Chapter 3
Ancient Clay Bricks: Manufacture and Properties

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3.1 Introduction

Clay brick masonry is one of the oldest and most durable construction techniques used by mankind. Masonry consists of manually built stable stacks of small elements, with or without mortar. It was a fundamental building material in the Mesopotamian, Egyptian and Roman periods. During the Roman period, the use of clay brick increased and became specialized in order to maximize its benefits. Clay brick masonry continued to be used during medieval and modern times. Despite several modifications of the clay brick uses, shape and manufacture along thousands of years of constant evolution, the simplicity that made its success remained.

Numerous buildings built with clay bricks prevailed until the 21st century, which testifies to the strength of this material along centuries of rain storms, snow, thaw-freezing cycles, high temperatures and human induced deterioration. Moreover, brick could be easily, inexpensively and rapidly handled and produced with a simple manufacturing process. It is based on fired clay, a raw material available in large quantities all over the Earth. Its wide use proved that clay brick was an effective construction material that could provide both resistance to prevalent climatic conditions and insulation from cold and heat.

It is known that the properties of ancient clay brick masonry rely essentially on the properties of the brick units, which depend on the quality of the raw materials used, together with the manufacturing process technology. The analysis of clay brick production and final properties are therefore fundamental. Generally, it is crucial to obtain information on the main physical, chemical and mechanical properties of clay bricks as well as the characteristics of the raw materials used and their manufacturing process.

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A large number of studies exist dealing with ancient structures and materials, fostered by the immense cultural and economic importance given to ancient monuments. Most of them have focused on the physical, chemical and mineralogical composition of ancient clay bricks (López-Arce et al. 2003; Cardiano et al. 2004; Pauri et al. 1994), durability and deterioration agents (Wijffels and Nijland 2004), neglecting the mechanical properties, which are more frequently retrieved in the case of the composite material (Binda et al. 2000a, b). Despite the importance of mechanical properties and its relevance for the resistance and durability of masonry, only a few of the published studies focus on the mechanical properties of clay bricks (Papayianni and Stefanidou 2000; Baronio and Binda 1985). In fact, the compressive strength of clay bricks is usually related to other properties, such as porosity and firing temperature, which are key parameters for durability (Cultrone et al. 2000) but can markedly affect the mechanical resistance of bricks (Cultrone et al. 2004).

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As the properties of ancient bricks vary considerably in terms of raw materials, production methodology and period, attention here is paid to clay brick production and analysis of its properties in numerous examples recovered from a literature study and from samples of old bricks taken from six Portuguese monuments (Church of Outeiro, OU, Monastery of Pombeiro, PO, Monastery of Salzedas, SA, Monastery of São João de Tarouca, TA, Monastery of Tibães, TI and the Christ Cloister in Tomar, TO) dated to the period of 12th–18th centuries. The main physical, chemical and mechanical properties were determined.

Instead of the laboratory testing of highly invasive uniaxial compressive strength, a new on-site minor-destructive-technique to assess the drilling resistance of old clay bricks was tested.

3.2 Manufacturing Process

The manufacture of fired clay bricks can be divided into four stages according to basic principles followed during thousands of years. Firstly, the extraction and preparation of the raw clay takes place. As soon as the raw material is extracted, it is accumulated and moved to an open air storage area. During this period, the raw material is rummaged in order to reduce soluble salts to a minimum, leading to a more homogeneous material. The analysis of the constituents of historic bricks that have survived up until our day showed that they were not always produced using treated clays. In some cases, bad quality clays were used. Vitruvius (1960) stated, in the 1st century B.C., that the choice of the raw material was essential to improve the performance and durability of the bricks. Despite this fact, the selection of raw materials depended mostly on its availability at the construction location or nearby (Álvarez de Buergo and Limón 1994).

After storage, clay is further crushed and mixed with water, in an operation designated as tempering. In the early times, the mixing was carried out by hand, in a crude and often ineffective manner; but, later, horse-driven heavy rollers or wheels in a ring-pit were used. The amount of water used depends on the type of element being produced and, usually, smaller and thinner clay elements would require a greater amount of water. The resulting mix must be characterized by enough plasticity to facilitate the molding, but not “too plastic”, as it can lead to severe shrinkage during the drying phase, resulting in warping, twisting or cracking. In this case, plasticity of the clay can be reduced adding sand, for example. Early brick makers often used a mix of about 30% of sand and 70% of plastic clay (Weaver 1997; Vekey 1998). The moulds in the past were bottomless wooden moulds placed down over the ground or over tables, which usually were protected with a thin film of sand in order to avoid letting the brick remain attached to the bottom base during the drying process. The excess clay was removed with the aid of a rope, wooden ruler or with bare hands.

The still crude clay elements were removed from the mould and dried in a covered space, which was generally a shelter made of scraps of wood and with a straw thatched roof: these shelters were known as hovels. Although inexpensive, this primitive method required a lot of open free space and was severely conditioned by climatic conditions. Generally, drying of clay bricks lasted for a week or more. In hot temperature regions, drying was faster but bricks had to be protected from direct sunlight since they could undergo warping and cracking. In colder regions, drying took more time due to the low temperatures and moisture conditions. The importance of the drying phase was mentioned by Vitruvius, who wrote that “bricks should be made in Spring or Autumn, so that they may dry uniformly”. Moreover, a too fast drying hardened the surface faster than the core, which remains crude for a longer time. Again, Vitruvius stated that bricks “made in summer are defective, because the fierce heat of the sun bakes their surface and makes the brick seem dry while inside it is not dry”.

Finally, the last stage was the hardening of the bricks in order to acquire additional resistance. Bricks were further sun dried, in the open air, or were put in a kiln or clamp with temperatures in the order of 1,000ºC, where they were fired, acquiring in this way much more resistance from both a mechanical and chemical point of view. Early kilns used wood or straw as combustibles and took several days to finish combustion. Coal was not commonly used until the last quarter of the 19th century. During this phase, complex chemical reactions took place, creating diverse ceramic products, according to the firing temperature and the quality of the clay. The firing conditions were crucial for the final properties of bricks, whose quality strongly affects the strength and durability of the masonry. According to Vitruvius, sun-dried clay bricks needed a minimum of two years to dry. To illustrate this statement, he gave the example of Utica, where the clay bricks used to build the walls had to be five years old. Here, attention is focused on fired clay bricks only.

3.3 Properties of Fired Bricks

Clay bricks exhibit a set of properties that are important in the evaluation of strength and durability. The properties are closely related to the quality of the raw clay and directly associated with the conditions of manufacture.

When working with old clay bricks, additional parameters related to weathering mechanisms, material ageing and long term effects must be considered, like cracking, peeling or efflorescence. These effects are usually increased by atmospheric agents such as wind and water. Thus, the properties exhibited today by old clay bricks do not necessarily represent their original properties.

Nevertheless, the physical, mechanical, chemical and mineralogical parameters are relevant to the evaluation of the durability and resistance of old clay bricks.

3.3.1 Physical Properties

3.3.1.1 Porosity

Firing of clay bricks produces a series of mineralogical, textural and physical changes that depend on many factors that influence porosity. Porosity can be defined as the ratio between the volume of void spaces (pores and cracks) and the total volume of the specimen. Porosity is an important parameter concerning clay bricks due to its influence on properties such as chemical reactivity, mechanical strength, durability and the general quality of the brick.

Old clay bricks exhibit high porosity values, ranging between 15 and 40 vol.% (Esbert et al. 1997). The porosity of bricks from the Byzantine period was reported to be between 15 and 35 vol.%, while 70–80% of the pores had a diameter size of 70–250 µm, independently of the type and origin of the clay (Papayianni and Stefanidou 2000). Livingston (1993) reported that the porosity of bricks in the Church of Hagia Sophia is in a range of 26–30 vol.% for the red coloured bricks and 40–55 vol.% for the beige ones; while Maierhofer et al. (1998) obtained porosity values between 21 and 35 vol.% in bricks from the 9th–10th and 13th centuries, respectively. Fernandes (2006) reported the value of porosity of clay bricks from the 12th to 18th centuries as ranging from 12 to 43 vol.% with a mean value of 18 vol.%. In this case, around 80% of the samples exhibited a porosity larger than 25 vol.% and the vast majority between 25 and 35 vol.%, as illustrated in Fig. 3.1.

The dimension and distribution of the pores is influenced by the quality of the raw clay, the presence of additives or impurities, the amount of water and the firing temperature. Mamillan (1979) and Cultrone et al. (2004) observed that if the firing temperature increases, the proportion of large pores (3–15 µm) increases and the connectivity between pores is reduced, whereas the amount of small pores diminishes. This has a strong impact on the durability of the bricks as it has been shown that large pores are less influenced by soluble salts and freeze/thaw cycles. Furthermore, several studies by Cultrone et al. (2004) and Elert et al. (2003) reported that the formation of small pores, with a diameter below 1 µm, is promoted by carbonates in the raw clay (low quality material) and by a firing temperature between 800 and 1,000°C. Such pore sizes negatively influence the quality of the bricks, as their capacity to absorb and retain water increases. A similar conclusion was given by Winslow et al. (1988) for bricks with a pore size smaller to 1.5 µm.

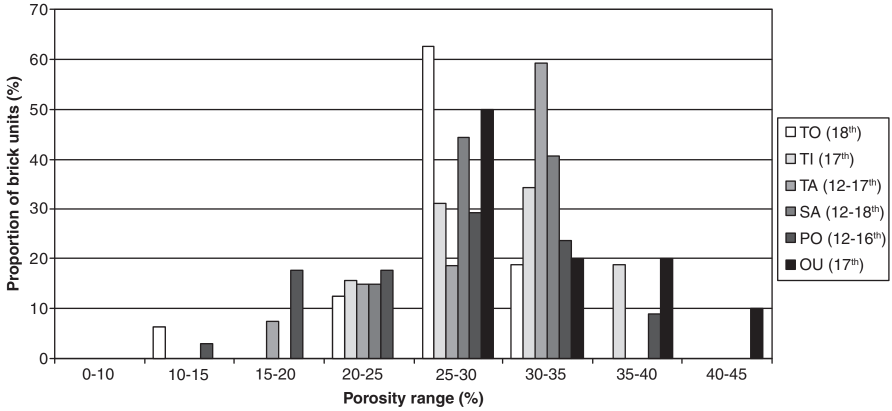

Fig. 3.1 Distribution of porosity for the complete set of clay bricks (Fernandes 2006)

3.3.1.2 Apparent Density

Apparent density is described as the ratio between the dry brick weight and the volume of the clay brick, measuring the proportion of matter (clay) found in the volume. It is evident from this description that the higher this value is, the denser the brick is, and obviously, the better its mechanical and durability properties are. Typical values for the apparent density range from 1,200 to 1,900 g m^{-3} (Table 3.1).

3.3.1.3 Water Absorption

Pores constitute a large part of the brick's volume, and when the bricks are exposed to rainfall or rising damp, water generally penetrates into the pores. Water absorption then determines the capacity of the fluid to be stored and to circulate within the brick, favouring deterioration and reduction of mechanical strength. In countries where temperatures fall below 0°C, the water inside the pores can freeze leading to surface delaminations, disintegration or cracking. Moreover, in the presence of soluble salts, water tends to react with them and to cause efflorescence. Though this is mostly an aesthetic deterioration of the surface of the brick, the volume increase caused by the crystallization of the salts can cause severe damage.

The values found in the literature are significantly scattered, with a large quantity of bricks with higher than average water absorption rates. Binda et al. (2000b) reported different absorption rates with respect to the colour exhibited by 8th–13th century bricks from the bell-tower of the Cathedral of Cremona, Italy. Brown and red bricks were found to have a water absorption of about 20.1 and 24.9 wt.%. In bricks from the 9th–10th centuries, values of water absorption between 18 and 19 wt.% were found, whereas values of 12 and 24% were attributed to bricks from the 13th century (Maierhofer et al. 1998). Moreover, clay bricks from the 12th to 18th centuries (Fernandes 2006) exhibited values between 6 and 32 wt.%,

Table 3.1 Typical values of apparent density of old bricks

Period (century)	Monuments and their location	Apparent density (kg m^{-3})	References
1st–5th	Walls, pillars, vaults and ovens of buildings	1400–1900	Papayianni and Stefanidou (2000)
3rd–4th	Church of S. Lorenzo, Milan, Italy	1550–1650	Baronio et al. (1985), Baronio and Binda (1985)
6th	Basilica of Hagia Sophia, Turkey	1600–2000	Livingston (1993)
9th–10th	Bricks of the Church of S. Maria Rossa	1600	Maierhofer et al. (1998)
12th–13th	Bricks from the city of Toledo, Spain	1600	López-Arce et al. (2003)
13th	Bricks of the Church of S. Maria Rossa	1830	Maierhofer et al. (1998)
13th–14th	Bricks from the city of Toledo, Spain	1510	López-Arce et al. (2003)
12th–16th	Monastery of Pombeiro	1680–1840	Fernandes (2006)
12th–17th	Monastery of São João de Tarouca	1710–1820	Fernandes (2006)
15th–16th	Church of S. Maria Incoronata, Milan, Italy	1550–1850	Baronio and Binda (1985)
16th	Clay bricks from Italian buildings	1550	Bati and Ranocchiai (1994)
17th	Church of Outeiro	1700–1780	Fernandes (2006)
17th	Monastery of Tibães	1680–1790	Fernandes (2006)
17th–18th	Cloister of the Church of S. Eustorgio, Milan, Italy	1650	Baronio and Binda (1985)
18th	Monastery of Salzedas	1550–1870	Fernandes (2006), Lourenço et al. (2000)
18th	Christ Cloister in Tomar	1560–1800	Fernandes (2006)

with an average value of 17 wt.%, and more than 90% of the values in the range 10–25 wt.%.

Another relevant parameter is the velocity of water absorption, measured by suction rate. The water is sucked by the pores as a result of capillary tension along the walls of the pores. López-Arce et al. (2003) pointed out that tension is stronger in small pores than in large ones. Generally, old bricks exhibit absorption values between 0.5 and 3.5 kg m^{-2} min^{-1}, which were further confirmed by Fernandes (2006), who reported values in the range 0.7–2.5 kg m^{-2} min^{-1}.

3.3.1.4 Moisture Expansion

The expansion or shrinkage observed in clay bricks can be partially or totally reversible due to wetting/drying, being not so relevant for old clay bricks. Moisture expansion in clay bricks is influenced by the contents of argillaceous minerals and by the presence of lime nodules. Typical values of 0.1–0.2% were indicated by Álvarez de Buergo and Limón (1994) and Esbert et al. (1997).

3.3.2 Mechanical Properties

Masonry is a heterogeneous material, and therefore its compressive strength depends on the strength of the components: brick, mortar and brick-mortar interface. Nevertheless, experimental results indicate that masonry compressive strength is mostly influenced by the strength of the brick units. Therefore, brick mechanics is very relevant to the safety assessment of existing brick masonry structures. The mechanical properties of old bricks are frequently reported in the literature, so it is possible to gather a large amount of data.

In traditional masonry shapes, such as columns, walls, arches and vaults, bricks are mostly subjected to compressive stresses. The adopted structural shapes for these elements make full use of properties of clay bricks, namely reasonable strength in compression and low strength in tension.

3.3.2.1 Compressive Strength

Compressive strength is strongly influenced by the characteristics of the raw material and by the production process. It is known that the raw clay of old bricks was often of low quality and the manufacturing process was relatively primitive and inefficient. Other characteristics of existing old bricks can provide an indication about compressive strength, such as mineral composition, texture, crack pattern and porosity level, by revealing the conditions of drying and firing.

On the other hand, the evaluation of the mechanical strength of bricks belonging to old buildings is often difficult due to the high variability in production and additional variability caused by deterioration from the weather or chemical agents such as soluble salts, freeze–thawing cycles or load–unload cycles. Moreover, clay bricks in a given structural element or building can belong to different construction periods or productions. Finally, the experimental test set-up conditions (dimensions and moisture content of the sample, boundary conditions, temperature, etc.) can also influence the results. According to Pauri et al. (1994), the original properties of old clay bricks would only be obtained through the manufacture of bricks using traditional methodologies and raw materials recovered from indications in archives, which is impossible. The range of values found in the literature is quite wide (about 1.5–32 MPa), meaning that in situ testing or destructive testing of samples must be carried out when the compressive strength of the brick is required. Typical values of the compressive strength are reported in Table 3.2, even though they have been obtained using different testing equipments and procedures.

A wide range of compressive strengths was reported by Fernandes (2006) on clay bricks from six monasteries in Portugal that were built during the 12th–18th centuries period. The selection of the buildings was made according to the works being carried out by the University of Minho in these locations, and as a means to provide a broad knowledge on Portuguese clay bricks. It must be noted that most bricks were collected from vaults, buried remains, soil deposits and infill material, while clay bricks from two particular monasteries were obtained from building ele-

Table 3.2 Typical values of uniaxial compressive strength and modulus of elasticity of old bricks

Period (century)	Monuments and their location	Uniaxial compressive strength (MPa)	Modulus of elasticity (GPa)	Reference
1st–5th	Walls, pillars, vaults and ovens of buildings	9.2–18.0	n. d.	Papayianni and Stefanidou (2000)
1st–5th	Monuments from the Byzantine period	n. d.	2.6–10.8	Papayianni and Stefanidou (2000)
8th–13th	Bell-tower of the Cathedral of Cremona, Italy	8.0–25.4	1–4.4	Binda et al. (2000a, b)
11th–13th	Vaults of Our Lady Monastery, Magdeburg, Germany	13.1–14.1	n. d.	Marzahn et al. (2004)
13th–17th	Siena's exterior wall, Italy	27.9	5.8	Barbi et al. (2002)
15th	Pienza Episcopal Palace, Italy	n. d.	7.3–18.6	Barbi et al. (2002), Bati and Ranocchiai (1994)
15th	Colle Val d'Else exterior wall, Italy (1479)	19.9–30.0	4.1	Barbi et al. (2002), Bati and Ranocchiai (1994)
16th	Hospital of Las Cinco Llagas de Sevilla, Spain	14.3–32.9	n. d.	Barrios et al. (2000)
	Monastery of Monte Oliveto Maggiore library wall, Italy	31.1	6.3	Barbi et al. (2002)
	Bell-tower of the Cathedral of Monza, Italy, (1592–1605)	4.0–12.0	n. d.	Binda et al. (2000a, b)
17th	Salzedas monastery vaults, Portugal	5.2	7.3	Lourenço et al. (2000)
18th	Lazzaretto de Ancona, Italy (1733)	18.5	4.2	Barbi et al. (2002)
18th–19th	Centenary chimney from the ceramic industry, Spain	20.8	n. d.	Jimenez et al. (2000)

n. d. = not determined

ments. Therefore, environmental actions and deterioration might have influenced the results obtained. The values range from 6.7 to 21.8 MPa and exhibit a very high coefficient of variation (up to 60%). Most studies indicate low values for compressive strength and a large dispersion of the values, with coefficients of variation ranging between 25 and 55%; but unusual strengths, higher than 50 MPa, were reported by Pauri et al. (1994).

The large variability of historical clay bricks is evident in several cases. As an example, in the 15th century Episcopal Palace of Pienza, Barbi et al. (2002) found an average value of about 26.9 MPa; while Bati and Ranocchiai (1994) reported strengths between 21.7 and 51.4 MPa, though a large majority of bricks exhibited compressive strengths between 20 and 30 MPa. A second example is given in two studies by Baronio and Binda (1985, 1986), who analysed the bricks from the Church of S. Lorenzo in Milan (3rd–4th centuries). An average compressive strength of 12.5–27.5 MPa and 34.5 MPa respectively, was found.

3.3.2.2 Modulus of Elasticity

The modulus of elasticity is frequently found in the literature and is also characterized by large variability (Table 3.2). Significant differences have even been found between values proceeding from distinct studies of the same monument, which confirm the difficulty in defining this parameter. Moreover, it is not always clear how authors measured the values presented, even if most standards refer the use of the linear part of the stress–strain curve in a range of 30–50% of the maximum stress value. The values found range from 1 to 18 GPa, which represents a range between 125 and 1,400 f_c, where f_c is the compressive strength. Most common values are in the range of 200 f_c, with an average value of 350 f_c.

3.3.2.3 Tensile Strength

In the presence of tensile stresses, clay bricks behave similarly to other quasi-brittle materials such as concrete or stone. After microcracking and maximum load are reached, post-peak behaviour is characterized by the progressive decrease of the tensile strength due to localization of deformation at a single crack. Tensile strength is very low when compared to compressive strength, being often neglected. Tensile strength depends mostly on the strength of mineral grains and of the matrix that binds them. Additionally, there is some dependence on the chemical composition, inclusions and the amount and dimension of pores. Because the strength depends heavily on the weaker zones, homogeneous raw clay with little impurities provides higher tensile strength.

Tensile strength is frequently reported as a percentage of the respective compressive strength, usually between 3% and 10%, and sometimes up to 13.5%. Binda et al. (2000a, b) reported tensile strengths between 0.1 and 2.6 MPa for the bricks of the bell-tower of the Cathedral of Cremona, Italy, which represent 1% and 10% of the respective compressive strengths. Baronio and Binda (1986) found a tensile strength of 5.5 MPa, which corresponds to 5–6.5% of the respective compressive strengths. It is noted that the tensile strength is rather dependent on the test set-up (Van Mier 1984). Flexural tensile strength is frequently confused with the true uniaxial tensile strength measured by a direct test, and often results in tensile strengths much higher than the real values.

3.3.3 Chemistry of Clay Bricks

3.3.3.1 General Composition

Raw clay can be characterized by means of chemical and mineralogical studies (Moropoulou et al. 1993; Cultrone et al. 2004; Pauri et al. 1994). These are frequent in archaeology for characterizing old ceramics and pottery, and in the characterization of old mortar properties (Barrios et al. 2000; Binda et al. 2000a). The determination of the chemical composition of old bricks allows the identification of possible deficiencies that occurred during their production, like the presence of organic matter, lime nodules, harmful soluble salts and other impurities that might influence the durability of the brick (Robinson and Borchelt 1994). Soluble salts and other impurities are one of the most important factors of brick decay and are frequently found in old clay brick fabrics (Baronio et al. 1985; Brocken and Nijland 2004). Chemical composition can also provide information about firing temperature and degree of vitrification (Cultrone et al. 2000), which is relevant for the manufacturing of new replacement bricks (Elert et al. 2003; Cardiano et al. 2004; López-Arce et al. 2003). Finally, chemical composition can explain, to a certain extent, the brick colour by indicating the presence of colorants and other additives.

Chemical oxides commonly found in clay bricks are the following: silica (SiO_2), alumina (Al_2O_3), iron (Fe_2O_3) or ferrous oxide (Fe_3O_4), potassium oxide (K_2O), titanium dioxide (TiO_2) as well as sodium (Na_2O), calcium (CaO) and magnesium (MgO) oxides. Silica and alumina constitute the base elements of clay and are usually found in the following proportions: about 50% for SiO_2 and 15–20% for Al_2O_3. Other components might be considered like barium (Ba), zirconium (Zr), strontium (Sr), rubidium (Rb) and manganese (Mn). However, these elements are always present in very small quantities and expressed in parts per million (ppm), while the proportion of the main components is expressed in percentage of the material volume.

Figure 3.2 reports the proportion of the main chemical constituents of clay bricks from the 12th to 18th centuries, with proportions of silica in the range of 53–61% and alumina in the range of 22–32% (Fernandes 2006). The variability of these constituents is rather low, suggesting that the raw clay material is similar in most bricks. The oxides CaO, Na_2O, Fe_2O_3 and TiO_2 exhibit a significant dispersion. The presence of the first two components is usually due to the contamination by lime mortars and food preparation, respectively; while the remaining oxides are natural colorants of clay bricks, giving a characteristic reddish and yellowish colouring if present in small quantities, respectively. In particular, a low amount of Fe_2O_3 provides a light colour for the bricks.

Chemical composition can differ substantially in old bricks, with reports of clay bricks from the 12th to 13th centuries showing 38% of silica, 21.5% of alumina and 32.5% of ferrous oxide (López-Arce et al. 2003). Also, Moropoulou et al. (1993) reported the chemical composition of clay bricks from the Basilica of Hagia Sophia, which exhibits a much higher proportion of silica (30–70%) and a lower proportion of alumina (8–16%) than normal clay bricks.

3.3.3.2 Provenance Determination

Chemical composition can provide an estimation of the provenance of the clay (Capedri and Venturelli 2005), making it possible to manufacture replacement bricks with the highest possible compatibility with the existing ones. For this task,

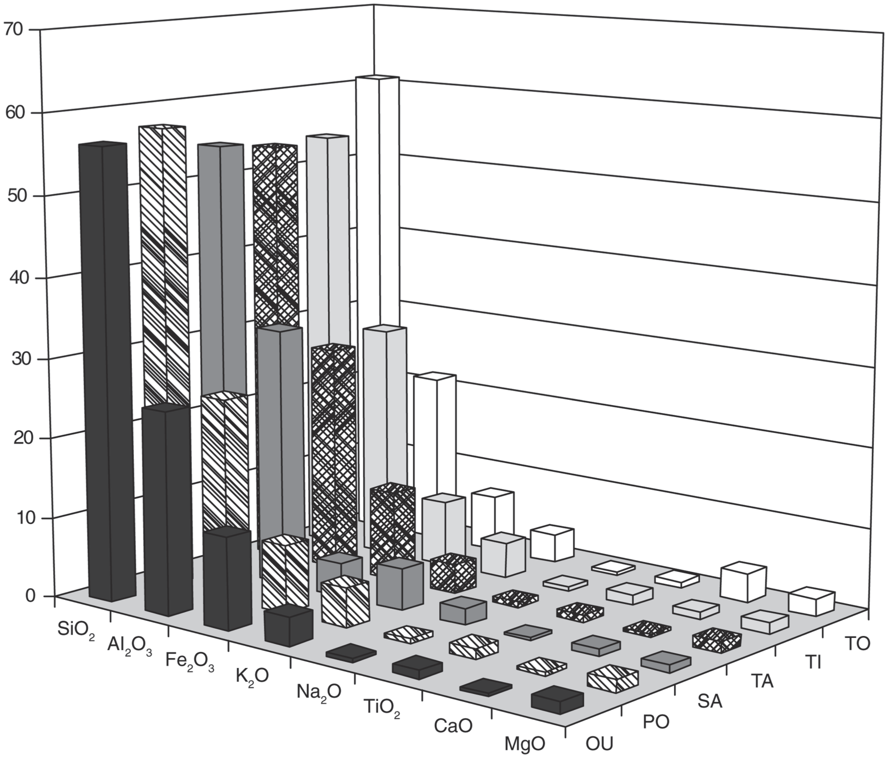

Fig. 3.2 Average proportion of the principal chemical components of old clay bricks

brick samples can be analysed using a statistical methodology described in Castro (1999), based on the comparison between the Euclidean distances of the ‘chemical composition’ vectors between different groups.

Specimens can be grouped according to their chemical similarity, being the groups characterized by the average values and respective standard deviation for the various determined chemical elements. The analysis of the bricks in Fernandes (2006) revealed that most bricks are similar within each provenance and that the component SiO_2, which is the largest component in clays, contributes very little to the distinction between old samples and cannot be used to distinguish any particular characteristic of bricks. Besides, no single component was found to strongly influence a particular group of bricks, meaning that bricks characterization is influenced by all chemical constituents. Moreover, in certain cases, bricks that are territorially very close exhibit different chemical characteristics. In this case, the period of manufacture and the evolution of the clay treatment and production process produced such results.

The brick groups found were compared with groups present in a database containing the chemical constituents of archaeological and ethnographical ceramics coming from diverse places in Portugal (Castro 1999). At this very large level of database comparison, it was found that the bricks from Tibães and Pombeiro

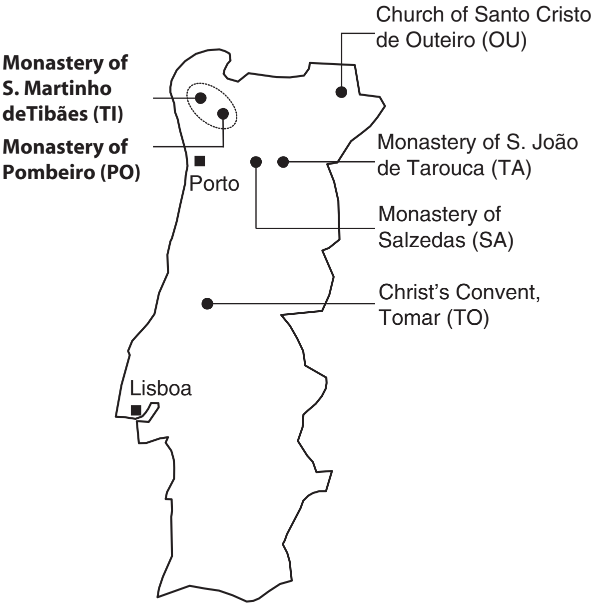

Fig. 3.3 Map showing the location of the monuments where the bricks where gathered

monasteries exhibit a strong similarity and present the typical composition of clays from ethnographical ceramic samples found in the same area (Fig. 3.3). For the remaining groups, it was not possible to determine any type of correspondence, suggesting that archaeological ceramics cannot be compared with old building bricks.

3.4 Drilling Resistance

3.4.1 Description of the Technique

Mechanical characterization of old materials is fundamental to adequately diagnose the conservation state of monuments; and for this purpose destructive tests in laboratories and on site inspections provide valuable information. However, material sampling and destructive tests should be limited in cultural heritage buildings. In order to overcome this constraint, different non-destructive testing methods have been developed as an attempt to obtain the necessary results without causing damage to the structure. Several tests allow one to obtain qualitative results, especially those based on wave propagation, unfortunately with poor correlation with mechanical properties. Impact techniques, such as the Schmidt hammer, do not provide data on the in-depth strength variation. Minor-destructive tests (MDT) provide reliable results related to internal cohesion and mechanical properties.

Special equipment, the drilling resistance measurement system (DRMS), was adopted by Fernandes and Lourenço (2007) to measure, continuously and reliably, the superficial resistance and in-depth cohesion properties of old clay bricks. Further information about technical and scientific backgrounds can be found in Exadaktylos et al. (2000). The DRMS, originally developed to determine the effectiveness of the treatments based on consolidants (Tiano 2001; Tiano et al. 2000a), was adapted to obtaining data that could be correlated with the compressive strength of old clay bricks.

The DRMS enables the user to obtain the drilling resistance based on the measurement of the force (in Newton, N) and torque (in mN m) necessary to drill a hole under specific operative conditions: diameter, penetration rate (*PR*), rotational speed (*RS*) and depth. The prototype used in the experiments and illustrated in Fig. 3.4 was provided by SINT Technology, and consists of the followings components: (i) a mechanical device equipped with positioning and drilling engines as well as force and torque load cells, with 100 N and 100 mN m of maximum capacity, respectively; (ii) an electronic unit that contains the power unit, control boards for DC and stepper engines, signal amplifiers for load cells, computers for test procedure, graphic visualization and data storage; (iii) a tripod; two steel plates with three threaded bars and lock nuts to hold specimens for laboratory testing, three adjustable sharp-pointed bolts to provide the support during in situ tests over regular and irregular surfaces.

3.4.2 Experiment

A set of bricks from the 12th to 18th centuries taken from six monasteries in Portugal was drilled in a laboratory environment; and the drilling resistance, DR_σ, of each unit was obtained. For microdrilling measurements, the specimens were fixed between the steel plates of the special equipment part, with a zero stress state. The test parameters are essentially material dependent and low penetration rates and rotational speeds increase the returned thrust and torque (Tiano et al. 2000b).

Old clay bricks are mainly made of soft material (clay mass). The presence of hard and highly abrasive sand grains and stone fragments requires an adequate choice of values for *PR* and *RS,* considering the low resistance of the clay mass and the high resistance of harder elements. From preliminary experiments, the system parameters were fixed to: $PR = 10$ mm min^{-1} and $RS = 600$ RPM. In typical old masonry elements, the brick units are laid down in the direction of the bed surface and the only visible and accessible surfaces are the ones in the bed plane. So, drilling was carried out in the accessible surfaces, preferentially located in the central area of the specimen in order to avoid any possible edge effects.

The value used to characterize the microdrilling resistance, DR_σ, is the drilling force divided by the cross-section of the drill bit. The presence of high strength inclusions such as sand grains or stone fragments inside the brick specimens, and the presence of voids and cracks, severely affects the average drilling resistance of bricks just in the same way they can influence the compressive strength. However, the contribution of these local defects in the behaviour of the whole brick is less relevant.

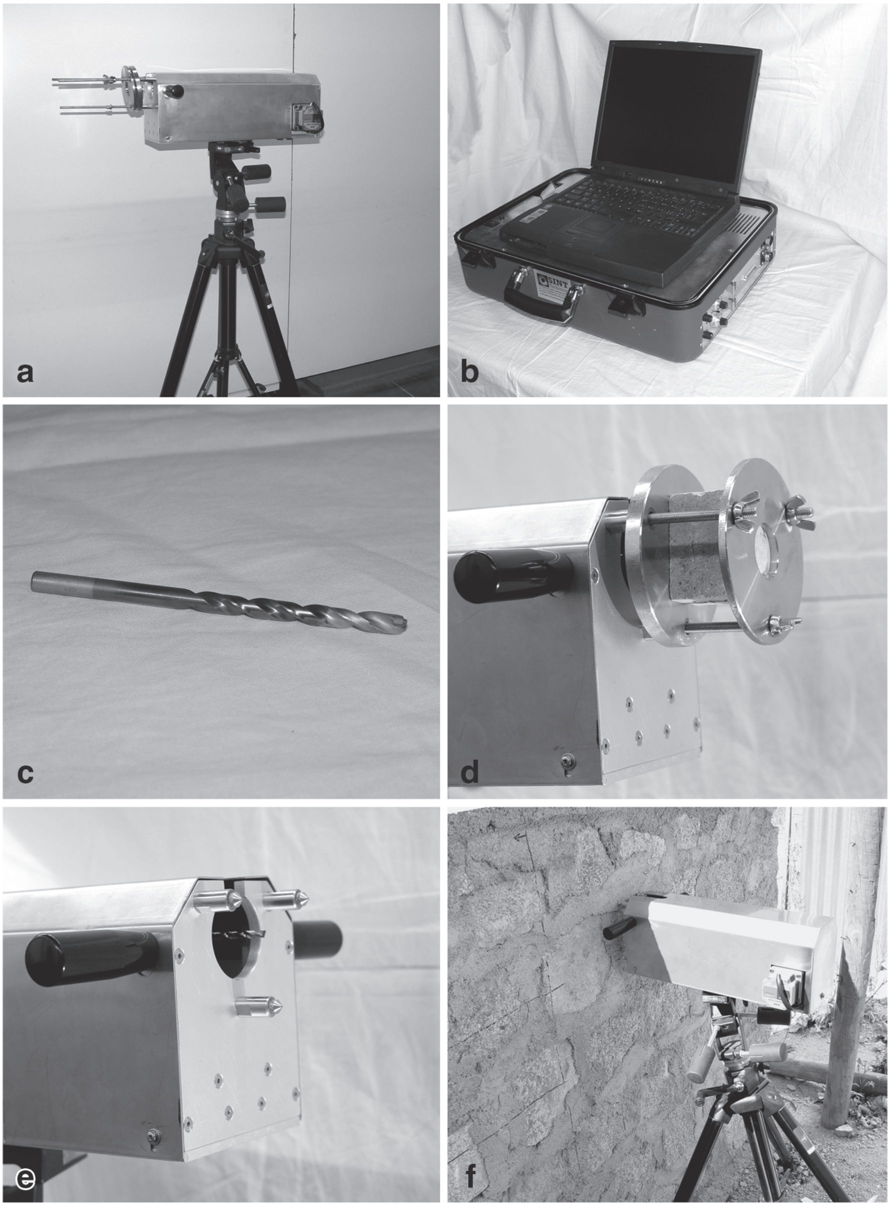

Fig. 3.4 Equipment and operation possibilities of the DRMS equipment: **a** mechanical device in tripod with drilling engine, **b** control unit with data visualization and storage unit, **c** special DIABER (Italy) drill bit, **d** sample ready for testing, in the steel plates clamping system and **e** view of the three adjustable sharp-pointed screws for **f** in situ usage of the equipment

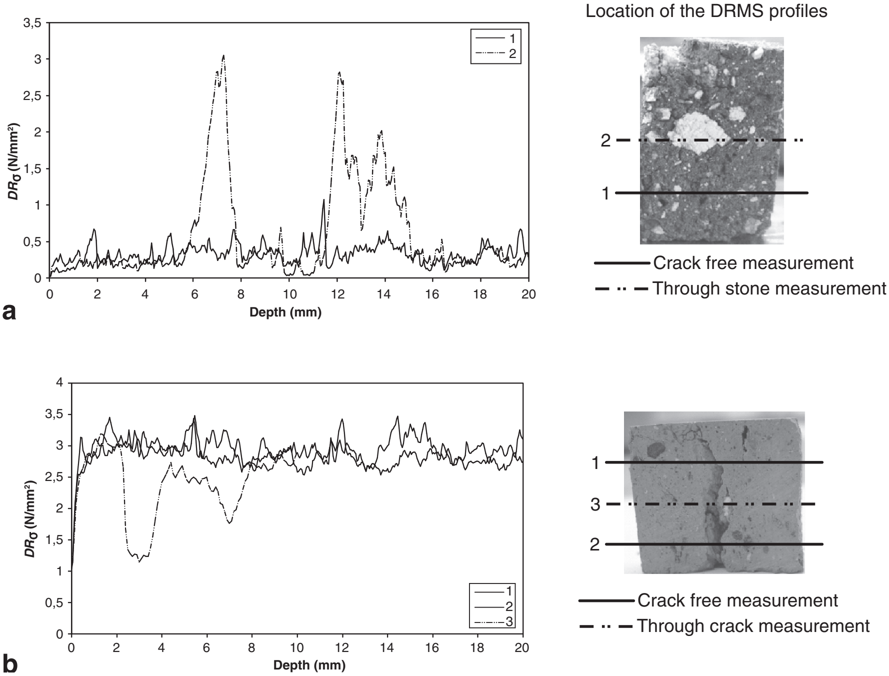

Fig. 3.5 Example of the drilling resistance measurement when crossing **a** a stone fragment and **b** an internal crack

Figure 3.5 illustrates the result of drilling through a stone fragment and through a crack in the interior of the brick. In both cases, rather homogeneous resistance profiles with moderate irregularities, due to the microstructure of brick, are observed (in black) together with one profile showing the influence of the anomalies previously described (in grey). As a result, the average drilling resistance of the profile that crossed the stone fragment is 80% higher than the average of the remaining profiles; while in the case of the profile crossing an internal crack, the drilling resistance decreased 20% relatively to the other ones.

In this case, three to five holes were carried out in each specimen, taking into account its size and difference between consecutive measurements. Low strength dips and high strength peaks were systematically removed. As an example, Fig. 3.6 shows the portion of data removed from the profile as well as the data used to calculate the average drilling resistance.

3.4.3 Correlation of Drilling Resistance and Compressive Strength

The values for the drilling resistance of old clay bricks DR_σ range from 0.83 to 3.19 N mm^{-2}. In order to obtain mechanical data without sampling, a model had

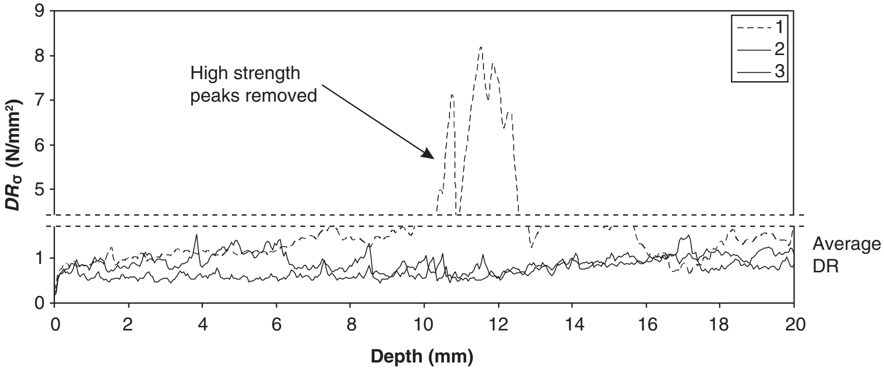

Fig. 3.6 Example of the calculation of the average DR_σ of specimen TO15

to be made to indirectly obtain mechanical data from drilling resistance data. The graph illustrated in Fig. 3.7 shows that the relation between the drilling resistance and the compressive strength of the clay brick exhibits a similar trend, which confirms the existence of a possible relationship between these two properties. Note that here only the average values for each set are shown, and not the full results.

The complete results of all test specimens regarding the correlation between drilling resistance and compressive strength are shown in Fig. 3.8. A non-linear fit was computed with a power curve using: $f_c = 9.196\ DR_\sigma^{0.609}$, which provided a R^2 of 0.74. This result is in line with other studies that proposed a power law to correlate the compressive strength of old clay bricks from ultrasonic velocity and Schmidt hammer rebound tests (Kirka and Erdem 2005). The regression line is shown over the complete dataset in Fig. 3.8, being applicable also for modern traditionally

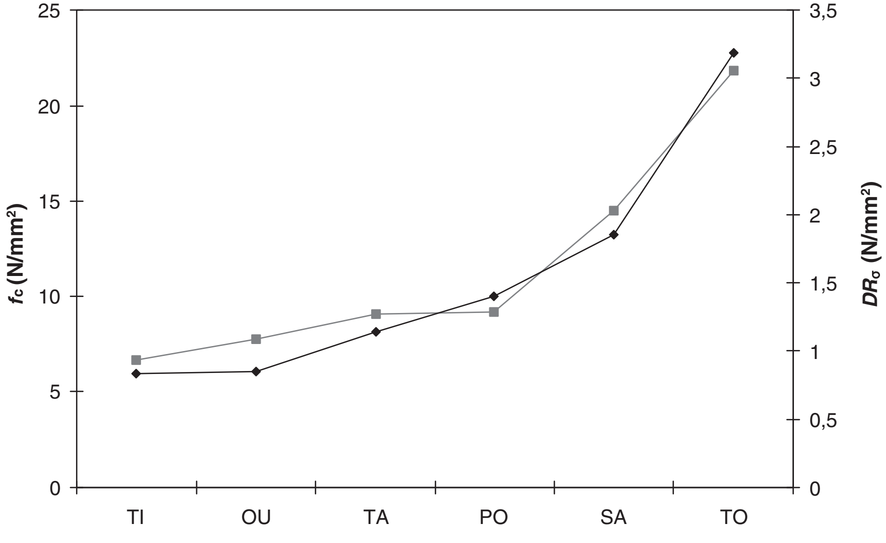

Fig. 3.7 Comparison between drilling resistance and compressive strength of old bricks

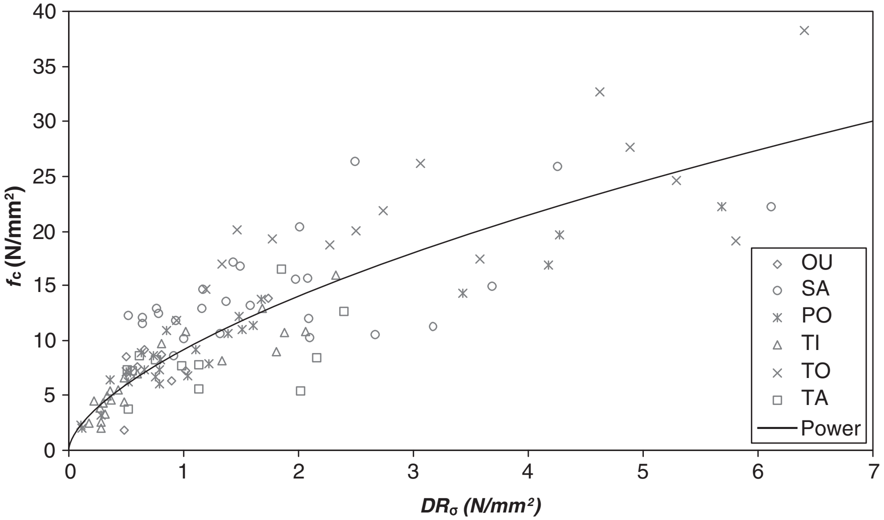

Fig. 3.8 Linear and non-linear correlations between compressive strength f_c and drilling resistance stress DR_σ for the entire sample

handmade fired clay bricks (Fernandes and Lourenço 2007). The reason for the wide scatter is that old bricks have no uniform properties and DRMS is a local measure, much influenced by cracks and inclusions.

3.5 Conclusions

Old clay bricks are difficult to characterize, due to the wide diversity of raw materials, manufacturing processes and conservation states. The physical, mechanical and chemical properties of historical clay brick exhibit a large spectrum and a significant variability. The literature survey and the authors' tests indicate a high porosity (15–40 vol.%) and water absorption (10–20 vol.%). The suction can be rather high (up to 0.35 g cm^{-2} min^{-1}), while the apparent density is low (1,500–1,800 kg m^{-3}). The compressive strength shows a huge scattering with values mostly ranging from 1.5 to 30 MPa. No trends could be found regarding age or origin, as the amount of data is limited.

In general, raw clays used in old clay bricks seem to have some consistency with respect to the proportion of the main chemical constituents; while bricks of the same origin generally exhibit a strong chemical similarity. It is also noted that clay bricks have a chemical composition different from the ceramic products of archaeological remains since no similarities with available archaeological data have been found.

Finally, it was shown that a minor-destructive test (microdrilling) allows adequate assessment of the compressive strength of old clay bricks, using appropriate correlations.

References

Álvarez De Buergo M, Limón TG (1994) Restauración de Edificios Monumentales, Estudio de materiales y técnicas instrumentales. Centro de Estudios y Experimentación de Obras Públicas, Madrid

Barbi L, Briccoli Bati S, Ranocchiai G (2002) Mechanical properties of ancient bricks: statistical analysis of data. In: 7th international seminar on structural masonry for developing countries, Belo Horizonte, 27–33

Baronio G, Binda L (1985) Physico-mechanical characteristics and durability of bricks from some monuments in Milan. Masonry International 4:29–35

Baronio G, Binda L (1986) Consolidation and durability of masonry materials: study of mortars, bricks and plasters of an ancient monument of Milan. The tower of the church of S. Lorenzo. In: Evaluation and retrofit of masonry structures, pp 440–448

Baronio G, Binda L, Charola AE (1985) Deterioration of bricks with and without perforations due to salt crystallization. In: 7th international brick masonry conference, Melbourne, 267–276

Barrios A, Barrios J, Pólo J, Rodríguez C, Padura C, Vorsevi SA (2000) Estúdio de las Fábricas de Ladrillo del Hospital de Las Cinco Llagas de Sevilla, actual sede del parlamento de Andalucía. In: 12th international brick/block masonry conference, Madrid, 203–214

Bati S, Ranocchiai G (1994) A critical review of experimental techniques for brick material. In: 10th international brick/block masonry conference, Calgary, 1247–1255

Binda L, Saisi A, Tiraboschi C (2000a) Investigation procedures for the diagnosis of historic masonries. Construction and Building Materials 14:199–233

Binda L, Tongini Folli R, Mirabella Roberti G (2000b) Survey and investigation for the diagnosis of damaged masonry structures: the torrazzo of Cremona. In: 12th international brick/block masonry conference, Madrid, 237–257

Brocken H, Nijland T (2004) White efflorescence on brick masonry: towards prediction of efflorescence risk.” In: 13th international brick/block masonry conference, Amsterdam

Capedri S, Venturelli G (2005) Provenance determination of trachytic lavas, employed as blocks in the romanesque cathedral of Modena (Northern Italy), using magnetic susceptibility, and petrographic and chemical parameters. Journal of Cultural Heritage 6:7–19

Cardiano P, Ioppolo S, Stefano C, Pettignano A, Sergi S, Piraino P (2004) Study and characterization of the ancient bricks of monastery of “San Filippo di Fragalà” in Frazzanò (Sicily). Analytica Chimica Acta 519(1):103–111

Castro F (1999) Statistical and analytical procedures for estimation of the provenance of archaeological ceramics. In: 4th European congress on old ceramics, Andorra, 52–58

Cultrone G, De La Torre MJ, Sebastian EM, Cazalla O, Rodriguez-Navarro C (2000) Behavior of brick samples in aggressive environments. Water Air and Soil Pollution 119:191–207

Cultrone, G, Sebastián E, Elert K, De La Torre MJ, Cazalla O, Rodriguez-Navarro C (2004) Influence of mineralogy and firing temperature on the porosity of bricks. Journal of the European Ceramic Society 24:547–564

Elert K, Cultrone G, Navarro CR, Pardo SE (2003) Durability of bricks used in the conservation of historic buildings—influence of composition and microstructure. Journal of Cultural Heritage 2:91–99

Esbert RM, Ordaz J, Alonso J, Montoto M (1997) Propriedades físicas [de los materiales pétreos]. Manual de Diagnosis y Tratamiento de Materiales Pétreos y Cerâmicos, Collegi d'Aparelladors i Arquitectes de Barcelona, pp 21–38

Exadaktylos G, Tiano P, Filareto C (2000) Validation of a model of rotary drilling of rocks with the drilling force measurement system. Internationale Zeitschrift fur Bauinstandsetzen und Baudenkmalpflege 6(2):307–340

Fernandes FM (2006) Evaluation of two novel NDT techniques: Microdrilling of clay bricks and ground penetrating radar in masonry. PhD thesis, University of Minho, Guimarães

Fernandes F, Lourenço PB (2007) Evaluation of the compressive strength of ancient clay bricks using microdrilling, Journal of Materials in Civil Engineering ASCE 19(9):91–800

Jimenez J, Zalbide M, Bengoetxea J, Espina S, Rodriguez-Maribona I (2000) Analysis of the brick masonry of a centenary chimney in Basque Country. In: 12th international brick/block masonry conference, Madrid, 545–565

Kirka O, Erdem TK (2005) An experimental study on the construction materials of the Ankara Citadel. In: 4th international conference on structural analysis of historical constructions, Padova, Italy, 223–229

Livingston RA (1993) Materials analysis of the masonry of the Hagia Sophia Basilica, Istanbul. In: 3rd international conference on structural studies, repairs and maintenance of historical building, 15–31

López-Arce P, Garcia-Guinea J, Gracia M, Obis J (2003) Bricks in historical buildings of Toledo City: characterization and restoration. Materials Characterization 50:59–68

Lourenço PB, Vasconcelos G, Ramos L (2000) Diagnóstico sobre as condições de estabilidade do claustro do séc. XVIII—Mosteiro de Salzedas. Report LEC 31/2000, University of Minho, Guimarães

Maierhofer C, Leipold S, Schaurich D, Binda L, Saisi A (1998) Determination of the moisture distribution in the outside walls of S. Maria Rossa using radar. In: 7th international conference on ground penetrating radar, Kansas, 509–514

Mamillan M (1979) Méthodes d'essais au gel des pierres, Problems Raised by Frost Action. In: 6th international congress of the fondation française d'Etudes Nordiques, Le Havre, 225–238

Marzahn GA, Jahnel R, Tue NV (2004) Finite element analysis of two ancient groined masonry vaults. In: 13th international brick/block masonry conference, Amsterdam, Netherlands, 147–156

~~Mecha CO (1998) Patología físico-química del ladrillo. In: Adell Argilés JM, Arce I, Abásolo A, Acha Román C, (eds) Tratado de Rehabilitación, Patología y técnicas de intervención. Elementos estructurales, Tome 3. Editorial Munilla-Lería, Madrid, pp 185–192~~ AQ2

Moropoulou A, Christaras B, Lavas G, Penelis G, Zias N, Biscontin G, Kollias E, Paisios A, Theoulakis P, Bisbikou K, Bakolas A, Theodoraki A (1993) Weathering phenomena on the Hagia Sophia Basilica, Konstantinople. In: Brebbia CA (ed) Structural repair and maintenance of historical buildings III. WIT Press Publications, Southampton, UK, pp 47–66

Papayianni I, Stefanidou M (2000) Characteristics of bricks of Byzantine period. In: 12th international brick/block masonry conference, Madrid, 1729–1736

Pauri M, Stazi A, Mastrosanti F, D'Orazio M, (1994) The decay of ancient building masonry, a case study. In: 10th international brick/block masonry conference, Calgary, 1295–1304

Robinson G, Borchelt J (1994) Characterization of bricks and their resistance to deterioration mechanisms. In: 10th international brick/block masonry conference, Calgary, 1295–1304

Tiano P (2001) The use of microdrilling techniques for the characterization of stone materials. In: On site control and non destructive evaluation of masonry structures and materials, Mantova, Italy, pp 1–10

Tiano P, Delgado Rodrigues J, De Witte E, Vergès-Belmin V, Massey S, Snethlage R, Costa D, Cadot-Leroux L, Garrod E, Singer B (2000a) The conservation of monuments: a new method to evaluate consolidating treatments. Internationale Zeitschrift fur Bauinstandsetzen und Baudenkmalpflege 6(2):133–150

Tiano P, Filareto C, Ponticelli S, Ferrari M, Valentini E (2000b) Drilling force measurement system, a new standardisable methodology to determine the stone cohesion: prototype design and validation. In: Internationale Zeitschrift fur Bauinstandsetzen und Baudenkmalpflege 6(2):115–132

Van Mier JGM (1984) Strain-softening of concrete under multiaxial loading conditions. Doctoral thesis, Eindhoven University of Technology, Eindhoven

Vekey RC (1998) Brickwork and blockwork, In: Illston JM (ed) Construction materials—their nature and behaviour. E & FN SPON, London, pp 251–315

Vitruvius Pollio M (1960) The ten books on architecture. (MH Morgan, Trans.) Courier Dover Publications, New York

Weaver ME (1997) Architectural ceramics. Conserving buildings—a manual of techniques and materials. Wiley, New York, pp 99–132

Wijffels T, Nijland TG (2004) Deterioration of historic brick masonry due to combined gypsum, ettringite and thaumasite: a case study. In: 13th international brick/block masonry conference, Amsterdam, 809–815

Winslow DN, Kilgour CL, Crooks RW (1988) Predicting the durability of bricks. ASTM Journal of Testing and Evaluation 16(6):527–531

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