MATERIALS PROPERTIES OF CONTEMPORARY SOLID BRICKS AND THEIR ASSESSMENT IN REFERENCE TO THE HISTORIC BRICKS

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ABSTRACT

MATERIALS PROPERTIES OF CONTEMPORARY SOLID BRICKS AND THEIR ASSESSMENT IN REFERENCE TO THE HISTORIC BRICKS

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A comprehensive study was done to assess the performance properties of contemporary solid bricks and their compatibility was discussed in reference to the performance properties of historical bricks, which survived for hundreds of years. The handmade and factory solid bricks, which are used particularly in the repair works of historical buildings, are expected to be compatible with the performance properties of the historical bricks.

In this regard, some types of contemporary solid burnt bricks, namely hand-made and factory-made (pressed and not-pressed) bricks, which were collected from local producers in Turkey, were examined with laboratory analyses in terms of basic physical, physicomechanical and mechanical properties together with the firing temperature and with a focus on their porosity and hygric properties.

The contemporary hand-made bricks are lightweight and porous bricks, which are burnt at firing temperature in the range of 750-900°C. The basic physical properties of the contemporary handmade bricks are similar with the historical bricks while their physicomechanical and mechanical properties are higher than the historical bricks. All contemporary handmade and factory solid bricks have high level of saturation coefficient above 0.80 which signal that they may suffer from freezing-thawing cycles. Among those bricks, some hand-made brick products which have higher effective porosity, lower fine porosity ($<0.5\mu$) and higher water vapour permeability and drying rates are expected to be less susceptible to freezing-thawing cycles.

However, the factory-made bricks are considerably denser, less porous and less breathable brick types with considerably higher physicomechanical and mechanical properties when compared to the hand-made bricks and historical bricks; therefore . they are not compatible with the historical bricks.

There is necessity to develop standards in which the performance properties of qualified hand-made bricks are defined. The involvement of some specific parameters, such as ultrasonic pulse velocity, saturation coefficient, water vapour diffusion resistance factor and fine porosity ratio index, into those standards should be provided. The data achieved and discussed in the study can be used as reference data for the performance properties of qualified contemporary hand-made bricks and be guiding for the improvement of relevant standards.

Keywords: Contemporary handmade and factory-made solid bricks, historic bricks, performance properties, hygric properties, firing temperature

ÖZ

GÜNÜMÜZ DOLU TUĞLALARIN MALZEME ÖZELLİKLERİ VE TARİHİ TUĞLALAR İLE İLİŞKİLİ OLARAK DEĞERLENDİRİLMESİ

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Günümüz dolu tuğlaların performans özelliklerini değerlendirmek için kapsamlı bir çalışma yapılmış ve yıllar boyunca ayakta kalan tarihi tuğlaların performans özellikleri ile ilişkili olarak uyumlulukları tartışılmıştır. Özellikle tarihi yapıların onarımlarında kullanılan günümüz harman tuğlası ve dolu fabrika tuğlasının, tarihi tuğlaların performans özellikleriyle uyumlu olması beklenmektedir.

Bu bağlamda, Türkiye'deki yerel üreticilerden toplanan harman ve fabrika tuğlaları (preslenmiş ve preslenmemiş), temel fiziksel, fizikomekanik ve mekanik özellikleri ve pişme sıcaklıklarıyla birlikte gözeneklilik ve higrik özelliklerine odaklanarak laboratuvar analizleri ile incelenmiştir.

Günümüz harman tuğlaları 750-900°C aralığında pişmiş, hafif ve gözenekli tuğlalardır. Harman tuğlaların temel fiziksel özellikleri tarihi tuğlalarla benzerlik gösterirken, fizikomekanik ve mekanik özellikleri tarihi tuğlalardan daha yüksektir. Günümüz harman ve dolu fabrika tuğlalarının tümü, 0,80'in üzerinde yüksek doygunluk katsayısına sahip olmaları nedeniyle donma-çözünme döngülerine karşı hassastır. Bu tuğlalar arasında, yüksek etkin gözenekliliğe, düşük ince gözenekliliğe (<0,5µ) ve daha yüksek su buharı geçirimliliğine ve kuruma hızına sahip bazı harman tuğlalarının donma-çözünme döngülerine daha az duyarlı olması beklenmektedir. Bununla birlikte, fabrika tuğlaları harman tuğlası ve tarihi tuğlalarla karşılaştırıldığında oldukça yüksek fizikomekanik ve mekanik özelliklere sahip, daha yoğun, daha az gözenekli ve daha az nefes alabilen tuğla türleridir ve bu nedenle tarihi tuğlalarla uyumlu değillerdir.

Nitelikli harman tuğlalarının performans özelliklerinin tanımlandığı standartların geliştirilmesi gerekmektedir. Ultrasonik geçiş hızı, doygunluk katsayısı, su buharı difüzyon direnç faktörü ve ince gözeneklilik oranı gibi bazı özellikli parametrelerin bu standartlara dahil edilmesi sağlanmalıdır. Araştırmada elde edilen ve tartışılan veriler, nitelikli harman tuğlalarının performans özellikleri için referans veri olarak kullanılabilir ve ilgili standartların iyileştirilmesi için yol gösterici olması beklenmektedir.

Anahtar Kelimeler: Günümüz harman tuğlası ve dolu fabrika tuğlası, tarihi tuğla, performans özellikleri, higrik özellikler, pişme sıcaklığı

To my beloved family,

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CHAPTER 1

INTRODUCTION

Brick, which is generally known as a clay-based masonry unit, is one of the building material mostly used throughout the construction history. The brick manufacturing, a sort of ceramic material production, is based on clay-rich specific types of earth available in nature and presence of resources for burning process (Dalkılıç and Nabikoğlu, 2017; Fernandes, Lourenço and Castro, 2010; Aras, 2004).

The earliest brick dates back to Neolithic Period used for sheltering produced in air-dried form (Lourenco, Fernandes, and Castro, 2010; Houben and Guillaud, 1994). Following the invention of fire, fired bricks were first used around Mesopotamia by the end of third millennium B.C. (Wright, 2005; Davey, 1961). Due to the burning process, some of chemical reactions occurs that the properties of brick are completely changed and it becomes hard and strong, and more resistant to environmental conditions (Punmia, Jain and Jain, 2003; Davey, 1961). Thus, fired/burnt bricks were used as a superior/leading building material and their use were specialized in particular requirements in ancient times. There is a considerable amount of surviving historical buildings built of fired/burnt brick in Anatolia dates back to Roman, Byzantine, Anatolian Seljuk, Period of Principalities and Ottoman Periods. These historical bricks are well-known with their lightweight, porous, highly-breathable and pozzolanic nature together with enough mechanical strength and thermal resistance, all of which resulting in long-term durability characteristics (Uğurlu Sağın and Böke, 2013; Garcia-Ten, Orts, Saburit, Silva, 2010).

Nowadays, there are several types of bricks used in masonry construction. Handmade fired brick, which is the most labor-intensive, and age-old brick type used for centuries requires craftsmanship to prepare and fill molds by hand resulting in unique characteristics for each brick type. Since modern times, the brick production technologies have been influenced by the industrial revolution through the technological developments together with the invention of industrial machinery and mass production. However, handmade fired bricks and their traditional production techniques have never been forgotten due to their uniqueness and their material performance properties. These handmade bricks are classified as a solid section type and they are preferred due to their lightweight and porous properties mostly in the repair works of historical buildings. Furthermore, factory solid bricks are also used as an equivalent type of these bricks.

In this research, from a broader perspective, handmade fired bricks and factory solid bricks are investigated by comprehensive material analyses, composed of standard and advanced laboratory tests in order to define their technological properties. Moreover, a comprehensive literature survey on historical brick properties are presented to discuss the performance properties, which contribute to their long-term durability. Furthermore, defining technological properties of contemporary solid bricks is expected to help Turkish standards improve or generate for both conservation and contemporary works.

In this chapter are presented the argument, aim and objectives of the study on which this thesis is based. Furthermore, general approaches to studies on the properties of brick material and motivation behind the study together with the disposition of the thesis are presented in following subheadings.

1.1 Argument

Nowadays, two types of solid bricks, handmade and factory solid bricks, are being used particularly in the repair of historical buildings as well as in the construction of contemporary masonry buildings. The contemporary solid bricks used in the repair works of historical buildings should be compatible with the performance properties of the historical ones, in terms of basic physical, physico-mechanical and mechanical properties in order to maintain the long-term durability of historical buildings and keep their authentic features for new generations (Sasse and Snethlage 1997; Tuncoku *et al*., 1993). Throughout the history, there is a plenty of historical buildings, which were constructed with wide openings, dome and vault superstructures built of historical bricks and mortars. These masonry structures were able to survive with a good thermal and breating properties for centuries. However, with today's solid bricks and cement mortars, such high quality masonry superstructures cannot be constructed. This implies that today's brick technology and related standards need to be improved. For these reasons, researches should be carried out in order to provide a better understanding of the similarities and differences of the performance properties of contemporary solid bricks in reference to the qualified historic bricks.

The material properties of the brick and mortar used in the historical brick structures, which have proven their long-term durability by standing for centuries, represent the performance characteristics of the well-known historical brick technology developed over centuries in Anatolia. Unfortunately, there are no standards that describe the performance properties and production techniques of contemporary solid bricks that have been developed by utilizing the accumulated knowledge in historical building technology. However, these bricks are required to be high-quality products, which are lightweight, porous, and have sufficiently mechanical strength in order to be used efficiently in long-term durable structures.

Up to today, the standards related with handmade and factory solid bricks, are either cancelled or unexecuted (TS 704:1979; TS 705:1985). There is only one standard in Turkish Standards called TS EN 771-1 2011+A1:2016, which is translated from European Standards without taking into consideration the knowledge gained from historical brick technology in Anatolia/Turkey. The standards, which define the specifications on their production and materials properties, have to be improved in reference to the data based on scientific researches on technological properties of historical bricks and contemporary ones. Therefore, comprehensive studies are needed to:

- sum up the knowledge on historical brick technology,
- determine performance properties of contemporary handmade bricks, and

- improve specifications on their production and materials properties as well as relevant standards.

There are several scientific studies on materials properties of historical brick and its compositional properties. However, there are deficiencies in transferring that knowledge to cultural heritage conservation practices, resulting in wrong and/or unqualified repair works. The repair bricks and mortars have to be prepared and then used in fields of cultural heritage conservation by taking into account the traditional/historical materials and their construction technologies. In current situation, there are several local manufacturer/producer who produce contemporary handmade fired bricks to be used in repair works. There are also some factories which produce factory-made solid bricks as well to be used in contemporary buildings and veneering purposes. Some types of factory bricks are molded into the similar sizes with historical bricks and produced in factory conditions means that they are adapted some type of bricks to be used in conservation practice and search field in the market for themselves. However, there is scarcity of scientific research on performance and durability properties of those contemporary bricks and their raw materials and compositional properties, which have direct impact on their materials performances. The technological knowledge on production of historical brick and its performances achieved in time has vital importance for the production of repair bricks, which are compatible with the historic ones, and for sustaining the particular building technologies of historical structures. Besides, as a result of disappearing of master-apprentice relationship, the knowledge of production technologies cannot be transferred from historical bricks.

Compared to today's building materials which are predominantly used building materials such as cement-based concrete, mortar and plaster, the historic bricks are building materials with a low bulk density, high porosity, high water vapour permeability, high thermal resistance and high pozzolanic activity. Furthermore, they have low but sufficient/enough mechanical properties. Since today's building materials have denser, less porous, low-permeable and high strength characteristics, both handmade and factory solid brick industry have a tendency to produce bricks having high mechanical strength compatible with cement-based mortars and plasters. The handmade brick producers are directed to produce high mechanical strength properties due to compete with factory bricks while the properties of product become different from good qualified historical bricks. In the near future, there is a risk that handmade bricks could turn into factory bricks with less dense, less porous, lower thermal resistance and higher mechanical strength features.

1.2 Aim and Objectives

The main goal of the research is:

- to produce knowledge on performance and technological properties of today's handmade-fired solid bricks and factory-made solid bricks that will be guiding for the production of qualified ones,
- to assess the material properties of contemporary solid bricks in reference to qualified historic bricks proved their long-term durability,
- to produce knowledge for the improvement of the standards related with the materials specifications of contemporary solid bricks in terms of performance properties and production techniques.

For those purposes, the laboratory analyses are conducted on contemporary solid bricks (handmade and factory solid fired-bricks) produced by several manufacturers in Turkey in order to:

- determine their performance properties in terms of basic physical, physicomechanical, mechanical properties,
- to examine their porosity characteristics in terms of water and moisture (vapour) related (hygric) properties and discuss those performances in relation to their durability,
- determine their raw materials specifications of contemporary in terms of mineralogical composition, pozzolanic activity, salt content and firing temperature,
- compare the data achieved in the study on the contemporary solid bricks and the data compiled from the literature on the qualified historical ones.

By the end of this study, it is expected to:

- establish the data on the performance and raw materials properties of contemporary solid bricks examined in this study,
- compile the reference data on qualified historical bricks proved their long-term durability,
- interpret the data on today's solid bricks in reference to the historical ones and reveal differences and similarities between them,
- point out guiding remarks for the improvement of qualified solid brick products and the relevant TS standards.

The results of the study and the concluded remarks are also expected to be guiding for professions, companies, associations and institutions related with the brick manufacturing, brick masonry constructions and their design and the relevant standards. The transfer of the knowledge achieved in the past to the today's materials technology is expected to serve for the sustainability of advanced historical technologies and for the improvement of contemporary materials technology. Considering all, the study is expected to contribute to the relevant research and practice fields of building materials science, materials conservation science and contemporary brick manufacturing technology.

1.3 Disposition

This study is presented in 6 chapters, of which this introduction is the first. The argument, aim and objectives of the thesis are introduced and the structure of the thesis is briefly described in disposition part.

In the first part of the second chapter, literature survey is given on historical brick technology in order to reveal the potential knowledge gained from past experiences in history under the subheadings, respectively. Material performance and compatibility properties of some particular historical bricks have been discussed by the literature in detail mostly due to the establishment of conservation principles of selected studies. In the second place, historical mortars are briefly examined since bricks are constructed with mortar, which constitute the overall wall section. Lastly, technological properties of contemporary solid bricks are discussed by giving general information about the types and production technologies of contemporary bricks together with the applied current standards. The requirements for contemporary solid bricks given in the standards are defined to improve or generate standards for further applications.

Brick samples, which are taken from four different local handmade brick factories and two different large-scale factories in Turkey, are described in more detail as the material of the study in the third chapter. Furthermore, experimental procedures of the laboratory tests conducted for the study are described clearly under the headings of basic physical, physicomechanical, mechanical, raw materials and microstructural properties.

In the fourth chapter, the experimental results are presented with relevant figures, graphics and tables. The handmade and factory solid bricks are defined in terms of the properties explained in the material and methods section.

In fifth chapter, the results are discussed in terms of performance properties of handmade fired and factory solid bricks. The appropriateness of contemporary solid bricks to be used in wall masonry and repair works are presented by the comparative evaluations. The emphasis is given on porosity properties, raw materials and firing temperatures. The compatibility criterion with historical bricks is evaluated in terms of some performance and technological properties of contemporary bricks. Deficiencies and benefits of these contemporary bricks are determined to improve material standards.

The summary of the study together with the findings, recommendations and improvements for future works is presented in conclusion part as the last chapter. Some further studies are also suggested.

CHAPTER 2

LITERATURE REVIEW

In this chapter, a brief literature survey was done especially on the technological properties of historical bricks, specifically handmade fired bricks belonging to ancient times, Anatolian Seljuks and Ottoman Periods. A specific care was given to the performance properties of those bricks together with their porosity, hygric properties, raw material and microstructural properties, which contribute to their particular performances and long-term durability. Here, compatibility properties of historical brick was discussed in relation to its mortar since the historical brick and mortar both establish the historical brick masonry structures which can withstand time through the centuries. In addition, a summary on technological properties of contemporary bricks, specifically factory-made solid brick and contemporary handmade fired brick, were given to better-define the differences between factory brick and contemporary handmade fired brick in terms of production technologies and materials properties.

2.1 Technological Properties of Historical Brick

In order to improve the material technology of contemporary bricks, it is important to understand the technological properties of historical bricks, which proved their long-term durability performances. For this reason, historical development of brick material, production technologies and mineralogical composition of some particular historical bricks and their performance properties were comprehensively studied in this section.

2.1.1 A brief history of historical fired brick

Brick is one of the oldest man-made earthen building material in the world according to historians. Since Neolithic times, brick has been used as sun-dried mud blocks owing to its abundantly available, easily workable and usable features. Since Neolithic villages, in which families built their own houses with mud bricks, had become ancient cities, the desire to build more complex structures gained importance in parallel with architectural developments and innovations in building materials (Love, 2013; Lourenco *et al*., 2010; Wright, 2005; Houben and Guillaud, 1994). The technological evolution on mud-bricks was made to produce fired bricks allowing people to make larger buildings more resistant to environmental conditions (Davey, 1961).

The first fired bricks were used in 13th century B.C. around Mesopotamia before the technology of firing arrived to Europe and China from Middle East; Persia and India. In Europe, the Roman Empire discovered that brick has advantages on building structural elements in the 1st century B.C. After that period, Romans used fired bricks as a superstructure material for constructing domes, arches, vaults and any parts of a building above its foundation and Byzantines enhanced the material to use for decorative expressions. Fired brick was used as a superior/leading building material for special requirements such as, solidity, durability and impermeability during the Roman period. Romans introduced selection and preparation of the raw material and the design of the kilns into brick making technology (Scalenghe *et al*., 2015; Adam, 2005). They were used systematically in buildings beginning from the 4th century B.C. in Roman and Byzantine period. Besides the contribution of Romans, fired brick masonries of Byzantium offered a variety of structural and decorative elements such as, domes, arches, pillars (Stefanidou *et al*., 2015; Davey, 1961).

The first use of fired bricks in Anatolia was influenced by Roman Empire in the period of Lydian Empire in 4th century B.C. (Dalkılıç and Nabikoğlu, 2017; Görçiz, 1996; Ward-Perkins, 1981). After Romans, Byzantines and Seljuks improved the use of brick and tile in the historical buildings in Anatolia. Ottomans were impressed by the use of bricks in the architecture of Byzantine and Seljuk and they set the first standards in brick and tile production; however, no further improvement was made until the industrial revolution (Akkuzugil, 1997; Görçiz, 1996; Bakırer, 1981).

2.1.2 Production technologies for historical fired brick

Brick manufacturing consists of different processes, which have a remarkable impact on the quality of products, such as raw material preparation from soil, molding, drying and firing. Vitruvius (Ebhardt, 1962) stated that the durability and performance of the brick material depends on mostly the raw materials used in the manufacture of bricks. However, most of the raw material sources were located nearby construction sites, which sometimes resulted in poor quality clays used in some cases of historical buildings (Fernandes *et al*., 2010).

The main raw material of brick, which is clay and its minerals, exhibits plasticity features to brick when mixed with water in certain proportions that is essential for moulding. The water content during production are differed according to soil properties, plasticity and the climatic conditions of the production region (Scalenghe *et al*., 2015). Plasticity is the property of a material, which allows it to retain its shape after applied force has been removed which is influenced by the clay and molding process (Andrade, Al-Qureshi and Hotza, 2011; Ward-Perkins, 1981). The mixture must be enough plasticity properties to make the molding process easier that can be arranged by the amount of sand and clay mixture, which is a mix of about 30% of sand and 70% of plastic clay in traditional brick manufacturing (Fernandes *et al*., 2010). Drying is the process of extracting water added during the mixing phase by air-dying method. Vitruvius mentions that the most appropriate period for drying is during spring and autumn in order to avoid quick dryness of the surface and frost action due to wind or direct sun exposure (Ebhardt, 1962). The last process is the hardening of bricks by firing at a temperature around 800°C and ranges from 600°C to 950°C for ancient bricks documented by literature (Uğurlu-Sağın, 2017; Adam, 2005; Tite, 1995).

In Roman period, the selection of raw material source, which should contain high amount of clay, was an important process in the production of bricks. The selected source had been located close to the site within the range of 10 km and 50 km in some conditions to reach the proper raw material source (Uğurlu-Sağın, 2017; Scalenghe *et al*., 2015). Before sieving and mixing, the raw material extracted from soil had been left to rest and mature for a few days. (Stefanidou *et al*., 2015; Finlay, 2012; Wright, 2005; Davey, 1961). Romans specialized on the use of clay that adding sand improves the shape stability and reduce clay fraction while adding fibers acts as a reinforcement for the control of cracking. These additives can reduce shrinkage and improve their capability of releasing water slowly in order to produce brick having higher compressive strength (Quagliarini and Lenci, 2010; Adam, 2005). After checking the plasticity of the mixture, it had been casted in wooden moulds and carried to a drying floor where the frame was removed and the bricks left to dry for perhaps three or four weeks that the length of period depends on weather conditions such as, heat, humidity and wind. Dried bricks had been placed in the kiln, which is generally a continuous oven-type chamber. The kiln used in Roman period is known to have inadequate interior temperature distribution. The duration of firing process are changing according to the sizes of the kiln, atmospheric conditions and the material used for fuel and proceeding until having the required strength of bricks (Scalenghe *et al*., 2015; MacDonald, 1965).

Brickwork, which forms structural masonry in mostly historical buildings, have been developed by the requirements of the buildings. The material properties of fired bricks can be altered by changing the composition of raw materials and firing conditions in order to satisfy certain properties (Coletti *et al*., 2016; Wright, 2005; Davey, 1961). Throughout the history, different additives, clay minerals, fine and coarse aggregates or fibrous materials and manufacturing techniques have been used to improve the material characteristics and the behavior of old bricks. Raw materials, manufacturing techniques and material properties of brick have not changed through a long historic period that makes clay bricks in preferred position for many years (Dalkılıç and Nabikoğlu, 2017).

Production size is an important parameter for bricks to compare with today's production technology. In Rome, brick sizes were standardized for corresponding wall thicknesses. The larger bricks were cut into pieces for use as wall facing. These bricks were much thinner than modern ones, usually varying between 2.5 and 4.9 cm thick depending on the type of brick and the date. The thinner and wider form of bricks were probably chosen to facilitate the drying process so that cracking was less likely to occur (Ulrich and Quenemoen, 2013). In Anatolia, Ottomans made the first standards for tiles and bricks around 4.5 x 28 x 28 or 25 x 25cm and 30x60 cm of sizes (Görçiz, 1996). Furthermore, these standard sizes are still in use for particular restoration works and they are produced in handmade brick industry's production line.

2.1.3 Mineralogical composition of historical fired brick

Bricks are manufactured from soil-based raw materials, which are clay, silt and sand. These raw materials and different types of clay minerals are related with texture, plasticity, compactibility and cohesion properties of soil. These properties are investigated by identification tests for the suitability of soil before using in construction that needs technical expertise in brick manufacturing (Houben and Guillaud, 1994).

The clay which is formed by atmospheric weathering of rock and silicates, is technically known as hydrated silicate of alumina (Al_2O_3. $2SiO_2$. $2H_2O$). Several types of clay minerals such as, kaolinites, illites, montmorillonites and others (chlorite, muscovite, and so on) act as a binder between clay and non-clay minerals in soil and exhibit plasticity features to bricks when mixed with water in certain proportions (Torraca, 1988). Silt, sand, other minerals (non-clay minerals) and fibrous organic materials used as an inert filler improve resistance to water and reduce the linear drying shrinkage (Bories *et al*., 2015). Besides these properties, clay minerals in the case of containing amorphous materials like metakaolin fired at 600 to 800°C presents pozzolanic activity when mixed with lime and water (Baronio and Bindat, 1997).

The pozzolanic properties of clay have been used to build durable structures and foundations in the presence of moisture and water for many years. The use of calcined clay as pozzolanic additive to produce hydraulic mortar and plaster is still common in cement and concrete industry that the pozzolanic property depends on the firing temperature of clay and its mineralogy. The minerals occurred in higher firing temperatures cause to lose pozzolanic activities of bricks (Tekin and Kurugöl, 2011; Böke *et al*., 2004). Firing temperature at least up to about 900°C causes to decompose amorphous substances, which occurs between 20 and 30 degrees 2θ in the XRD pattern. (Lee, Kim, Moon, 1999). The amorphous substance (alumina silicate) of clay like metakaolin reacts with lime in the presence of water to form calcium silicate hydrate that increases pozzolanic activity of brick (Uğurlu Sağın and Böke, 2013; Baronio and Bindat, 1997). The presence of metakaolin is occurred by the transformation of kaolin in the raw material at the firing temperature between 450°C and 800°C that extends up to 1000°C until mullite crystals occur above 1100°C (Lee *et al*., 1999). Furthermore, pozzolans increase the binding capacity and material strength, which contributes the durability of historic structures that needs to be considered in conservation works (Böke *et al*., 2004; Moropoulou *et al*., 2000).

Brick is formed by firing the air-dried clayey mixture to make them stable and durable. During firing, the brick undergoes some physical and chemical changes and transforms into new artificial material. Minerals occurred by firing depends on the firing temperature and the composition of the minerals in clay matrix. As the firing temperature increases, melting develops between clay matrix and mineral temper grains (silt and sand). Herewith, mineral phases and pore structure change their forms (Riccardi *et al*., 1999; Torraca, 1988). The characterization of mineralogical, chemical and textural composition by various techniques like XRD, FTIR and SEM make possible to determine approximate firing temperature (Kılıç *et al*., 2017; Trindade *et al*., 2008; Cultrone *et al*., 2004b). The raw material properties, burning conditions (oxidizing or reducing atmosphere) and firing temperature reached during firing have an impact on the mineralogical phases and colours of fired bricks (Maggetti, 1982).

As a ceramic-based material, the mineralogical composition of bricks have been investigated by Riederer (2004), that quartz composes the coarser components and temper of ceramics with high resistance to chemical and mechanical transformations. The inclusion of decay forms of quartz originated from sedimentary rocks to clay particles takes millions of years. Feldspar minerals, known as potassium, calcium and sodium silicate group, can be identified by their morphology, which is characteristic for their origin like quartz. Silicates (quartz, feldspar, mica, amphiboles and pyroxenes) have a large variety of members and a wide range of properties, which are used for determining the provenience of ceramics.

Calcite, which occurs frequently in ancient ceramics and reduces melting temperatures, is formed by decomposing lime (CaO) with carbon dioxide (CO2) release at around 700°C (Trindade *et al*., 2008; Tite, 1995). It reacts with silica to form calcium silicate diopside and disappers in higher temperatures at around 850°C (Riederer, 2004). At the same firing temperature (850°C), while gehlenite is formed by the reaction of calcite and clay minerals, compositional zoning of micas (biotite, chlorite, glauconite and muscovite) decreases (Riccardi *et al*., 1999). Higher temperature minerals like mullite, known as an aluminum silicate is formed by decomposing of phyllosilicates like muscovite at 950°C while spinel is formed by decomposing of illite-chlorite clays (Viani, *et al*., 2016). The content of plagioclase feldspar (albite) decreases while the content of hematite increases well crystallized at 900°C. High temperature minerals like mullite, cristobalite and spinel start to appear at 1040°C. The feldspar peaks visibly vanishes at around 1150°C. (Franke and Schoppe, 1988). Transformations above 1000°C are slow or may not take place, however silica-phase transitions like quartz to cristobalite occurs at around 1100°C. At 1100°C, vitrification starts in all types of mineralogical composition due to the melting of clay particles and releasing gases (Cultrone *et al*., 2004a).

Hematite, which is a form of iron oxide in the group of ore minerals, gives the main pigmentation in the oxidation conditions. It is abundantly used to provide red color of ancient brick both artificially and naturally in raw materials (Kılıç *et al*., 2017; Cultrone *et al*., 2004b). As the temperature increases, the concentration of hematite rises which is used as an indicator of firing temperature (Rodrigues *et al*., 2015; Cultrone *et al*., 2004a). It is occurred at about 800°C and well-crystallized starting from 900°C (Kılıç *et al*., 2017; Trindade *et al*., 2008; Maggetti, 1982). The hematite mineral inside the raw material is either comes from the iron present in phyllosilicates (Viani *et al*., 2016) or form during firing. The bricks containing iron oxides under different burning conditions are seen in different colours; the shades of red colour in oxidizing conditions which is rich in oxygen and the shades of black colour in reducing conditions which is rich in carbon monoxide (Pavía, 2006; Maniatis *et al*., 1983; Maggetti, 1982). These minerals and burning conditions have been used to produce different colours of fired bricks in ancient ceramic technology throughout the history.

2.1.4 Performance Properties of Historical Brick Masonry

Physical, physicomechanical, mechanical, raw material and microstructural properties of historical materials are considered as performance properties all of which contributes to their long-term durability. The durability of historical buildings is depending on appropriate maintenance and interventions by using repair materials, which are compatible with the original ones. It is possible only if the repair material characteristics and manufacturing techniques are studied by comprehensive analyses. Many studies have been conducted on historical bricks to define their performance properties used in historical structures built by brick masonry. This section aims to collect the knowledge gained in history.

Water and moisture related phenomena in materials are defined as the hygric properties of porous materials. Porosity indicates the capacity of water storage and circulation within the pores. Water flow in the pore structure is used to assess the hygric properties of materials by following parameters: water and moisture absorption and desorption properties such as; water vapour permeability, capillary water uptake, and drying behaviour (Laho *et al*., 2010; Benavente *et al*., 2007). Understanding these properties of porous materials is important for predicting the durability. Since water and moisture in materials and their expansion causes damage and decay in porous building materials due to the expansion in dimension, the pore structure, their distribution and the relationship between pores are related with frost resistance. The pore structure of a burnt-brick material is influenced by raw materials, manufacturing techniques, firing temperature and duration time (Benavente, 2011; Ordonez *et al*., 1997; Camuffo, 1995; Nieminen and Romu, 1988; Hansen and Kung, 1988; Maage, 1984). Water transport in porous materials goes from coarser to finer pores under the influence of capillarity since the rate of water uptake from coarser pores is faster than that of fine pores (RILEM, 2009; Laho *et al*., 2010). The capillary action is the ability of water to flow through narrow spaces without external forces like gravity or wind. Studies examining the relationships between pore sizes and capillary absorption characteristics, pores between 0.1 and 100 micrometers (r=0.1-100μm) absorbed capillaries in materials such as stone, brick, concrete (which are independent of the acceleration of gravity and wind) states that it is responsible (Wesolowska and Kaczmerek, 2017; Coletti *et al*., 2016; Thomson *et al*., 2004). Since porous building materials have different shapes and sizes of pores opened to water movement, their pore structures should be examined in detail.

Performance properties are closely related with the materials durability. Durability indexes for bricks based on total porosity, pore size distribution and the relationship of the pores with each other because variations in porosity notably affect the mechanical resistance of building materials (Topal and Sözmen, 2003; Lu *et al*., 1999; Winkler, 1986). Studies examining the resistance of porous materials to deterioration cycles have shown that in addition to the total porosity and saturation coefficient, the pore size distribution, in particular the ratio of fine pores to the large pores, is another determining parameter (Benavente, 2011; Ordonez vd., 1997; Hoffman *et al*., 1996; Nieminen and Romu, 1988; Nakamura, 1988; Sosim *et al*., 1985; Maage 1984; Robinson 1984). The low porosity of fine pores in less porous natural stones compared to large pores is one of the pore properties that weaken the resistance of these stones to freeze-thaw and salt crystallization cycles (Fitzner, 1993; Camuffo, 1984). Pore size and pore size distribution is an important parameter for predicting the durability that there are some studies on the relationship between the pore structure and frost resistance of burnt-bricks:

-the presence of pores (r=1-3µm) with pore diameter (r) above 1-3 micrometers, making the brick material resistant to frost (Arnott, 1990),
-2 micrometers pore diameter can be considered as the average pore diameter (r_{avg}) and the r_{avg} value of 2 micrometers and above (r_{avg}>2µm) is calculated that the bricks may be resistant to frost (Robinson, 1984),
-the bricks having a pore diameter of 2 micrometers and above are 10% above ($Vr_{2µm}$>10%) may be resistant to frost (Ordonez, 1997; Nieminen ve Romu, 1988).
-pores having a pore diameter below 0.2 micrometers (r<0.2µm) have low resistance to frost (Nakamura, 1988),
-pores with a pore diameter of 0.1 and 1 micrometer (r=0.1-1µm) are rapidly filled with capillary suction but slowly dry, so that the presence and volume of pores in this range can reduce the resistaance of the brick material to frost. According to a study on extruded bricks, bricks having high total porosity, high saturation coefficient and a large percentage of pores between 0.1 and 1 µm were found to be less resistant to degradation cycles (Davison, 1980).

The water saturation coefficient is considered to be one of the parameters used to assess the resistance of porous materials to freeze-thaw cycles. However, as an indirect durability test method, the reliability/consistency of saturation coefficient is still discussed by some studies (Topal and Sözmen, 2003; Ordonez *et al.*, 2003). The saturation coefficient of 0.80 is considered to be a threshold value for natural stones and it is stated that the natural stones having 80% of water saturation and above this value are sensitive to freezing-thawing cycles. (Chen, 2004; Hirschwald, 1908; BRE, 1997; RILEM, 1980). Studies investigating the durability of bricks against deterioration cycles and trying to describe the properties that the bricks must have according to conditions of deterioration that (ASTM C216-17a, 2017; Hansen and Kung, 1988):
-the threshold value of 0.80 for natural stones is also valid for bricks,
-bricks with a saturation coefficient of less than 0.75 are resistant to freezing and thawing,
-bricks that will be exposed to difficult/severe climatic conditions should have a maximum value of 0.78,

-bricks that will not be exposed to difficult/severe climatic conditions should have a maximum value of 0.88 is acceptable.

The critical moisture content measured according to RILEM (1980) standard is considered to be a threshold value for porous materials. The value of the critical moisture content of materials with different pore structure varies. Besides these information (Karagiannis vd.,2017; Tavukçuoğlu and Grinzato, 2006; Camuffo, 1995; Massari ve Massari, 1993; Torraca, 1988):
-The capillary pores in wet material at critical moisture content are filled with water,
-above this level, water is transported from one place to another by capillary absorption; thus wetting-drying and freeze-thaw cycles are more destructive in wet material on this level,
-under this level, it is not possible to transport water from one place to another by capillary absorption; water vapour diffusion is known to carry/transport water vapour between pores.

Water vapour permeability is one of the most important physical and hygroscopic parameters that express the ability of porous materials to allow water vapour to pass through their pores under the influence of water vapour density difference. Materials used in the restoration of historic buildings are expected to be compatible with each other. Water vapour permeability, flexibility modulus and thermal / moisture dilatation properties are one of the well-known compatibility parameters that contribute to the long-term durability of construction materials and structures (Atikoğlu *et al*., 2017; Tavukçuoğlu *et al*., 2013). Studies revealed that the brick, mortar and plaster layers that make up the historical masonry are composed of high water vapor permeable materials, thus maintaining continuity in water vapor passage between the layers (Örs *et al*., 2008; Esen *et al*., 2004). The fact that the materials in contact with each other are composed of breathing materials is a compatibility feature that must be observed in repairs.

The proportion of fine pores in low porous natural stones is greater than that of large pores is one of the pore qualities that weaken the resistance of these stones to freeze-thaw and salt crystallization cycles (Fitzner, 1993; Massari and Massari, 1993). However, various parameters have been defined in the literature for pore size classifications. For instance, the critical pore size diameter for rocks are determined to be 5 μm and below this average pore size, the durability of rocks decreases due to the difficulty in water draining (Topal and Doyuran, 1998). The capillary water absorption coefficient is the highest for porous rocks having a dominant pore diameter between 5 and 10 μm, which increases the deterioration (Dinçer and Orhan, 2016). Besides the size of pores, the shape of interconnecting pores also gives information about hygric behaviour of materials depending on particular geometry of cavity (Hansen and Kung, 1988; Camuffo, 1984).

All porous materials have critical level of moisture content, which is an important parameter used for predicting drying times of materials and not depending on air velocity and temperature (ambient conditions). Above the level, the water diffuses from the surface of saturated state as a function of ambient conditions. The weathering cycles are more damaging above that level. The transition of saturated state to humid state is critical because at that bending point capillary suction starts. Below the level, the water only evaporates through internal moisture migration related with porosity characteristics and drying behaviour of materials (Tavukçuoğlu and Grinzato, 2006; Derdour *et al*., 1998; Massari and Massari, 1993). Venetian bricks have 18% of critical moisture content, that these bricks are exposed to serious water and rising damp problems (Vos, 1971). On the other hand, San Marco bricks have %16.1 of critical moisture content which should be considered as one of the basic physical property of porous materials (Tavukçuoğlu and Grinzato, 2006).

Thermal properties are exhibited by a material when heat passed through it. These properties are evaluated as a broader topic of physical properties. Thermal properties of construction materials can reduce the heat losses and increase the energy efficiency which are necessary for current regulations. In this study, thermo-physical properties were investigated in terms of specific heat capacity, thermal conductivity, thermal effusivity and diffusivity characterisitics. Thermal conductivity of a brick material, which is a clay-based and ceramic material, is related with bulk density and porosity in the context of environmental conditions such as moisture content and ambient temperature (Garcia-Ten *et al*., 2010). When the pore sizes of a material increase, the material can conduct more heat and the thermal conductivity increases as well (Çiçek, 2009; Akkuzugil, 1997; Tye, 1994). Furhermore, the moisture content in materials increases the thermal conductivity and specific heat due to the increase in bulk density. That means materials with higher moisture content have higher thermal conductivity and thermal diffusivity properties than the dry materials resulting in contributing further heat losses (Tye, 1994). Thermal effusivity is a material's ability to transfer heat with its surroundings that materials with relatively high thermal effusivity cannot store heat longer when temperature decreases. Therefore, building materials such as clay-brick or stone are expected to have lower thermal effusivity properties to conserve heat during long period of time (Çiçek, 2009). The thermal performance of buildings such as, the heat transfer, air leakage and solar radiation are satisfied when all forms of water and moisture content in material and/or building component is under control (Ceranic et al., 2018). Thermal properties of contemporary solid bricks used in wall masonry, which are defined in TS EN 771-1 standard, are given in TS 825 standard. Thermal conductivity properties of contemporary solid bricks were given for two types of bricks with two different density values (TS 825, 1988) and their specific heat values are calculated in the study.The data was compiled in **Table 2.1**.

Table 2.1. Thermal properties of contemporary solid bricks in terms of bulk density and thermal conductivity

Material type	Bulk Density kg/m^3	Thermal Conductivity W/mK	Specific Heat J/kgK
Solid factory bricks*	1800	0.81	calculated in the study
	2200	1.20	calculated in the study
*: There are masonry blocks made of bricks in accordance with TS EN 771-1, solid clinker, clinker with vertical holes			

The selection of raw material and techniques of preparation play an important role on the performance properties of burnt bricks. The aim for raw material is to contain sufficient clay for plasticity and other minerals enable to be fired at a wide temperature range (Hughes and Bargh, 1982). The technology used for brick manufacturing has not been changed for a long period of time in history. As Stefanidou *et al*., (2015) conducted a comparative study on Roman and Byzantine bricks to determine their materials characteristics that the manufacturing technology and physicomechanical and mechanical properties are alike. The compressive strength and modulus of elasticity values are ranging between 10 and 15 MPa and 3 and 6 GPa, respectively. Except from the higher values, bulk density and water absorption values are determined to be around 1.7 g/cm^3 and 15%, respectively. Surface roughness of Roman bricks are smooth while Byzantine bricks are intentionally rough which increases the brick-mortar bond by the reaction of hydrated lime of mortar and amorphous silica of brick. The main minerals are determined to be quartz, illite and smectite (clay minerals), calcite and gypsum by XRD analyses showed that the bricks are fired at low temperatures, which also enable pozzolanic activity of bricks. Firing process induces most of the characteristics of brick material such as; strength, porosity, water vapour permeability, colour and texture properties. Increased strength and decreased water absorption, moisture and thermal expansion (dilatation characteristics), which contribute the brick durability, are provided by optimum level of firing temperature and firing conditions (Hughes and Bargh, 1982). The effect of firing on porosity have been studied on burnt bricks that during firing porosity changes under the influence of mineralogy and decreases due to extensive melting as the firing temperature rises (Hansen and Kung, 1988; Cultrone *et al*. 2004a). Non-calcareous bricks fired over 1000°C have limited amount of fine pores due to vitrification/melting that increase mechanical resistance. Since high amount of fine pores (pore size smaller than 1.5 μm) negatively influences the durability of brick. However, calcareous bricks fired at lower temperatures induces higher vitrification, strength and textural outgrowth compared to non-calcareous ones (Elert *et al*., 2003).

In order to benefit from the knowledge gained by historical building materials, there is a need for organizing these properties specific to historical structure and its construction period especially those located in Turkey. The historical buildings themselves, which have still survived for centuries, prove their longer durability and as well as long-term durability of their building materials. Therefore, the studies, which examine the materials properties of those historical structures, exhibit the materials specifications of those durable materials. Here, the materials properties determined in the studies on historical buildings belonging to Anatolian Seljuk, Principalities and Ottoman Periods were gathered and evaluated to better understand the performance properties of brick materials. In those buildings, walls are made of historic brick and/or stone masonry and most superstructures, such as domes, vaults and arches, are made of historic brick masonry. This means that the historical brick units and neighbouring historical mortar used as jointing compose the domes and vaults passing larger spans in those structures. Their particular physical, phyicomechanical and mechanical properties the historical brick and mortars and their compatibility with each other contributed to form lightweight large-span superstructures with enough strength and their long-term durability. Considering such a particular relationship between the brick and mortar, not only the performance properties of historic brick but also the performance properties of historic mortars neighbouring to the brick units were investigated in the literature and the data gathered was summarized in **Table 2.2.** The basic physical, physicomechanical and mechanical properties of the historical brick and mortar are given in **Table 2.2** that exhibits the performance properties of brick masonry materials used in the historical buildings in Anatolia belonging to Anatolian Seljuks, Principalities and Ottoman periods. The modulus of elasticity values gathered from the literature and given in **Table 2.2** were calculated by using ultrasonic pulse velocity and bulk density values of the materials. The uniaxial cmporessive strength of the materials gathered from the literature and given in **Table 2.2** were measured by Point Load testing.

Table 2.2. The compiled data on basic physical, physico-mechanical and mechanical properties of historical bricks and their mortars in Anatolia

Historical Structures	Construction Period	Location	Sample Type	Bulk Density	Porosity	Water absorption capacity	Specific Heat	Thermal Conduct.	Water vapour diffus. resist. index - μ	Ultrasonic pulse velocity	Modulus of elasticity	Uniaxial comp. strength
				g/cm^3	% by vol.	% by wt.	J/kgK	W/mK	unitless	m/s	GPa	MPa
Tahir and Zühre Mescidi[1]	13th c. Seljuks	Konya	Brick	1.41	47.9	35.0	-	-	-	-	1.1	7.8
			Mortar	1.53	40.0	26.0	-	-	-	-	0.7	5.1
Güdük Minare Mescidi[2]	13th c. Seljuks	Konya/ Akşehir	Brick	1.45	39.0	26.5	-	-	-	-	-	-
			Mortar	1.45	43.7	30.6	-	-	-	1180	1.9	6.6
Çukur Hamam[3]	14th c. Principalities	Manisa	Brick	1.55	36.8	25.7	1038	0.53	-	1607	3.7	-
			Mortar	1.67	38.6	15.7	-	-	3.6	1123	2.0	-
Gazi Mihal Bey Hamamı[4]	15th c. Ottoman	Edirne	Brick	1.65	35.8	21.7	-	-	-	1587	4.1	10.4
			Mortar	1.69	33.9	20.1	-	-	-	1217	2.5	5.6
Hersekzade Ahmet Paşa Hamamı[5]	15th c. Ottoman	Urla/İzmir	Brick	1.52	38.9	25.6	891	0.60	-	-	-	-
Yalınayak Hamamı[6]	16th c. Ottoman	Tire/İzmir	Brick	1.28	49.3	37.9	879	0.56	4.5	879	1.8	13.3
			Mortar	1.59	40.5	25.7	-	-	7.0	684	1.3	4.7
Sokullu Mehmet Paşa Hamamı[7]	16th c. Ottoman	Havsa/Edirne	Brick	1.70	31.0	18.2	-	-	-	884	1.2	2.9
			Mortar	1.80	22.0	12.2	-	-	-	869	1.0	2.8
	18th c. Ottoman	Havsa/Edirne	Brick	1.60	33.4	20.9	-	-	-	902	0.9	3.0
			Mortar	1.50	42.2	28.1	-	-	-	682	1.1	2.7
Yeni Hamam[8]	18th c. Ottoman	Sivrihisar/ Eskişehir	Brick	1.43	43.0	30.1	-	-	4.4	1362	2.6	-
			Mortar	1.70	35.0	20.6	-	-	3.5	1032	1.7	-
Ermeni Hamamı[9]	19th c. Ottoman	Sivrihisar/ Eskişehir	Brick	1.80	27.2	15.1	-	-	6.5	1218	2.4	9.0
			Mortar	1.62	33.0	20.4	-	-	4.7	1445	3.2	-
Bartın Kırtepe Mektebi[10]	19th c. Ottoman	Bartın	Brick	1.64	35.3	21.6	-	-	-	-	-	-
			Mortar	1.75	32.2	18.5	-	-	2.6	677	0.8	-

[1]: Aktaş *et al*., 2006; Tuncoku *et al*., 1993, [2]: Tuncoku *et al*., 1993, [3]: Esen *et. al*, 2004, [4]: METU MCL, 2012, [5]: Tavukçuoğlu *et al*., 2008, [6]: METU MCL, 2005, [7]: METU MCL, 2018, [8]: Madani *et al*., 2017, [9]: Aslzad *et al*., 2018, [10]: METU MCL, 2013

The data in **Table 2.2** is described in the following paragraphs in which the historical building and the performance properties of its brick and mortar were explained in detail:

– The historical masjid named 'Tahir ile Zühre Mescidi' was built in 13th century Anatolian Seljuk Period, in Konya. The upper parts of the walls and superstructure composed of domes and vaults were constructed by brick masonry (Aktaş *et al*., 2006; Tuncoku *et al*., 1993). Bulk density and porosity values brick and mortar samples are 1.41 and 1.53 g/cm^3 and 47.9 and 40.0% by volume, respectively. Water absorptiom capacity (WAC) values of brick and mortar samples are 35.0 and 26.0% by weight. Modulus of elasticity (MoE) and uniaxial compressive strength (UCS) values of brick and mortar samples are 1.1 and 0.68 GPa, 7.8 and 5.1 MPa, respectively. Basic physicomechanical and mechanical properties show that brick samples have higher modulus of elasticity and higher uniaxial compressive strength than mortar samples.

– 'Güdük Minare Mescidi' is a 13th century Anatolian Seljuk Period structure in Akşehir, Konya. It is a masjid building composed of stone masonry at lower parts and brick masonry at upper parts of the walls and minaret structure built of brick (Tuncoku *et al*., 1993). Bulk density, porosity and WAC values of brick samples are 1.45 g/cm^3, 39.0% by volume and 26.5% by weight, respectively. Mortars used with historical bricks have similar physical properties: bulk density, porosity and WAC values of mortar samples are 1.45 g/cm^3, 43.7% by volume and 30.6% by weight. UPV, MoE and UCS values of mortar samples are 1180 m/s, 1.90 GPa and 6.6 MPa, respectively.

– 'Çukur Hamam', which was built in 14th century period of Beyliks in Manisa, is a bath structure composed of stone masonry, brick domes and vaults. Material properties of historical brick, rarely used brick and mortar were selected for evaluation. Bulk density, porosity and water absorption capacity (WAC) values of brick and mortar are 1.55 g/cm^3 and 1.67 g/cm^3; 36.8% and 38.7% by volume; 25.72% and 15.65% by weight, respectively. Thermal properties of brick samples used in Çukur Hamam were compiled from literature (Esen et. al, 2004) that specific heat capacity and thermal conductivity of these bricks are 1038 J/kgK and 0.53 W/mK. Water vapor diffusion resistance index (μ) of mortar is 3.58. Some basic physicomechanical properties of brick and mortar samples were given in terms of ultrasonic pulse velocity (UPV) and modulus of elasticity (MoE). UPV and MoE values of brick and mortar samples are 1607 and 1123 m/s; 3.7 and 2.0 GPa, respectively (Esen et. al, 2004).

– 'Gazi Mihal Bey Hamamı' is a 15th century Ottoman Period bath structure located in Edirne. The historical building is composed of stone and brick masonry and brick dome structure classified as a first degree of protection (METU MCL, 2012). Bulk density and porosity values of brick and mortar samples are 1.65 and 1.69 g/cm^3; 35.8 and 33.9% by volume, respectively. WAC values of brick and mortar samples are 21.7 and 20.1% by weight. UPV and MoE values of brick and mortar samples are 1587 and 1217 m/s; 4.1 and 2.5 GPa while UCS values of these samples are 10.4 and 5.6 MPa, respectively. Some basic physico-mechanical and mechanical properties of brick samples are relatively higher than these properties of mortar samples, as expected. In addition, the physical properties of brick and mortar samples are similar.

– 'Hersekzade Ahmet Paşa Hamamı' is a 15th century Ottoman Period bath structure located in Urla, İzmir. The bath has two parts namely, women and men. It has a double-vaulted plan for two hot spaces (sıcaklık) and a dome in the middle. The basic physical properties of historical brick samples used in Hersekzade Ahmet Paşa Hamamı were compiled from literature (Tavukçuoğlu *et al.*, 2008). Bulk density and porosity values of brick samples are 1.52 g/cm^3 and 38.9% by volume. Water absorption capacity of brick samples is 25.6% by weight. Specific heat capacity and thermal conductivity values are 891 J/kgK and 0.60 W/mK.

– 'Yalınayak Hamamı' was built in 16th century Ottoman period in Tire/İzmir. It is a Turkish bath structure composed of stone masonry, brick dome and fountain (METU MCL, 2005). Bulk density, porosity and water absorption capacity (WAC) values of brick and mortar samples taken from historical bath are 1.28 and 1.59 g/cm^3; 49.3 and 40.5% by volume; 37.9 and 25.7% by weight, respectively. Thermo-physical properties of these bricks were compiled from the literature (METU MCL, 2005) that specific heat capacity and thermal conductivity of these bricks are 879 J/kgK and 0.56 W/mK. Water vapour diffusion resistance index (μ) values of brick and mortar samples are 4.46 and 6.96 respectively. Physical properties of brick and mortar are similar with each other. UPV and MoE values of brick and mortar samples are 879 and 684 m/s; 1.8 and 1.3 GPa while UCS values of these samples are 13.3 and 4.7 MPa, respectively.

Physical and physicomechanical properties of brick and mortar samples similar while mechanical properties of brick is higher than that of mortar.

– ‘Sokullu Mehmet Paşa Hamamı’ was built in 16^{th} century Ottoman period in Havsa, Edirne. There is stone and brick masonry structure located in historical building which was restorated in 18^{th} century in Ottoman period with original material (METU MCL, 2018). Bulk density and porosity values of 16^{th} century period brick and mortar samples are 1.7 and 1.8 g/cm^3; 31 and 22% by volume while these values of 18^{th} century period brick and mortar samples are 1.6 and 1.5 g/cm^3; 33.4 and 42.2% by volume, respectively. WAC values of 16^{th} century brick and mortar samples are 18.2 and 12.2% by weight, while WAC values of 18^{th} century brick and mortar samples are 20.9 and 28.1% by weight. UPV and MoE values of 16^{th} century brick and mortar samples are 884 and 869 m/s; 1.2 and 1.0 GPa while these values of 18^{th} century brick and mortar samples are 902 and 682 m/s; 0.9 and 1.1 GPa, respectively. UCS values of 16^{th} century brick and mortar samples are 2.9 and 2.8 MPa while UCS values of 18^{th} century brick and mortar are 3.0 and 2.7 MPa, respectively. These properties of the historical brick and mortar show that these historical materials have still adequate and qualified properties that constitute the overall wall section of the masonry or dome structures.

– ‘Yeni Hamam’ is an 18^{th} century Ottoman Period bath structure located in Sivrihisar, Eskişehir. The historical bath was built of stone and brick masonry and brick dome structure (Madani *et al*., 2017). Bulk density and porosity of brick and mortar samples are 1.43 and 1.7 g/cm^3; 43 and 35% by volume, respectively. WAC values of brick and mortar samples are 30.1 and 20.6% by weigt. Water vapor diffision resistance index (μ) values of brick and mortar samples are 4.4 and 3.5, respectively. Basic physicomechanical properties of brick and mortar samples were given in terms of UPV and MoE values, which are 1362, and 1032 m/s; 2.6 and 1.7 GPa, respectively. Physical and physico-mechanical properties of these historical brick and mortar are similar with each other. Besides, the breathing properties of these materials are similar with each other.

– ‘Ermeni Hamamı’ was built as a bath structure in 19^{th} century Ottoman Period in Sivrihisar, Eskişehir. The wall masonry and superstructure are composed of brick, stone and mortar (Aslzad *et al*., 2018). Some basic physical properties of brick and mortar samples were given in terms of bulk density and porosity values, which are 1.79 and 1.62 g/cm^3; 28 and 33% by volume, respectively. WAC values of brick and mortar samples are 15.1 and 20.4% by weight. Water vapour diffusion resistance index (μ) values of brick and mortar samples are 6.5 and 4.7, respectively. These physical properties of brick are similar to mortar samples while mortars are slightly less dense, more porous and water vapour permeable than bricks, as expected. UPV and MoE values of brick and mortar samples are 1218 and 1445 m/s; 2.5 and 3.2 GPa, respectively. Brick samples have slightly lower physicomechanical properties than brick mortar samples that result may be due to the higher salt content of mortar samples all of which results in performing enough physico-mechanical performances.

— 'Bartın Kırtepe Mektebi' was built in late 19th century Ottoman Period as a school building which has been restored after being damaged from the earthquake. The walls of the building was constructed with stone and brick as the main construction materials (METU MCL, 2013). Bulk density, porosity and WAC values of brick and mortar samples are 1.64 and 1.75 g/cm^3; 35.3 and 32.2% by volume; 21.6 and 18.5% by weight, respectively. WAC values of brick and mortar samples are 21.6 and 18.5% by weight. Water vapor diffusion resistance index (μ) of mortar sample is 2.6. UPV and MoE values of mortar samples are 677 m/s and 0.8 GPa, respectively. Some basic physical properties of brick and mortar samples are similar to each other that this feature contributes to their long-term durability of building envelope.

Another study on the ancient bricks and their properties belonging to the Roman Period presents that the performance properties of Roman bricks in Anatolia are similar with the bricks belonging to the 13th-19th centuries produced in Anatolia (**Table 2.3**). The study examined the brick and its mortar of the Serapis Temple, which is a monumental structure located in Pergamon, İzmir in 2nd century BC (Before Christ) Roman Period Anatolia (Aslan-Özkaya and Böke, 2009). Bulk density and porosity values of historical brick and mortar are within the ranges of 1.65 - 1.5 g/cm^3, 35 - 36% by volume, respectively. The uniaxial compressive strengths of the brick and mortar are 6.0 and 6.6 MPa, respectively while modulus of elasticity of mortar is 0.6 GPa. These values show that Roman bricks and mortars have similar physical and mechanical properties, contributing to their long-term durability by the compatibility of these materials. The similarities between the performance properties of brick and brick mortar used in the historical building in Anatolia belonging to the Roman Period and the Periods of Anatolian Seljuks, Principalities and Ottoman highlight the continuity in historical brick production technology in Anatolia during centuries that reached the advanced level in Ottoman Period.

Table 2.3. The compiled data on basic physical, physico-mechanical and mechanical properties of Roman bricks in Anatolia used in Serapis Temple (İzmir, Pergamon, Turkey) belonging to the 2nd century BC (Aslan-Özkaya and Böke, 2009)

in İzmir	Sample Type	Bulk Density	Porosity	Water absorption capacity	Modulus of Elasticity	Uniaxial Compressive Strength (*)
		(g/cm^3)	(% vol.)	(% wt.)	GPa	MPa
Roman Period	Brick	1.65	35.0	21.2	-	6.0
	Mortar	1.50	36.0	24.0	0.6	6.6

There is a comprehensive study conducted on the performance properties of historical bricks used in the monuments in İstanbul with a focus on Byzantine period (between 4th and 14th centuries) in terms of physical, physico-mechanical and mechanical properties (**Table 2.4**). The bulk density and porosity values of those bricks examined by Kahya (1992) are given in the range of 1.63 - 1.86 g/cm^3 and 28.4 - 34.3% by volume, respectively. Their water absorption capacity values are in the range of 15.4 and 20.6% by weight. The ultrasonic pulse velocity and uniaxial compressive strength of those Byzantine bricks are given in the range of 1890 - 3070 m/s and 18.1 - 33.4 MPa, respectively. The testing method used to measure the compressive strength of Byzantine bricks was mentioned as the hydraulic press testing instrument (Kahya, 1992). The comparison of the data on Byzantine bricks in İstanbul (**Table 2.4**) and the data on the Anatolian historical bricks (**Table 2.3**) show that Byzantine bricks (4th – 14th centuries) used in historical structures in İstanbul are denser and less porous bricks with considerably higher physicomechanical and mechanical properties. That difference in materials properties between the historical bricks in İstanbul and Anatolia needs to be investgated by further analyses with a focus on their production technology, raw materials and firing temperature. In the same study, it was observed that 15th century Ottoman bricks in İstanbul have similar physical and physicomechanical properties with the Byzantine bricks while those 15th century

Ottoman bricks having considerably low compressive strength than the Byzantine ones in İstanbul (**Table 2.4**). The material characteristics of those Ottoman bricks in İstanbul fall into the data range on the Anatolian historical bricks compiled from the results given in the literature (**Table 2.2**).

Table 2.4. The compiled data on basic physical, physico-mechanical and mechanical properties of Byzantine bricks used in the monuments in İstanbul belonging to between 4th to 14th centuries (Kahya, 1992)

in İstanbul	Century	Bulk Density	Porosity	Water absorption capacity	Ultrasonic Pulse Velocity	Uniaxial Compressive Strength (*)
		(g/cm^3)	(% vol.)	(% wt.)	m/s	MPa
Byzantine Period	4-6	1.63-1.67	32.1-34.3	19.9-20.6	2160-3150	18.1-28.4
	8-10	1.76	27.7-30.0	15.8-17.1	2600-3070	20.7-33.4
	11-12	1.64	30.9-33.0	19.0-20.1	1890-2270	24.8-27.1
	14	1.86	28.4	15.4	2650	26.2
Ottoman Period	15	1.81	26.4	14.7	2200	11.8

Briefly, historical bricks are structural materials with low bulk density, high porosity, high water vapour permeability, high thermal resistance, and have low but sufficient mechanical properties. In literature, it is emphasized that the historical mortars and plasters, which are in direct contact with the historical brick, have similar physical and physico-mechanical properties with the bricks. Those performance properties and compatibility between the neighbouring materials allowed forming lightweight superstructures with breathable nature and enough strength and contributed contributed to their long-term durability.

2.2 Compatibility Criterion Provided in Historical Brick Masonry

Compatibility of a material can be defined as its suitability with other building materials used together in terms of some material properties, which should be similar with each other in order to prevent any failure of the assembly (Tuncoku *et al*., 1993; Williams and Williams, 1994). The selection of compatible materials for the replacement of original bricks is crucial in order to avoid damage to the historical structure. The literature shows that the most important thing to be considered in the conservation works of the ancient materials is that the intervention of historical materials should be compatible with the original material and should not do any damage in the long term. This requires knowing about the properties of original materials as well as the problems of deterioration (Aslan-Özkaya and Böke, 2009; Elert *et al*., 2003; Sasse and Snethlage 1997; Tuncoku *et al*., 1993).

Brick masonry is constructed by brick units and mortar, which constitute the overall section of the wall structure. The mortar used in brick masonry is the key ingredient to assemble brick units and fills the irregular gaps between them. Brick masonry can be constructed as either solo (brick and its mortar) or with cladding application. The properties of material used with the brick units should be prepared compatible with each other and considering their function in the building. Studies conducted on historical bath structures show that the brick material and its mortar have similar physical, physicomechanical and raw material properties which means, there is conscious material selection in history. Historic brick-lime mortars taken from 14^{th} and 15^{th} century Ottoman baths show that bulk density and porosity values of mortar samples, which are similar with brick samples and they are found to be 1.7 g/cm^3 and %37 by volume, respectively. Their compressive strength are higher than 10 MPa and the brick aggregates used in mortar samples are determined to be good pozzolan. XRD analyses show that calcite, quartz and feldspar are the main minerals in mortar samples (Uğurlu and Böke, 2009; Böke *et al*., 2006). The adhesion capacities of historical mortar have also been studied to improve bonding together with their microstructural characteristics, which are used to assess compatibility (Moropoulou *et al*., 2000)

The compatibility of materials is an important topic in the conservation of historical structures for the sake of protecting their original appearance and sustaining their durability. Using wrong materials leads to rapid deterioration, loss of their historical values due to damaging original materials. Manufacturing repair materials with specific properties compatible with original ones requires to defining material characteristics before interfering historical structures (Coletti *et al*., 2016; Cardiano *et al*., 2004)

2.3 Technological Properties of Contemporary Bricks

Understanding the technological properties of contemporary bricks is important for evaluating the state of affair of brick technology. In the scope of technological properties, it is important to discuss the evaluation since the beginning of brick material used as a construction material. The contemporary brick types, production technology of today's bricks have been investigated in present conditions. Moreover, related standards written/formed for handmade fired brick and factory solid bricks have been examined to show the lack of knowledge and inadequacy of this field in literature.

2.3.1 Brick Types –Handmade and Factory-Made Fired Solid Bricks

Brick production has been developed since ancient times because of the extensive use of brick material as a leading construction material at present. The improvements in technology and industrial revolution affect the brick production incrementally by the invention of machines and mass production. However, handmade bricks and their traditional production techniques have never been forgotten due to their uniqueness and properties. Nowadays, they are used in constructions for many reasons and mostly in conservation works due to their similar production technology with historical bricks.

Bricks are generally categorized by manufacturing methods, which are mud bricks/air-dried and fired bricks. Different processes such as; extruded and moulded are used to form fired clay bricks. In the extruded type of bricks, clay mix is forced through an opening in a steel die and cut by wire after extrusion (pressed type). In the moulded type of bricks, clay mix is shaped in moulds by hand (handmade) or by machine (not-pressed type) (Hughes and Bargh, 1982). These types of bricks are classified by their use such as; solid, perforated, cellular or hollow. Solid type of machine moulded and solid type of extruded bricks are one of the specialized use of factory solid bricks instead of handmade bricks in order to extend these handmade bricks and repair bricks market share.

Handmade bricks are distinguished from factory bricks by their hand-moulded method of manufacturing. They are prepared and moulded individually resulting uniformly different bricks in uniquely varied range of colours and textures by altering the composition of raw materials and/or firing temperatures to adjust them to every sort of structural and architectural requirements. Handmade brick producers create their own product range according to the specific area of usage with different brick types however, their production techniques remain same and all these bricks has a solid-section. Their product range vary from floor and vault brick to wall and cladding/decorative brick. Some of these producers classifies a specific type of handmade brick as repair brick considering the historical period of repair work. These types of bricks are formed in desired sizes and colours.

The bricks may be prepared in various sizes depending upon the custom and practice of locality. However, the size of brick should be such that it can be easily placed with one hand, during construction. Non-standard size bricks will give non-uniform construction. For instance, standards recommended the following dimensions of a burnt brick: Length: 190 mm Width: 90 mm Thickness: 90 mm. Total size becomes 200 mm x 100 mm x 100 mm with mortar thickness as the normal size of modular brick. Brick length should be twice the width plus the thickness of vertical joint 10 mm. Furthermore, the natural colour of a burnt brick depends upon natural colour of clay and its chemical composition, natural colour of sand, state of dryness before burning, type of fuel used for burning, quantity of air during burning and the temperature attained during burning.

2.3.2 Production Technology for Contemporary Handmade and Factory-made Fired Solid Bricks

Turkey has an abundance of natural sources and its mining industry is one of the sectors showing steady growth. The requirements of raw material to produce ceramic products are widely available locally. There were a number of fundamental investigations to evaluate the quantity and quality of ceramic raw materials in Turkey (Aras *et al*., 2007). As an interdisciplinary field, clayey soil which is known as fertile rich soil, has been constrained the clayey soils of particular regions not to be used as a raw material in brick production by the ministry of environment and urbanization in the cities due to agricultural policies. Herewith, brick factories have been scattered to the rural areas where the producers can take license to use the resources of clayey soil as a raw material in brick production. These resources are mostly used for agricultural purposes and therefore the number of handmade brick factories are decreased by the policies in process of time. Nowadays, there is a few number of handmade brick producers who are active in close vicinity of large cities. Along with these producers are small-scaled enterprises, their current output are very limited considering the needs of handmade bricks.

The heritage of knowledge on the production techniques of bricks is based on the accumulated empirical knowledge obtained from ancient times. Studies conducted on historical bricks show that both raw materials and the manufacturing techniques used for brick production had not changed through a long historic period (Stefanidou *et al*., 2005). Earth is used to produce brick as a raw material if there is sufficient clay and its minerals, which gives adhesion capabilities. Earth contains several families of clay minerals such as; kaolinites, illites, montmorillionites and others (chlorite, muscovite, etc.). The workability and plasticity of clay depends on the clay minerals in soil. Kaolinite and illite are more stable in contact with water while other types are not stable and suffer from swell (Reeves *et al*., 2006; Houben and Guillaud, 1994). Different additives are also used to improve the material's properties such as fine and coarse aggregates or fibrous materials (Stefanidou *et al*., 2005). Handmade bricks are produced depending on traditional production methods, which are shown below (**Figure 2.1**):

- Preparation of raw material
- Forming by hand
- Air-drying
- Firing in a great oven
- Packaging and storage

Figure 2.1. Showing the handmade brick production methods in order: preparation of raw material (upper left), forming by hand in desk (upper right), air-drying (lower left), firing in great oven (lower right).

The first step of brick manufacturing is selecting the suitable soil and transferring it to the site. The soil is remained for 3 weeks to be purified and mature enough (Davey, 1961). The clay is manually sieved and mixed with water and added additives if necessary. The amount of water depends on the water absorption capacity of the soil (Andrade *et al*., 2011; Dalkılıç and Nabikoğlu, 2017). The mixture is left to stabilize and increase the plasticity. Wooden moulds are used to shape the mixture by hand. These moulds are aligned in an open space for drying process. In the last step, air-dried bricks are installed in an oven for firing process. During firing, brick takes its final form of hardness, strength and colour due to the changing in mineral phases (Riccardi *et al*., 1999).

Handmade brick factories are active in particular months of a year due to selecting optimum drying periods and minimize seasonal effects. In Turkey, spring and autumn months are the most productive periods for handmade brick manufacturing throughout the year. There is a need for protecting the bricks from direct sunlight, which causes cracks due to rapid drying (Quagliarini and Lenci, 2010). Furthermore, the site selected for the manufacturing should have sufficient quantity of suitable brick making earth, available water and transportation facilities. The site should be slightly away from the populated area due to the pollution caused by burning process. The drying area should be plain with no undulation and no vegetation to prevent wrong implications. These manufacturers also produce mudbrick from the same raw material, which is air-dried without burning phase according to the needs of market.

Factory-made fired solid bricks are one of the brick types produced by modern techniques in large-scale brick factories. The production volumes of these factories are significantly higher than handmade factories that decreases operating costs throughout the year. This industry requires large inputs of resources, which demands environmental assessments related with energy use and carbon emissions (Koroneos and Dompros, 2007). The production stages are basically similar with handmade brick production, however factory bricks become different due to systematically/automatically usage of machines and technological advances. After the preparation of raw material, the clay is passed through the rotating cylinders to reduce particle sizes. The raw material rests to mature in dampness for approximately 20 days or 3 weeks. The clay is mixed with water and barium carbonate solution for salification with salt types (sulphates) in order to purify from salt problems in laboratory conditions that is learnt by one of the solid brick producer. The mixture is shaped by steel extrusion die or by moulds using pressure before drying in cooling chamber. Firing process is also different from handmade bricks that the coaches are used inside the furnace that operates approximately at 1000°C. Brick factories intent to produce the product look traditional with present day equipment; however the raw materials, molding operations and firing practices differ significantly (Livinston, 1988).

2.3.3 Requirements for Contemporary Solid Bricks Defined in Standards

Turkish standards (TS 704:1979; TS 705: 1985; TS EN 771-1 + A1: 2015) related with handmade and factory bricks were given in **Table 2.5**. The only and the latest standard mentions and gives basic reference data on handmade bricks is the TS 704:1979. In this standard, handmade fired bricks are defined as clay bricks used in wall construction. Those bricks are not exposed to extrusion and/or pressure applications. This standard includes two types of handmade fired bricks; solid and hollowed types. Solid handmade bricks have solid form without holes. Hollowed handmade bricks are accepted to have vertical cells perpendicular to the lower and upper faces. Cross-sectional area of these vertical cells should not be larger than 25% of face area of brick which is marked as (1) in **Table 2.5**. Depending on their compressive strengths, they are classified as moderately-strength (medium) or slightly-strength (low) bricks. Additionally, the water absorption capacity of these bricks should not be greater than 20% by weight.

In 1985, new standard was produced for factory bricks since they were produced extensively. The standard, namely TS 705:1985 mentions the standard/reference data for the bricks shaped in machines and fired at higher temperatures in ovens. These bricks are solid and vertically perforated bricks used in wall construction. These factory bricks are classified as solid, sparsely and slightly perforated bricks in different bulk densities by giving their compressive strength values. In these several types of factory bricks, the data for solid bricks are used for evaluation in the scope of the study while sparsely and slightly perforated bricks are neglected. However, the hole rate of solid bricks is given up to 15 % of upper face area which is accepted as solid type in TS 705:1985 which is marked as (2) in Table, as well.

TS EN 771-1+A1:2015 is the current standard for clay masonry units prepared by Technical Committee CEN/TC 125 for European Standard and accepted as Turkish Standard by TSE. Requirements for clay masonry units are given for both protected (P unit) and unprotected (U unit) masonry units in **Table 2.6**. Protected masonry is protected against water penetration by rendering or cladding while unprotected masonry is exposed to water without a suitable protection. These P and U units may or may not be used as loadbearing.

Their configurations are given according to the relevant uses for clay masonry units placed on the market. In the configurations, solid, frogged or vertically perforated units are given in the examples of U units while the examples of P units are all vertically or horizontally perforated units. In this standard, each requirements has their own classification type, which are given by 3 examples; two of them are P units (example I and II) and one of them is U unit (example III) as shown in **Table 2.5**. The requirements related with clay units are given below:

- The bulk density and average compressive strength values of two P unit examples are 0.75 and 0.65 g/cm^3 and 8.5 and 10.0 MPa, respectively while these values are 1.9 g/cm^3 and 43.8 MPa for the example of U unit.
- Thermal conductivity values of these examples are 0.140, 0.090 W/mK and NPD (No Performance Determined) for example I, II and III. Their water vapor permeability through the water vapor diffusion coefficient values are NPD, 5/10 and 50/100, respectively.
- Example I and II have NPD (no performance determined) for mean net dry density, volume of frog and water absorption capacity values while example III is specified as 2.1 g/cm^3, lower than 20% and lower than 6%, respectively.
- The bond strength (initial shear strength) in combination with mortar is declared 0.15 MPa for example I while NPD is declared for example II and III.

Other requirements such as, freeze/thaw resistance, dimensional tolerance, range category and active soluble salt contents are given according to their classifications or categories, which are shown in **Table 2.6**. The requirements are explained for each one below:

- The freeze/thaw resistance category is given as F0 for both P units (example I and II) which is required from the masonry elements to be suitable for passive exposure while the resistance is given as F2 for U unit (example III) which is required the masonry element to be suitable for severe exposure.

- Dimensional tolerance is given T2 for P units and T1 for U unit while range category is given R2 for P units and R1 for U unit.
- Active soluble salt content is given S0 for P units in which there is no requirement, while it is given S1 for U unit in which the amount of Na^+ and K^+ ions must be maximum 0.17% by mass and the amount of Mg^{2+} ion must be maximum 0.08% by mass.
- NPD is declared for moisture movement for all examples, it shall be declared to the provisions valid in the intended place of use.
- The manufacturer shall declare the reaction to fire classification as A1 for all type of masonry units.

Table 2.5. Turkish Standards related with handmade bricks, solid factory bricks and clay masonry units given in TS 704:1979; TS 705:1985; TS EN 771-1+A1: 2015

Requirements related with clay units	**TURKISH STANDARDS RELATED WITH HANDMADE AND FACTORY CLAY BRICKS**										
	TS 704: 1979				**TS 705: 1985**				**TS EN 771-1 + A1: 2015**		
	Solid Handmade Brick		Hollowed Handmade Brick (1)		Factory Bricks (2)				Clay Masonry Units		
	Medium-Strength	Low-Strength	Medium-Strength	Low-Strength	Solid Brick (2000 kg/m3)		Solid Brick (1800 kg/m3)		P unit (Example I)	P unit (Example II)	U unit (Example III)
					Max	Min	Max	Min			
Bulk density (g/cm^3)	not limited	not limited	1.4	1.4	2.0	1.8	1.8	1.6	0.75	0.65	1.9
Average compressive strength (MPa)	5.0	3.0	5.0	3.0	17.6		15.4		8.5	10.0	43.8
Lowest compressive strength (MPa)	4.0	2.5	4.0	2.8	14.0		12.3		-	-	-
Dimensions (length x width x height) (mm)	-	-	-	-	-	-	-	-	240x300x238	250x365x249	240x115x71
Dimensional tolerance	-	-	-	-	-	-	-	-	T2	T2	T1
Range category	-	-	-	-	-	-	-	-	R2	R2	R1
Volume of frog (%)	-	-	-	-	-	-	-	-	-	-	≤20%
Mean net dry density (g/cm^3)	-	-	-	-	-	-	-	-	NPD	NPD	2.1
Thermal conductivity (W/mK)	-	-	-	-	-	-	-	-	0.140	0.090	NPD
Freeze/thaw resistance	-	-	-	-	-	-	-	-	F0	F0	F2
Water absorbtion capacity (%)	-	-	-	-	-	-	-	-	NPD	NPD	< 6%
Active soluble salts content	-	-	-	-	-	-	-	-	S0	S0	S1
Moisture movement	-	-	-	-	-	-	-	-	NPD	NPD	NPD
Reaction to fire	-	-	-	-	-	-	-	-	A1	A1	A1
Water vapor permeability	-	-	-	-	-	-	-	-	NPD	5/10	50/100
Bond strength (MPa)	-	-	-	-	-	-	-	-	0.15	NPD	NPD

In TS 704:1979 and TS 705:1985, bulk density, average and lowest compressive strength values were similarly given for each type of brick which are solid and hollowed handmade bricks and solid factory bricks. In TS 704:1979, the bulk density of solid handmade bricks are not limited for both low and medium strength types, while the bulk density of hollowed bricks are classified as 1.4 g/cm^3 for both types. Their average compressive strength values are the same which are 5.0 and 3.0 MPa for medium and low strength types, respectively while lowest compressive strength values are 4.0 (medium strength) and 2.5 (low strength) MPa for solid handmade bricks and 4.0 (medium strength) and 2.8 (low strength) MPa for hollowed handmade bricks. There is no other classification related with solid and hollowed type of handmade bricks declared in TS 704:1979.

TS 705:1985 classifies solid factory bricks into two different categories, namely 2000 kg/m^3 and 1800 kg/m^3 types. Maximum and minimum bulk densities of 2000 kg/m^3 type are given 2.0 and 1.8 g/cm^3 while maximum and minimum bulk densities of 1800 kg/m^3 are given 1.8 and 1.6 g/cm^3, respectively. Their average compressive strength values are given 17.6 and 15.4 MPa while lowest compressive strength values are given 14.0 and 12.3 MPa for 2000kg/m^3 and 1800 kg/m^3 types, respectively. There is no other classification related with solid factory bricks declared in TS 705:1985.

Since TS EN 771-1+A1:2015 is adapted from European Standard (EN 771-1+A1), some of the terms and definitions differs from each other. However, the characteristics, classifications and performance requirements for masonry units manufactured from clay for use in masonry construction are the same for both Turkish and European standards. In European standard, requirements are given for LD and HD units, which are the main differences of these two standards that are given for P and U units in Turkish standard. LD units are identified as clay masonry units with a gross dry density of less than 1000 kg/m^3 in protected masonry. However, HD units are identified in two ways, which are all clay masonry units for unprotected masonry and clay masonry units with a gross dry density greater than 1000 kg/m^3 in protected masonry. The requirements and properties are defined in terms of test methods, procedures and production evaluation for manufacturers.

Table 2.6. The classifications or categories of requirements given for clay masonry units in TS EN 771-1+A1: 2015

Requirements for clay masonry units				
Dimensional tolerances	T1	± 0.40 √(work size dimension) mm or 3 mm whichever is greater		
	T2	± 0.25 √(work size dimension) mm or 2 mm whichever is greater		
	Tm	deviation declared by manufacturer		
	R1	0.6 √(work size dimension) mm		
	R2	0.3 √(work size dimension) mm		
	Rm	range declared by manufacturer		
Size of voids- Percentage of voids	The shape of the brick and direction of any perforations should be stated. The number of perforations, the volume and shape of these and frogs and the thickness of the shells and webs			
Dry density tolerances	D1	10%		
	D2	5%		
	Dm	deviation declared by manufacturer		
Compressive strength	Declared by manufacturer and tested in accordance with EN 772-1			
	Category I	probability of failure not exceeding 5%		
	CategoryII	the level of confidence as placed on category I does not apply		
Thermal properties	When thermal insulation requirement is relevant, it shall be done by reference to EN 1745			
Freeze/thaw resistance	F0	Suitable for passive exposure		
	F1	Suitable for moderate exposure		
	F2	Suitable for severe exposure		
Water absorption capacity	Declared by manufacturer and tested in accordance with the method in EN 772-11			
Active soluble salt max content	Wall type	Na+ + K+	Mg2+	Soluble sulfates (sodium, potassium and magnesium)
	S0	No requirement	No requirement	S0: Completely protected walls
	S1	0.17	0.08	S1: Walls with sulfate resisting cement in mortar
	S2	0.06	0.03	S2: Walls with ordinary Portland cement in mortar
Moisture movement	When there is a requirement, it shall be declared to the provisions valid in the intended place of use.			
Reaction to fire	For units subject to fire requirements, the manufacturer shall declare the reaction to fire classification of masonry unit.			
Water vapour permeability	For units intended for external elements the manufacturer shall provide information on WVP values given in EN 1745.			
Bond strength	The bond strength in combination with mortar shall be declared in accordance with EN 1052-3 (initial shear strength).			

CHAPTER 3

MATERIAL AND METHOD

In this chapter, the definition of brick samples, sample preparation and the laboratory analyses are explained in detail under respective subheadings.

3.1 Sample Preparation

In the study, some types of contemporary solid bricks were investigated to determine their physical, physicomechanical and compositional properties. For that purpose, mainly two groups of burnt-clay solid bricks produced in Turkey, namely “handmade/hand-moulded bricks” and “factory-made bricks” were examined (**Figure 3.1**). Handmade solid bricks are produced in Turkey particularly as repair bricks for the purposes of cultural heritage conservation while the factory solid bricks are used commonly as brick veneering tiles for the external façade cladding in contemporary buildings. On the other hand, there is a tendency for the use of factory solid bricks in repairs of historical masonry structures.

Figure 3.1. Brick units taken from the manufacturers used for the sample preparation. (From left side, respectively; factory-made brick (pressed burnt-clay) in 21.5 cm, factory-made brick (not-pressed burnt-clay) in 22 cm, handmade burnt-clay brick in 19 cm and handmade burnt-clay brick in 24 cm sizes.

Handmade burnt-clay brick samples were taken from the small-scale factories/enterprises located in four different cities of Turkey, namely Çorum, Eskişehir, İzmir and Manisa. Factory solid brick samples were taken from two different factories located in İzmir and Bartın. The names of the manufacturers are given in Appendix A. All brick types are the products commonly-used either in repairs of historic masonry walls or facade veneering of contemporary structures. In addition, those brick samples were selected since the manufacturers of those brick units allowed performance analyses of their products by means of laboratory analyses.

Ten samples of handmade bricks and four samples of factory solid bricks were prepared for the analyses. The definition of the brick samples are summarized in **Table 3.1** in terms of sample code, production region, description of the sample and their visible colour and dimensions. All handmade-burnt bricks (C.V.p.HB1, C.V.b.HB2, C.V.p.HB3, C.U.lb.HB4, E.A.r.HB5, E.A.db.HB6, I.A.r.HB7, I.A.p.HB8, M.S.lb.HB9, M.S.p.HB10) are produced by means of hand moulding of adobe soil mixture and not compacted with pressing and extrusion processes. Among four factory solid bricks, the first one (I.D.db.FB1) is machine-moulded brick but not compacted with pressing and extrusion processes, while the other three samples (I.D.r.FB2, B.I.r.FB3, B.I.gb.FB4) are the types of pressed bricks which are compacted with extrusion process.

All samples were mainly classified according to their types, namely “handmade brick” and “factory solid brick”. Each sample is coded with letters and numbers related with the “region” where the samples are produced, “company name”, “visible colour”, brick type” and “number of the sample”, respectively. The explanation of the sample code (nomenclature of the sample) for the samples C.V.p.HB1 and I.D.db.FB1 are shown in **Figure 3.2**.

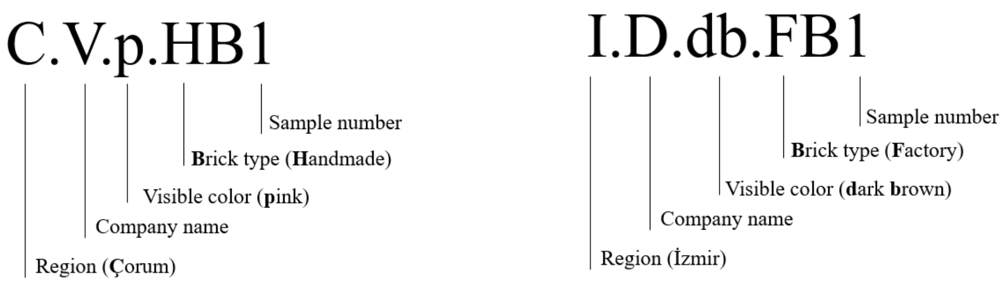


Figure 3.2. Explanation of the nomenclature for the samples C.V.p.HB1 (at the left) and I.D.db.FB1(at the right) (See the company names in Appendix A).

Table 3.1. Brief definition of the brick samples examined in the study.

Sample Code	Region	Description	Visible Colour	Sizes in cm. (length x width x height)
C.V.p.HB1	**Ç**orum (Merkez)	**H**andmade burnt-clay **B**rick – solid cross section	**p**ink	19.0 x 9.0 x 6.0
C.V.b.HB2	**Ç**orum (Merkez)	**H**andmade burnt-clay **B**rick – solid cross section	**b**rown	19.0 x 9.0 x 6.0
C.V.p.HB3	**Ç**orum (Merkez)	**H**andmade burnt-clay **B**rick – solid cross section	**p**ink	24.5 x 12.0 x 6.0
C.U.lb.HB4	**Ç**orum (Merkez)	**H**andmade burnt-clay **B**rick – solid cross section	**l**ight **b**rown	19.0 x 9.0 x 6.0
E.A.r.HB5	**E**skişehir – (Sakintepe)	**H**andmade burnt-clay **B**rick – solid cross section	**r**ed	18.5 x 8.5 x 5.5
E.A.db.HB6	**E**skişehir – (Sakintepe)	**H**andmade burnt-clay **B**rick – solid cross section	**d**ark **b**rown	21.5 x 10.0 x 6.0
I.A.r.HB7	**İ**zmir – (Torbalı/Subaşı)	**H**andmade burnt-clay **B**rick – solid cross section	**r**ed	18.0 x 8.0 x 6.0
I.A.p.HB8	**İ**zmir - (Torbalı/Subaşı)	**H**andmade burnt-clay **B**rick – solid cross section	**p**ink	22.0 x 9.5 x 6.0
M.S.lb.HB9	**M**anisa – (Muradiye)	**H**andmade burnt-clay **B**rick – solid cross section	**l**ight **b**rown	18.0 x 8.0 x 5.0
M.S.p.HB10	**M**anisa - (Muradiye)	**H**andmade burnt-clay **B**rick – solid cross section	**p**ink	21.0x 9.5 x 6.0
I.D.db.FB1	**İ**zmir – (Torbalı)	**F**actory-made **B**rick (Not-Pressed or uncompressed burnt-clay brick) – solid cross section	**d**ark **b**rown	22.0x 10.2 x 6.0
I.D.r.FB2	**İ**zmir – (Torbalı)	**F**actory-made **B**rick (Pressed burnt-clay brick) – solid cross section	**r**ed	21.5 x 10.3 x 6.2
B.I.r.FB3	**B**artın – (Ağdacı)	**F**actory-made **B**rick (Pressed burnt-clay brick) – solid cross section	**r**ed	22.0 x 10.4 x 6.4
B.I.gb.FB4	**B**artın – (Ağdacı)	**F**actory-made **B**rick (Pressed burnt-clay brick) – solid cross section	**g**reyish **b**rown	21.5 x 10.3 x 6.3

The analyses of material properties and their methods performed on brick samples are given in **Table 3.2**. Material properties involve physical, physicomechanical and mechanical properties, raw materials and microstructural properties of brick samples. Besides, the soluble salt content and their types of brick samples are analysed in the scope of the study.

Table 3.2. The material analyses and their methods conducted on all brick samples

Material Property	Analysis Method
Material Property	**Analysis Method**
Physical Properties (Porosity, breathing, drying, thermal and colour properties)	
Bulk density-(ρ), (g/cm^3)	Teutonico, 1988; RILEM, 1980
Porosity-(φ), (% by volume)	
Fine porosity- ($\varphi_{0.5\mu}$), (% by volume)	Tavukçuoğlu *et al.*, 2016; Caner-Saltık *et al.*, 1998; Massa ve Amadori, 1990; De Castro, 1978
Rate of fine porosity to total porosity- ($R_{0.5\mu}$), (%)	
Water absorption capacity- (θ), (% by weight)	Teutonico, 1988; RILEM, 1980
Saturation coefficient- (*S-value*, unitless)	RILEM, 1980
Water vapour diffusion resistance index - (μ, unitless)	ASTM E96/E96M:2016; TS EN 1015-19/A1:2013; TS EN ISO 7783:2012; TS EN ISO 12572; 2001; Teutonico, 1988; RILEM, 1980
Water vapour transmission rate- (*RT*, g/hm^2)	
Equivalent air thickness of water vapor permeability –(*SD*, m)	
Maximum evaporation rate as a function of moisture content vapour flow rate (Drying rate)- (R_E, kg/m^2h)	Tavukçuoğlu and Grinzato, 2006; BS EN ISO 13788: 2002; Garrecht, 1996; Massari and Massari, 1993; Torraca, 1988; RILEM, 1980
Critical moisture content - (θ_C, % by volume)	
Specific heat capacity – (*c*, J/kg.K)	TS 4048, 2013
Colour measurements	Munsell soil colour charts (Munsell, 1971)
Physicomechanical and Mechanical Properties	
Ultrasonic pulse velocity (perpendicular to surface)- UPV_{DIRECT} (m/s)	ASTM D 2845-08:2017; Christaras, 2003; Topal and Doyuran, 1995; Kahraman *et al.*, 2008; RILEM, 1980
Ultrasonic pulse velocity (parallel to surface)- $UPV_{INDIRECT}$ (m/s)	
Conversion factor $UPV_{INDIRECT}/UPV_{DIRECT}$	
Modulus of Elasticity- (GPa)	ASTM D 2845-08:2017; Tunçoku, 2001; Topal, 1995; RILEM, 1980; Timoshenko, 1970
Uniaxial compressive strength- (MPa)	ISRM Point Load Test 1985; Winkler, 1986, Topal, 1999
Raw Materials and Microstructural Properties	
Mineralogical content (Clay type and other minerals)	X-Ray Diffractometer analyses
Pozzolanic activity	Volumetric titration by EDTA and Conductivity Measurement (Luxan *et. al.*, 1989)
Cross section analyses	Cutting saw -Isomet 4000 Linear Precision Saw Model and Stereo binocular microscope; Leica Stereo Optic Microscope Model Procedure
Qualitative and Quantitative (Soluble) salt analyses	
Type of salt	Teutonico, 1988 (spot tests for the presence of phosphate, sulphate, chloride, nitrite, nitrate, and carbonate)
Salt content (% by weight)	RILEM, 1980; Black, 1965

3.2 Determination of Physical Properties

The laboratory analyses on physical properties of brick samples were done to determine their bulk density (ρ), porosity (φ), fine porosity ($\varphi_{0.5\mu}$), rate of fine porosity to total porosity ($R_{0.5\mu}$), water absorption capacity (θ), saturation coefficient (*S-value*), water vapour diffusion resistance index (μ), water vapour transmission rate (*RT*), evaporation rate (R_E), critical moisture content (θ_C) and specific heat (*c*) characteristics. The relevant experimental methods, terminologies and equations are described in the following subheadings. Those physical properties of the samples were discussed to better understand the hygric behaviour and pore structure of the samples. Furthermore, the colour analyses were determined by Munsell soil colour charts as a physical property, which was used to evaluate further analyses.

3.2.1 Bulk Density, Porosity, Water Absorption Capacity, Saturation Coefficient and Fine Pore Porosity

For the analyses of these physical properties including bulk density, porosity, fine pore porosity, water absorption capacity and saturation coefficient of handmade brick samples from each region and factory-made solid bricks were cut into cubes shaped in 5 x 5 x 5cm of sizes and three different series from each brick samples were prepared. Samples were dried in the oven at 35°C to constant weight and they were recorded as the dry weights of the samples (M_{DRY}).

The samples were completely submerged into distilled water for 24 hours and measured the weights of the samples ($M_{24HOURS}$). Afterwards, they were placed in vacuum by using a HEREUS vacuum chamber at 0,132 atm (100 torr) pressure. The weights of the water-saturated samples were recorded as saturated weights (M_{SAT}). These samples were submerged into distilled water once more and their weights were recorded as their Archimedes weights (M_{ARCH}). Afterwards, these brick samples were dried in the oven at 60°C, they were kept waiting in a desiccator that is filled with calcium chloride ($CaCl_2$) in order to dehumidify and reach to room temperature. Then these dried brick samples were placed in a desiccator with saturated barium chloride solution ($BaCl_2.2H_2O$) and left them under 88% relative humidity conditions during a week until their weights were constant. They were recorded as the equilibrium moisture content weights in higher relative humidity conditions ($M_{88\%}$). Barium chloride is an inorganic compound and one of the most common water-soluble salts of barium that high relative humidity conditions were arranged by using the solution of saturated barium chloride in order to let water into the finest pores. Data logger measured temperature and relative humidity in order to control the condensation problem during the week (**Figure 3.3**). The saturated solution in contact with an excess of a definite solid phase maintains constant humidity in an enclosed space. According to Lange (1967), barium chloride solution ($BaCl_2.2H_2O$) provides 88% constant humidity at 24.5°C temperature. As an inorganic compound, saturated solution of barium chloride $BaCl_2.2H_2O$ were procured by preparing barium chloride ($BaCl_2$) and water ($2H_2O$) according to their weights of solubility by **Equation 3.1** (Lange, 1967).

$$BaCl_2 + 2H_2O \rightarrow BaCl_2.\ 2H_2O \qquad \textbf{(3.1)}$$

Figure 3.3. Samples kept under higher relative humidity conditions with a data logger – Test procedure of fine pore percentage

All weights were measured with the sensitivity 0,0001 g and used in the calculation of bulk density, porosity water absorption capacity, saturation coefficient and fine pore ratio of the samples. This procedure was repeated on three different series of all the samples in order to find the standard deviations.

Bulk density (ρ) is the ratio of the mass to the bulk volume of the sample. It is expressed in g/cm^3 and calculated using **Equation 3.2** (Teutonico, 1988; RILEM, 1980).

$$\rho = \frac{M_{DRY}}{M_{SAT} - M_{ARCH}}, g/cm^3 \quad \textbf{(3.2)}$$

Porosity (φ) is the fraction of the total volume of a porous material occupied by pores or, more simply, the empty or voids in the mass. Porosity is expressed by the percentage of volume. It is calculated by **Equation 3.3** (Teutonico, 1988; RILEM, 1980):

$$\varphi = \frac{M_{SAT} - M_{DRY}}{M_{SAT} - M_{ARCH}} \text{ x } 100, \% \quad \textbf{(3.3)}$$

Water absorption coefficient (θ) is the maximum quantity of water absorbed by a porous material immersed in distilled water and is expressed as a percentage of the dry mass of the sample. The water absorption capacity of a material is calculated by **Equation 3.4** given below (RILEM, 1980; Teutonico, 1988):

$$\theta = \frac{M_{SAT} - M_{DRY}}{M_{DRY}} x100, \% \quad \textbf{(3.4)}$$

Saturation coefficient (*S-value*) is the ratio that a porous material absorbs by complete immersion under atmospheric pressure in relation to the total volume of pores accessible to water (RILEM, 1980). It is dimensionless coefficient that expressed with a number between 0 and 1, and calculated by **Equation 3.5**:

$$S - value = \frac{M_{24HOURS} - M_{DRY}}{M_{SAT} - M_{DRY}}, (unitless) \quad \textbf{(3.5)}$$

Fine porosity ($\varphi_{0.5\mu m}$) is the ratio of fine pores in a material, which are smaller than 0.5 μm of sizes to the total volume as expressed by percentage. It is calculated by **Equation 3.6**: (Tavukçuoğlu *et al.*, 2016; Caner-Saltık *et al.*, 1998; Massa and Amadori, 1990; De Castro, 1978)

$$\varphi_{0.5\mu m} = \frac{M_{87\%}-M_{DRY}}{M_{SAT}-M_{ARCH}} x100, \% \qquad \textbf{(3.6)}$$

The ratio of fine porosity (fine pores smaller than 0.5µm of sizes) to the total porosity is expressed by percentage of volume ($R_{0.5\mu m}$). It is calculated by **Equation 3.7**: (Tavukçuoğlu *et al.*, 2016; Caner-Saltık *et al.*, 1998; Massa and Amadori, 1990; De Castro, 1978)

$$R_{0.5\mu m} = \frac{M_{87\%}-M_{DRY}}{M_{SAT}-M_{DRY}} x100, \% \qquad \textbf{(3.7)}$$

3.2.2 Water Vapour Permeability

For the analyses of water vapour permeability characteristics, equivalent air layer thickness of water vapour diffusion (*SD*, m), permeability (SD^{-1}, m^{-1}), water vapour diffusion resistance index (μ, unitless) and water vapour transmission rate (*RT*, g/hm^2) were investigated by measurable parameters defined in standards (ASTM E96/E96M: 2016; TS EN 1015-19/A1: 2013; TS EN ISO 7783, 2012; TS EN ISO 12572; 2001; Teutonico, 1988; RILEM, 1980).

The samples were cut into 5 x 5 x 2 cm sizes of tetragonal prism forms and the thickness of each sample were measured on four sides by using a vernier caliper to take the mean of these measurements and record as the width (*So*). The cylindrical containers were filled with distilled water till 2 cm air space between the sample and the water surface. The samples covering the containers were sealed with melted paraffin in order to prevent water vapour transmission from other edges. The ambient relative humidity, atmospheric pressure and the temperature were recorded. The samples were weighted and those weights were recorded as the initial values. They were weighed periodically in order to take the weight loss until weight loss per unit time became constant.

The aim of water vapour permeability analyses is to investigate the amount of water vapour passing through the material (due to the difference in partial vapour pressures on two sides of material) per unit time at constant boundary conditions and constant relative humidity and temperature. Water vapour permeability properties is expressed as equivalent air thickness of water vapour permeability (*SD*), which is calculated for a known thickness of the sample by the **Equation 3.8**. Permeability (SD^{-1}) is the water vapour permeability value of a material for a given thickness that is calculated dividing *SD* value by 1 (**Equation 3.9**). Water vapour diffusion resistance index (μ) is calculated by dividing *SD* value with the thickness of sample by the **Equation 3.10**. (ASTM E96/E96M: 2016; TS EN ISO 12572, 2012).

$$SD = (\Psi L x A x (P1 - P2)/I) - SL, m \quad \textbf{(3.8)}$$

$$SD^{-1} = 1/SD\,, m^{-1} \quad \textbf{(3.9)}$$

$$SD = \mu S_O, unitless \quad \textbf{(3.10)}$$

where,

SD: Equivalent air thickness of vapour permeability, (m)

SD^{-1}: Water vapour permeability value, (m^{-1})

μ: Water vapour diffusion resistance index = SD/ So, (unitless)

So: Thickness of the sample, (m)

ΨL: Constant= 6.89×10-6 (kg/mh (kg/m^2))

A: Area of the sample through which water vapour is evaporated, (m^2)

P_1, P_2: Partial vapour pressures on two sides of the sample – difference between 100%RH and 30%RH, (kg/m^2)

I: Weight change in unit time, (kg/h)

SL: Thickness of air beneath the sample, (m)

Water vapour transmission rate (*RT*) is defined as the steady water vapour flow in unit time through unit area of a body, normal to specific parallel surfaces, under specific conditions of temperature and humidity at each surface. It is calculated by **Equation 3.11**: (ASTM E96/E96M: 2016; TS EN ISO 7783:2012).

$$RT = \frac{G}{txA}, g/hm^2 \quad \textbf{(3.11)}$$

where,

RT= Rate of water vapor transmission, (g/hm^2)

G= Weight change, (g)

t= Time, (h)

A= Test area (cup mouth area), (m^2)

TS EN ISO 7783: 2012 classifies water vapour permeability according to equivalent layer thickness of water vapour permeability (*SD*, m) and water vapour transmission rate (*RT*, g/hm2) of building materials. It reports that *SD* values lower than 0.14m indicate high, values between 0.14m and 1.4m indicate medium, and values higher than 1.4 m indicate low permeability. *RT* values lower than 0.6 g/hm^2 indicate low, values between 0.6 and 6.0 g/hm^2 indicate medium, and values higher than 6.0 g/hm^2 indicate high permeability (**Table 3.3**).

Table 3.3. The classification of water vapour permeability for building materials according to *SD* and *RT* values.

Permeability class	***SD* (m)**	***RT* (g/hm^2)**
Low permeability	>1.4	<0.6
Medium permeability	0.14 – 1.4	0.6 – 6.0
High permeability	<0.14	>6.0

3.2.3 Evaporation Rate and Critical Moisture Content

Brick samples with 5 x 5 x 2 cm sizes were first dried in the oven at 35°C to constant weight. The samples were completely submerged into distilled water and kept in water for 24 hours. The samples in the water were put under vacuum at 0,132 atm (100torr) pressure for half an hour and their saturated weight was recorded as M_{SAT}. The five of the six surfaces of the samples were fully-sealed against evaporation by covering the surfaces for several times with stretch film. The area of the surfaces open to evaporation was the same for all samples (5 x5 cm) and the thickness was 2cm for all samples. The wet samples were then left for drying under almost constant conditions at 25°C±1 and 30%±5 relative humidity (**Figure 3.4**). The mass of each sample were weighted at certain time intervals (M_T): 15-30-60 minutes followed with 1-2-4-6-12 hours and then continued with 12 hours till the end of 6 days when all samples were completely dried. The dried samples were kept in a desiccator with calcium chloride ($CaCl_2$) where dry air below 30% RH was provided and the mass of fully-dried samples were recorded as M_{DRY} for the calculations. All weight measurements were recorded with the sensitivity of 0.0001 grams.

The moisture content (θ, % by volume) in each sample was calculated by using the **Equation 3.12** and then that data was plot as a function of time in order to produce drying curve of each sample as a graph (**Figure 3.5**) (Tavukçuoğlu and Grinzato, 2006; BS EN ISO 13788: 2002; Garrecht, 1996; Massari and Massari, 1993; Torraca, 1988; RILEM, 1980).

$$\theta = \frac{(M_T - M_{DRY})}{(M_{SAT} - M_{ARCH})} \times 100,\ \% \qquad \textbf{(3.12)}$$

Figure 3.4. Handmade fired and factory-made solid bricks left for drying at constant conditions of 25°C±1 and 30%±5 relative humidity.

In order to compare the samples having various bulk density and porosity characteristics, another drying curve graph was produced showing the weight loss from each sample in other words the remained water content the in sample as a function of time during drying period. For that purpose, the normalized water content ($\theta_{NORMALIZED}$, %) in each sample was calculated by the **Equation 3.13.**

$$\theta_{NORMALIZED} = \frac{M_T - M_{DRY}}{M_{SAT} - M_{DRY}} \times 100,\ \% \qquad \textbf{(3.13)}$$

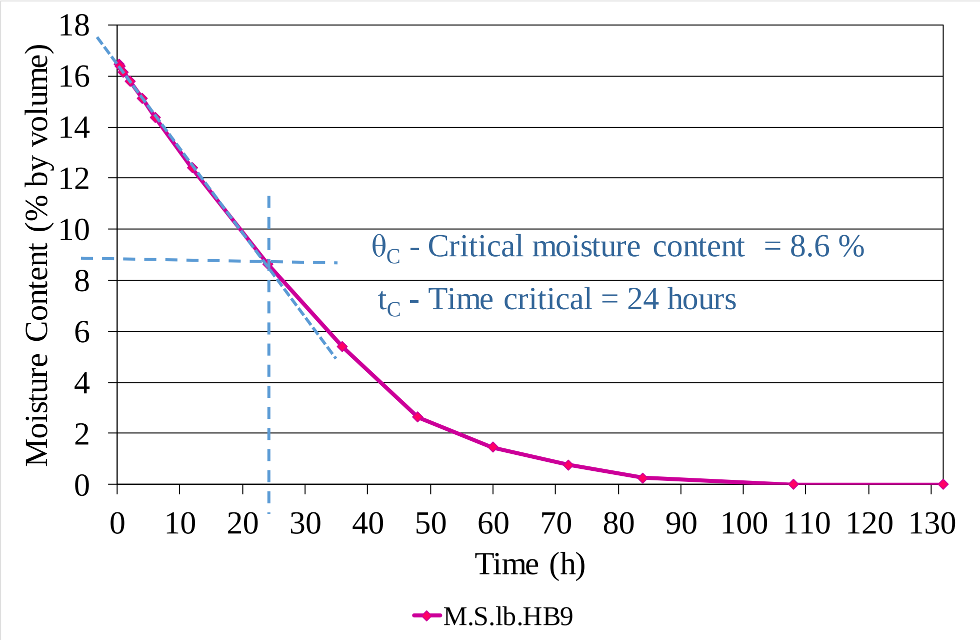


Figure 3.5. Drying curve of the brick sample (M.S.lb.HB9): the moisture content remained in the sample during its drying as a function of time showing that the drying rate is the fastest and constant for a certain period of time (till time critical - t_C) until the moisture content in the sample reduces to critical level (θ_C).

Critical moisture content ($\theta_{C,}$ % by volume) is one of the physical parameter specific for each material and for diagnostic studies it is essential to determine whether moisture content in damp zones of a structure is above or far below the θ_C. The weathering conditions, such as the cycles of freezing-thawing, wetting-drying and salt crystallization, are much more damaging for wet porous materials when their moisture content was above the θ_C (Tavukçuoğlu and Grinzato, 2006; Garrecht, 1996; Massari and Massari, 1993; Torraca, 1988; RILEM, 1980). For the identification of θ_C, the drying rate curve showing the evaporation rate of each sample during water/moisture desorption period as function of moisture content is provided (**Figure 3.6**).

There are two stages of drying for a water-saturated sample (Tavukçuoğlu and Grinzato, 2006; BS EN ISO 13788: 2002; Massari and Massari, 1993; Torraca, 1988; RILEM, 1980) and those stages are observed in the drying rate graph as two different evaporation rate characteristics (**Figure 3.6**). During the evaporation rate in the first stage, the material is wet and the R_E is dependent on the exposure conditions which defines the air's capacity to absorb water vapour and the weight loss from the evaporating surface and the evaporation rate is the fastest and constant. The second stage of drying starts with the decline of evaporation rate which is dependent on the porosity characteristics of the material being dried. That moisture content level between those drying stages is the transition stage between saturated and dry phases of porous material. Above that level, the liquid transfer starts through interconnected capillary pores and below that level, the drying process continues with vapour diffusion through the pores. That level is defined as critical moisture content (θ_C) in the literature and determined for the samples having same thicknesses by using drying rate graph. The time critical (t_C) is the period of time passes until the fastest evaporation rate starts to slow down (**Figure 3.5**).

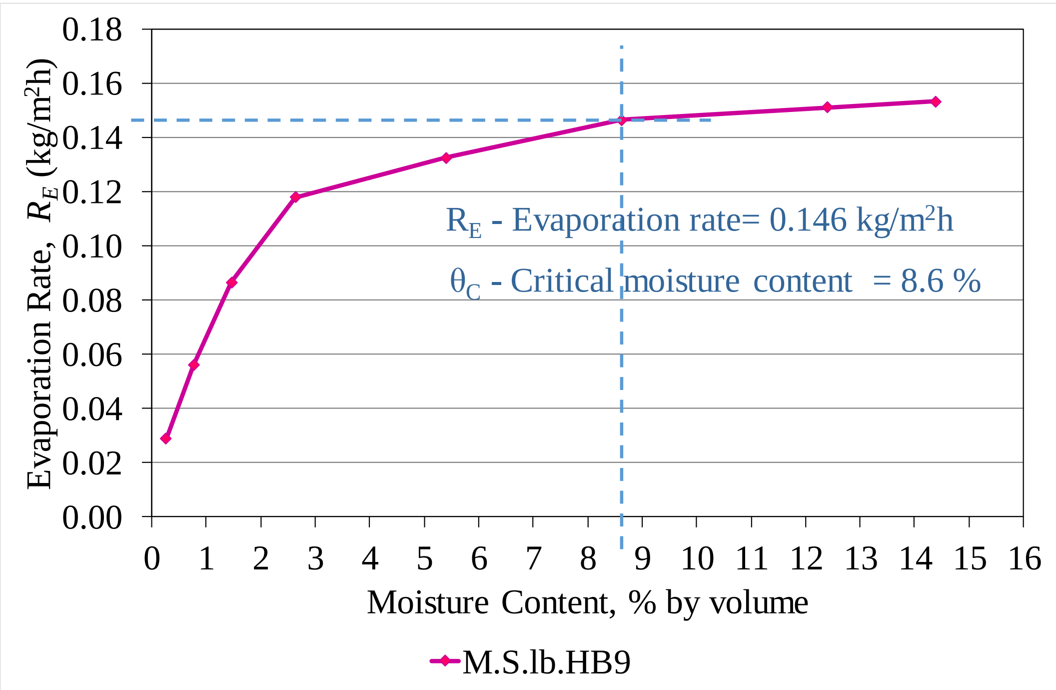


Figure 3.6. The drying rate curve of the brick sample (M.S.lb.HB9) showing the evaporation rate of each sample during water/moisture desorption period as function of moisture content Drying curve of the brick sample (M.S.lb.HB9): the evaporation rate is the fastest and constant when moisture content in the sample is above the critical level, while the evaporation rate declines when the moisture content is below the critical level

The standard test of evaporation rate (R_E, kg/m^{2}h) is based on the sample weight loss change in time. The R_E is a measurable parameter, which is calculated as change in mass per unit time versus the surface area open to evaporation by using **Equation 3.14** (RILEM, 1980):

$$R_E = \frac{dM}{A\,x\,dt}, kg/m^2.h \qquad \textbf{(3.14)}$$

where,

R_E: Evaporation rate ($kg/m^2.h$)

dM: Change in mass of the (wet) sample (kg)

A: Surface area open to evaporation (m^2)

t: Time interval (h)

The critical moisture content (θ_C) of each sample and the rate of evaporation (R_E) are determined by means of drying rate curve (**Figure 3.6**). The time critical (t_C) is determined in the drying curve which is the time corresponding to the critical moisture content level (**Figure 3.5**).

3.2.4 Specific Heat Capacity

Specific heat, 'c', which is expressed in J/kg.K as a thermophysical property of a material, is the amount of heat energy needed to raise the temperature of the material by one degree per unit of weight. Heat energy is a form of energy that is transferred due to the difference in temperature between two objects or regions. It is expressed in Joule or Calorie, as given with **Equation 3.15** below: (TS 4048, 2013)

$$q = M\,c\,\Delta T \qquad \textbf{(3.15)}$$

where,

M: Mass of the sample, kg

c: The specific heat capacity, J/kg.K

ΔT: The temperature change undergone by the sample, K

The principle used for this experimental method is the conservation of energy. Calorimeter was used to measure the transferred energy between two bodies; sample and distilled water at different temperatures. Energy slowly transfers across the material until thermal equilibrium is reached. The quantity of heat energy gained by water, which is initially colder than sample is equal to, lost energy from sample (**Equation 3.16**).

$$q_{GAINED} = q_{LOST} \qquad \textbf{(3.16)}$$

Specific heat capacity parameter is related with the thermal inertia and thermal diffusivity properties. Thermal inertia or effusivity (*e*) is a measure of the thermal mass and velocity of thermal wave at the surface of a material, which resists temperature changes. '*e*' is dependent on the square root of bulk density, thermal conductivity and specific heat of a material. Thermal conductivity (*k*) is a property that describes the ability to conduct heat and calculated by using **Equation 3.17**.

$$k = \frac{e^2}{c \times \rho}, \mathrm{W/mK} \qquad \textbf{(3.17)}$$

where,

e: Thermal effusivity, $Ws^{1/2}/m^2K$

c: Specific heat capacity, J/kgK

ρ: Bulk density, kg/m^3

Thermal diffusivity (α), m^2/s is a measure of heat flow in a material resulting from a temperature difference. It is calculated by dividing thermal conductivity to bulk density and specific heat capacity under constant pressure as given in **Equation 3.18**.

$$a = \frac{k}{c \times \rho}, m^2/s \qquad \textbf{(3.18)}$$

Thermal effusivity and diffusivity are the main parameters of thermal inertia and thermal diffusion characteristics. Both properties are related with bulk density, thermal conductivity and specific heat of the materials. The specific heat and bulk density of contemporary solid bricks were measured in the laboratory and their behavior in terms of thermal inertia (effusivity) and thermal diffusivity were discussed based on the data achived by the study and thermal conductivity data given in literature.

3.2.5 Colour Measurements

The colours of the samples were determined visually in broad daylight by using Munsell soil colour charts (Munsell, 1971). The colours of the bricks are related with the minerals inside the material, their quantity and the firing temperature (Franke and Schoppe, 1988). The analyses of colour are used to classify the building materials according to their hue, value and chroma properties. Hue is the color of the samples such as red (R), yellow (Y), green (G) and so on. Value determines the lightness of the color in descending order given in the chart. For instance, 2 is darker than 6. Chroma determines the strength of the color from weak (from the left) to strong (to the right) in the chart. For instance, 2 is weaker than 6.

3.3 Determination of Basic Physicomechanical and Mechanical Properties

Physicomechanical properties of brick samples were examined in terms of ultrasonic pulse velocity (UPV) and modulus of elasticity (MoE) properties while the mechanical properties were examined in terms of uniaxial compressive strength (UCS). The methods and sample preparation used for the analyses were explained in the following subheadings.

3.3.1 Ultrasonic Pulse Velocity and Modulus of Elasticity

The ultrasonic pulse velocity measurements were conducted on brick units with original sizes in direct and indirect modes. A pulse generating equipment, PUNDIT*plus*, with its probes, transmitter and receiver of 220 kHz probes was used for all samples. The time required the ultrasonic waves to traverse (pass through) the minimum cross section of the test specimen was measured. The data is written in seconds in calculations which is measured in microseconds by ultrasonic velocity test equipment (1 microsecond=1x10^{-6} second). The velocity of the waves is calculated by **Equation 3.19** (ASTM D 2845-08: 2017, RILEM, 1980);

$$V = \frac{d}{t}, m/s \quad \textbf{(3.19)}$$

where,
V: Velocity (m/s)
d: Distance traversed by the wave (m)
t: Travel time (s)

In direct transmission (UPV_{DIRECT}), the transmitter and receiver are placed in opposing sides. This arrangement is the most satisfactory method since the longitudinal pulse leaving the transmitter are mainly generated in the direction normal to the transducer face (Christaras, 2003). The indirect method ($UPV_{INDIRECT}$) is easily applicable for in-situ studies due to the arrangement of the transducers on the same surface. In this study, it is possible to conduct both methods on samples and establish a correction factor between direct and indirect methods ($UPV_{INDIRECT}/UPV_{DIRECT}$).

The aim of ultrasonic method is to measure the velocity of ultrasonic waves that pass through the sample in order to calculate the modulus of elasticity. The modulus of elasticity of samples is calculated by using their direct ultrasonic velocity and bulk density values in a proper equation. This experiment gives an idea about decay of materials by comparing them with standard values (Kahraman *et al*., 2008; Christaras, 2003; Topal and Doyuran, 1995; RILEM, 1980).

The modulus of elasticity (E_{mod}) is defined as the ratio of stress to strain and shows deformation ability of a material under external forces (Timoshenko, 1970). The modulus of elasticity is then obtained by **Equation 3.20**: (ASTM D 2845-08: 2017, RILEM, 1980)

$$E_{mod} = D.V^2.\frac{(1+V_{dyn})(1-2V_{dyn})}{V_{dyn}}, MPa \qquad \textbf{(3.20)}$$

where,
E_{mod}: Modulus of elasticity (MPa)
D: Bulk density of specimen (kg/m^3)
V: Wave velocity (m/s)
V_{dyn} : Poisson’s ratio

In this equation, Poission's ratio refers to the ratio of lateral expansion to the longitudinal reduction of the material under compression. Poission's ratio varies from 0.1 to 0.5. In this study, it was taken as 0.18 as a value considering the similarities between other case studies (Tunçoku, 2001; Topal, 1995; Timoshenko, 1970).

3.3.2 Uniaxial Compressive Strength

The uniaxial strength (UCS) are determined by measuring point load strength of the samples. Point load tests were conducted on 5x5x5 cm cubic forms of brick samples by using an ELE-point load test apparatus in order to determine point load index (I_s) using appropriate equations as indirect measurement by the **Equation 3.21** (Winkler, 1986; ISRM, 1985):

$$I_s = P/De^2 \qquad \textbf{(3.21)}$$

where,
P: Applied force (kN)
De: Equivalent core diameter (mm)

Equivalent core diameter (De) is given by the **Equation 3.22**, which is suggested for blocks and lumps:

$$De = \sqrt{\frac{4A}{\pi}} \qquad \textbf{(3.22)}$$

where, A is the minimum cross sectional area of the test specimen found by multiplying the width of the test specimen with its thickness.

The size-corrected point load strength, $I_{S(50)}$ is calculated by using uncorrected point load strength index, I_s, using equivalent core diameter method with the **Equation 3.23**:

$$I_{s(50)} = FxI_S \qquad \textbf{(3.23)}$$

where F, the size correction factor which is obtained from De, equivalent core diameter, by the **Equation 3.24**:

$$F = \sqrt[0.45]{\frac{De}{50}} \quad \textbf{(3.24)}$$

For the calculation of uniaxial compressive strength which is expressed in MPa, from $I_{S(50)}$, following the **Equation 3.25** is used based on a study on a weak tuffs (Topal, 1999).

$$UCS = 10.6471x\ I_{S(50)} + 2.4736, \text{MPa} \quad \textbf{(3.25)}$$

3.4 Raw Materials and Microstructural Analyses

The raw material and microstructural characteristics of brick samples were examined in terms of X-Ray Diffraction (XRD) analyses including the determination of type of clay and mineral content, pozzolanic activity analyses and imge analyses of cross-sectios.

3.4.1 XRD Analyses

Mineralogical content of brick samples were studied to define their clay types and other minerals by XRD analyses. The equipment used is Bruker's X-Ray Diffraction D8-Discover instrument connected to a computer used control the set-up and for data storage (**Figure 3.7**). Analyses were done using CuKα radiation, adjusted to 40 kV and 40 mA. The XRD traces were recorded in the 5° - 70° 2θ range.

The analyses were performed on brick powders less than 125μm sizes obtained by using sieves. The powder samples were pressed into a sample holder to achieve a smooth flat surface. All the samples were analysed in theses circumstances. The ideal sample is homogeneous and the crystallites are randomly distributed. The range (the interval of scan angle) and step (the rate of scan in degree per minute) were defined for the experiments particularly. The result is a set of raw data exhibiting the interplanar spaces, relative intensity and location of peaks at predefined range, which is called diffraction pattern. The main aim for investigating XRD patterns is to find out the main minerals inside the raw materials and the ranges of firing temperatures of each brick that has an impact on the mineralogical changes.

Figure 3.7. The Bruker X-Ray Diffraction D8-Discover Instrument

3.4.2 Pozzolanic Activity

Pozzolanic activity is the ability of a material, which reacts with lime in the presence of water and form water-insoluble compounds having binding properties of mortar and plasters. Thus, a material having higher pozzolanicity is expected to produce more water insoluble compounds such as various calcium silicate hydrates (CSH), which contribute to the strength of final product (Tunçoku, 2001; Davey, 1961).

In this study, two frequently used methods to measure pozzolanic activity were used; which are the measurement of the change in electrical conductivity (1), and direct method of chemical titration with Ethylenediamine tetra acetic acid (EDTA) (2).

For the first test, 5 g of brick powders smaller than 125 μm in size were mixed with 200 ml saturated $Ca(OH)_2$ solution and covered tightly. A container having saturated

$Ca(OH)_2$ solution without any brick powder was used as standard blank sample. The aqueous solutions of each samples were kept for 2 minutes with a magnetic mixer inside. The decrease in electrical conductivity (ΔEC in mS/cm) was recorded for the evaluation of pozzolanic activity by using Metrohm AG Herisau, Konduktometer E382 (TS EN 196, 2012; Luxan, *et al*., 1989). This method permits the classification of materials with respect to their pozzolanic properties that means, ΔEC values less than 0.4 mS/cm refer to non pozzolanic, ΔEC values between 0.4 and 1.2 mS/cm refer to variable pozzolanic, ΔEC values greater than 1.2 mS/cm refer to good pozzolanicity (Luxan *et al*., 1989).

For the second test, 0.2 g brick powders smaller than 125 μm in size were separated by means of a standard sieve and put into containers having 30 ml of $Ca(OH)_2$ saturated aqueous solution and covered tightly. A container having saturated $Ca(OH)_2$ solution without any brick powder was used as standard blank sample. After 14 days pozzolanic active particles were allowed to react with Ca^{2+} ions, the titration mechanism was set up to find the rest of Ca^{2+} ions consumed by EDTA. 10 ml of each solution was titrated with 0.01 M EDTA standard solution using an indicator (calgon). 1 ml of 10% NaOH solution was added to provide alkalinity (Black, 1965). Reaction mixture appeared as pink color. When EDTA consumed all the Ca^{2+} ions, the colour of the mixture turned into blue (**Figure 3.8**). The differences in concentration of Ca^{2+} ions between the sample solutions and blank solution can be obtained from the results of titration. The reactions taking place are as following the **Equation 3.26**:

$$Ca(OH)_2 + H_2SiO_4 \rightarrow Ca^{2+} + H_2SiO_4^{-2} + 2H_2O \rightarrow CaH_2SiO_4.2H_2O \qquad (\mathbf{3.26})$$

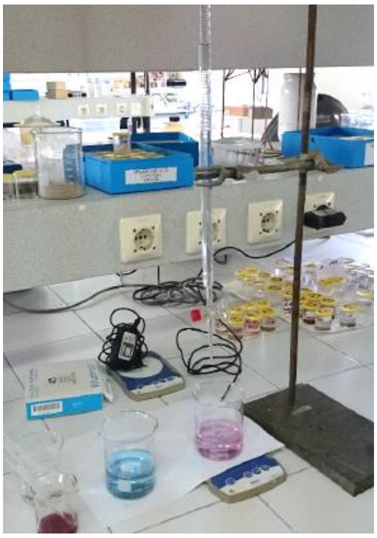


Figure 3.8. Showing the reaction of Ca^{+2} ions and EDTA turning the solution color from pink to blue.

3.4.3 Image Analyses of Cross Sections

Image analyses of cross sections produced for each sample were done by using optical microscopy in order to better understand the macro pores sizes and the differences in the textures of brick samples. The image analyses are the supportive analyses to better-interpret the data on physical properties of brick samples with a focus of porosity characteristics.

For those purposes, cross section of each sample was prepared by cutting samples by Isomet 4000 Linear Precision Saw Model and the image analyses were done under stereo binocular microscope (Leica Stereo Optic Microscope) by using 7x, 30x and 100x magnification lenses. Pouring resin was not necessary for brick samples because the samples were cut precisely that can be seen under the microscope.

3.5 Qualitative and Quantitative Analyses of Soluble Salts

The type of salts were analyzed on all the brick samples by spot tests to detect the anions of soluble salts in the scope of qualitative analyses. The most common soluble salts, which are sulphates (SO_4^-), chlorides (Cl^-), nitrates (NO_3^-), nitrites (NO_2^-), phosphates (PO_4^{-2}) and carbonates (CO_3^{2-}), were tested according to test procedure manual for each salt types (Teutonico, 1988).

The amount of salts were analyzed on all brick samples, as percent by weight, by the measurement of electrical conductivity. 1 g of each brick powder were mixed with 50 ml water in the centrifuge and the mixture were left for settlement of suspended particles. The conductivity measurements were done using a conductometer of Metrohm AG Herisau, Kondoktometer E382. The percentage of salt in the sample is calculated by the **Equation 3.27** and the **Equation 3.28**: (Black, 1965)

$$EC = [\frac{0.001411 x R_{std}}{R_{ext}})], \text{mmho.cm}^{-1} \quad \textbf{(3.27)}$$

where,

EC: Electrical conductivity, (mmho cm^{-1})

R_{std}: The cell resistance with standard solution (0.01 N KCl)

R_{ext}: The cell resistance with extract solution

$$Salt\ in\ sample = \left[\frac{A x V_{ext}}{1000}\right] x [\frac{100}{W_s}], \% \quad \textbf{(3.26)}$$

where,

A: Salt concentration (mg/l) = 640 x EC (mmho cm^{-1})

V_{ext}: Volume of the extract solution (ml)

W_s: Weight of the sample (mg)

CHAPTER 4

RESULTS

The results of the analyses on physical, physicomechanical, mechanical and raw materials characteristics of contemporary solid fired brick samples are given in the following sections. The presence of salts and their content in the samples were also examined and the relevant results are summarized under the relevant subheading as well.

4.1 Physical Properties of Contemporary Fired Bricks: Handmade and Factory Solid Bricks

The results of laboratory analyses on bulk density (ρ), effective porosity (φ), fine pore porosity ($\varphi_{0.5\mu}$), ratio of fine pore porosity to total open porosity ($R_{0.5\mu}$), water absorption capacity (θ), saturation coefficient (S), water vapour diffusion resistance index (μ), evaporation rate (R_E), critical moisture content (θ_C), specific heat (c) and colour identification are given in this section under respective subheadings.

4.1.1 Porosity Characteristics

Here, the data on bulk density, effective porosity, fine pore porosity, ratio of fine pore porosity to total open porosity, water absorption capacity, saturation coefficient characteristics of handmade fired bricks and factory solid bricks are given (**Table 4.1**).

Table 4.1. Physical properties; bulk density (ρ), effective porosity (φ), water absorption capacity (θ), fine pore porosity ($\varphi_{0.5\mu}$), ratio of fine pore porosity to total open porosity ($R_{0.5\mu}$) saturation coefficient (*S-value*) of brick samples obtained from laboratory analyses.

Samples	ρ	φ	θ	***S-value***	$\varphi_{0.5\mu}$	$R_{0.5\mu}$
	g/cm^3	% by volume	% by weight	unitless	% by volume	%
C.V.p.HB1	1.72±0.04	32.1±0.7	18.7±0.2	0.97±0.01	0.97±0.34	3.02±1.04
C.V.b.HB2	1.68±0.05	33.4±0.7	19.9±0.4	0.95±0.01	0.29±0.33	0.85±0.95
C.V.p.HB3	1.70±0.04	34.0±1.6	20.0±0.6	0.88±0.01	0.32±0.27	0.98±0.83
C.U.lb.HB4	1.72±0.05	32.4±0.7	18.8±0.2	0.97±0.01	1.04±0.27	3.21±0.85
E.A.r.HB5	1.72±0.04	33.9±1.9	19.7±0.8	0.87±0.03	0.15±0.07	0.43±0.20
E.A.db.HB6	1.83±0.05	31.7±0.7	17.3±0.3	0.87±0.02	2.12±0.77	6.71±2.50
I.A.r.HB7	1.62±0.07	36.2±1.3	22.3±0.9	0.88±0.02	0.41±0.17	1.15±0.52
I.A.p.HB8	1.65±0.07	34.4±1.7	20.9±0.5	0.90±0.01	0.23±0.04	0.68±0.14
M.S.lb.HB9	1.69±0.06	35.71.3	21.1±0.2	0.81±0.01	0.14±0.06	0.38±0.18
M.S.p.HB10	1.65±0.05	36.9±1.5	22.4±0.6	0.86±0.01	0.48±0.13	1.30±0.30
I.D.db.FB1	1.84±0.01	29.3±0.3	15.9±0.2	0.81±0.01	0.07±0.01	0.23±0.04
I.D.r.FB2	2.16±0.01	12.1±0.2	5.6±0.1	1.00	0.07±0.01	0.57±0.08
B.I.r.FB3	2.15±0.01	15.3±0.4	7.1±0.2	0.99	0.07±0.02	0.46±0.11
B.I.gb.FB4	2.26±0.01	10.2±0.2	4.5±0.1	1.03±0.02	0.05	0.49±0.01

In terms of their basic physical properties, the handmade and pressed factory solid bricks are considerably different from each other (**Table 4.1** and **Figure 4.1**):

– For handmade fired brick samples, their bulk density, effective porosity and water absorption capacity properties were determined to be in the range of 1.62±0.07 and 1.83±0.05 g/cm^3, 31.7±0.7 and 36.9±1.3% by volume, 17.3±0.3 and 22.4±0.4% by weight, respectively. The average values achieved for those properties (ρ, φ, θ) were found to be 1.70±0.06 g/cm^3, 34.1±1.8% by volume, 20.1±1.6% by weight, respectively.

– For factory solid brick samples (pressed ones), their bulk density, effective porosity and water absorption capacity properties were determined to be in the range of 2.15±0.01 and 2.26±0.01 g/cm^3, 10.2±0.2 and 15.3±0.4% by volume, 4.5±0.1 and 7.1±0.2% by weight, respectively. The average values of those properties (ρ, φ, θ) were found to be 2.19±0.06 g/cm^3, 12.5±2.6% by volume, 5.7±1.3% by weight, respectively.

– For the other type of factory solid brick but not pressed one (I.D.db.FB1), its bulk density, effective porosity and water absorption capacity properties were determined to be 1.84±0.01 g/cm^3, 29.3±0.3% by volume and 15.9±0.2% by weight, respectively.

In brief, the handmade bricks are noticeably lighter and almost three times more porous than factory solid bricks. Although being factory brick, the one which is not pressed (I.D.db.FB1) differs from the pressed factory bricks has physical properties close to the handmade bricks. Among handmade brick samples, the highest bulk density and lowest porosity characteristics belongs to E.A.db.HB6 while the lowest bulk density and highest porosity belongs to the samples I.A.r.HB7 and M.S.p.HB10. Among pressed factory brick samples, the highest bulk density and lowest porosity characteristics belongs to the sample B.I.gb.FB4.

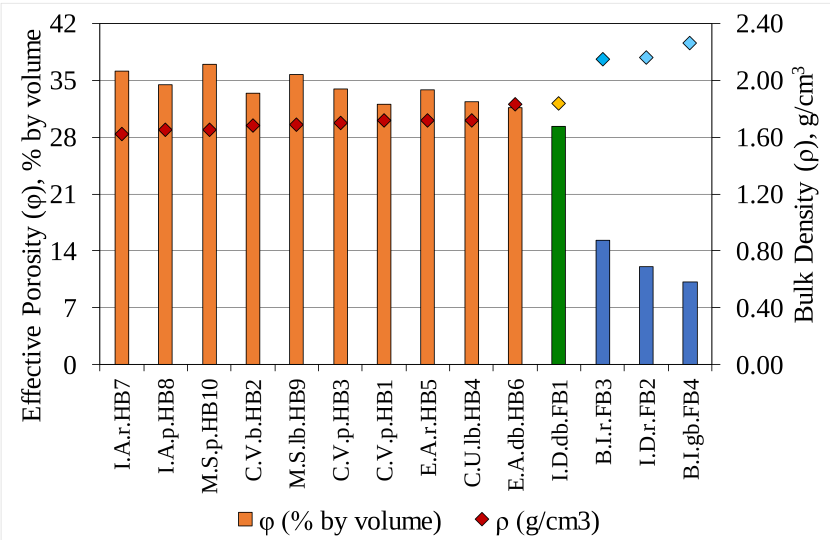


Figure 4.1. Bulk density (ρ) and porosity (φ) characteristics of handmade and factory bricks showing that pressed factory bricks are considerably denser and less porous than handmade bricks. While not-pressed factory brick has similar bulk density and porosity with the handmade bricks.

The porosity characteristics of brick samples in terms of fine pore porosity, ratio of fine pore porosity to total porosity, saturation coefficients are summarized below:

– For handmade fired brick samples, their fine pore porosity were determined to be in the range of 0.14±0.03 and 2.12±0.77% by volume with an average of 0.62±0.62%. This result means that the fine pore ratio (percentage of fine pores -below 0.5 micronsto the total porosity) falls into the range of 0.4±0.2 and 6.7±2.5%, in another words, the fine pores are 1.9±2.0% of the total porosity in average.

– Among the handmade brick samples, the sample E.A.db.HB6 has the highest fine pore ratio of 7% followed by the others C.V.p.HB1 and C.U.lb.HB4 with 3% fine pore ratio. Most have fine pore ratio of 1%.

– The pressed factory solid bricks presented the lowest fine pore porosity and the lowest total porosity.

– For factory solid brick samples (pressed ones), their fine pore porosity were determined to be in the range of 0.05 and 0.07±0.02% by volume with an average of 0.06±0.01% by volume. This result means that the percentage of fine pores (below 0.5μm) to the total porosity falls into the range of 0.46±0.06 and 0.57±0.07% with an average of 0.51±0.06% of the total porosity.

– For the other type of factory solid brick but not pressed one (I.D.db.FB1), its fine pore porosity was determined to be 0.07±0.01% by volume that means the percentage of fine pores (below 0.5microns falls) to the total porosity falls in 0.23±0.04% of the total porosity.

– The ratio of water absorption capacity to total porosity of all the samples which is saturation coefficient were found to be above 0.80 for all brick samples that the durability properties of these brick samples may be weak (BRE, 1997; RILEM,1980; Hirschwald, 1908).

4.1.2 Breathing Characteristics

The data on water vapour permeability characteristics of brick are summarized in **Table 4.2**. Both handmade fired and factory solid bricks were found to be in high and middle vapour permeable classes, which is classified by their *SD* values which is shown in **Figure 4.2** (TS EN ISO 7783: 2012). The results have shown that:

– Water vapour diffusion resistance index (μ) values of handmade fired bricks were found to be varying in a range of 3.76 and 8.64 with an average of 6.07±1.57. Equivalent air layer thickness of water vapour diffusion (*SD*) values of handmade fired bricks were determined to be high permeable between 0.08 and 0.19 m with an average of 0.13±0.03 m. Permeability (SD^{-1}) values of handmade bricks were determined to be between 5.40 and 12.90 m^{-1} with an average of 8.24±2.34 m^{-1}. Their water vapour transmission rate (*RT*) values were found to be between 5.61 and 11.80 g/hm^2 with an average of 8.07±1.94 g/hm^2.

– Water vapour diffusion resistance index (μ) values of factory solid bricks (pressed ones) were found to be varying in a range of 23.70 and 41.89 with an average of 31.68±9.29. Equivalent air layer thickness of water vapour diffusion (*SD*) values of factory bricks were determined to be middle permeable between 0.52 and 0.92 m with an average of 0.69±0.21 m. Permeability (SD^{-1}) values of factory solid bricks were determined to be between 1.09 and 1.94 m^{-1} with an average of 1.53±0.42 m^{-1}. Their water vapour transmission rate (*RT*) values were found to be between 1.23 and 2.15 g/hm^2 with an average of 1.71±0.46 g/hm^2.

– The μ, *SD*, SD^{-1}, *RT* values of not-pressed solid factory brick were determined to be 11.03, 0.24 m, 4.25 m^{-1}, 4.50 g/hm^2, respectively.

– Water vapour permeability properties of not-pressed solid factory brick were detected to have approximately two times more resistant than handmade fired bricks in terms of passing water vapour through the layers. Factory bricks were evidently determined to have different water vapour permeability properties compared to those handmade bricks that their permeability properties were found to be closer to cement-based mortars in terms of their water vapour resistance factor values which seemed to have higher resistance to water vapour permeation (Pfeifer *et al*., 2001; Williams and Williams, 1994).

Table 4.2. Showing water vapour permeability values of the samples

Sample Name	μ	SD	SD^{-1}	RT
	(unitless)	(m)	(m^{-1})	(g/hm^2)
C.V.p.HB1	6.27	0.13	7.41	7.42
C.V.b.HB2	6.54	0.14	7.07	7.13
C.V.p.HB3	5.56	0.12	8.42	8.30
C.U.lb.HB4	8.64	0.19	5.40	5.61
E.A.r.HB5	4.26	0.09	11.28	10.59
E.A.db.HB6	3.76	0.08	12.90	11.80
I.A.r.HB7	5.94	0.13	7.76	7.73
I.A.p.HB8	8.50	0.18	5.45	5.65
M.S.lb.HB9	5.84	0.13	7.98	7.92
M.S.p.HB10	5.42	0.11	8.70	8.53
I.D.db.FB1	11.03	0.24	4.25	4.50
I.D.r.FB2	29.45	0.64	1.57	1.75
B.I.r.FB3	23.70	0.52	1.94	2.15
B.I.gb.FB4	41.89	0.92	1.09	1.23

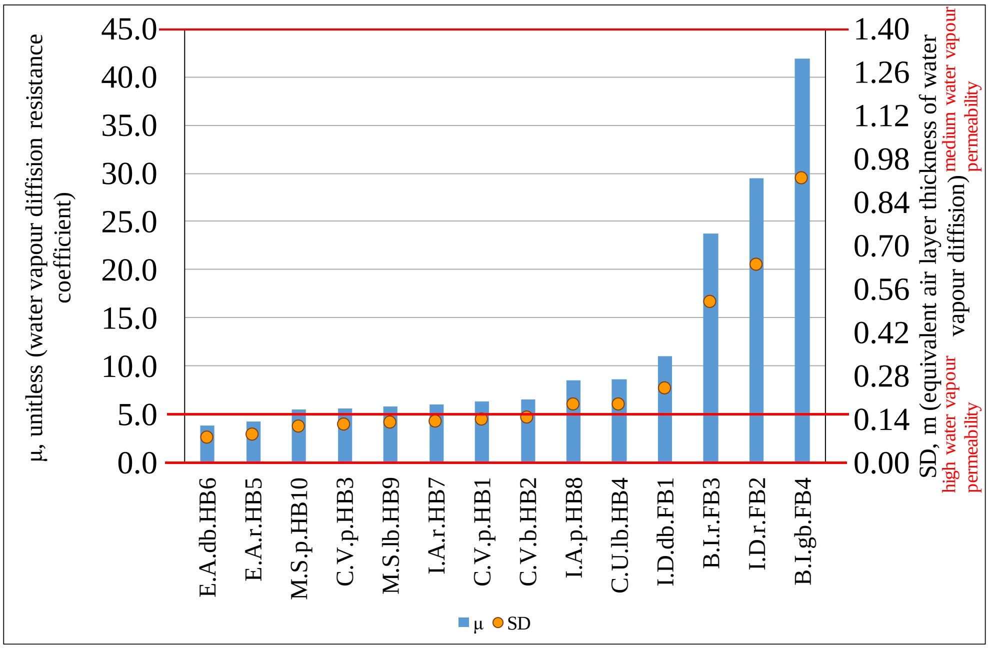


Figure 4.2. Showing water vapour permeability characteristics of contemporary solid brick samples by μ and SD values together with high and medium water vapour permeability boundaries.

4.1.3 Drying Characteristics

The drying curves of handmade and factory solid brick samples, showing moisture content as a function of time and weight loss as a function of time, are given in **Figure 4.3** and **Figure 4.4**, respectively. The drying rate curve for each sample, showing the evaporation rate as a function of moisture content, is given in **Figure 4.5** and **Figure 4.6**. The data on the bulk density, porosity, maximum evaporation rate, critical moisture content, the ratio of critical moisture content to porosity and time critical are given in **Table 4.3**. The results have shown that:

– The critical moisture content (θ_C) of handmade brick samples were found to be in the range of 7.1 and 11.9 % with an average of 8.8±1.5 % by volume. Time critical (t_C) values of handmade brick samples were found to vary between 12 and 24 h. The θ_C values of pressed factory solid brick samples were found to be in the range of 3.2 and 3.8 % with an average of 3.5±0.3 % by volume. The t_C values of these factory brick samples were found to vary between 4 and 9 h. The θ_C and t_C values of not-pressed factory brick sample (I.D.db.FB1) was found to be 9.2% by volume and 12 h, respectively.

– Those values mean that:

- for handmade brick samples when 25.8±4.1% of their total porosity fill with water,
- for pressed factory brick samples when 28.6±3.5% of their total porosity fill with water,
- for not-pressed factory brick sample (I.D.db.FB1) when 31.3% of its total porosity fills with water, those bricks will suffer more under weathering conditions.

– The fastest evaporation rate (R_{E1}) of the saturated handmade brick samples under 25°C and 35%RH were found to vary in the range of 0.146 and 0.168 kg/m^{2}h with an average value of 0.157±0.006 kg/m^{2}h. The evaporation rate of the handmade brick samples below critical moisture content (R_{E2}) were found to be in a range of 0.011 and 0.028 kg/m^{2}h with an average of 0.017±0.005 kg/m^{2}h. The R_{E1} values of pressed factory solid brick samples were found to be in the range of 0.143 and 0.161 kg/m^{2}h with an average of 0.152±0.002 kg/m^{2}h. The R_{E2} values of these factory brick samples were determined to be in the range of 0.005 and 0.007 kg/m^{2}h with an average of 0.006±0.001 kg/m^{2}h. The R_{E1} and R_{E2} values of not-pressed factory brick sample (I.D.db.FB1) was found to be 0.150 kg/m^{2}h and 0.014 kg/m^{2}h, respectively.

– Below critical moisture content, handmade bricks dry out faster than pressed factory bricks while not-pressed factory brick has similar drying behaviour with the handmade bricks.

Table 4.3. The results showing the bulk density (ρ), porosity (φ) , evaporation rates of first and second phases,(R_{E1} and R_{E2}), the critical moisture content (θ_C), the ratio of critical moisture content to porosity (θ_C/φ) and critical drying period (t_C)

Samples	Bulk Density, ρ	Porosity, φ	Evaporation Rate, R_{E1}	Evaporation Rate, R_{E2}	Critical Moisture Content, θ_C	θ_C / φ	Time-critical, t_C
	g/cm^3	% by vol.	kg/m^{2}h	kg/m^{2}h	% by vol.	%	h
C.V.p.HB1	1.72	32.1	0.1588	0.0157	8.6	26.7	18
C.V.b.HB2	1.68	33.4	0.1679	0.0159	7.1	21.2	18
C.V.p.HB3	1.70	34.0	0.1510	0.0131	8.0	23.4	18
C.U.lb.HB4	1.72	32.4	0.1561	0.0113	8.1	25.0	18
E.A.r.HB5	1.72	33.9	0.1599	0.0174	7.9	23.4	18
E.A.db.HB6	1.83	31.7	0.1587	0.0132	8.5	26.9	12
I.A.r.HB7	1.62	36.2	0.1461	0.0199	11.0	30.5	18
I.A.p.HB8	1.65	34.4	0.1582	0.0280	11.9	34.6	18
M.S.lb.HB9	1.69	35.7	0.1549	0.0210	8.6	24.2	24
M.S.p.HB10	1.65	36.9	0.1534	0.0190	8.1	21.9	24
I.D.db.FB1	1.84	29.3	0.1502	0.0135	9.2	31.3	12
I.D.r.FB2	2.16	12.1	0.1522	0.0055	3.7	30.3	6
B.I.r.FB3	2.15	15.3	0.1612	0.0065	3.8	24.6	9
B.I.gb.FB4	2.26	10.2	0.1429	0.0049	3.2	31.0	4

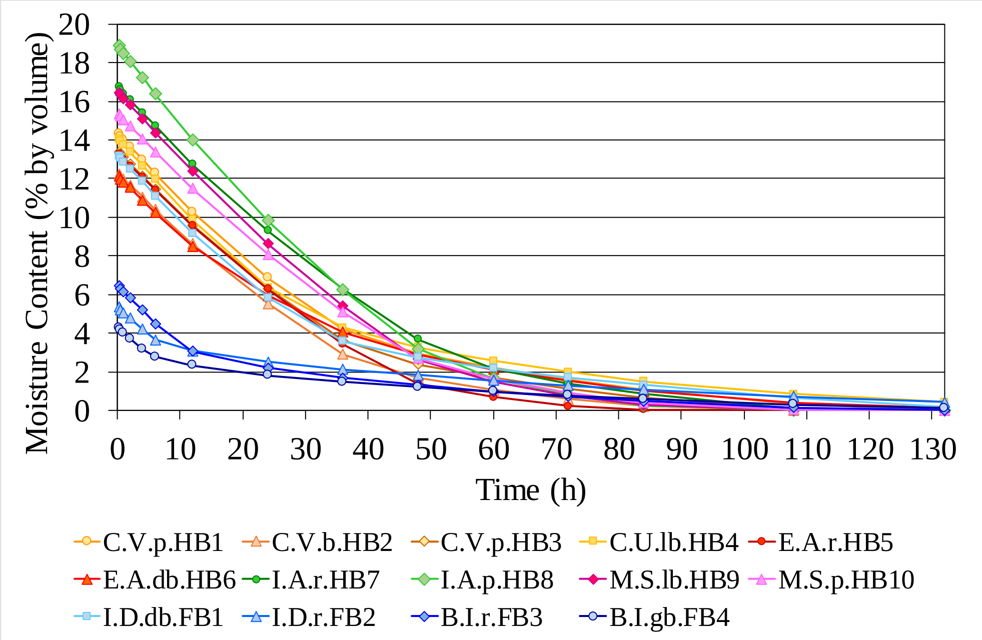


Figure 4.3. The drying curves of handmade fired and factory solid bricks showing moisture content (% by volume) versus time (h).

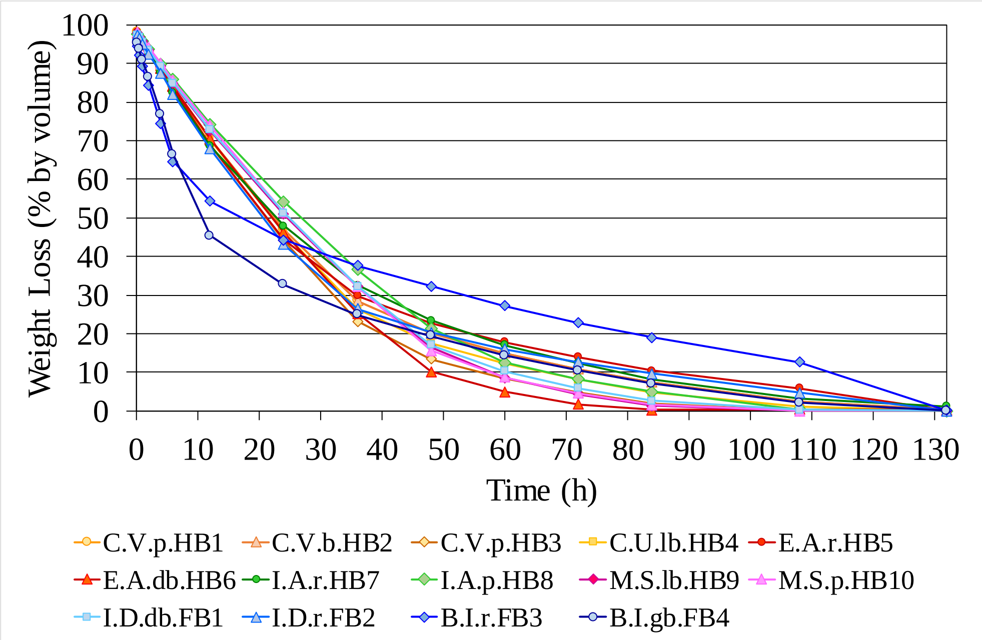


Figure 4.4. The drying curves of handmade fired and factory solid bricks showing percentage of the weight loss versus time (t).

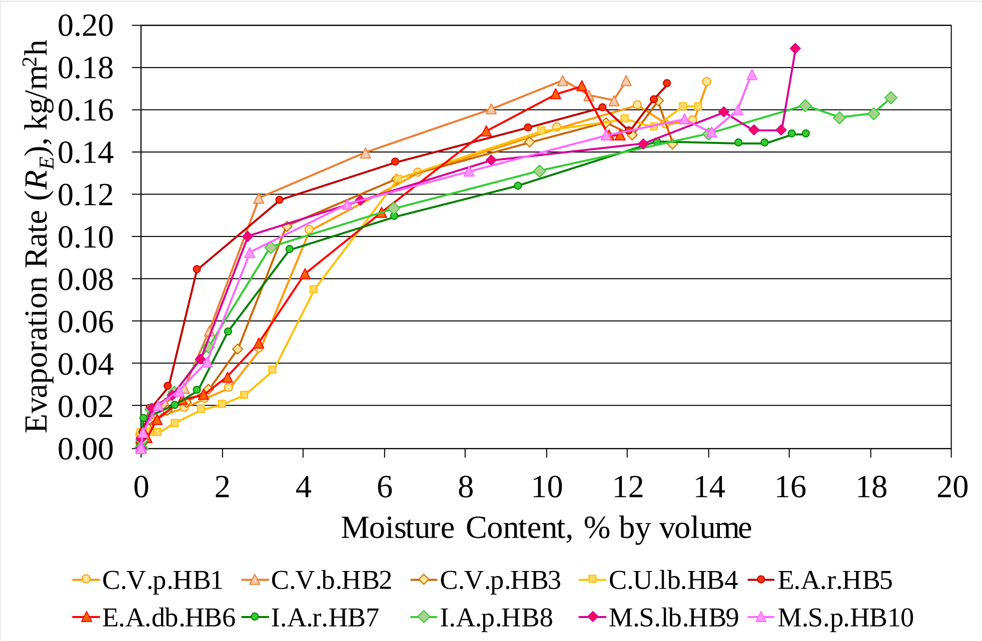


Figure 4.5. The drying rate curves of handmade fired bricks showing evaporation rate (kg/m^{2}h) versus moisture content (% by volume).

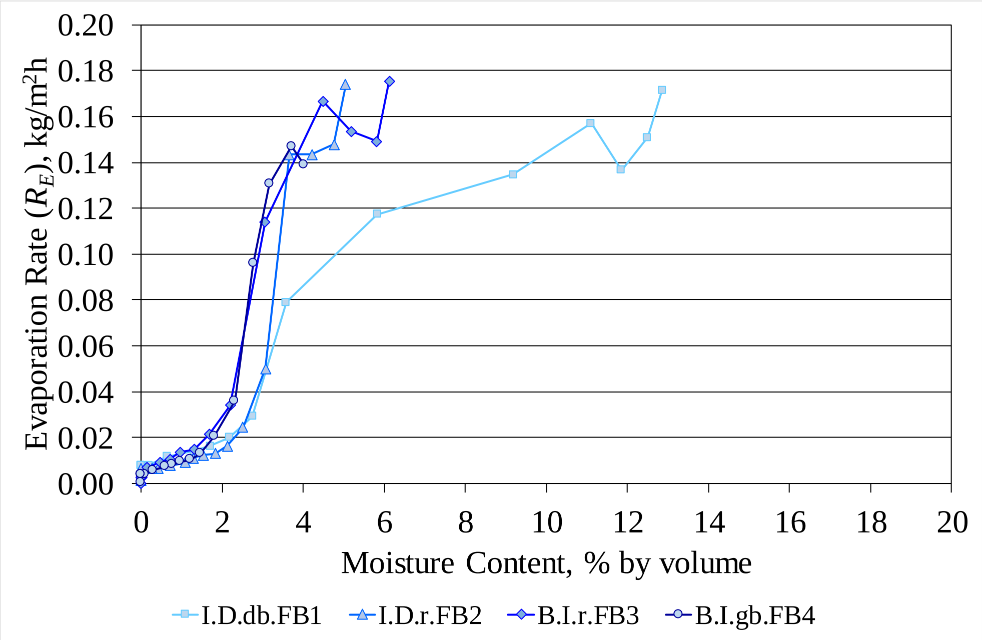


Figure 4.6. The drying rate curves of factory solid bricks showing evaporation rate (kg/m^{2}h) versus moisture content (% by volume).

4.1.4 Specific Heat Properties

The results of the specific heat capacity properties of brick samples are shown in **Figure 4.7**. The average specific heat capacity values of handmade fired bricks and factory solid bricks were found to be 743 J/kgK and 676 J/kg.K, respectively. Specific heat capacity (c) values of handmade fired brick samples were determined to be between 618 and 823 J/kg.K, while these values of factory solid brick samples were determined to be between 613 and 727 J/kg.K. The results showed that specific heat capacity of handmade bricks are higher than that of factory bricks. In other words, these results showed the amount of heat a material can absorb per unit weight that handmade bricks can absorb more heat contributing to the thermal characterisitics of buildings. Furthermore, the specific heat values of historical bricks used in Anatolia belonging to Principalities and Ottoman Periods (14^{th} -16^{th} century) are in the range of 879 – 1038 J/kgK as mentioned in **Figure 4.7**. The specific heat capacity values of all contemporary solid bricks are lower than the reference range of historical bricks (Çiçek, 2009; Tavukçuoğlu, Çiçek, Grinzato, 2008).

Thermal properties of contemporary handmade and factory solid bricks and the historic bricks were compiled in terms of bulk density, specific heat capacity, thermal conductivity, thermal effusivity and thermal diffusivity properties in **Table 4.4**. Bulk density and specific heat capacity properties of contemporary solid bricks were determined in the study. These properties and thermal conductivity properties given in literature were used to estimate thermal effusivity and diffusivity properties of contemporary bricks (TS 825, 1998). Bulk density, specific heat capacity and thermal conductivity properties of historic bricks mentioned in literature were given in **Table 4.4** and these properties were used to estimate thermal effusivity and diffusivity properties of historic bricks (Çiçek, 2009; Tavukçuoğlu et al., 2008). The results show that thermal effusivity of factory brick is the highest (1335 $Ws^{1/2}/m^2K$), while thermal inertia (effusivity) of handmade brick (1040 $Ws^{1/2}/m^2K$) is slightly higher than historical ones (872 $Ws^{1/2}/m^2K$). Thermal diffusivity of factory brick is the highest ($8.1x10^{-7}$ m^2/s), while thermal diffusivity of handmade brick ($6.1x10^{-7}$ m^2/s) is noticeably higher than historic bricks ($4.1x10^{-7}$ m^2/s). Therefore, handmade brick differs from historical ones in terms of thermal properties and thermal behavior of factory brick is completely different compared to historic materials.

Table 4.4. Thermal properties of contemporary handmade and factory solid bricks; bulk density (ρ) and specific heat (c) obtained from laboratory analyses, thermal conductivity (k) obtained from literature, thermal effusivity (e) and thermal diffusivity (α) obtained by calculation and thermal properties of historic bricks

Material type	*ρ* (kg/m^3)	*k* (W/mK)	*c* (J/kgK)	*e* (Ws$^{1/2}$/m^{2}K)	*a* (m^2/s)
Handmade Solid Brick	1800	0.81	743	1040	6.1 10^{-7}
Factory Solid Brick	2200	1.20	676	1335	8.1 10^{-7}
Historic Bricks	1450	0.56	936	872	4.1 10^{-7}

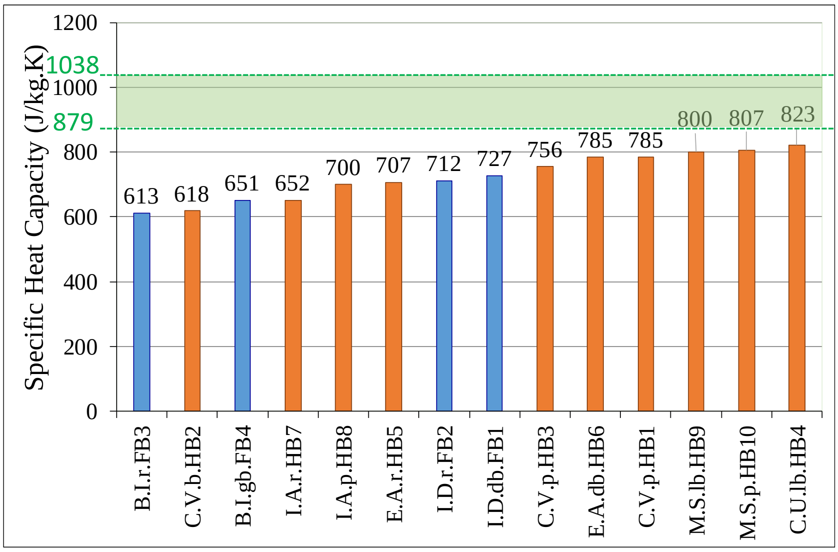


Figure 4.7. Showing specific heat capacity values of handmade (orange color) and solid factory bricks (blue color)

4.1.5 Colour Identification

The colours of bricks samples were determined using Munsell colour charts in **Table 4.5**. The total description (color-code) of the colours were given by hue, value and chroma of each samples and as well as their photographs taken from charts. The results show that hue of all samples is changing from 2.5YR, 5YR and 10R that indicates the reddish colors. Value of handmade bricks and factory bricks is 5.5 and 4.25 on average that means factory bricks are generally darker than handmade bricks. Chroma of all bricks is variably changing from 2 to 8 which shows the strength of the color.

The colors of bricks depends on the amount of minerals inside the raw materials, and the atmospheric conditions of the kiln. The presence iron (Fe) mineral, in the form of hematite (ferric iron oxide) in clay cause to produce reddish or brown tones of brick in oxidizing (oxygen-rich) atmosphere. The hematite in the raw material is inherited from sediment (naturally occurred) or formed during firing (Pavía, 2006; Maggetti, 1982). The presence of calcium (Ca) mineral in clay causes to produce iron oxides that leads to red colour in oxidizing conditions and brown colour in reducing conditions (removal of oxygen and other oxidizing gazes caused by fuel additions) (Pavía, 2006; Maniatis *et al*., 1983).

Table 4.5. Showing hue, value and chroma values of handmade and factory bricks determined from Munsell Soil Color Chart, respectively.

Samples	Hue	Value	Chroma	Color-Code	Color Images
C.V.p.HB1	10R	6	6	10R/6/6	
C.V.b.HB2	2.5YR	5	4	2.5YR/5/4	
C.V.p.HB3	2.5YR	6	6	2.5YR/6/6	
C.U.lb.HB4	5YR	6	6	5YR/6/6	
E.A.r.HB5	2.5YR	5	6	2.5YR/5/6	
E.A.db.HB6	2.5YR	4	4	2.5YR/4/4	
I.A.r.HB7	10R	5	6	10R/5/6	
I.A.p.HB8	2.5YR	6	6	2.5YR/6/6	
M.S.lb.HB9	5YR	6	6	5YR/6/6	
M.S.p.HB10	2.5YR	6	6	2.5YR/6/6	
I.D.db.FB1	2.5YR	3	6	2.5YR/3/6	
I.D.r.FB2	10R	5	6	10R/5/6	
B.I.r.FB3	10R	5	8	10R/5/8	
B.I.gb.FB4	2.5YR	4	2	2.5YR/4/2	

4.2 Basic Physicomechanical and Mechanical Properties

Ultrasonic pulse velocity, modulus of elasticity and uniaxial compressive strength values were determined for all samples considering physicomechanical and mechanical properties.

4.2.1 Ultrasonic Pulse Velocity and Modulus of Elasticity

Physicomechanical properties of brick samples are summarized in **Table 4.6**. Ultrasonic pulse velocity (UPV_{DIRECT}) values, which were taken from opposing sides of samples, were shown in this table with modulus of elasticity (E_{mod}) values calculated indirectly by bulk density and UPV_{DIRECT} values of samples (ASTM C 597, 1999). Moreover, indirect meausurements of ultrasonic pulse velocity, which were taken by transducers on the same surface, were conducted on samples to determine a correction factor between direct and indirect methods ($UPV_{INDIRECT}/UPV_{DIRECT}$) in **Table 4.7**.

The UPV_{DIRECT} values of handmade fired bricks with an average bulk density value of 1.70±0.06 g/cm^3 were found to be varying in a range of 1204 and 2530 m/s with an average of 1791±463 m/s. Their E_{mod} values were found to be varying in a range of 2.26 and 9.93 GPa with an average of 5.31±2.67 GPa.

The UPV_{DIRECT} values of factory solid bricks with an average bulk density value of 2.19±0.06 g/cm^3 were found to be varying in a range of 3331 and 3808 m/s with an average of 3513±257 m/s. Their E_{mod} values were found to be varying in a range of 22.06 and 30.21 GPa with an average of 25.06±4.48 GPa. UPV_{DIRECT} and E_{mod} values of not-pressed solid factory brick with a 1.84±0.01 g/cm^3 bulk density value were determined to be 1848±216 m/s and 5.79±1.06 GPa, respectively. These results show that handmade fired and factory solid bricks have different physicomechanical properties from each other that means the resistance of factory bricks to change their shape under force is significantly higher that of handmade bricks which is up to 4 times.

Table 4.6. UPV_{DIRECT}, E_{mod} and bulk density (ρ) values were summarized for handmade fired and factory solid bricks ascending sorted by ρ values, respectively.

Samples	ρ	UPV_{DIRECT}	E_{mod}
	g/cm^3	m/s	GPa
C.V.p.HB1	1.72	2227±58	7.85±1.10
C.V.b.HB2	1.68	2530±66	9.93±1.37
C.V.p.HB3	1.70	2096±64	6.86±2.04
C.U.lb.HB4	1.72	2241±78	7.96±1.96
E.A.r.HB5	1.72	1406±57	3.13±0.64
E.A.db.HB6	1.83	1384±91	3.23±0.73
I.A.r.HB7	1.62	1768±186	4.68±0.82
I.A.p.HB8	1.65	1755±126	4.67±1.43
M.S.lb.HB9	1.69	1211±59	2.28±0.57
M.S.p.HB10	1.65	1292±111	2.53±0.61
I.D.db.FB1	1.84	1848±216	5.79±1.06
I.D.r.FB2	2.16	3331±126	22.06±3.71
B.I.r.FB3	2.15	3401±99	22.91±2.67
B.I.gb.FB4	2.26	3808±117	30.21±1.99

Table 4.7. UPV_{DIRECT}, $UPV_{INDIRECT}$ and $UPV_{INDIRECT/DIRECT}$ values of handmade fired and factory solid bricks were given ascending sorted by $UPV_{INDIRECT/DIRECT}$ values, respectively.

Samples	UPV_{DIRECT}	$UPV_{INDIRECT}$	$UPV_{INDIRECT}$ / UPV_{DIRECT}
C.V.p.HB1	2227±58	1456±85	1.06±0.05
C.V.b.HB2	2530±66	1502±168	1.09±0.04
C.V.p.HB3	2096±64	1334±42	1.17±0.10
C.U.lb.HB4	2241±78	1209±177	1.12±0.07
E.A.r.HB5	1406±57	1038±77	1.10±0.08
E.A.db.HB6	1384±91	1046±48	1.15±0.08
I.A.r.HB7	1768±186	1297±157	1.14±0.06
I.A.p.HB8	1755±126	1045±149	1.12±0.10
M.S.lb.HB9	1211±59	969±108	1.12±0.09
M.S.p.HB10	1292±111	1046±96	0.97±0.11
I.D.db.FB1	1848±216	1635±252	0.88±0.08
I.D.r.FB2	3331±126	2466±181	0.74±0.07
B.I.r.FB3	3401±99	2517±177	0.74±0.05
B.I.gb.FB4	3808±117	2780±227	0.73±0.02

The $UPV_{INDIRECT}$ values of handmade fired bricks with an average UPV_{DIRECT} value of 1791±463 m/s were found to be varying in a range of 969 and 1502 m/s with an average of 1194±193 m/s. Their $UPV_{INDIRECT/DIRECT}$ values were found to be varying in a range of 0.97 and 1.17 with an average of 1.10±0.06.

The $UPV_{INDIRECT}$ values of factory solid bricks with an average UPV_{DIRECT} value of 3513±257 m/s were found to be varying in a range of 2466 and 2780 m/s with an average of 2588±168 m/s. Their $UPV_{INDIRECT/DIRECT}$ values were found to be varying in a range of 0.73 and 0.74 with an average of 0.74±0.01. $UPV_{INDIRECT}$ and $UPV_{INDIRECT/DIRECT}$ values of not-pressed solid factory brick with a 1848±216 m/s UPV_{DIRECT} value were determined to be 1635±252 m/s and 0.88±0.08, respectively.

The results show that $UPV_{INDIRECT/DIRECT}$ values of handmade fired bricks were determined to be slightly higher than factory solid bricks while their UPV_{DIRECT} and $UPV_{INDIRECT}$ values are slightly lower. UPV values of handmade fired bricks proved that their physicomechanical properties were close to the values of historical bricks more than UPV values of factory bricks which are considered in compatibility criterion.

4.2.2 Uniaxial Compressive Strength

Mechanical properties of brick samples were determined by uniaxial compressive strength (UCS). UCS values of all samples carried out by point load measurements in dry state of samples were given in **Table 4.8**.

The UCS values of handmade fired bricks with an average porosity value of 34.1±1.8% by volume were found to be varying in a range of 8.88 and 29.62 MPa with an average of 17.88±7.71 MPa. Their $Is_{(50)}$ values were found to be varying in a range of 0.60 and 2.55 MPa with an average of 1.45±0.72 MPa.

The UCS values of factory solid bricks with an average porosity value of 12.52±2.57% by volume were found to be varying in a range of 61.70 and 85.94 MPa with an average of 71.97±12.54 MPa. Their $Is_{(50)}$ values were found to be varying in a range of 5.56 and 7.84 MPa with an average of 6.53±1.18 MPa. UCS and $Is_{(50)}$ values of not-pressed solid factory brick with a 29.28% by volume porosity value were determined to be 30.91 MPa and 2.67 MPa, respectively. The results show that solid pressed factory bricks have higher uniaxial compressive strength than handmade bricks and solid not-pressed factory brick.

Table 4.8. Mechanical properties of handmade fired and factory solid brick samples given by porosity, size corrected point load strength ($Is_{(50)}$), and uniaxial compressive strength values ascending sorted by UCS values, respectively.

Samples	Porosity (% by volume)	$Is_{(50)}$ (MPa)	UCS (MPa)
C.V.p.HB1	32.1±0.7	2.41	28.14
C.V.b.HB2	33.4±0.7	2.05	24.26
C.V.p.HB3	34.0±1.6	1.83	21.95
C.U.lb.HB4	32.4±0.7	2.55	29.62
E.A.r.HB5	33.9±1.9	0.68	9.75
E.A.db.HB6	31.7±0.7	0.60	8.88
I.A.r.HB7	36.2±1.3	0.91	12.18
I.A.p.HB8	34.4±1.7	1.28	16.14
M.S.lb.HB9	35.7±1.3	0.77	10.64
M.S.p.HB10	36.9±1.5	1.39	17.29
I.D.db.FB1	29.3±0.3	2.67	30.91
I.D.r.FB2	12.1±0.2	5.56	61.70
B.I.r.FB3	15.3±0.4	6.18	68.25
B.I.gb.FB4	10.2±0.2	7.84	85.94

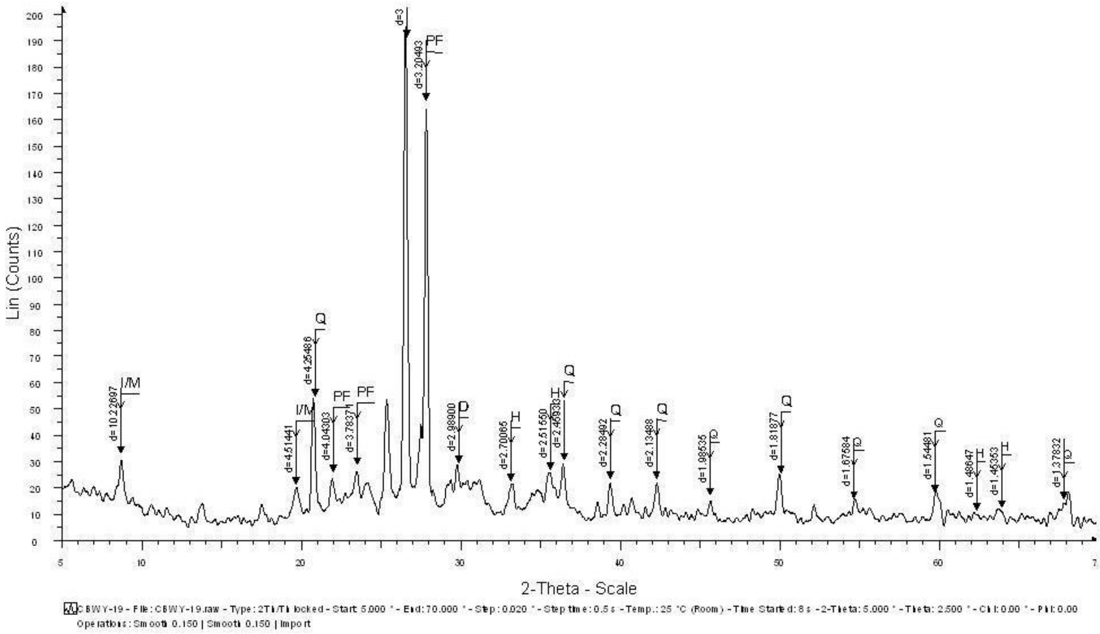
4.3 Raw Materials and Microstructural Analyses

XRD analyses, pozzolanic activity measurements and image analyses of cross-sections of handmade and solid factory bricks were done in the scope of raw materials and microstructural analyses in the related subheadings. The main minerals determined by XRD analyses allowed to determine the firing temperatures of brick samples. The results of these analyses were given for each brick sample, respectively.

4.3.1 XRD Analyses

The XRD analyses were performed on powdered forms of brick samples in order to determine major minerals in the compositions and the minerals that may be formed during different degrees of firing. Major mineral composition gives general information about the raw material sources that all of which were produced in different regions. Major minerals as well as the minerals that may be formed during firing helps to make an estimation of firing temperature. XRD results of all brick samples (C.V.p.HB1, C.V.b.HB2, C.V.p.HB3, C.U.lb.HB4, E.A.r.HB5, E.A.db.HB6, I.A.r.HB7, I.A.p.HB8, M.S.lb.HB9, M.S.p.HB10, I.D.db.FB1, I.D.r.FB2, B.I.r.FB3, B.I.gb.FB4) were given with their region and size of production, and color measurements (hue, value and chroma values) in **Figure 4.8, 4.9, 4.10, 4.11, 4.12, 4.13, 4.14, 4.15, 4.16, 4.17, 4.18, 4.19, 4.20, 4.21**, respectively. The difference in the main minerals and their peaks belongs to the XRD traces of both handmade and factory bricks is related with their raw materials, firing temperatures and burning conditions. The minerals and exact firing temperatures can not be detected by only XRD traces, it should be confirmed by thin sections of these bricks and other raw material analyses. (SEM-EDX analyses, FTIR analyses, Raman Spectroscopy, etc.).

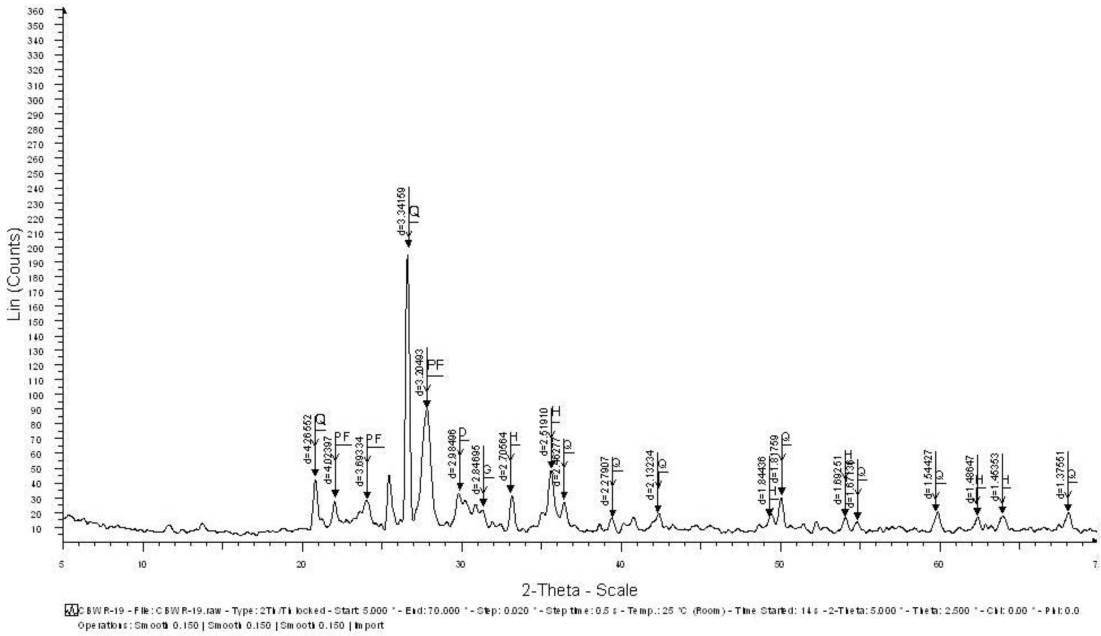
Quartz, plagioclase feldspar, hematite, diopside and illite/mica group were found in the XRD traces of C.V.p.HB1. The presence of illite/mica group was detected at the d value of 10.2. Besides, the notable d value of 2.84 belongs to gehlenite was slightly seen from the peaks that gehlenite formation was started by the reaction of calcite and clay minerals at 800°C and increasing at 900°C. High temperature minerals such as; diopside formation is occured by the crystallization of calcium silicates or aluminium silicates (Cultrone *et al*., 2004a; Maggetti, 1982). The red colour of the sample, which was determined by Munsell color chart, was supported by relatively high amount of hematite peaks. The intensity of hematite peaks, the presence of diopside and the beginning of gehlenite formation showed that the firing temperature of C.V.p.HB1 was determined to be between 850 and 900°C (**Figure 4.8**).



2θ° Cu K_{α}

Figure 4.8. XRD traces of C.V.p.HB1 - handmade fired brick produced in Çorum- with color code of 10R 6/6 (Q: Quartz, H: Hematite, PF: Plagioclase Feldspar, I/M: Illite/Mica, D: Diopside)

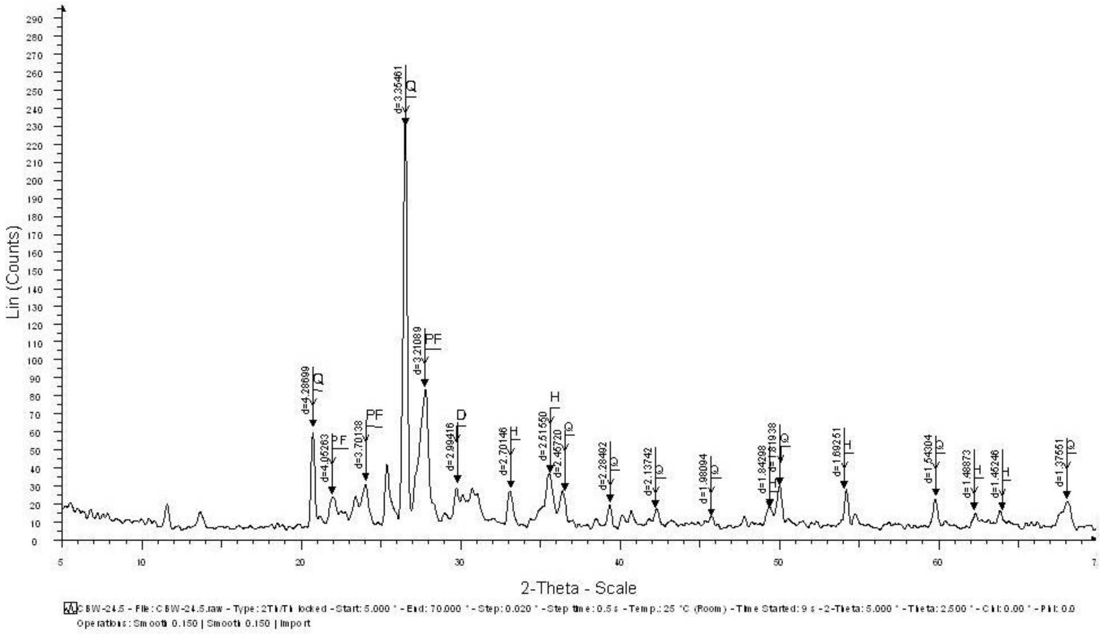
Quartz, plagioclase feldspar, hematite, diopside and gehlenite were found in the XRD traces of C.V.b.HB2. The peaks of illite/mica group was not clearly seen from the XRD traces. The formation of gehlenite was seen from the peaks of d value of 2.84, which belongs to gehlenite mineral formed by the reaction of calcite and clay minerals. The notable d value of 2.98 belongs to diopside mineral and the formation of gehlenite mineral were seen from the peaks that the raw material is rich in calcium carbonate compound ($CaCO_3$). Diopside ($CaMgSi_2O_6$) is formed by the reaction of calcite and silica at 850°C firing temperature (Riederer, 2004). The relatively higher peaks of hematite and the presence of diopside referred to relatively higher temperatures, which was determined to be approximately 900°C (**Figure 4.9**).



$2\theta°$ Cu K_{α}

Figure 4.9. XRD traces of C.V.b.HB2 **-** handmade fired brick produced in Çorum- with color code of 2.5YR 5/4 (Q: Quartz, H: Hematite, PF: Plagioclase Feldspar, D: Diopside, G: Gehlenite)

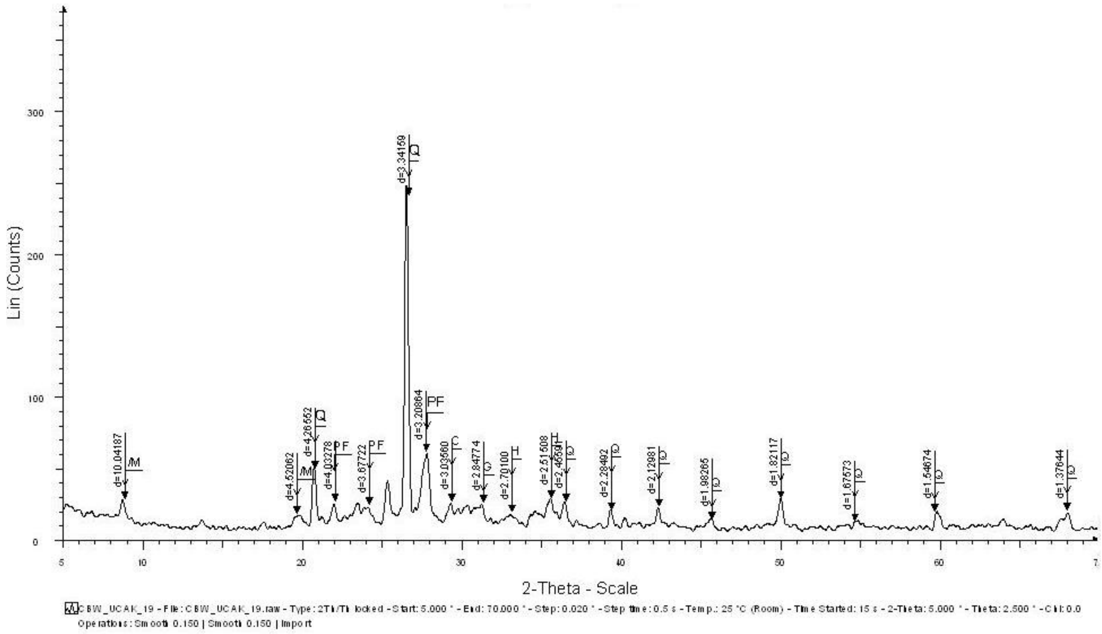
Quartz, plagioclase feldspar, hematite and diopside were found in the XRD traces of C.V.p.HB3. The peaks of illite/mica group was not clearly seen from the XRD traces. The main peaks of diopside (d=2.98) were seen from the XRD traces. The notable d value of 2.84 belongs to gehlenite was slightly/barely seen from the peaks that gehlenite formation was started by the reaction of calcite and clay minerals. The presence of these minerals shows that the raw material is rich in calcium carbonate compound ($CaCO_3$). The firing temperature was determined to be about 900°C due to the higher peaks of hematite and the presence of diopside (**Figure 4.10**).



2θ° Cu K_{α}

Figure 4.10. XRD traces of C.V.p.HB3 - handmade fired brick produced in Çorum- with color code of 2.5YR 6/6 (Q: Quartz, H: Hematite, PF: Plagioclase Feldspar, D: Diopside)

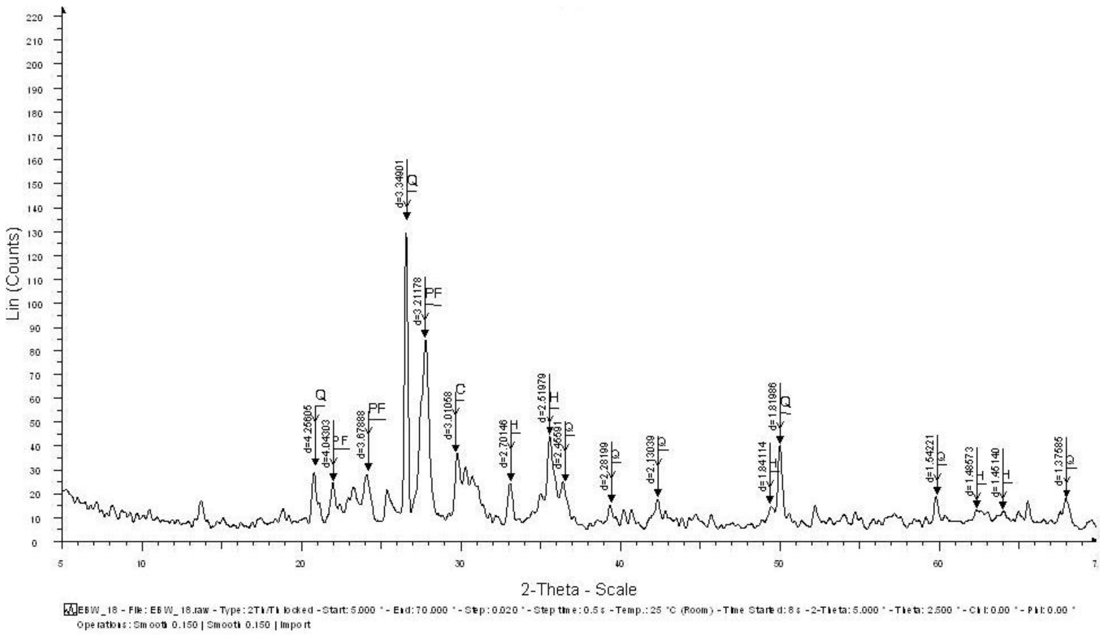
Quartz, plagioclase feldspar, calcite, hematite, gehlenite and illite/mica group were found in the XRD traces of C.U.lb.HB4. The main peak of calcite (d=3.03) was seen from the XRD traces. The presence of calcite mineral allows to assume the firing temperature below 850°C since calcite yields from decomposing calcium carbonate compound ($CaCO_3$) at increasing temperatures (Kılıç *et al.*,2017; Riccardi *et al.*, 1999; Trindade *et al.*, 2008). The notable d values of 2.70 and 2.51 belong to hematite mineral was not seen apparently from the peaks that comes from the iron present in phyllosilicates (Viani *et al.*, 2016). The lower peaks of hematite and the presence of calcite showed that the firing temperature was determined to be between 750 and 800°C (**Figure 4.11**).



2θ° Cu K_{α}

Figure 4.11. XRD traces of C.U.lb.HB4 - handmade fired brick produced in Çorum- with color code of 5YR 6/6 (Q: Quartz, H: Hematite, PF: Plagioclase Feldspar, C: Calcite, G: Gehlenite)

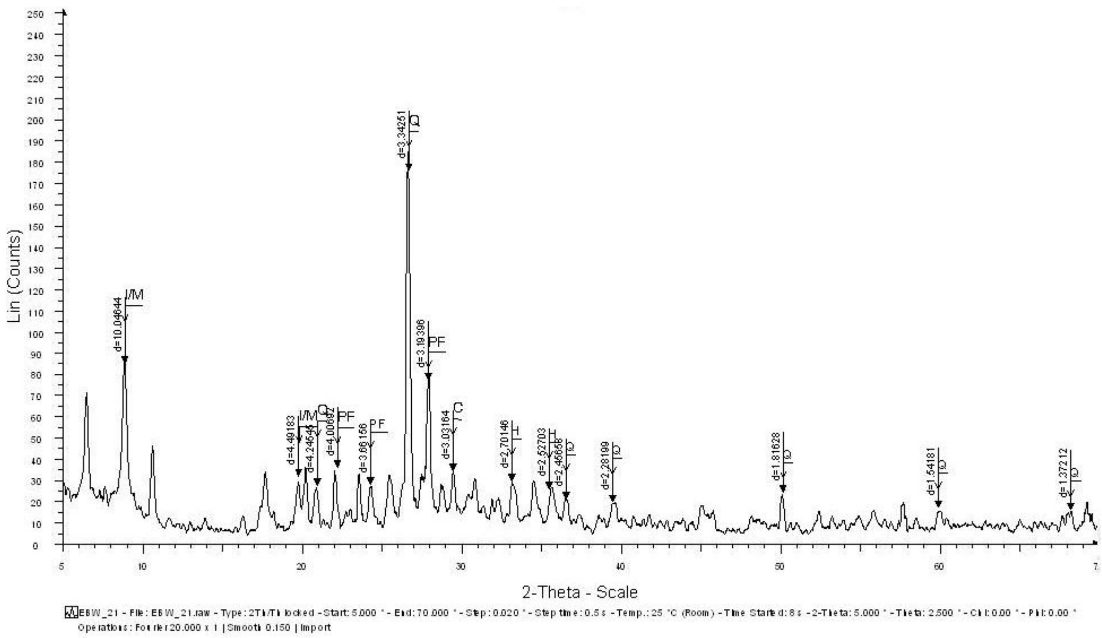
Quartz, plagioclase feldspar, calcite and hematite were found in the XRD traces of E.A.r.HB5. The peaks of illite/mica group were not detected while the peaks of hematite was clearly seen at d value of 2.70 and 2.51. The peaks of hematite minerals, which is one of the distinguishable minerals, occur at 800°C firing temperature, and well-crystallized at 900°C. However, the presence of calcite mineral allows to assume the firing temperature below 850°C since calcite yields from decomposing calcium carbonate compound ($CaCO_3$) at increasing temperatures (Kılıç *et al.*,2017; Riccardi *et al.*, 1999; Trindade *et al.*, 2008). The minerals and their quantities showed that the firing temperature was determined to be around 800 and 850°C (**Figure 4.12**).



2θ° Cu K_{α}

Figure 4.12. XRD traces of E.A.r.HB5 - handmade fired brick produced in Eskişehir- with color code of 2.5YR 5/6 (Q: Quartz, H: Hematite, PF: Plagioclase Feldspar, C: Calcite)

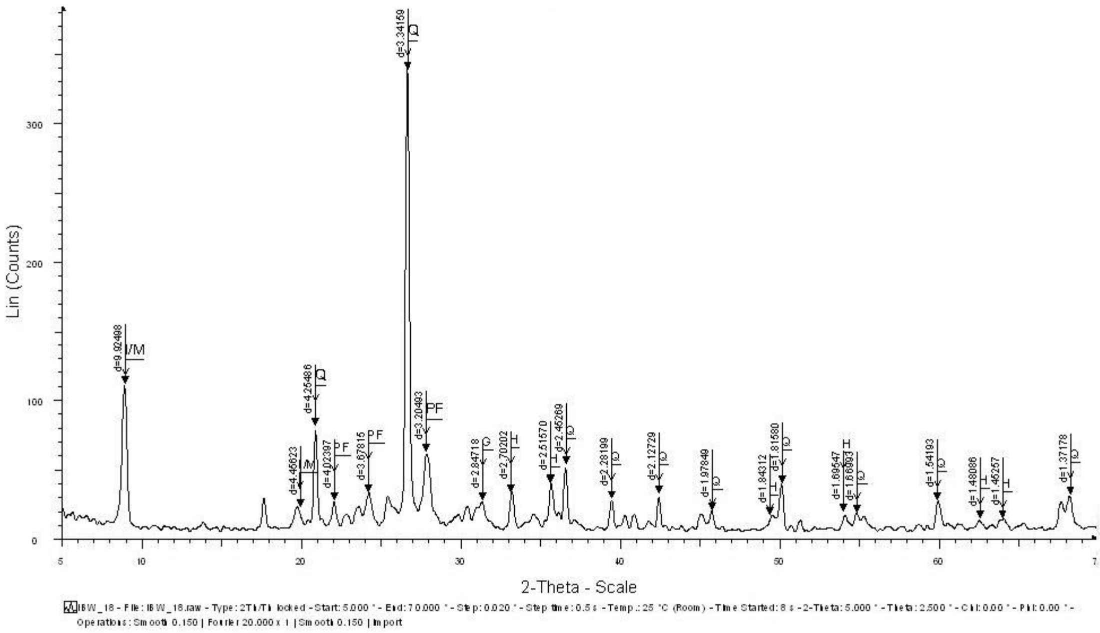
Quartz, plagioclase feldspar, calcite, hematite and illite/mica group were found in the XRD traces of E.A.db.HB6. The peaks of clay minerals were clearly seen at their d values that means these minerals are dominant in raw material. Furthermore, the peaks of illite/mica group were detected at their d values. Calcite mineral were apparently seen from the peaks at d values of 3.03 that means the raw material is rich in calcium carbonate compound ($CaCO_3$) and the firing temperature is below 850°C, as it is also seen in the sample of E.A.r.HB5. The firing temperature was determined to be between 750 and 800°C due to the presence of calcite and the intensity of hematite peaks (**Figure 4.13**).



2θ° Cu K_{α}

Figure 4.13. XRD traces of E.A.db.HB6 - handmade fired brick produced in Eskişehir- with color code of 2.5YR 4/4 (Q: Quartz, H: Hematite, PF: Plagioclase Feldspar, I/M: Illite/Mica, C: Calcite)

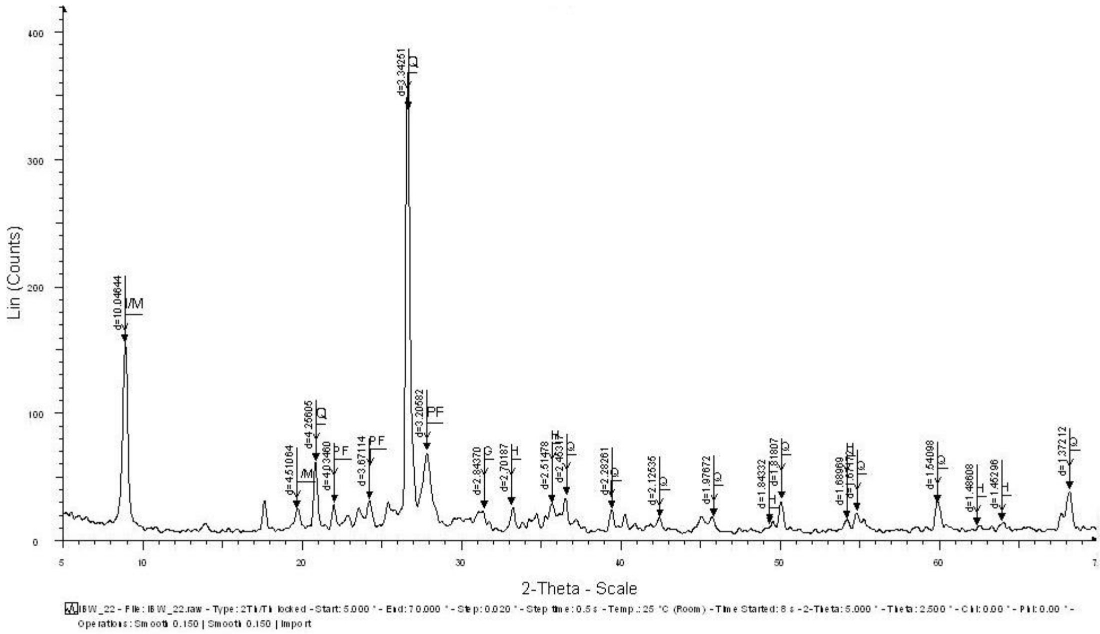
Quartz, plagioclase feldspar, hematite, gehlenite and illite/mica group were found in the XRD traces of I.A.r.HB7. The peaks of illite/mica group were clearly seen from traces. The intensity of hematite peaks confirmed the analyses of color measurements, which was determined as 10R by Munsell soil color chart (compared to the lower hematite peaks of I.A.r.HB8, which was was produced in the same region and 2.5YR was determined for I.A.r.HB8 by color measurements). The notable d value of 2.84 belongs to gehlenite mineral ($Ca_2Al[AlSiO_7]$) was seen from the traces that gehlenite was formed by reaction of calcite and clay minerals beginning from the firing temperature at 800°C and increasing at 900°C. However, the absence of calcite gives hints about the firing temperature exceeding 850°C. All of these minerals and their quantities showed that the firing temperature was determined to be between 850 and 900°C (**Figure 4.14**).



2θ° Cu K_{α}

Figure 4.14. XRD traces of I.A.r.HB7 - handmade fired brick produced in İzmir- with color code of 10R 5/6 (Q: Quartz, H: Hematite, PF: Plagioclase Feldspar, I/M: Illite/Mica, G: Gehlenite)

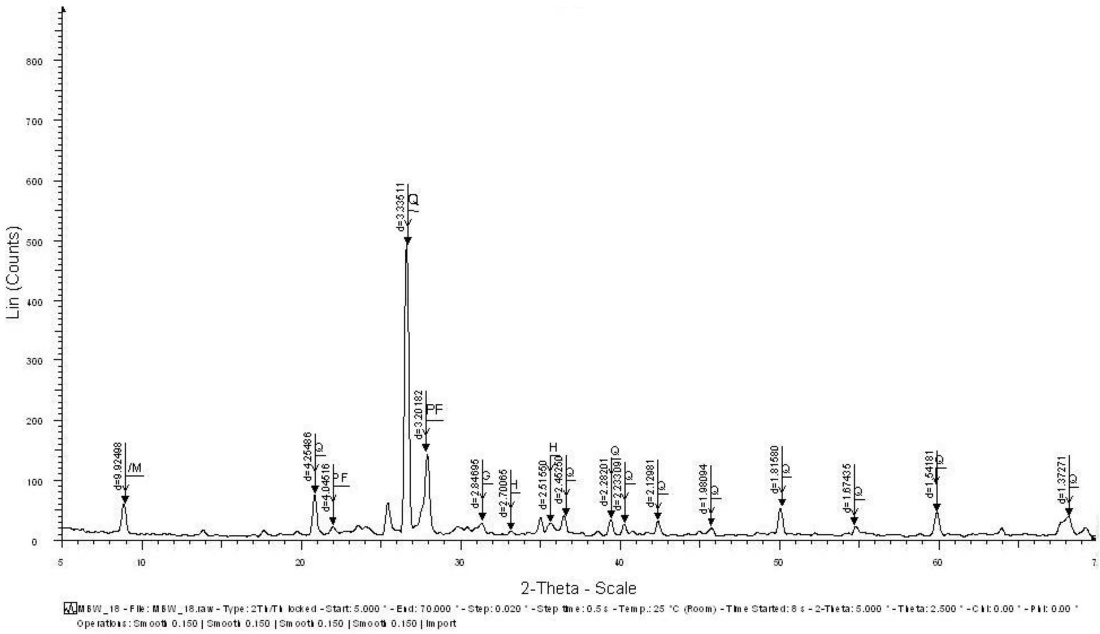
Quartz, plagioclase feldspar, hematite, gehlenite and illite/mica group were found in the XRD traces of I.A.p.HB8. The high intensity of the peaks belongs to illite/mica group minerals are clearly seen from the XRD traces that these minerals are dominant in raw material. Gehlenite mineral was detected from the peaks that it is formed by reaction of calcite and clay minerals while calcite mineral was not found in the raw clay that means it either is decomposed to other minerals (such as gehlenite or diopside) by firing or it is absent in raw material. The lower peaks of hematite confirms the firing temperature relatively lower and the colour analyses determined by Munsell Color Chart (which is found 2.5YR 6/6). The firing temperature was determined to be between 800 and 850°C due to all of these minerals and their intensities (**Figure 4.15**).



$2\theta°$ Cu K_{α}

Figure 4.15. XRD traces of I.A.p.HB8 **-** handmade fired brick produced in İzmir- with color code of 2.5YR 6/6 (Q: Quartz, H: Hematite, PF: Plagioclase Feldspar, I/M: Illite/Mica, G: Gehlenite)

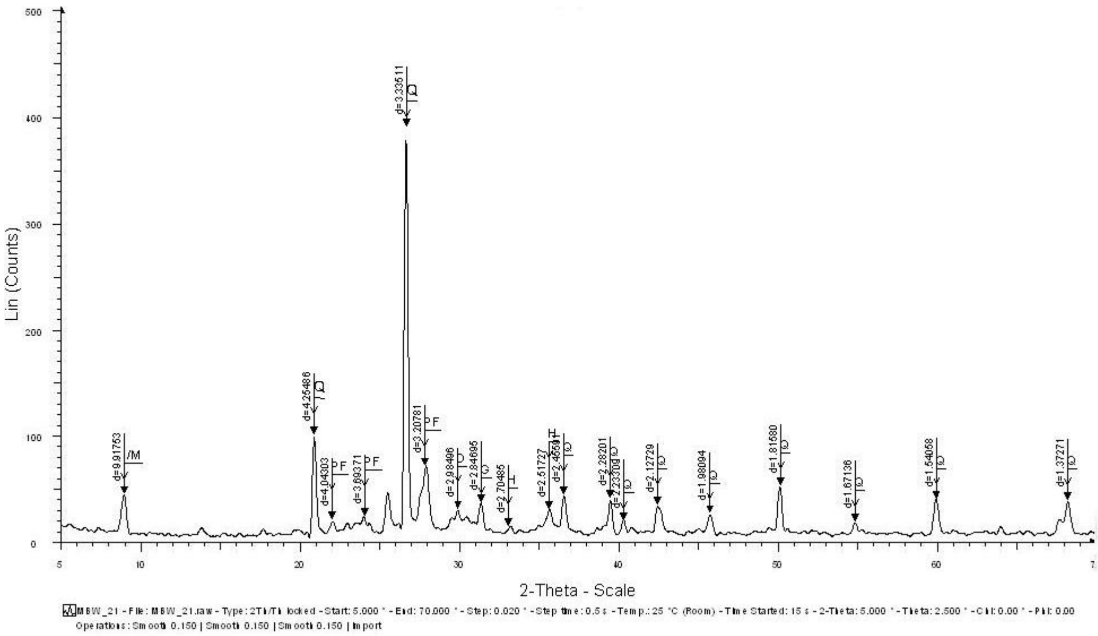
Quartz, plagioclase feldspar, hematite, gehlenite and illite/mica group were found in the XRD traces of M.S.lb.HB9. The presence of illite/mica group was detected at the d value of 9.92. The lower peaks of hematite refered to relatively lower firing temperatures. The main peak of gehlenite was occurred by the formation of calcite and clay minerals. Calcite peak was vanished by either the formation of gehlenite and other minerals or the absence of calcium (Ca) in the raw material. The firing temperature was determined to be around 800°C considering all of these minerals and their quantities (**Figure 4.16**).



2θ° Cu K_{α}

Figure 4.16. XRD traces of M.S.lb.HB9 - handmade fired brick produced in Manisa- with color code of 5YR 6/6 (Q: Quartz, H: Hematite, PF: Plagioclase Feldspar, I/M: Illite/Mica, G: Gehlenite)

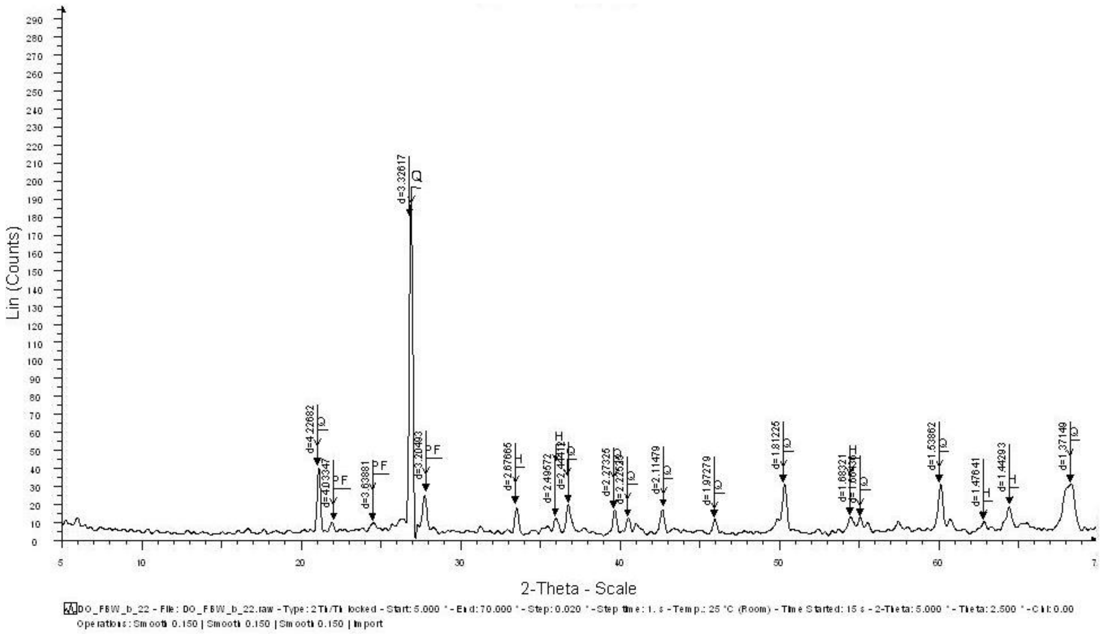
Quartz, plagioclase feldspar, hematite, diopside, gehlenite and illite/mica group were found in the XRD traces of M.S.p.HB10. The presence of illite/mica group was detected at the d value of 9.92. The lower peaks of hematite refered to relatively lower firing temperatures. The notable d value of 2.84 belongs to gehlenite mineral ($Ca_2Al[AlSiO_7]$) was seen from the traces that gehlenite was formed by reaction of calcite and clay minerals and increased due to higher firing temperatures at 900 °C. The main peak of diopside mineral ($CaMgSi_2O_6$) was barely seen that is formed by the reaction of calcite and silica at 850°C firing temperature (Riederer, 2004). The peaks of gehlenite and hematite were relatively apparent compared to M.S.lb.HB9, which was produced in the same region. All of these minerals and their quantities showed that the firing temperature was determined to be between 800 and 900°C (**Figure 4.17**).



2θ° Cu K_{α}

Figure 4.17. XRD traces of M.S.p.HB10 - handmade fired brick produced in Manisa- with color code of 2.5YR 6/6 (Q: Quartz, H: Hematite, PF: Plagioclase Feldspar, I/M: Illite/Mica, G: Gehlenite, D: Diopside)

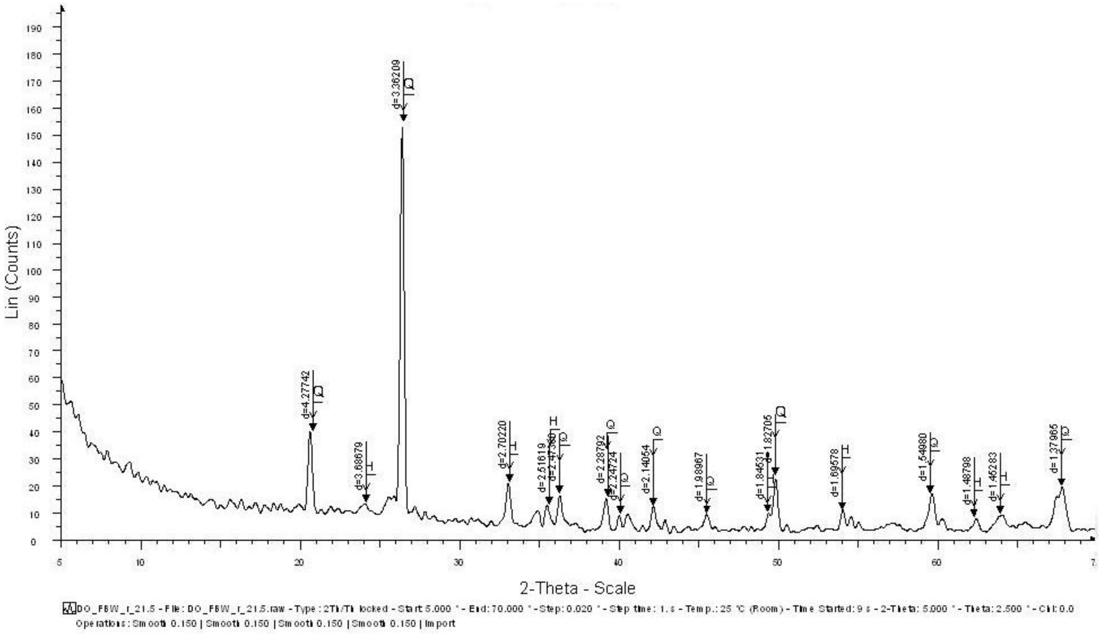
Quartz, plagioclase feldspar and hematite were found in the XRD traces of I.D.db.FB1. Clay minerals were not detected at their d values. The content of feldspar minerals started to decrease and the shape and intensity of feldspar minerals changed above 900°C of higher firing temperatures, which was seen from the XRD traces (Franke and Shoppe, 1988). The intensity of hematite peaks, the absence of calcite minerals (which is seen up to 850°C firing temperature) showed that firing temperature was determined to be between 900 and 950°C (**Figure 4.18**).



2θ° Cu K_{α}

Figure 4.18. XRD traces of I.D.db.FB1 – not-pressed solid factory brick produced in İzmir- with color code of 2.5YR 3/6 (Q: Quartz, H: Hematite, PF: Plagioclase Feldspar)

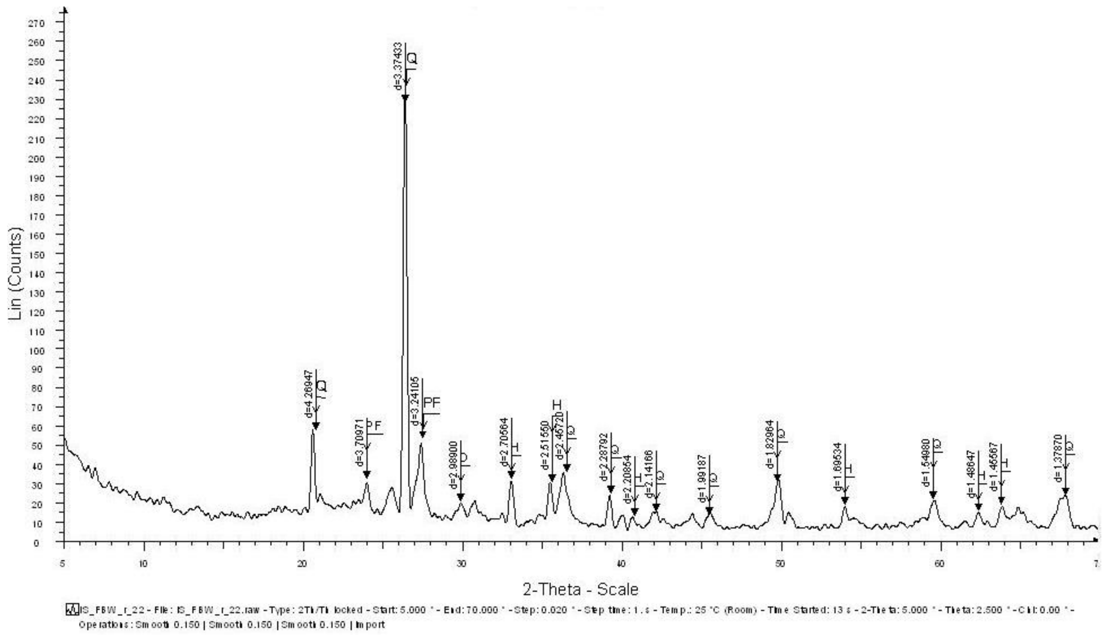
Quartz and hematite were found in the XRD traces of I.D.r.FB2. Clay minerals were not detected at their d values. Higher peaks of hematite indicated the stronger red color which was also determined as 10R by Munsell soil color chart. The hematite peaks were increased while feldspar peaks were decreased and almost vanished due to the higher firing temperature at above 900°C. The intensity of hematite peaks and the absence of plagioclase feldspar peaks showed that firing temperature was determined to be between 950 and 1000°C (**Figure 4.19**).



2θ° Cu K_{α}

Figure 4.19. XRD traces of I.D.r.FB2 – pressed solid factory brick produced in İzmir- with color code of 10R 5/6 (Q: Quartz, H: Hematite)

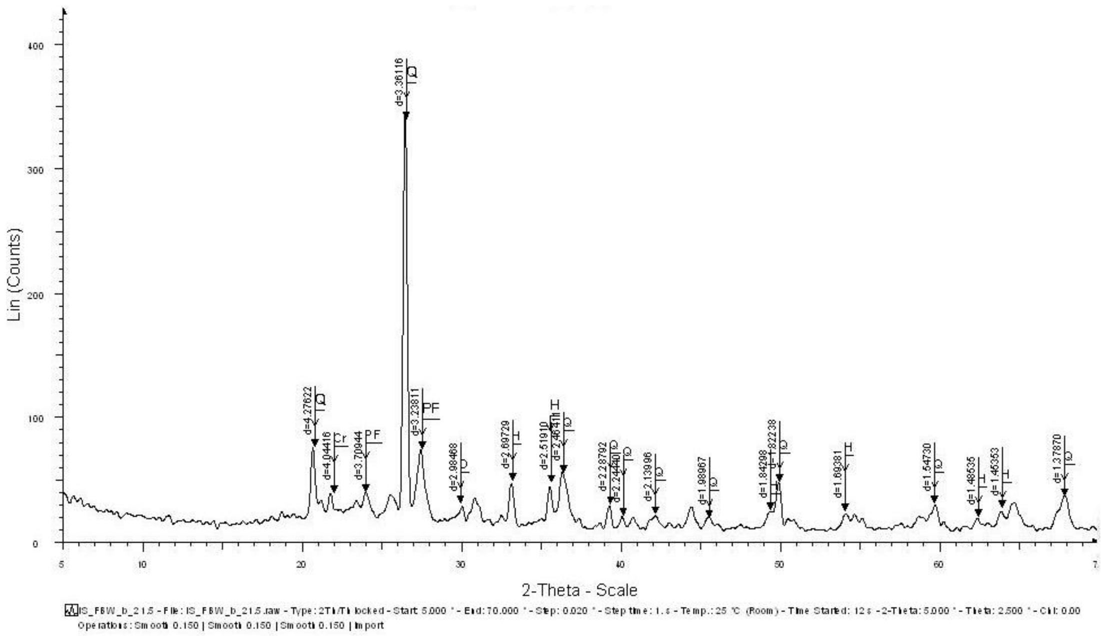
Quartz, plagioclase feldspar, diopside and hematite were found in the XRD traces of B.I.r.FB3. Clay minerals were not detected at their d values. The notable d value of 2.98 belongs to diopside mineral was seen from the traces that diopside mineral ($CaMgSi_2O_6$) was formed by the reaction of calcite and silica. This result showed that firing temperature must have well reached at high temperatures around 900°C and stayed there for some time. Higher peaks of hematite indicated the stronger red colour which was also determined as 10R by Munsell soil colour chart. The hematite peaks were increased while plagioclase feldspar peaks were decreased due to the higher firing temperature which was determined to be between 900 and 1000°C (**Figure 4.20**).



2θ° Cu K_{α}

Figure 4.20. XRD traces of B.I.r.FB3 – pressed solid factory brick produced in Bartın- with color code of 10R 5/8 (Q: Quartz, H: Hematite, PF: Plagioclase feldspar, D: Diopside)

Quartz, plagioclase feldspar, hematite, diopside and cristobalite were found in the XRD traces of B.I.gb.FB4. Clay minerals were not detected at their d values. The notable d value of 2.98 belongs to diopside mineral was seen from the traces that diopside mineral ($CaMgSi_2O_6$) was formed by the reaction of calcite and silica at higher temperatures. The notable d value of 4.04 belongs to cristobalite was seen from the XRD traces due to higher firing temperature. Cristobalite is occurred by the transformation of quartz or vitreous compounds at 1050°C (Riederer, 2004; Franke and Schoppe, 1988). Increasing temperature caused to higher peaks of hematite, formation of cristobalite, decrease and change the shape and intensity of feldspar peaks and transform calcite completely to other minerals such as diopside and other minerals. Overall, the XRD traces showed that the firing temperature was determined to be around 1050°C (**Figure 4.21**).



2θ° Cu K_α

Figure 4.21. XRD traces of B.I.gb.FB4 – pressed solid factory brick produced in Bartın- with color code of 2.5YR 4/2 (Q: Quartz, H: Hematite, PF: Plagioclase feldspar, D: Diopside, Cr: Cristobalite)

4.3.2 Pozzolanic Activity

The results of pozzolanic activity measurements were expressed in terms of consumed EDTA standard solution together with saturated $Ca(OH)_2$ solution and difference in electrical conductivity values in **Table 4.9**. Pozzolanic activity is the ability of the material to react with calcium hydroxide to form calcium silicate hydrate (C-S-H) bonds. Bricks with high pozzolanic activity are expected to have a high adhesion/bonding capacity with mortar and plaster with lime binder (Tuncoku and Caner-Saltık, 2006; Tuncoku, 2001).

The consumed amount of EDTA solution of handmade fired bricks were found to be between 15.4±0.5 and 20.8±0.1 ml with an average of 18.2±0.2 ml which are inversely proportional to consumed amount of $Ca(OH)_2$ solution and their pozzolanic activities. The amount of Ca^{2+} consumption of the reference or blank solution, which is not pozzolan, is 48.9 mg. According to the reference or blank solution, the consumed amount of $Ca(OH)_2$ solution of handmade fired bricks were found to be between

140.0±0.1 and 169.9±1.6 mg with an average of 156.1±0.8 mg. The change in the electrical conductivity of handmade fired bricks were found to be between 0.52 and 0.80 mS/cm with an average of 0.68 mS/cm which were determined to be variable pozzolanic (between 0.4 and 1.2 mS/cm) according to classification made by Luxan (1989).

The consumed amount of EDTA solution of factory solid bricks were found to be between 19.4±0.1 and 22.2±1.1 ml with an average of 20.5±0.2 ml. According to the reference or blank solution, the consumed amount of $Ca(OH)_2$ solution of factory solid bricks were found to be between 137.0±2.3 and 153.6±0.4 mg with an average of 145.9±0.9 mg. The change in the electrical conductivity of factory solid bricks were found to be between 1.01 and 1.46 mS/cm with an average of 1.26 mS/cm which were determined to be good pozzolanic (ΔEC values greater than 1.2 mS/cm). The results showed that the pozzolanic activities of handmade bricks are higher than factory bricks in terms of direct method of chemical titration with EDTA while their pozzolanic activities were found to be lower than factory bricks in terms of the measurement of the change in electrical conductivity by Luxan.

Table 4.9. Pozzolanic activity of handmade and factory bricks.

Name of Sample	**Consumed EDTA (ml)**	**Consumed $Ca(OH)_2$ (mg)**	**ΔEC (mS/cm)**
C.V.p.HB1	18.3±1.1	159.6±5.5	0.52
C.V.b.HB2	17.9±0.5	163.7±2.6	0.76
C.V.p.HB3	16.7±2.3	150.5±10.9	0.71
C.U.lb.HB4	15.4±0.5	160.7±2.4	0.61
E.A.r.HB5	20.1±0.1	140.0±0.1	0.80
E.A.db.HB6	17.5±0.1	164.4±0.4	0.52
I.A.r.HB7	18.0±0.3	169.9±1.6	0.61
I.A.p.HB8	17.9±0.3	153.5±1.4	0.80
M.S.lb.HB9	20.8±0.1	144.1±0.4	0.61
M.S.p.HB10	20.0±0.1	155.0±0.8	0.80
I.D.db.FB1	20.6±0.9	146.9±4.4	1.01
I.D.r.FB2	20.0±0.5	137.0±2.3	1.34
B.I.r.FB3	19.4±0.1	153.6±0.4	1.22
B.I.gb.FB4	22.2±1.1	146.0±6.2	1.46
Blank sample	0	48.9	0

4.3.3 Image Analyses of Cross Sections

The images taken from cross sections of handmade and solid factory brick samples were given in **Figure 4.22, 4.23, 4.24, 4.25, 4.26, 4.27, 4.28, 4.29, 4.30, 4.31, 4.32, 4.33, 4.34, 4.35,** respectively. The images of cross sections were analysed in 7x, 30x and 100x magnification lenses by streomicroscope, respectively (left, middle and right images of each sample). These magnified images allowed to examine visible pores (macro pores) with a diameter of ~10-20 µm and above in terms of their form, size and distribution as well as whether those macro pores are interconnected or not. The results of image analyses showed that handmade bricks have more large pores than factory bricks that property contributes to their resistance to weathering cycles. However, bricks are illustrious with capillarity and this capillary pores can be seen form the texture of both handmade and factory bricks. The results of the image analyses are given as below:

- The largest pore in handmade brick C.V.p.HB1 is about 1.3mm while the largest aggregate in this brick is about 2.2mm that can be seen from 7x magnification of image. Pores with circular shapes and splinter shapes caused by straw-bale are abundant which are interconnected in the texture of brick. Pores with a diameter of ~10µm can be seen from the 100x magnification of image (**Figure 4.22**).
- The largest pore in handmade brick C.V.b.HB2 is about 2.1mm while the largest aggregate in this brick is about 2.5mm that can be seen from 7x magnification of image. Furthermore, difference in texture and color and shrinkage cracks are seen which may be related with higher firing temperature and/or irregularity of firing process (at around 900°C) (**Figure 4.23**).
- The largest aggregate in handmade brick C.V.p.HB3 is about 4mm while pores are distributed regularly with a maximum diameter of 1mm. Entrapped air-voids cause macro-sized pores in irregular shapes can be seen in the interconnected texture of the brick (**Figure 4.24**).
- Most of the large pores are in splinter shape caused by using straw-bale in raw material of handmade brick C.U.lb.HB4. The length of these pores are in between 1 and 3mm sizes. However, the texture of the brick is interconnected with binder and aggregates (**Figure 4.25**).

— The largest pore in handmade brick E.A.r.HB5 is about 1.5mm while the largest aggregate in this brick is about 2mm. This brick has relatively less amount of large pores considering bricks produced in Çorum region. Fine pores and tiny shrinkage cracks can be seen in **Figure 4.26**.

— The largest pore in handmade brick E.A.db.HB6 is about 2.7mm while the largest aggregate in this brick is about 1.5mm. Entrapped air-voids cause macro-sized pores in irregular shapes can be seen in the texture of the brick. This brick has also fine pores and shrinkage cracks which are clearly seen in **Figure 4.27**.

— The handmade brick I.A.r.HB7 has a crack in 5mm size length. The pores and aggregates of this brick are in smaller sizes varied in 0.3 to 0.8mm while these pores and aggregates are distributed regularly in the homogeneous texture of brick. The binder and aggregates of this brick have darker color which is confirmed by the firing temperature (850-900°C) and Munsell color chart analysis (10R/5/6) (**Figure 4.28**).

— The largest pore in handmade brick I.A.p.HB8 is about 1.3mm while the aggregates in this brick are in considerably smaller sizes. The color difference in the texture of the brick is seen clearly, which is may be related with irregular firing conditions. However, the distribution of interconnected pores and aggregates are regular which is seen in 30x and 100x magnified images (**Figure 4.29**)

— The largest pore in handmade brick M.S.lb.HB9 is about 1.5mm while the largest aggregate in this brick is about 1.2mm. Furthermore, tiny pieces of brick are used as aggregates in this brick up to 2.5mm sizes. The irregular distribution of pores and aggregates in different sizes and shapes are seen in magnified images (**Figure 4.30**)

— The largest pore in handmade brick M.S.p.HB10 is about 1.3mm while the largest aggregate in this brick is about 1.2mm. There is a large number of large pores and aggregates in 7x magnified image. These interconnected pores and aggregates are distributed irregulary which is seen in **Figure 4.31**.

— Solid not-pressed factory brick I.D.db.FB1 has a large number of huge cracks, which may be related with the molding process. Most of the porosity of this brick is composed of these huge cracks up to 2.5mm size in length, which have a significant effect on the disconnected and fractal texture of brick. The larger pores and aggregates are distributed irregularly which are disassociated between each other (**Figure 4.32**).

— The largest pore in solid pressed factory brick I.D.r.FB2 is about 1.1mm while the largest aggregate in this brick is about 3.2mm. The pores and aggregates of this brick are interconnected in a tight texture. However, the number of large pores are less than that of handmade bricks (**Figure 4.33**).

— The largest pore in solid pressed factory brick B.I.r.FB3 is about 1.5mm while the largest aggregate in this brick is about 1.6mm. Tiny pieces of brick are used as aggregates which are disconnected to the texture of this brick. Furthermore, the distribution of pores and aggregates is irregular as seen in **Figure 4.34**.

— The largest aggregate in solid pressed factory brick B.I.gb.FB4 is about 1.5mm while no large pore is seen in this brick. This may be related with the lowest porosity value of this brick among others. Tiny pieces of brick are used as aggregates which are interconnected in the texture. The color of this brick is greyish brown which may be related with raw materials and/or highest firing temperature (around 1050°C) (**Figure 4.35**).

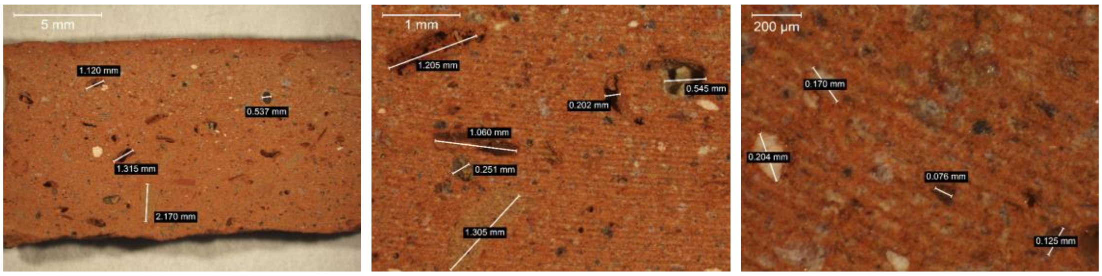


Figure 4.22. Magnified images (7x-left, 30x-middle, 100x-right by streomicroscope) taken form handmade brick C.V.p.HB1 - burnt at between 850 and 900°C

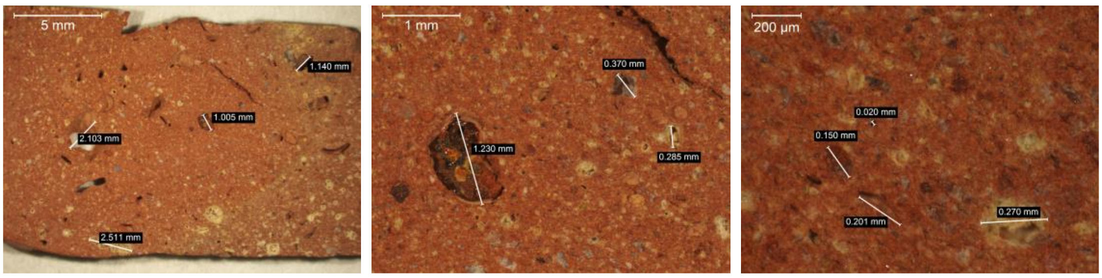


Figure 4.23. Magnified images (7x-left, 30x-middle, 100x-right by streomicroscope) taken form handmade brick C.V.b.HB2 - burnt at around 900°C

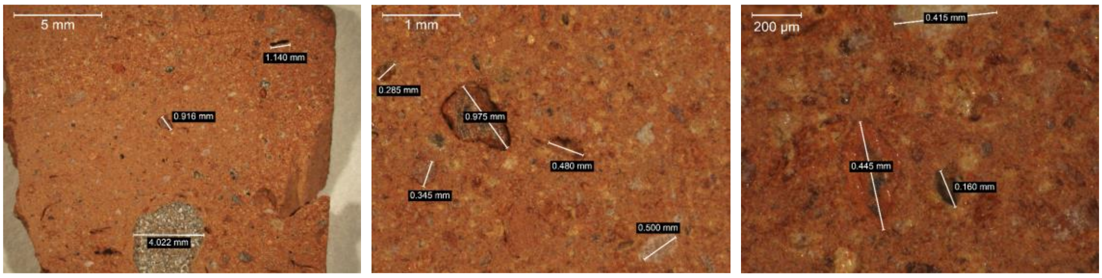


Figure 4.24. Magnified images (7x-left, 30x-middle, 100x-right by streomicroscope) taken form handmade brick C.V.p.HB3 - burnt at around 900°C

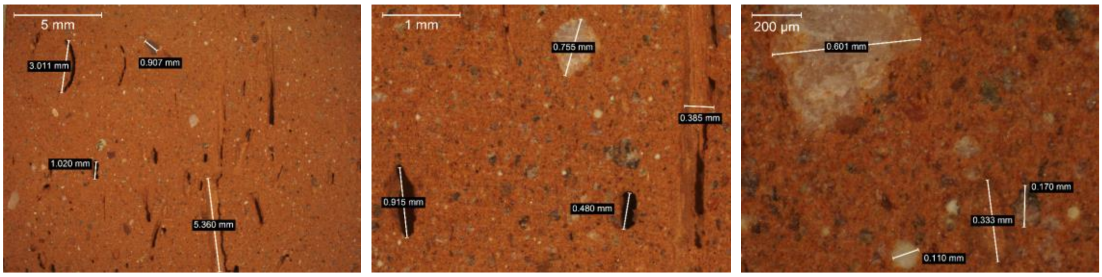


Figure 4.25. Magnified images (7x-left, 30x-middle, 100x-right by streomicroscope) taken form handmade brick C.U.lb.HB4 - burnt at between 750 and 800°C

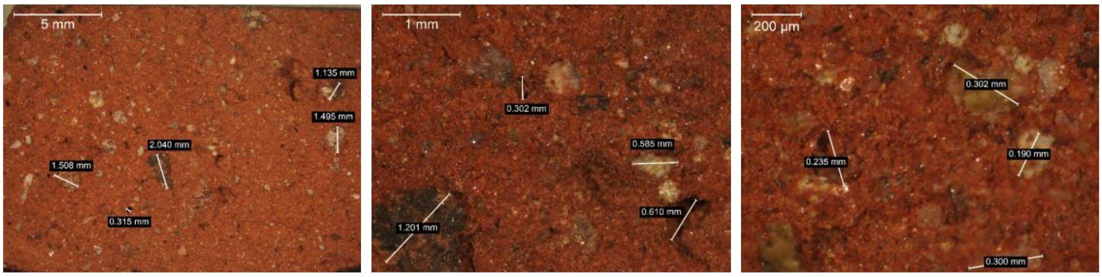


Figure 4.26. Magnified images (7x-left, 30x-middle, 100x-right by streomicroscope) taken form handmade brick E.A.r.HB5 - burnt at between 800 and 850°C

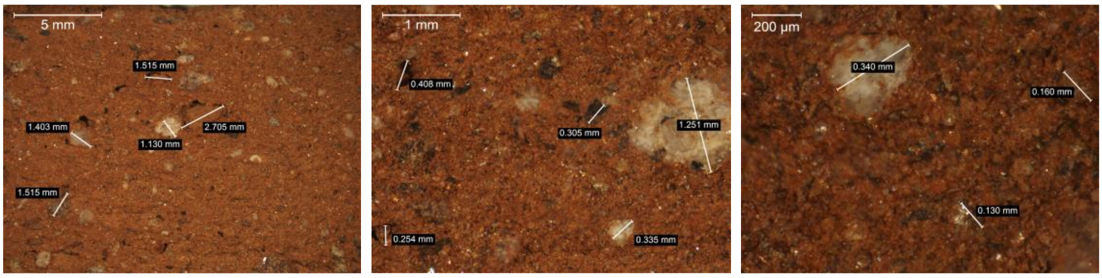


Figure 4.27. Magnified images (7x-left, 30x-middle, 100x-right by streomicroscope) taken form handmade brick E.A.db.HB6 - burnt at between 750 and 800°C

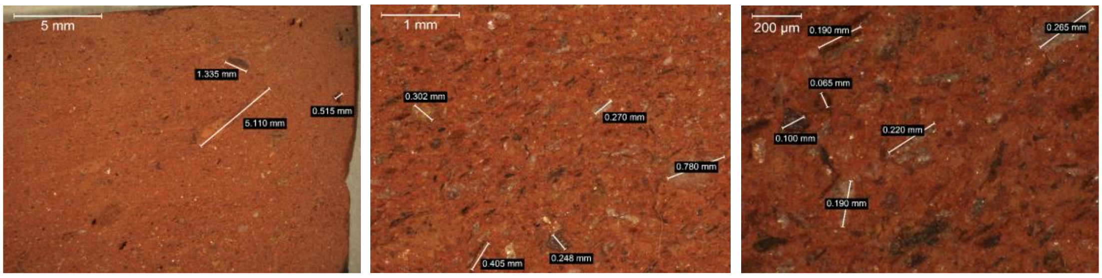


Figure 4.28. Magnified images (7x-left, 30x-middle, 100x-right by streomicroscope) taken form handmade brick I.A.r.HB7 - burnt at between 850 and 900°C

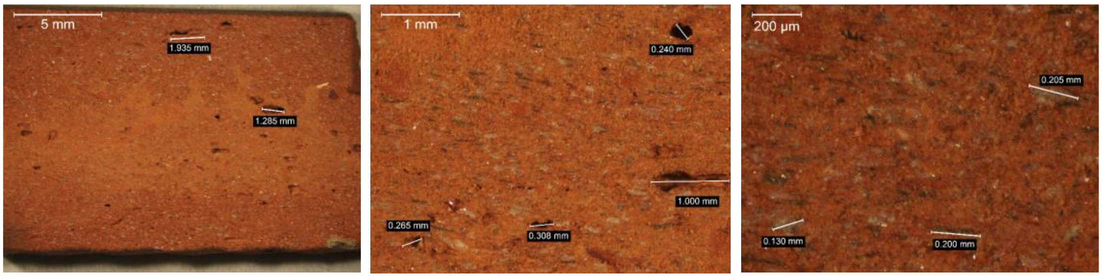


Figure 4.29. Magnified images (7x-left, 30x-middle, 100x-right by streomicroscope) taken form handmade brick I.A.p.HB8 - burnt at between 800 and 850°C

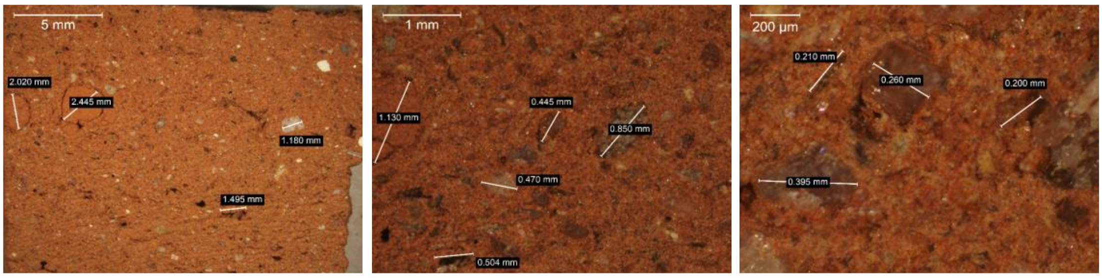


Figure 4.30. Magnified images (7x-left, 30x-middle, 100x-right by streomicroscope) taken form handmade brick M.S.lb.HB9 - burnt at around 800°C

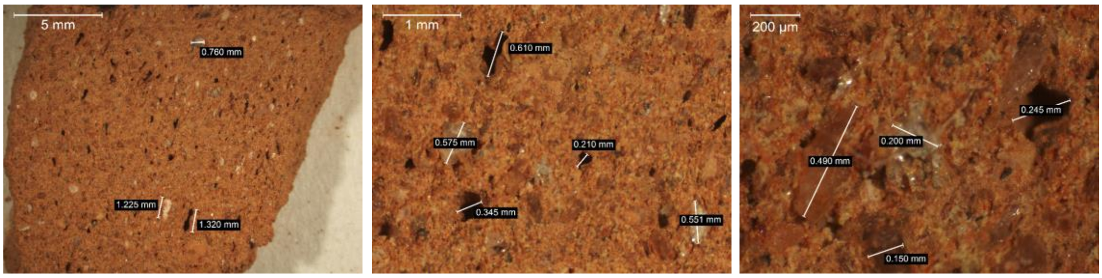


Figure 4.31. Magnified images (7x-left, 30x-middle, 100x-right by streomicroscope) taken form handmade brick M.S.p.HB10 - burnt at between 800 and 900°C

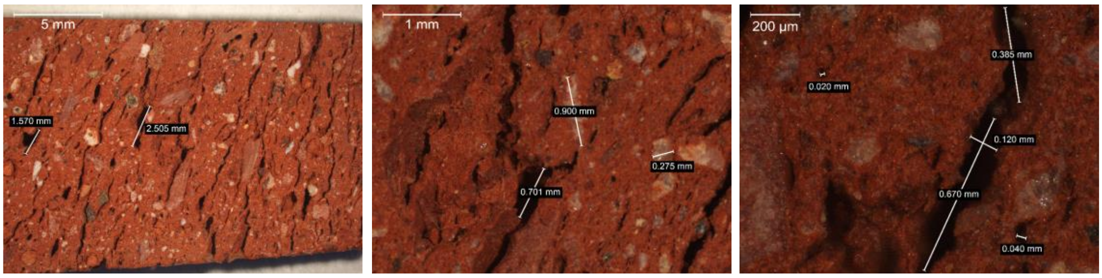


Figure 4.32. Magnified images (7x-left, 30x-middle, 100x-right by streomicroscope) taken form solid not-pressed factory brick I.D.db.FB1 - burnt at firing temperature between 900 and 950°C

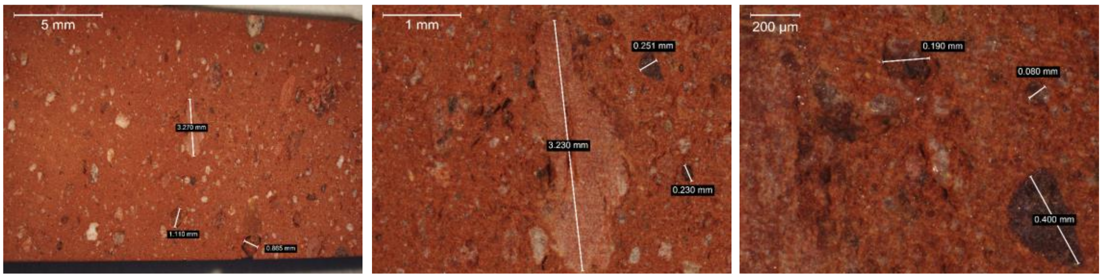


Figure 4.33. Magnified images (7x-left, 30x-middle, 100x-right by streomicroscope) taken form solid pressed factory brick I.D.r.FB2 - burnt at firing temperature between 950 and 1000°C

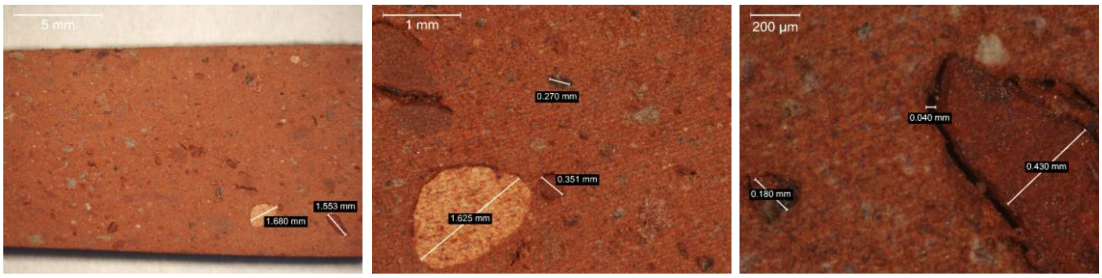


Figure 4.34. Magnified images (7x-left, 30x-middle, 100x-right by streomicroscope) taken form solid pressed factory brick B.I.r.FB3 - burnt at firing temperature between 900 and 1000°C

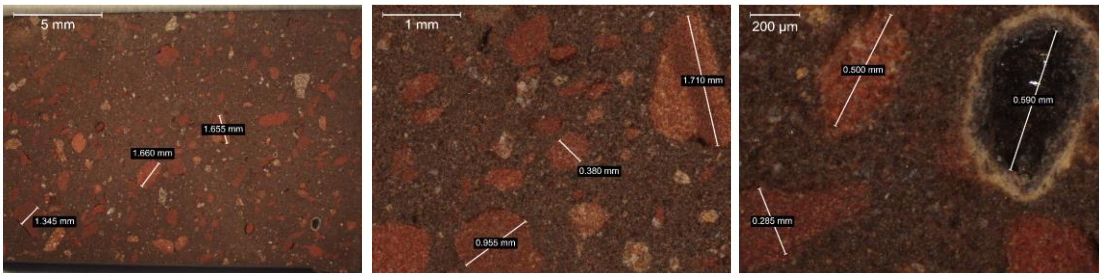


Figure 4.35. Magnified images (7x-left, 30x-middle, 100x-right by streomicroscope) taken form solid pressed factory brick B.I.gb.FB4 burnt at around 1050°C

4.4 Qualitative and Quantitative Analyses of Soluble Salts

The results for determining the presence of soluble salts (phosphate, sulphate, chloride, nitrite, nitrate, and carbonate) in brick samples and the quantity of these salts were shown in **Table 4.10**. Salts cause damage to building materials due to deterioration cycles such as salt crystallization. The results of the salt analyses showed both the type and the amount of salts in the raw materials of contemporary brick samples. These analyses were done to detect the origination and the severity of salt problem in materials.

The presence of sulphate, chlorite and nitrate were determined in handmade bricks while the presence of chloride and nitrate were only determined in factory bricks. Carbonate ions were determined only in the handmade fired bricks produced in Çorum region that was different from other samples.

The amount of soluble salts in handmade brick samples was found to be between 0.89% and 4.32% by weight while the amount of soluble salts in factory solid brick samples was found to be between 0.10% and 0.67% by weight. The average amount of soluble salts in handmade brick samples was found to be 2.16%, which is six times more than factory solid brick samples of 0.38% by weight. High amount of salt in contemporary handmade bricks may be due to the raw materials and the technology used in the production of these bricks. However, the factory solid bricks have salts in small quantities. Factory brick production is more controlled than handmade bricks that prevents the products from salt deposit generating from raw material sources and environmental conditions.There is also desalination phase during production in factories. However, some of handmade bricks are suffered from higher amount of salts compared to others that needs to be controlled during production. The salt problem occurred in handmade brick production needs to be solved by desalination methods since the brick products may suffer from salt attacks that cause internal stress, material loss and structural problems in masonry walls.

Table 4.10. Showing the results of soluble salt types and amount of salts

Samples	$PO_4^{(2-)}$	$SO_4^{(2-)}$	$Cl^{(-)}$	$NO_2^{(-)}$	$NO_3^{(-)}$	$CO_3^{(2-)}$	Amount of salt (%)
C.V.p.HB1	(-)	(+)	(+)	(-)	(-)	(-)	2.51
C.V.b.HB2	(-)	(+)	(-)	(-)	(+)	(+)	1.92
C.V.p.HB3	(-)	(+)	(+)	(-)	(-)	(-)	2.34
C.U.lb.HB4	(-)	(-)	(+)	(-)	(+)	(-)	1.97
E.A.r.HB5	(-)	(+)	(-)	(-)	(-)	(-)	0.89
E.A.db.HB6	(-)	(+)	(-)	(-)	(-)	(-)	4.32
I.A.r.HB7	(-)	(-)	(+)	(-)	(+)	(-)	1.15
I.A.p.HB8	(-)	(-)	(-)	(-)	(-)	(-)	1.13
M.S.lb.HB9	(-)	(-)	(-)	(-)	(-)	(-)	2.68
M.S.p.HB10	(-)	(-)	(-)	(-)	(-)	(-)	2.71
I.D.db.FB1	(-)	(-)	(+)	(-)	(+)	(-)	0.12
I.D.r.FB2	(-)	(-)	(+)	(-)	(+)	(-)	0.10
B.I.r.FB3	(-)	(-)	(+)	(-)	(-)	(-)	0.62
B.I.gb.FB4	(-)	(-)	(+)	(-)	(-)	(-)	0.67

CHAPTER 5

DISCUSSION

The data on materials characteristics of the contemporary solid brick samples were discussed to better understand the performance properties of handmade and factory-made burnt-clay bricks in relation to their hygric behaviour, pore structure, mechanical strength, raw materials characteristics and firing temperatures. The differences between the handmade and factory-made solid bricks were examined in terms of their use in contemporary masonry constructions and in repairs of historical masonry structures. Their porosity characteristics and their relationship with durability were assessed in detail in terms of their hygric properties. In addition, the results of the study were evaluated to be guiding for the improvement of national standards related with the performance specifications of contemporary handmade bricks and their manufacturing.

5.1 Assessment of Firing Temperature and Raw Materials Characterictics

The mineralogical composition and firing temperature of hand-made solid bricks and not-pressed and pressed solid factory bricks were discussed according to the data obtained with XRD, colour and pozzolanic activity analyses. The minerals determined by XRD analyses of bricks were given in **Table 5.1**. The ratio of intensity values of hematite to quartz mineral and plagioclase feldspar to quartz mineral and color-codes determined by Munsell color chart were given in **Table 5.2**. The image analyses of brick samples were also discussed in this section considering microstructural properties. These results were produced for the joint interpretation of the data for brick types.

Table 5.1. The minerals determined by XRD analyses of contemporary solid brick samples (Q: Quartz, H: Hematite, PL: Plagioclase feldspar, I/M: Illite/Mica group, C: Calcite, D: Diopside, G: Gehlenite, Cr: Cristobalite)

Sample	Q	H	PL	I/M	C	D	G	Cr
C.V.p.HB1	✓	✓	✓	✓	×	✓	×	×
C.V.b.HB2	✓	✓	✓	×	×	✓	✓	×
C.V.p.HB3	✓	✓	✓	×	×	✓	×	×
C.U.lb.HB4	✓	✓	✓	✓	✓	×	✓	×
E.A.r.HB5	✓	✓	✓	×	✓	×	×	×
E.A.db.HB6	✓	✓	✓	✓	✓	×	×	×
I.A.r.HB7	✓	✓	✓	✓	×	×	✓	×
I.A.p.HB8	✓	✓	✓	✓	×	×	✓	×
M.S.lb.HB9	✓	✓	✓	✓	×	×	✓	×
M.S.p.HB10	✓	✓	✓	✓	×	✓	✓	×
I.D.db.FB1	✓	✓	✓	×	×	×	×	×
I.D.r.FB2	✓	✓	×	×	×	×	×	×
B.I.r.FB3	✓	✓	✓	×	×	✓	×	×
B.I.gb.FB4	✓	✓	✓	×	×	✓	×	✓

Table 5.2. The ratio of intensity values of hematite (d=2.70) to quartz (d=3.34) minerals and plagioclase feldspar (d=3.20) to quartz (d=3.34) minerals, and the color-code (determined by Munsell color chart) of contemporary solid brick samples

Sample	Ratio of hematite to quartz peaks	Ratio of plagioclase feldspar to quartz peaks	Color-code	Color-code image	Firing Temperature (°C)
C.V.p.HB1	0.10	0.82	10R/6/6		850-900
C.V.b.HB2	0.15	0.47	2.5YR/5/4		~900
C.V.p.HB3	0.11	0.37	2.5YR/6/6		~900
C.U.lb.HB4	0.06	0.24	5YR/6/6		750-800
E.A.r.HB5	0.19	0.65	2.5YR/5/6		800-850
E.A.db.HB6	0.16	0.44	2.5YR/4/4		750-800
I.A.r.HB7	0.10	0.32	10R/5/6		850-900
I.A.p.HB8	0.09	0.20	2.5YR/6/6		800-850
M.S.lb.HB9	0.02	0.28	5YR/6/6		~800
M.S.p.HB10	0.04	0.20	2.5YR/6/6		800-900
I.D.db.FB1	0.11	0.13	2.5YR/3/6		900-950
I.D.r.FB2	0.14	0	10R/5/6		950-1000
B.I.r.FB3	0.14	0.22	10R/5/8		900-1000
B.I.gb.FB4	0.14	0.22	2.5YR/4/2		~1050

— Quartz, plagioclase feldspar and hematite are the main minerals of handmade bricks determined by XRD analyses (**Table 5.1**). Clay minerals were also determined in most of the XRD traces of handmade bricks. Calcite were found in some of handmade bricks that is an indicator of firing temperature below 850°C. Furthermore, gehlenite and diopside minerals were typically found in these bricks due to the transformations of calcite mineral in higher temperatures. The presence of these minerals shows that these bricks are rich in calcium. The higher ratio of hematite to quartz peaks is an indicator of relatively higher firing temperatures that is supported by the ratio of hematite peaks to quartz peaks. The intensity of hematite peaks is also related with colour analyses since the red color of the brick is due to hematite content in raw material (**Table 5.2**). The type of clay minerals cannot be determined since firing changes their crystalline matrix to amorphous phase, moreover the analyses were done on the fired products. The results of the firing temperatures for each handmade bricks showed that these bricks were fired between 750°C and 900°C. This range indicates the difference in raw materials, firing temperatures and firing conditions of these bricks between them that has an impact on their porosity characteristics and mechanical properties as seen in the literature.

— Quartz and hematite are the main minerals determined in all samples of factory bricks (**Table 5.1**). Plagioclase feldspar was determined only in a few samples of factory bricks and its presence and composition indicate regional differences in raw materials resources. Minerals like diopside and cristobalite are higher firing temperature minerals and those minerals were found in the XRD traces of factory bricks which are generally fired above 900-950°C. Clay minerals were not observed in XRD traces of all factory bricks. In case that illite and smectite types of clay minerals have been used in the mixture/composition of factory bricks, those minerals seemed to be disappeared in their XRD traces. In comparison to the XRD traces of hand-made brick samples, presence of diopside with or without cristobalite and absence of clay minerals indicate that all factory bricks are burnt at higher firing temperatures between 900°C and 1050°C.

— The not-pressed factory brick I.D.db.FB1 and pressed factory brick I.D.r.FB2, which were produced in the same region by the same company using the same raw material resource, were compared with each other in terms of hematite peaks to quartz peaks and plagioclase feldspar peaks to quartz peaks (**Table 5.2**). While the ratio of hematite to quartz peaks increases, the ratio of plagioclase feldspar to quartz peaks decreases to zero for the presed one. The increase in content of hematite and the disappear of feldspar in pressed brick may also support that pressed factory brick is fired at higher temperatures than not-pressed one.

— The ratio of hematite peaks to quartz peaks in pressed factory bricks (0.14) is considerably higher than that of handmade bricks (average ratio of hematite=0.10) while the ratio of feldspar peaks to quartz peaks in pressed factory bricks (0.22) is lower than that of handmade bricks (average ratio of feldspar=0.40). This may be due to the mineralogical composition that signal the absence of feldspar minerals in factory bricks. Besides, higher firing temperature is related with higher peaks of hematite and lower peaks of feldspar minerals. Higher firing temperature and different manufacturing techniques cause to produce lower porosity and higher mechanical properties for factory bricks.

— The pozzolanic activity of the brick samples analyzed by the titration of EDTA method showed that the amount of consumed $Ca(OH)_2$ for handmade bricks is 156.1±9.6 mg while that amount for factory bricks is 145.9±6.8 mg. These results show the ability of these bricks to form calcium silicate hydrate (C-S-H) bonds during two weeks. Although, the firing temperatures of handmade bricks (750-900°C) and factory bricks (900-1050°C) are high, these bricks have high pozzolanicity compared to the materials, which are known to be pozzolans in literature. For instance, the pozzolanic activity of brick powders in eight days is determined 30.7 mg for consumed $Ca(OH)_2$ and 2.1 mS/cm for the difference in electrical conductivity (Güney, 2012).

— The pozzolanic activity of the brick samples analyzed by Luxan (1989) method showed that the difference in electrical conductivity for handmade bricks is 0.68±0.11mS/cm while the difference for factory bricks is 1.26±0.19 mS/cm. These results indicate classifications for the pozzolanic activity of these bricks in two minutes made by Luxan (1989) presenting variable pozzolanicity for handmade bricks (between 0.4 and 1.2 mS/cm) while good pozzolanicity for factory bricks (above 1.2 mS/cm).

— **Figure 5.1** shows the results of the relationship between the pozzolanic activity measurements of these bricks in two weeks determined by the consumption of

$Ca(OH)_2$ and in two minutes determined by the difference in electrical conductivity of bricks. Factory bricks are highly pozzolanic materials and their pozzolanic reaction start fastly. Handmade bricks are also highly pozzolanic materials while their reaction start slowly compared to others. In short, all bricks show high pozzolanicity that is originated from the natural and/or artificial pozzolanic reaction products used in raw materials. Further analyses are needed to identify these pozzolanic additives for both handmade and solid factory bricks.

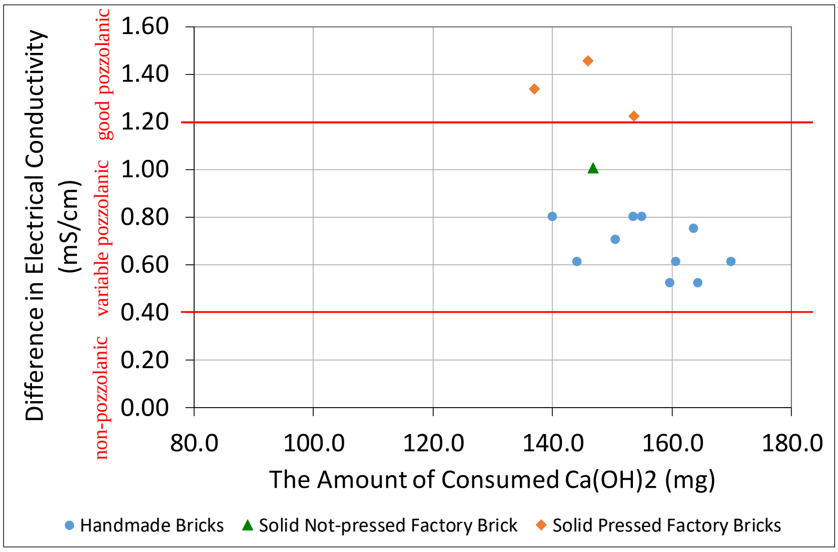


Figure 5.1. The relationship between the difference in electrical conductivity and the amount of consumed $Ca(OH)_2$ of contemporary solid bricks

— The image analyses conducted on cross-sections of each brick sample were evaluated considering their texture, colour, pore size distribution, pore connections and particle size distribution. The results show that:

- Handmade bricks have more large pores than solid pressed factory bricks, that property decreases capillary action and contributes to their frost resistance.
- Macro-sized pores in handmade bricks are irregular in shape and distribution and straw-bale is used in some of handmade bricks as aggregates, which are lost due to firing and seen as pores in splinter shape.
- Shrinkage cracks are seen in some of handmade bricks that may be related with molding and drying processes. However, solid not-pressed factory brick has huge cracks throughout the texture of the sample. The pores are expanded

vertically and the bond between the pores are nearly disappeared due to the expansion. This kind of distribution may be due to the molding and manufacturing process of this brick, which is differed from others.

- Tiny pieces of brick are used in factory brick samples as aggregates that are distributed irregularly in different sizes. These brick pieces may have pozzolanic additives contributing to their pozzolanic activity.
- The color of factory bricks are darker and the texture of these bricks are tighter than that of handmade bricks. This may be related with higher firing temperature and manufacturing process of factory bricks.

5.2 Performance Properties of Contemporary Solid Bricks

In this section, performance properties of brick samples were discussed in terms of basic physical, physico-mechanical and mechanical properties. The concluded results of these properties are as follows:

— Handmade brick samples have bulk density of 1.70±0.06 g/cm^3, effective/total porosity of 34.1±1.8% by volume, and water absorption capacity of 20.1±1.6% by weight. The ultrasonic pulse velocities of these bricks are 1790±464 m/s, the modulus of elasticities are 5.3±2.7GPa, and the uniaxial compressive strength values are 17.9±7.7MPa. It is noteworthy that the handmade bricks, which have similar properties in terms of their basic physical properties, differ in terms of their physical and mechanical properties. For example, E.A.r.HB5 and C.U.lb.HB4 coded handmade bricks have the same basic physical properties as the 1.72 g/cm^3 bulk density and 33% by volume total porosity values. The ultrasonic pulse velocities of the same bricks are 1406m/s and 2241m/s, the modulus of elasticity values are 3.1GPa and 8.0GPa and their uniaxial compressive strengths are different values such as 9.8MPa and 29.6MPa, respectively. These differences show that these bricks have different pore structures, and these results can also be related to raw material properties and firing temperatures.

— The factory bricks have bulk density of 2.19±0.06 g/cm^3, effective/total porosity of 12.5±2.6% by volume, and the water absorption capacity of 5.7±1.3% by weight. The ultrasonic pulse velocities of these bricks are 3513±257 m/s, the modulus of elasticities are 25.1±4.5 GPa, and the uniaxial compressive strength values are

72.0±12.5 MPa. Although the bulk densities of the factory bricks are very similar, their total porosity values are different; as the total porosity decreased, a noticeable increase in mechanical properties was observed. For example, solid pressed factory bricks B.FB3 and B.FB4 have an average bulk density of 2.20 g/cm^3, whereas total porosity values are 15% and 10%, respectively. The modulus of elasticities of the same bricks are 22.9 GPa and 30.2 GPa, their uniaxial compressive strength values are 61.7 MPa and 85.9 MPa that values are different from each other. The obtained data suggest that the raw material/compositional properties and firing temperatures of these two products may be different.

— The solid not-pressed factory brick (I.D.db.FB1) has different physical, physico-mechanical and mechanical properties from the solid pressed factory bricks. The bulk density of this brick is 1,84±0,01 g/cm^3, the total/effective porosity is 29,3±0,3% by volume and the water absorption capacity is 15,9±0,2% by weight. The ultrasonic velocity of the same brick type is 1848±216 m/s, the modulus of elasticity is 5,79±1,06 GPa and the uniaxial compressive strength is 30,9±0,9 MPa, respectively. It has been determined that these properties are noticeably lighter, more porous and have lower physico-mechanical and mechanical properties than the pressed factory bricks. In terms of basic physical, physico-mechanical and mechanical properties, it is understood that this product is a brick type which is closer to the performance properties of handmade bricks. However, compared to the handmade bricks, it has the highest bulk density, the lowest porosity and the highest uniaxial compressive strength.

— Generally, handmade bricks are light, very porous and have sufficient physicomechanical and mechanical properties. Factory bricks have different performance characteristics than handmade bricks; they are noticeably heavier, less porous masonry units and have high mechanical properties compared to handmade bricks.

— The data obtained indicates the existence of a linear relationship with ultrasonic pulse velocity between modulus of elasticity and uniaxial compressive strength (**Figure 5.2**). For this reason, ultrasonic velocity data is considered a determining parameter for monitoring the differences in the pore structures and mechanical properties of brick products with similar basic physical properties.

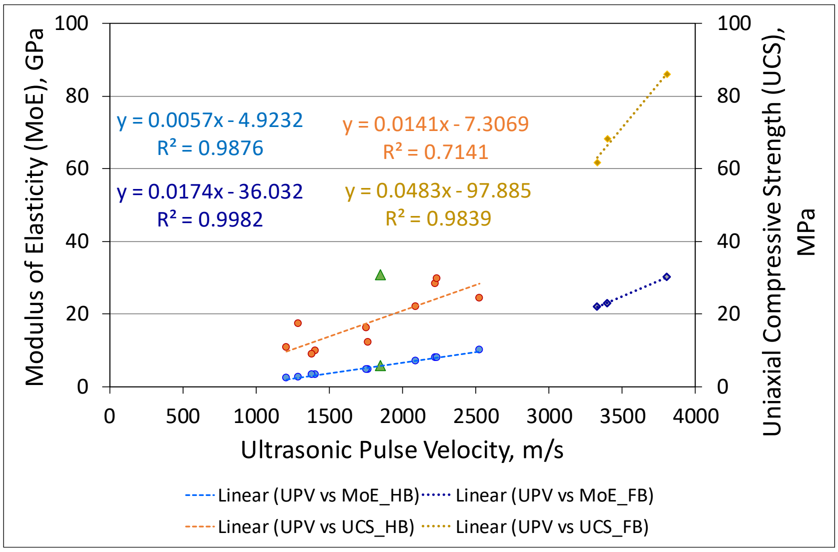


Figure 5.2. Graph showing the relationships between ultrasonic velocities (UPV) and the modulus of elasticities (E_{mod}) and uniaxial compressive strengths (UCS) of handmade (HB) and factory bricks (FB)

5.3 Performance Comparison of Contemporary Solid Bricks in Relation to the Historical Ones

The performance of todays handmade and factory solid bricks were compared and then discussed with the performance properties of historical bricks in Anatolia. Those bricks have been used to construct lightweight brick masonry superstructures, which have passed large spans and have proved their long-term durability with their survival for centuries. For the comparisons and discussions, the data on those Anatolian historical bricks belonging to the Roman, Anatolian Seljuk, Principalities and Ottoman Periods were evaluated and then compiled as the reference data.

The performance properties of historical bricks in Anatolia compiled from the literature were summarized in **Table 5.3** in terms of bulk density, porosity, water absorption capacity, vapor diffusion resistance index, ultrasonic pulse velocity, modulus of elascticity and uniaxial compressive strength. The performance properties of Anatolian historical bricks compiled from the results of ten historical buildings in Anatolia belonging to the Roman Period, Seljuk Period, Principalities Period and Ottoman Period presented a wide range of data on physical, physico-mechanical and mechanical properties (**Table 5.3**). Considering all, the bricks used in Anatolian Seljuk, Principalities and Ottoman Periods including the 2nd century BC Roman bricks present similar performance properties in terms of physical, physicomechnical and mechanical properties (**Table 5.3**). Those performance properties represent the specifications of historic brick technology that achieved to its advanced level in Ottoman Period. Those historical bricks are lightweight and highly porous bricks with enough mechanical strength. It is interesting that the ancient bricks belonging to Roman Period (2nd century BC) present similar properties with those historical bricks. On the other hand, the bricks belonging to the Byzantine Period in İstanbul seem to differ from the historical bricks belonging to the Anatolian Seljuk, Principalities and Ottoman Periods (**Table 2.4**). The Byzantine bricks are denser, less porous bricks with considerably higher physicomechnical properties and mechanical strength (**Table 2.4**).

In short, the basic performance properties of Anatolian historical bricks (**Table 5.3**) used as reference data are summarized below:

- bulk density values within the range of 1.28 and 1.80 g/cm^3,
- effective (total) porosity values within the range of 27 and 49% by volume,
- water absorption capacity values within the range of 15 and 38% by weight,
- water vapour diffusion resistance index (μ) within the range of 4 and 7 (unitless),
- thermal conductivity values within the range of 0.53 and 0.60 W/mK,
- specific heat capacity values within the range of 879 and 1038 J/kgK,
- ultrasonic pulse velocity values within the range of 879 and 1607 m/s,
- modulus of elasticity values within the range of 0.9 and 4.1 GPa,
- uniaxial compressive strength values within the range of 2.9 and 13.3MPa.

Table 5.3. The compiled data on basic physical, physico-mechanical and mechanical properties of historical bricks produced in Anatolia belonging to Roman Period, Seljuk Period, Principalities Period and Ottoman Period

Historical Structures	Construction Period	Location	Bulk Density	Porosity	Water absorption capacity	Water vapour diffusion factor - μ	Specific Heat	Thermal Conductivity	Ultrasonic pulse velocity	Modulus of elasticity	Uniaxial compressive strength
			g/cm^3	% by vol.	% by wt.	unitless	J/kgK	W/mK	m/s	GPa	MPa
Serapis Temple[1]	2nd c. BC Roman	Pergamon/İzmir	1.65	35.0	21.2	-	-	-	-	-	6.0
Tahir and Zühre Mescidi[2]	13th c. Seljuks	Konya	1.41	47.9	35.0	-	-	-	-	1.1	7.8
Güdük Minare Mescidi[3]	13th c. Seljuks	Konya/Akşehir	1.45	39.0	26.5	-	-	-	-	-	-
Çukur Hamam[4]	14th c. Principalities	Manisa	1.55	36.8	25.7	-	1038	0.53	1607	3.7	-
Gazi Mihal Bey Hamamı[5]	15th c. Ottoman	Edirne	1.65	35.8	21.7	-	-	-	1587	4.1	10.4
Hersekzade Paşa Hamamı[6]	15th c. Ottoman	Urla/İzmir	1.52	38.9	25.6	-	891	0.60	-	-	-
Yalınayak Hamamı[7]	16th c. Ottoman	Tire/İzmir	1.28	49.3	37.9	4.5	879	0.56	879	1.8	13.3
Sokullu Mehmet Paşa Hamamı[8]	16th c. Ottoman	Havsa/Edirne	1.70	31.0	18.2	-	-	-	884	1.2	2.9
	18th c. Ottoman	Havsa/Edirne	1.60	33.4	20.9	-	-	-	902	0.9	3.0
Yeni Hamam[9]	18th c. Ottoman	Sivrihisar/Eskişehir	1.43	43.0	30.1	4.4	-	-	1362	2.6	-
Ermeni Hamamı[10]	19th c. Ottoman	Sivrihisar/Eskişehir	1.80	27.2	15.1	6.5	-	-	1218	2.4	9.0
Bartın Kırtepe Mektebi[11]	19th c. Ottoman	Bartın	1.64	35.3	21.6	-	-	-	-	-	-

[1]: Aslan-Özkaya and Böke, 2009, [2]: Aktaş *et al*., 2006; Tuncoku *et al*., 1993, [3]: Tuncoku *et al*., 1993, [4]: Esen *et. al*, 2004, [5]: METU MCL, 2012, [6]: Tavukçuoğlu *et al*., 2008, [7]: METU MCL, 2005, [8]: METU MCL, 2018, [9]: Madani *et al*., 2017, [10]: Aslzad *et al*., 2018, [11]: METU MCL, 2013

The performance properties of those contemporary solid bricks used as repair bricks have to be similar with the performance properties of historical ones for their survival. However, the data describing the basic physical and mechanical properties of both handmade and factory solid bricks shows that only a few handmade bricks are included in the data ranges referenced for the historical bricks (**Figure 5.3**). These few handmade bricks are similar to the data of historical bricks with less bulk density and less porosity values in this reference range. The uniaxial compressive strength of the handmade bricks is higher than that of the historical bricks. Although the physical and mechanical properties of most of the historical bricks used in the construction of masonry superstructures and walls in historical buildings are lower than those of the handmade bricks, they are sufficient to survive for centuries. In short, today's handmade bricks are different from historical bricks in terms of their mechanical properties, although they appear to be products close to historical bricks in terms of their physical properties. The factory bricks, which are produced with and without compression, are completely different in terms of their mechanical properties compared to the historical bricks (**Figure 5.4**).

The data describing the water vapour diffusion resistant index (μ) values of contemporary handmade and factory solid bricks shows that handmade bricks are included in the data ranges of those reference values for the historic bricks (**Figure 5.4**). However, modulus of elasticity (E_{mod}) values of some contemporary handmade bricks are outside the reference values and E_{mod} values of the rest of these handmade bricks fall into the range of upper bound values of historic bricks. Although the modulus of elasticity property of not-pressed type factory brick (I.D.db.FB1) is similar with handmade bricks and close to the reference values, the breathing property of this brick is lower than that of historical and handmade bricks. Furthermore, pressed type of factory bricks are exceed the reference limits for both breathing and modulus of elasticity properties. These properties are considered for compatibility and durability of materials, which constitute the overall wall section. Modulus of elasticity is determined to define the relationships between physical and mechanical properties of materials. Similar modulus of elasticity is required since incompatibility of these materials used in the repairs may cause damage to historical masonry due to the break in homogenous continuity of those superstructures (RILEM, 2009; van Balen *et al.*, 2005).

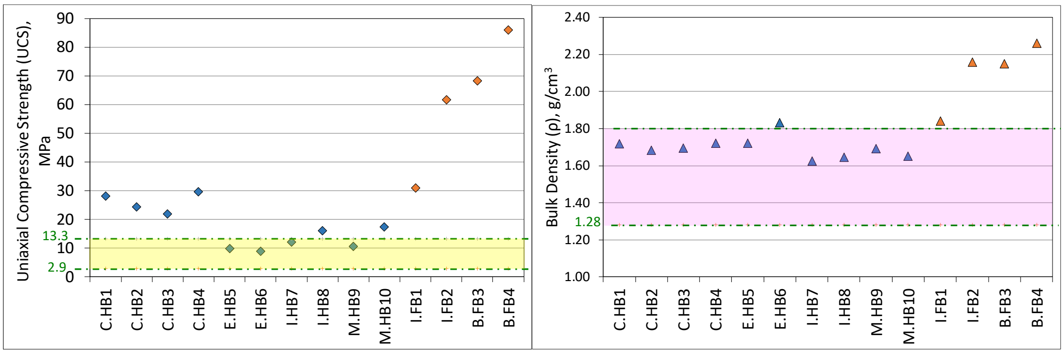


Figure 5.3. The reference range of bulk density values (1.28-1.80 g/cm^3, left) and uniaxial compressive strength values (2.9-13.3 MPa, right) for historic bricks were shown with the distribution of data for solid bricks

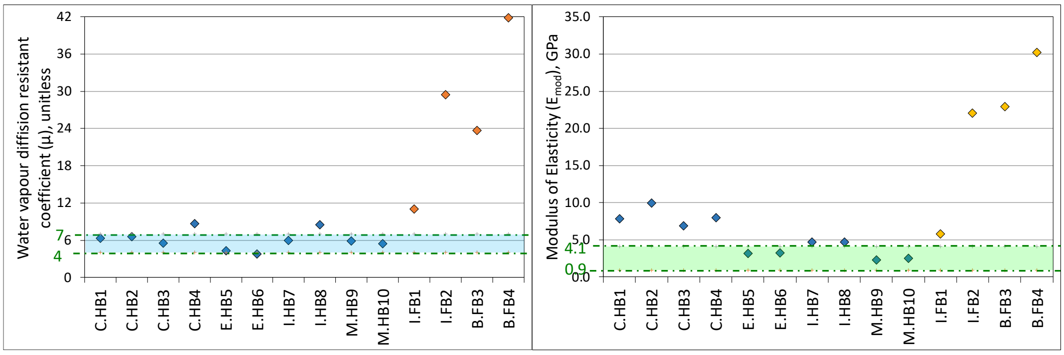


Figure 5.4. The reference range of water vapour diffusion resistant index values (4 -7, left) and modulus of elasticity values (0.9 - 4.1 GPa, right) for historic bricks were shown with the distribution of data for solid bricks

Performance properties of these brick materials, which is directly related with durability, can be evaluated by microstructural (porosity properties, which is also determined by water, and moisture related/hygric properties) and raw material properties, as well. The minerals inside the raw material and the firing temperature, which leads to physical and chemical changes, have an impact on pore structure of a material and the hygric behaviour in moisture related conditions. In order to discuss the similarities and differences between the historical bricks and today's bricks, there is a need for comprehensive analyses on the pore structure/microstructure and raw material properties of the historical and today's bricks.

The only thermal parameter, specific heat could be measured for the contemporary solid bricks. The data showed that the specific heat of contemporary handmade with a bulk density of 1.70 g/cm^3 and factory solid bricks with a bulk density of 2.19 g/cm^3 in average are similar with each other with the values of 618-823 J/kgK and 613-727 J/kgK, respectively. Those values are lower than the specific heat of historic bricks with a bulk density of 1.45 g/cm^3, which have the specific heat values in the range of 879-1038 J/kgK. In comparison to the historical bricks, the contemporary solid bricks have higher bulk density, higher thermal conductivity and lower specific heat. Such characteristics signal that factory solid brick are expected to have the highest thermal inertia and thermal diffusion characterictics while the contemporary handmade solid bricks are expected to have higher thermal inertia and thermal diffusion than the historical bricks.

5.4 Assessment of Porosity Characteritics of Contemporary Solid Bricks in Terms of their Hygric Properties

The water and moisture-related performance characteristics of contemporary solid brick samples are discussed by water saturation coefficient, fine porosity, critical moisture content and breathability features. The properties focused were porosity and pore structure characteristics, breathing capability, drying behaviour of both handmade and factory solid brick samples. The concluded results of these properties are as follows:

— The water saturation coefficients of the handmade brick samples ranged from 0.81 to 0.97. The saturation coefficient of the factory brick (I.D.db.FB1), which is only not-pressed type between the factory bricks, is 0.81 and the saturation coefficient of the factory bricks is between 0.99 and 1.00. These data show that both the handmade bricks and the factory bricks can reach a fast saturated level under conditions where they are exposed to water, and thus can be damaged by freeze-thaw cycles in cold climatic conditions. In this case, the protection of brick samples from the conditions directly exposed to water; for instance, it is necessary to protect the brick structure with the plastering of the external surfaces, the rainwater drainage systems that will quickly remove the rain and snow water from the building and its immediate surroundings. Among the types of bricks examined, those with a saturation coefficient above 0.88 may be expected to be slightly more sensitive to freezing-thawing cycles that is given in literature review.

— The ultrasonic velocities of the handmade bricks with high saturation coefficients were also increased (**Figure 5.5**). The samples with high saturation coefficients, in other words, that were wetted more rapidly when exposed to water, were found to have higher ultrasonic velocities. The handmade brick samples with higher ultrasonic velocity data have higher uniaxial compressive strengths (**Figure 5.2**). For example, although C.V.p.HB1, C.V.b.HB2, C.V.p.HB3, C.U.lb.HB4 and I.A.p.HB8 samples, compared to others, have a much more sensitive pore structure against frost (Saturation Coefficient Values>0.88), they were produced with better physico-mechanical and mechanical properties. This situation is interesting. The water saturation coefficient can be a useful measure to define the sensitivity of materials to frost in terms of the pore structure; however, it is understood that it is not a sufficient parameter in the studies evaluating the frost resistance properties and it will be beneficial to evaluate with ultrasonic velocity data.

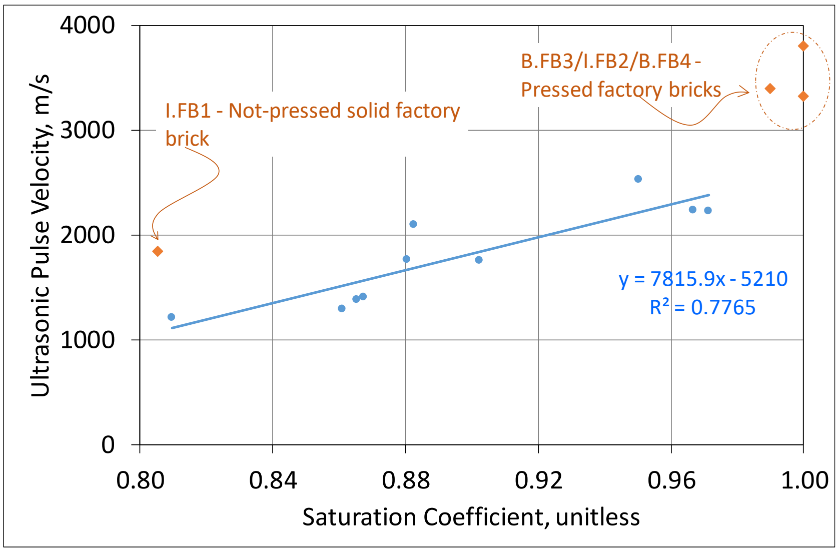


Figure 5.5. Graphs showing the relationship between ultrasonic pulse velocity and saturation coefficient of handmade bricks (HB) and factory bricks (FB)

— The fine porosity ($\varphi_{0.5\mu}$) of ten types of handmade bricks smaller than 0.5 micrometres (pore diameter<0.5μm) is between 0.14% and 2.12% by volume. The ratio of fine porosity to total porosity ($R_{0.5\mu}$) of these handmade bricks is found between 0.38% and 6.71%. The fine porosity ratio of these samples were distributed in three different ranges as 0.8±0.4%, 3.1±0.1% and 6.7±2.5% (**Figure 5.6**). Among these handmade bricks, E.A.db.HB6 has a fine porosity value up to 9.2%. This handmade brick, which has low ultrasonic velocity and high saturation coefficient, has much more fine porosity and lowest uniaxial compressive strength compared to other handmade bricks, suggesting that its resistance to deterioration cycles may be weaker.

— The fine porosity ($\varphi_{0.5\mu}$) of the pressed factory solid bricks smaller than 0.5 micrometers (pore diameter<0.5μm) is much less than that of the handmade bricks and the average is 0.06±0.01% by volume. The ratio of fine porosity to total porosity ($R_{0.5\mu}$) of these factory brick samples is also in the range of 0.5±0.1%. It is noteworthy that the fine porosity ratio of most of the handmade bricks and factory bricks are close to each other, even though they have less than one third less porosity and water absorption properties (**Figure 5.6**)

— The fine porosity ($\varphi_{0.5\mu}$) of the single sample not-pressed type bricks (I.D.db.FB1) is 0.07±0.01% by volume and corresponds to 0.23±0.04% of the total volume. Compared to other brick samples, the fine pore structure of the sample I.D.db.FB1 differs from the handmade bricks and other solid pressed factory bricks, since it has a minimum fine porosity and a minimum fine porosity ratio. The handmade brick sample, which appears closest to this fine porosity structure is M.S.lb.HB9. However, the handmade bricks sample M.S.lb.HB9 has the ability to dry faster than the not-pressed factory solid brick and to breathe more; their physical, physicomechanical and mechanical properties are very different from each other.

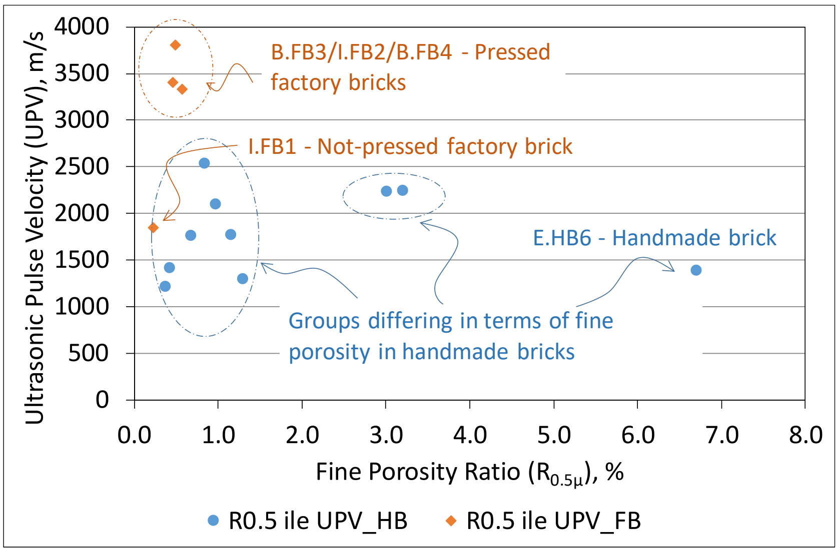


Figure 5.6. Graphs showing the relationship between fine porosity ratio ($R_{0,5\mu}$) and ultrasonic pulse velocity of handmade bricks (HB) and factory bricks (FB)

— The critical moisture content (θ_C) of the investigated handmade bricks is 8,78±1,50% (**Figure 5.7**). This value also refers to the percentage by volume of fine pores in the capillary size. The capillary pores correspond to 26±4% of the total pore volume. The critical moisture content (θ_C) of pressed factory bricks are 3.53±0.32% by volume. The capillary pores of these bricks constitute 29±3% of the total pore volume. That means capillary suction starts at lower moisture content around 3.5% by volume in pressed factory bricks compared to handmade bricks which have critical level at around 8.8% by weight.

— The critical moisture content (θ_C) of the not-pressed factory solid brick (I.D.db.FB1) produced without compression is 9,18±0.21% by volume and capillary pores constitute 31% of the total pore volume (**Figure 5.7**). This factory brick sample is similar to the handmade bricks according to critical moisture content and capillary porosity volume data. However, compared to handmade bricks, their fine porosity differs from the handmade bricks in terms of their volume, ratio of lower porosity, their breathability is weaker, and their uniaxial compressive strength is higher.

— Water vapour permeability is one of the most important measurable parameters of the breathing properties of materials. Breathing properties of brick samples, data obtained from water vapour diffusion resistance index (μ) and drying rate (R_{E2}) values, were discussed and evaluated together (**Figure 5.8**). Materials in contact with each other are composed of similar breathing properties is a compatibility feature that must be considered in repairs. Data from many studies investigating the historical bricks in Anatolia have shown that water vapour diffusion resistance index (μ) values in the range of 4-7 (unitless) can be considered as reference ranges given in **Table 5.3**.

— The water vapour diffusion resistance index (μ) of the investigated handmade bricks is 6.07±1.57, μ value of pressed factory solid bricks is 31.68±9.29 and μ value of not-pressed factory solid brick (I.D.db.FB1) is 11.03±0.06 (**Figure 5.8**). The μ values of handmade bricks are within the reference ranges (μ values) of historical bricks and it is understood that they are breathing brick products. The data showed that pressed factory solid bricks have similar μ values with cementitious plasters (Tavukçuoğlu *et al*., 2013;Williams and Williams, 1994) and that the handmade bricks could breathe five times more than factory bricks. The not-pressed factory solid brick (I.D.db.FB1) with a μ value of approximately 11 is a breathable product; however, it has a higher resistance to water vapour permeability, than historic bricks and handmade bricks.

— The drying rates (R_{E2}) of handmade bricks, solid pressed type factory bricks and not-pressed factory solid brick (I.D.db.FB1) are 0.017±0.005 kg/m^{2}h, 0.006±0.001 kg/m^{2}h and 0.014 kg/m^{2}h, respectively. These data showed that the damp handmade bricks dry out three times faster than the wet factory bricks of the same thickness that these results of breathing properties are also confirmed by water vapour resistance factor, similarly.

— Further analyses are needed to better identify/understand pore structure of those samples, particularly 3-dimensional distribution and reasons of high saturation coefficient. Those data show the presence and amounts of large pores in the fabric of brick. Having large size pores in larger amounts can provide advantage in terms of weathering cycles. Furthermore, the data is supported with the image analyses of cross-sections representing the texture and pore structure of each sample.

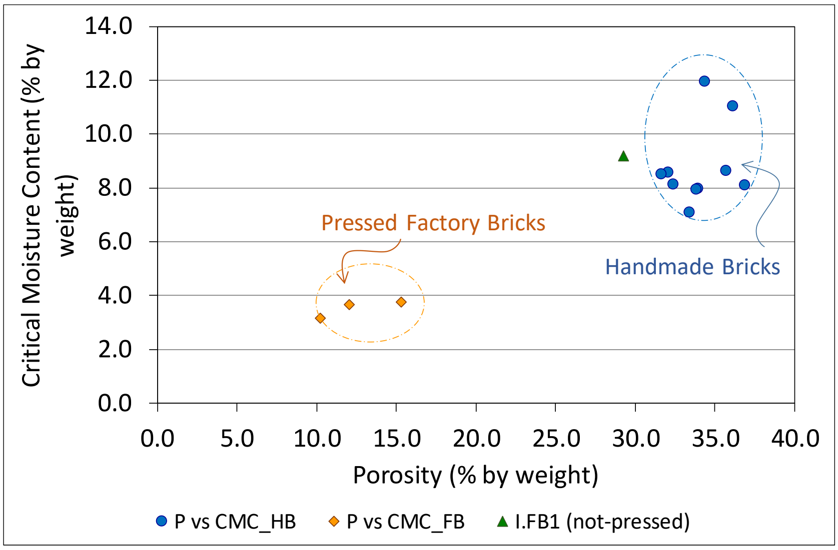


Figure 5.7. Graphs showing the relationship between porosity (φ) and critical moisture content (θ_C) of handmade bricks (HB) and factory bricks (FB)

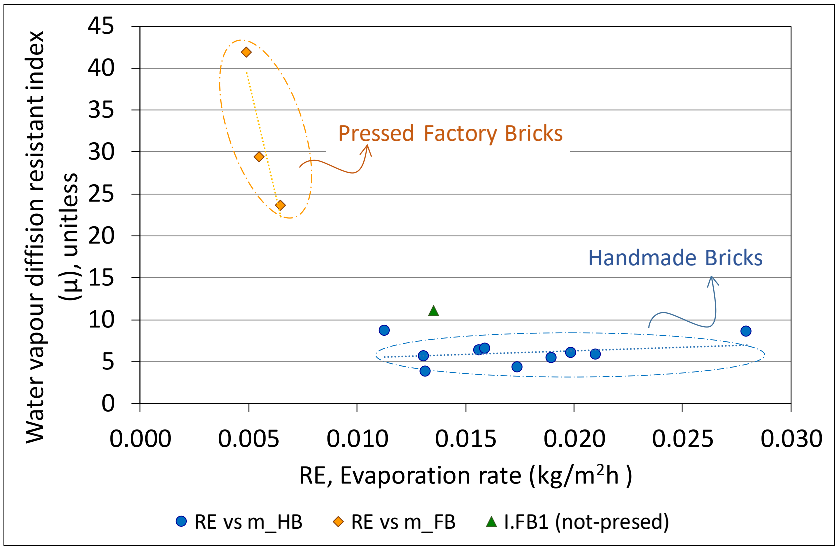


Figure 5.8. Graphs showing the relationship between evaporation rate (R_{E2}) and water vapour diffusion resistant index (μ) of contemporary solid bricks; handmade bricks (HB) and factory bricks (FB)

5.5 Guiding Remarks for the Improvement of Relevant Standards and Specifications for Qualified Handmade and Factory Solid Bricks

In 1970's the solid handmade brick products were required to have compressive strength in the range of 5.0 MPa and 2.5 MPa (TS 704: 1979). In the relevant Turkish standard, the solid bricks were defined as the masonry units without holes or perforation in its cross section while the hollowed bricks were defined as the masonry units with vertical holes covering at most 25% of the unit volume. Although the bulk density values of hollowed bricks were given, this property is given as not limited for solid bricks. The basic physical properties, such as bulk density and porosity, of solid handmade bricks have not been defined in the standard while the only materials specification was the uniaxial compressive strength of brick units.

In 1980's, the definition of handmade bricks was removed in the text of standard (TS 705:1985) and all solid bricks were mentioned as factory bricks. In the relevant standard, the types of solid bricks were classified in two groups depending on their bulk density ranged from 1.6 and 2.0 g/cm^3 and compressive strength values range from 12.3 and 17.6 MPa. Here the definition of solid bricks were defined as the units with or without hole/perforation covering at most 15% of unit volume. Therefore, this standard does not mention the specification and manufacturing process for handmade bricks.

In 2000's the European standard (EN 771-1) substituted for TS 704 and TS 705 and TS EN 771-1 was defined as 'Specification for masonry units – Part 1: Clay masonry units'. The definition of bricks has been changed by TS EN 771-1 that specifies the characteristics and requirements of the clay masonry units either loadbering or non-loadbearing. However, the new terms and definitions does not correspond to handmade bricks that means there is no valid standard for these solid bricks. Turkish Standards, which are directly related with handmade and solid factory bricks, are either withdrawn or cancelled. Handmade bricks may be evaluated in TS EN 771-1 as both P and U units, which are protected and unprotected unit types according to their use in masonry. Nevertheless, these bricks should be kept away from adverse conditions, which cause direct water penetration and absorption. Comprehensive analyses related with porosity and hygric properties; such as, saturation coefficient, fine porosity, critical moisture content, evaporation rate and water vapour permeability are conducted on contemporary solid burnt bricks to assess their durability properties. These parameters should be included in the standards. The firing temperature, raw material and compositional properties have an impact on the material properties of bricks that need to be determined in the manufacturing process. The results of these properties should be considered to be used as a reference data for production of contemporary solid bricks. The standards must specify the requirements of these properties for production and manufacturing process.

The literature survey shows that there are lack of studies and standards for material characteristics of contemporary solid bricks based on an investigation of today's brick technology. Nowadays, two types of solid bricks; handmade and factory solid bricks (pressed and not-pressed) are produced to use in the repair works of historical buildings. However, handmade bricks are the ones which are produced by traditional methods used for many years. After the development of brick production technology, solid brick production has been started by mass manufacturing in factories. The convenience of factory solid bricks instead of handmade bricks is evaluated that their material properties and production technologies clearly differ from each other. The results show that it is difficult to produce brick that appears handmade or historic on present day equipment since the technological evolutions for brickmaking differs from traditional processes such as, raw materials, molding operations and firing practices. For this reason, there is a need for producing new standards or specifications especially for those repair works of historic bricks. Another conservative approach is to determine the material properties of historic bricks specifically to obtain reference data for the replacement of these bricks before making any intervention. In addition, handmade and solid brick production must become widespread in the view of such information. Further analyses are needed to constitute the reference data for qualified handmade brick into Turkish standards.

CHAPTER 6

CONCLUSION

This research is conducted to reveal the performance properties of contemporary solid bricks, their potentials and weaknesses in terms of their compatibility with the historical ones since they are commonly-use for repair purposes and to improve technological knowledge on the production of qualified solid bricks. In this regard, material properties of contemporary solid bricks, namely handmade, solid pressed and solid not-pressed factory bricks, representing today's some handmade and factory production technologies were investigated in terms of physical, physico-mechanical, mechanical and raw material properties. The porosity characteristics of these bricks were examined in detail by water and moisture related properties. In addition to the laboratory analyses, a comprehensive review on the performance properties of the historical bricks given in literature was done and the knowledge on the materials specification on qualified historical bricks which have proved their long-term durability were considered as the reference data for comparisons.

The analyses exhibited the similarities and differences among the contemporary hand-made and factory-made pressed and not-pressed solid bricks as follows:

- The handmade solid bricks are lightweight and very porous bricks with highly breathable properties. Those bricks present similar basic physical properties while their physicomechanical and mechanical performances vary in a certain extent.
- Compared to handmade bricks, the factory-made pressed solid bricks are considerably more dense, less porous, less water absorptive brick types with considerably-higher mechanical strength. On the other hand, the factory pressed bricks get wet faster when exposed to water due to lower critical moisture level and dry out slower than the more porous handmade bricks.

- The factory-made not-pressed solid brick (I.D.db.FB1), on the other hand, has similarities with the handmade bricks in terms of basic physical, physico-mechanical and mechanical properties, especially with the ones having higher bulk density, lower porosity and higher mechanical strength, such as CHB1-HB4.
- The factory-made not-pressed solid brick (I.D.db.FB1) is a breathable brick product due it low resistance to water vapour permeability. However, it is not as highly-breathable as hand-made bricks and particulary this performance property differs it from the handmade solid bricks.
- The water saturation coefficient values of all handmade and factory solid bricks are very high. That property signals that all these contemporary solid bricks can get wet fastly when exposed to water and are under risk of frost damage in very cold and humid weathers. Having higher level of critical moisture content can be an advantageous feature for the hand made bricks that can slow down water absorption by capillary suction. Having higher physicomechnaical properties and mechanical strength can be advantegous features for the factory solid bricks that make them more durable against freezing-thawing cycles compared to the handmade bricks.
- Only a few of the handmade solid brick samples, namely the brick samples I.A.r.HB7, M.S.lb.HB9, M.S.p.HB10, are considered to have better porosity characteristics due to their higher effective porosity, lower fine porosity and higher drying rate than the others. Those porosity features are expected to strengthen the resistance of those bricks against frost damage.

— The handmade bricks, which are fired between 750 and 900°C, have quartz, plagioclase feldspar, hematite, calcite and clay minerals in common. Diopside and gehlenite minerals are seen in handmade bricks fired at higher temperatures above 800°C. Despite these temperatures, all handmade bricks are highly pozzolanic materials. Pozzolanic activity can be attributed to the use of natural or artificial pozzolans fired up to 850°C. The pozzolanic activites of these brick samples enhance the physical, mechanical and durability properties of these bricks due to the calcium silicate hydrate (C-S-H) networks in the presence of water and moisture.

— The factory solid bricks, which are fired between 900 and 1050°C, have quartz and hematite minerals in common. High temperature phases like diopside and cristobalite minerals are seen in these bricks. Plagioclase feldspar is lost in some pressed factory bricks due to high firing temperatures. Although, these bricks are fired at considerably higher temperatures, they are still highly pozzolanic materials. In this case, there is a contradiction between pozzolanic activity and high firing temperature. Besides, clay sized aggregates, such as volcanic dust and fly ashes may be used as natural pozzolanic additives or kaolinite type of clays in the mixture like metakaolin may be used as artificial pozzolanic additives in the raw materials. Further analyses are needed to find out the type of pozzolanic additives, raw materials and the effect of particle sizes in the clay matrix.

The analyses exhibited the similarities and differences between the contemporary handmade bricks and historical bricks as follows:

- The contemporary handmade bricks have basic physical properties similar to the historical ones in terms of bulk density, porosity and water absorption capacity.
- Water vapour permeability properties of handmade bricks are also similar to historic bricks that means contemporary handmade bricks are breathable products.
- On the other hand, the physicomechanical and mechanical properties of contemporary ones fall into the upper ranges of the data achieved for historical bricks, and above that range. This means that some contemporary handmade bricks have ultrasonic pulse velocity, modulus of elasticity and uniaxial compressive strength similar with the historical bricks while the others have higher physicomechanical and mechanical strength than the historical bricks.
- The contemporary handmade bricks have lower specific heat capacity than historic bricks. Based on the estimated thermal effusivity and thermal diffusivity properties, contemporary handmade bricks differ from historic bricks in terms of thermal properties.

Considering the varieties in physical, physicomechanical and mechanical properties of contemporary handmade brick samples, it is observed that some handmade brick samples with lower bulk density and higher porosity provide higher mechanical strength than the ones with higher bulk density and lower porosity. Such performances are also observed in historical bricks. The historical bricks are well-known with their lightweight, highly-porous, -breathable and -pozzolanic characteristics while providing enough strength for their use in historic building wall and superstructure constructions. Those particular characteristics of historical bricks are related with conscious selection of raw materials and firing temperature. Among today's handmade bricks, there are few samples, having similar properties with historical bricks, therefore fulfilling the requirements expected from repair bricks. The results of the study exhibited that illlite and/or kaolinite type of clays, presence of calcite, removal of soluble salts in the clay mixture and firing temperature below 850°C contribute to the qualified properties of historical bricks. However, further studies on micro and nano structure of clay mixtures and fired-clay product are needed to discover the impact of raw materials and mineralogical composition of clay mixture to the qualified pore structure of solid bricks resulting in particular and long-term performances.

The long-term durability of the contemporary brick masonry structures is also related with the type and performance properties of joint mortar. As learnt from the historical structures, the lime-based mortars with pozzolanic additives have been used to build up masonry walls and superstructures and the compatibility between brick and mortar contributes to the long-term durability of brick masonry. In today's constructions, contemporary solid bricks are used together with cement based or cement-lime mixed mortars. Such an application results in dampness and salt deposit problems. Therefore, further analyses are needed to define performance and raw materials characteristics for the joint mortars compatible with today's solid bricks and to improve the standards related with the specifications on performance properties of joint mortars and their preparation.

Saturation coefficient shows the critical level of water saturation, in other words threshold percentage of voids in porous material above which frost or freezing-thawing actions damage its inherent pore structure. This parameter can be used as a practical index to estimate frost resistance particularly for natural stones while its reliability is still under discussion according to some researchers (Topal and Sözmen, 2003; Ordonez *et al*., 1997). For the burnt-clay brick samples, the reference saturation coefficient value of 0.8 is used in this study for the evaluation of frost damage susceptibility in relation to saturation coefficient data. However, this reference value may vary in the range of 0.70 and 0.85 depending on the inherent pore structure of natural stones (Topal and Doyuran, 1998; Chen *et al*., 2004; Al-Omari *et al*., 2015). Studies on bricks mention that saturation coefficient in the range of 0.75 and 0.80 can be the threshold level to define the susceptibility of bricks to frost damage. (Hansen and Kung, 1988). Considering the variety of brick types and evolution of brick manufacturing in time, further studies are needed to discover saturation coefficient ranges for different types of bricks and to examine other measurable parameters related with pore structure for durability assessment.

Understanding 3-dimensional pore structure of these bricks is important for the assessment of durability properties. However, the commonly-used standard testing methods to identify the pore structure of solid bricks, such as mercury porosimetry, is a destructive testing method in certain extent since the technique uses various pressure for mercury intrusion into the matrix of soft brick product and the intrusion process destroys the existing pore structure. However, the practical testing methods in laboratory, such as fine porosity, critical moisture content, evaporation rate and saturation coefficient tests as well image analyses of cross sections, produce data on fine porosity characteristics of fired-clay products. Therefore, the joint interpretation of hygric properties and magnified images are useful to examine the durability properties of brick products.

The findings and evaluation of the data presented the hints to improve the TS standards related with handmade and factory solid bricks. Briefly, the involvement of crucial measurable parameters, such as ultrasonic pulse velocity, saturation coefficient, water vapour diffusion resistance factor and fine porosity ratio index, into the content of is necessary for the preparation of qualified solid bricks. The data obtained in this study is useful for defining the performance properties of contemporary solid bricks and for the development of relevant standards.

All things considered that it is suggested to use qualified handmade bricks as repair bricks in historic masonry. Qualified repair bricks should be produced less dense, highly porous, highly breathable and highly pozzolanic and have enough mechanical strength compared to existing products. There is a necessity to define porosity characterisitics in standards to achieve long-term durable handmade bricks. There are some specific parameters to define the porosity structure of brick material. Among handmade bricks, only some of them exhibit preferred porosity characteristics to be more durable since they have higher effective porosity, lower fine porosity, high drying rate and lower water vapor resistance factor and enough mechanical strength. In addition to these parameters, ultrasonic velocity testing should be used to reveal the relationship between these porosity and mechanical properties. The minerals inside the raw material should also be taken into consideration in the preparation of repair bricks since they have an effect upon the porosity properties. Apart from these suggestions, the performance properties of historical bricks should be considered as the specifications for the compatible repair bricks The material properties of historic bricks and the compatibility properties with neighbouring materials should be identified before intervention.

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APPENDIX

LIST OF CONTEMPORARY SOLID BRICK SAMPLES INCLUDING THE COMPANY NAMES OF THEIR MANUFACTURERS

Table A. List of contemporary solid brick samples including sample code, produced city, the company names of manufacturers, color and sample description

Sample CODE	CITY - where brick samples are produced	COMPANY NAME - Manufacturer	Color of brick samples	DESCRIPTION
C.V.p.HB1	**Ç**orum (Merkez)	**V**ESFA	**p**ink	**H**and-made fired brick
C.V.b.HB2	**Ç**orum (Merkez)	**V**ESFA	**b**rown	**H**and-made fired brick
C.V.p.HB3	**Ç**orum (Merkez)	**U**ÇAK	**p**ink	**H**and-made fired brick
C.U.lb.HB4	**Ç**orum (Merkez)	**V**ESFA	**l**ight **b**rown	**H**and-made fired brick
E.A.r.HB5	**E**skişehir – (Sakintepe)	**A**RDA	**r**ed	**H**and-made fired brick
E.A.db.HB6	**E**skişehir – (Sakintepe)	**A**RDA	**d**ark **b**rown	**H**and-made fired brick
I.A.r.HB7	**İ**zmir – (Torbalı/Subaşı)	**A**KPINAR	**r**ed	**H**and-made fired brick
I.A.p.HB8	**İ**zmir - (Torbalı/Subaşı)	**A**KPINAR	**p**ink	**H**and-made fired brick
M.S.lb.HB9	**M**anisa – (Muradiye)	**S**OĞUKPINAR	**l**ight **b**rown	**H**and-made fired brick
M.S.p.HB10	**M**anisa - (Muradiye)	**S**OĞUKPINAR	**p**ink	**H**and-made fired brick
I.D.db.FB1	**İ**zmir – (Torbalı)	**D**OĞANAY	**d**ark **b**rown	Solid and Not-Pressed **F**actory **B**rick
I.D.r.FB2	**İ**zmir – (Torbalı)	**D**OĞANAY	**r**ed	Solid and Pressed **F**actory **B**rick
B.I.r.FB3	**B**artın – (Ağdacı)	**I**ŞIKLAR	**r**ed	Solid/pressed **F**actory **B**rick
B.I.gb.FB4	**B**artın – (Ağdacı)	**I**ŞIKLAR	**g**reyish **b**rown	Solid/pressed **F**actory **B**rick