3.5-4	38	10B:84	
						brick	4	37-38	10B:91	
						brick			10B:88	
							6	60	10B:126	
	Chora Monastery	Kariye Mosque	Edirnekapi	534		1B/1S, 3B/4S, 1/4	3.5	33	3B:22	
						4B/4S	3.5	33.5-36.5	4B:31-32	
	Hagios Polyeuktus		Saracane	6th century	light reddish brown reddish brown	5B/4S	4 min:3.3 max:4.5	37 min:35 max:39.5	5B:43-44	6 min:4 max:7.5
						4B/4S				
	Theotokos Kriyiotissa Church	Kalenderhane Mosque	Fatih-Şehzadepaşa	6th century		brick	2.8-3	30	10B:68-69	
						brick	3.3-4	33	10B:86	
				1204-1261					5B:37	
						5B/1S, 1B/1S	4	37	5B:36.5	
						5B/1S	3.5	37	5B:33.5, 35.5	
						1B/1S, 1B/6S	4-4.5	36.5-37	5B:42.5	
	Myrelaion	Bodrum Mosque	Eminönü-Laleli	740-755	light reddish brown	alternating	4	30-35		5.5-6
						brick				
							5-5.5	38	2B:18, 5B:43	
						brick	3.5-4		10B:91	
	Bukoleon Palace		Kadrga	8th-10th centuries	reddish brown	brick	4.8	35 - 39	10B:92-95	3.5-7
					reddish brown	brick	4.2 max:4.7	34 min:31 max:35	10B:86-89	3.5-8
	Hagios Nikolaus Church	Kefeli Mesjid	Fatih-Karagümruk	9th century		4B/5S, 4B/4S	4	35-36	4B:31.5	
	Ayia Teodosia Church	Gül Mosque	Fatih-Ayakapi	late 9th century		recessed brick	3.5-4		4B:43	
	Constatine Lips Monastery	Fenari Isa Mosque	Fatih-Çapa	10th century			4.5	32-33	5B:46	
						1B/1S, 1/5, 1/6	4-4.5	36-38	10B:41.5	
						5B/6S			5B:39, 6B:49-50	
				1290		1B/1S, 2B/1S, 5B/1S	4		2B:10.5, 5B:33.5	
		Toklu Dede Mesjid		late 11th century		4B/3S, 4B/1S	3.5	37-38	4B:28.5-30.5	
	Hagios Ioannes en te	Hırami Ahmet Paşa Mesjid	Fatih-Çarşamba	11th-12th centuries		4B/4S, 5B/4S	4	27.5-28.5	5B:35.5	
		Sekbanbaşı Mesjid	Eminönü-Unkapanı	late 11th century or early 12th century		brick	4-5	35-36	3B:36	
	Pantokrator Church	Zeyrek Kilise Mosque	Eminönü-Zeyrek	1183-1143	yellowish red	recessed brick	4.5-5.5	38 min:33.5 max:39		4-6
							3	31 min:29 max:32		
							4.5-5	38		
							3	24		
						1B/1S, 1/5				
		Manastır Mesjid	Topkapı	1261-1300		4B/4S	3.5	31.5	4B:30.5	
	Anonymous Church	Esekapi Mesjid	Fatih-Kocamustafapaşa	1300-1325		3B/3S, 3/6	3.5-4	36-37	3B:20	
						recessed brick				
		Sinan Paşa Mesjid	Okmeydanı	1300-1325		4B/3S	3.5	31-32	4B:34	
	Hagia Theodore	Vefa Kilise Mosque (Molla Gürani Mosque)	Eminönü	1300-1350		1B/1S, 2B/1S, 3B/1S, 4B/1S	2-5.5	30-34	4B:28.5-30.5	
							2-4		3B:21.5, 2B:13.5-14	
							3-4		2B:13.5, 3B:21	
							4-5		4B:31.5-33, 3B:21	
									2B:10.5, 3B:17	
						2B/1S	3.5-4	27.5-28	2B:14.5	
	Boğdan Palace Chapel			1300-1350		4B/4S	3.5	31.5	4B:26.5	
	Theodokos Pammakaristos	Fethiye Mosque		1315		4B/4S	3.5-4	30-33.5	4B:27	
				1292-1294		4S/4B	4-4.5	30-35.5	4B:30	
						recessed brick				
E A R L Y O T T O M A N		Tahtakale Hamam	Eminönü	1435	light red , red	cut-stone, rubble stone	3.5	29.5		3.5
		Murat Paşa Mosque	Aksaray	1472		2B/1S				
		Mahmut Paşa Mosque	Fatih-Mahmutpaşa	1464			3.5	27		2.5-3 (0.5 cm grooved)
		Cinili Kiosk	Eminönü-Gülhane	1472	red		5.5-6	21-22		1-2 (grooved)
		Seyh Vefa Türbesi	Fatih-Vefa	1490-1491		5B/1S				
		Cendereci Türbesi	Fatih-Vefa	1492-1493		1B/1S				
		Atik Mustafa Paşa Mosque				1/3, 3B/3S	3.5-4	35-38.5	3B:26, 4B:32	
		Davutpaşa Madrasa	Fatih-Kocamustafapaşa	1499-1500	red	stone	4	28 max:29.2		2.6-4.6
		Beyazıt Hamam	Eminönü-Beyazıt	1506-1507	red	stone	3.5	28 - 28.5		3.5
		İshakpaşa Hamam	Çankurtaran-Ahırkapı	15th century	yellowish red	stone	3.5	27.5		3.5-4

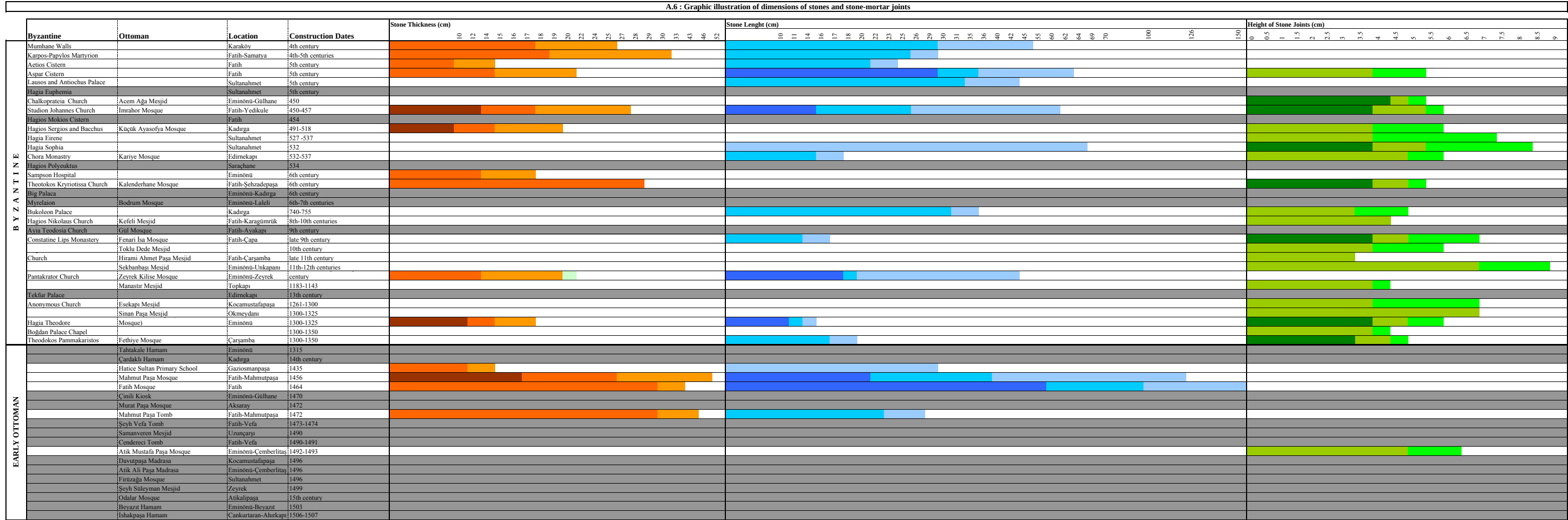


* Table A.4 is the graphic illustration of the numeric thickness and length data of brick and brick-mortar joint heights from Table A.3.

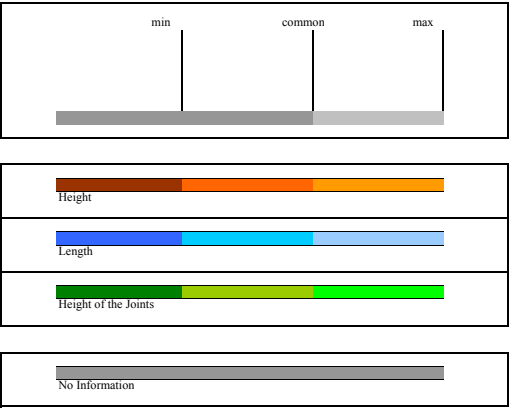


A.5 : Table of types and dimensions of stones and stone courses used

	Byzantine	Ottoman	Location	Construction Dates	Stone Type	Course Pattern	Thickness cm	Length cm	Height of Stone Course cm	Height of Stone Joints cm
B Y Z A N T I N E	Mumhane Walls		Karaköy	4th century		5B/1S	18-27	30-55	3.9-4.7	
						6B/1S				
	Karpos Papylos Martyrion		Fatih-Samatya	4th-5th centuries		brick				
					od stone from Bakirkoy	5B/3S, 5B/4S, 5B/5S	19-33	26-30	5S:104	
						5B/3S, 5B/4S	19-33	26-30	4S:82	
	Aetios Cistern		Fatih	5th century		4B/10S	10-15	23-25	4.8-5.5	
						4B/10S		22-25	10S:148	
	Aspar Cistern		Fatih	5th century		5B/6S	15-22	30-60		4-5.4
						5B/6S		36-64	10S:140	
	Lausos and Antiochus Palace		Sultanahmet	5th century				35-45		
					cut limestone					
					brick/crushed limestone					
						5B/4S				
	Studion Johannes Church	İmrahor Mosque	Fatih-Yedikule	454		5B/3S	18-28	26-60	58-60	
									64-68	
								16-26	3S:64.5-68	5.5
									3S:60-66	4-6
							16-17	40	3S:50	
							14-22	38	3S:58	
							16-24	42-62	3S:68	
	Hagios Mokios Cistern		Fatih	491-518		5B/S				
	Hagios Sergios and Bacchus	Küçük Ayasofya Mosque		527 -537		roughly-cut stone	15-20		15-20	
						6B/3S	10-20			
						20B/1S				
						irregular repeating rates				4-6
	Hagia Eirene		Sultanahmet	532		recessed brick, grooved mortar				7.5
				740	od stone	19B/1S, 20B/1S				4-7
						4B/5S, 5B/5S				
	Hagia Sophia		Sultanahmet	532-537		5B/rubble				4-6
					od stone from Karamürsel	5B/1S		max:69		8-8.5
						brick				5-7
						20B/15S, 20B/1S				4.5-5.5
						brick				4.5-5
						brick				4-5
						brick				4-5
	Chora Monastery	Kariye Mosque	Edirnekapı	534		1B/1S, 3B/4S, 1/4			4S:65	5-6
						4B/4S		16-18	4S:70-72	5-6
	Hagios Polyeuktus		Saraçhane	6th century		5B/4S	14-18		62-64	
	Theotokos Kryriotissa Church	Kalenderhane Mosque	Fatih-Şehzadepaşa	6th century		brick	29			4-5
						brick				5-5.2
						5B/1S, 1B/1S				4
						5B/1S				4
						1B/1S, 1B/6S			6S:107	5-5.5
				1204-1261					3S:54, 4S:58-60	
	Myrelaion	Bodrum Mosque	Eminönü-Laleli	740-755	cut stone	alternating courses				
	Bukoleon Palace		Kadırga	8th-10th centuries		brick		31-35.4		3.6-4.8
	Hagios Nikolaus Church	Kefeli Mesjid	Fatih-Karagümrük	9th century		4B/5S, 4B/4S			4S:61, 5S:76	4.5
Ayia Teodosia Church	Gül Mosque	Fatih-Ayakapı	late 9th century		recessed brick					
Constatine Lips Monastery	Fenari İsa Mosque	Fatih-Çapa	10th century					4S:90		
								5S:76	6.5-7	
					1B/1S, 1/5, 1/6		14		4-5	
					5B/6S					
			1290		1B/1S, 2B/1S, 5B/1S		14.5-17		4.5-5	
	Toklu Dede Mesjid		late 11th century		4B/3S, 4B/1S			3S:54	4-6	
Hagios Ioannes en te	Hırami Ahmet Paşa Mesjid	Fatih-Çarşamba	11th-12th centuries		4B/4S, 5B/4S			4S:92	3.5	
	Sekbanbaşı Mesjid	Eminönü-Unkapanı	late 11th century or early 12th century		brick				7-9	
Pantakrator Church	Zeyrek Kilise mosque	Eminönü-Zeyrek	1183-1143		recessed brick	14-20	30-45			
				cut limestone	1B/1S, 1/3		18-20			
	Manastır Mesjid	Topkapı	1261-1300		4B/4S			4S:67	4-4.5	
Anonymous Church	Esekapı Mesjid	Fatih-Kocamustafapaşa	1300-1325		3B/3S, 3/6			3S:56, 6S:95	4-7	
	Sinan Paşa Mesjid	Okmeydanı	1300-1325		4B/3S			3S:64	7	
Hagia Theodore	Vefa Kilise Mosque (Molla Gürani Mosque)	Eminönü	1300-1350		1B/1S, 2B/1S, 3B/1S, 4B/1S		14-16		4-6	
							11.5-16		4-6	
						14-17			4-6	
						12-17.5			4.5-5	
						15				
					2B/1S	14-16			5.5	
Boğdan Palace Chapel			1300-1350		4B/4S			4S:67-70	4-4.5	
Theodokos Pammakaristos	Fethiye Mosque		1315		4B/4S			4S:58-60	3.5-5	
			1292-1294		4S/4B		17-20	4S:75	4.5-5	
E A R L Y O T T O M A N		Tahtakale Hamam	Eminönü	1435	cut stone and rubble stone	stone				
		Hatice Sultan Primary School	Gaziosmanpaşa	1456			12-15	10-30		
		Mahmut Paşa Mosque	Fatih-Mahmutpaşa	1464	Bakırköy Kufeki		25-43	40-126		
							17-52	22-70		
		Fatih Mosque		1470	Bakırköy Kufeki, roughly cut stone, cut stone		30-43	60-100 max:140-150		
		Murat Paşa Mosque	Aksaray	1472	cut stone	2B/1S				
		Mahmut Paşa Tomb	Fatih-Mahmutpaşa	1473-1474			30-46	23-29		
		Şeyh Vefa Tomb	Fatih-Vefa	1490-1491	cut stone	3B/1S				
		Cendereci Tomb	Fatih-Vefa	1492-1493		1B/1S				
		Atik Mustafa Paşa Mosque		9th		1/3,3B/3S			3S:56	5-6.5
		Davutpaşa Madrasa	Fatih-Kocamustafapaşa	1499-1500	roughly cut stone	stone				
		Atik Ali Paşa Madrasa	Eminönü-Çemberlitaş	1496	cut stone	stone				
		Firûzağa Mosque	Sultanahmet	1496	cut stone	stone				
		Beyazıt Hamam	Eminönü-Beyazıt	1506-1507		stone				
	İshakpaşa Hamam	Cankurtaran-Ahırkapı	15th century		stone					



* Table A.6 is the graphic illustration of the numeric thickness and length data of stone and stone-mortar joint heights from Table A.5



A.7 : Table of experimental results of mortars used during Byzantine and early Ottoman periods

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A.8 : Table of experimental results of bricks used during Byzantine and early Ottoman periods

					Density (gr/cm ³)	Specific Gravity (gr/cm ³)	Porosity (%)	Water Absorption (by weight) (%)	Water Absorption (by volume) (%)	Water Saturation Coefficient	Hardness (Mohs)	Hardness (Schmidt)	Ultrasound (mm/μs)	Compressive Strength (N/mm ²)
	Byzantine	Ottoman	Location	Construction Dates										
B Y Z A N T I N E	Mumhane Walls		Karaköy	4th century	1.55	2.72	39.04	25.16	39.04	1.94	2.5	30	2.35	16.88
	Karpos Papylos Martyrion		Fatih-Samatya	4th-5th centuries	1.72	2.78	31.00	17.99	31.01	2.03	3.0	34.9	2.08	19.84
	Aetios Cistern		Fatih	5th century	1.78	2.63	30.34	17.07	30.34	2.09	4.0	44	3.05	50.22
	Aspar Cistern		Fatih	5th century	1.79	2.74	27.66	15.50	27.66	2.06	2.5	38.1	1.96	24.15
					1.73	2.84	29.81	17.25	29.81	2.03	3.5	38.1	2.08	22.05
					1.66	2.75	32.37	19.58	32.37	1.97	3.0	41.1	2.45	28.43
	Lausos and Antiochus Palace		Sultanahmet	5th century										
	Hagia Euphemia		Sultanahmet	5th century										
	Chalkoprateia Church	Acem Ağa Mesjid	Eminönü-Gülhane	450-457	1.66	2.81	33.70	20.37	33.70	1.99	4.0	34.8	1.86	16.94
	Studion Johannes Church	Imrahor Mosque	Fatih-Yedikule	454	1.61	2.71	34.74	21.66	34.74	1.95	3.0	41.1	1.94	24.17
	Hagios Mokios Cistern		Fatih	491-518										
	Hagios Sergios and Bacchus	Küçük Ayasofya Mosque		527 -537	1.78		36.07							
					1.73		36.04							
					1.75		36.64							
	Hagia Eirene		Sultanahmet	532 740	2.02		17.83							
					1.58		42.18							
					1.85		41.60							
	Hagia Sophia		Sultanahmet	532-537	1.85		32.66							
					1.67	2.80	33.87	20.32	33.87	2.01	3.0	38.7	1.88	19.98
					1.55		41.46							
					1.65		47.21		35.77					
	Chora Monastery	Kariye Mosque	Edirnekapı	534										
	Hagios Polyeuktus		Saraçhane	6th century	1.67	2.84	34.70	20.84	34.70	2.01	3.0	32.9	3.33	29.90
					1.62	2.75	35.77	22.05	35.77	1.98	3.0	33.9	3.30	22.88
	Sampson Hospital		Eminönü	6th century										
	Theotokos Kryriotissa Church	Kalenderhane Mosque	Fatih-Şehzadepaşa	6th century										
	Big Palace		Eminönü-Kadirga	6th-7th centuries										
	Myrelaion	Bodrum Mosque	Eminönü-Laleli	740-755	1.80	2.63	27.34	15.24	27.34	2.07	3.0		3.34	22.65
	Bukoleon Palace		Kadirga	8th-10th centuries	1.81	2.62	23.74	13.13	23.74	2.05	3.0	36.6	2.45	19.15
	Hagios Nikolaus Church	Kefeli Mesjid	Fatih-Karagümrük	9th century										
	Ayia Teodosia Church	Gül Mosque	Fatih-Ayakapı	late 9th century										
	Constatine Lips Monastery	Fenari İsa Mosque	Fatih-Çapa	10th century										
		Toklu Dede Mesjid		late 11th century										
	Hagios Ioannes en te Trullo Church	Hirami Ahmet Paşa Mesjid	Fatih-Çarşamba	11th-12th centuries										
		Sekbanbaşı Mesjid	Eminönü-Unkapanı	late 11th century or early 12th century										
	Pantakrator Church	Zeyrek Kilise Mosque	Eminönü-Zeyrek	1183-1143	1.63	2.71	30.92	18.98	30.92	1.94	2.0	37.3	2.27	27.13
		Manastır Mesjid	Topkapı	1261-1300										
	Tekfur Place		Edirnekapı	14th century										
	Anonymous Church	Esekapı Mesjid	Fatih-Kocamustafapaşa	1300-1325										
		Sinan Paşa Mesjid	Okmeydanı	1300-1325										
	Hagia Theodore	Vefa Kilise Mosque (Molla Gürani Mosque)	Eminönü	1300-1350										
	Boğdan Palace Chapel			1300-1350										
	Theodokos Pammakaristos	Fethiye Mosque		1315										
E A R L Y O T T O M A N		Tahtakale Hamam	Eminönü	1435	1.79	2.71	28.85	16.17	28.85	2.07	3.0		2.45	13.99
		Çardaklı Hamam	Kadirga	14th century										
		Hatice Sultan Primary School	Gaziosmanpaşa	1456										
		Mahmut Paşa Mosque	Fatih-Mahmutpaşa	1464										
		Fatih Mosque		1470										
		Çinili Kiosk	Eminönü-Gülhane	1472										
		Murat Paşa Mosque	Aksaray	1472										
		Mahmut Paşa Tomb	Fatih-Mahmutpaşa	1473-1474										
		Şeyh Vefa Tomb	Fatih-Vefa	1490-1491										
		Samanveren Mesjid	Uzunçarşı	1490										
		Cendereci Tomb	Fatih-Vefa	1492-1493										
		Atik Mustafa Paşa Mosque	Eminönü-Çemberlitaş	1496										
		Davutpaşa Madrasa	Fatih-Kocamustafapaşa	1499-1500	1.73	2.73	30.15	17.43	30.16	2.03	2.5	28	2.02	8.27
		Atik Ali Paşa Madrasa	Eminönü-Çemberlitaş	1496										
		Firüzağa Mosque	Sultanahmet	1496										
		Şeyh Süleyman Mesjid	Zeyrek	1499										
		Odalar Mosque	Atikalipaşa	15th century										
		Beyazıt Hamam	Eminönü-Beyazıt	1506-1507	1.82	2.78	20.30	11.19	20.30	2.02	3.0		2.29	12.75
		İshakpaşa Hamam	Cankurtaran-Ahırkapı	15th century	1.89	2.71	26.25	13.91	26.25	2.15	2.5		2.02	12.02

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