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RESEARCH

THE MECHANICAL PERFORMANCE OF TRADITIONAL ADOBE MASONRY COMPONENTS: AN EXPERIMENTAL-ANALYTICAL CHARACTERIZATION OF SOIL BRICKS AND MUD MORTAR

Tiziano Li Piani,[1,2,3]* Dennis Krabbenborg,[3] Jaap Weerheijm,[1,2] Lambertus Koene,[3] and Lambertus J. Sluijs[1]

ABSTRACT

Adobe is an ancient building technology made of sun dried bricks joined together by mud mortar. This paper deals with the physical and mechanical characterization of three different typologies of adobe bricks and one typology of mud mortar produced in Europe. They differed in terms of internal soil element proportions and amount of organic content. Physical tests consisted of granulometry, moisture content and density tests. The mechanical characterization consisted of uniaxial compressive tests and three point bending tests. Tests were performed according to modern material standards. The main mechanical properties both in tension and compression were determined at different curing conditions. The outcome provided in this study offers a general overview on the assessment of the mechanical performance of adobe in relation to the properties and interactions of its soil constituents. In fact, the comparison between components with the same soil mineralogical family and production process made it possible to assess both at a qualitative and quantitative level the effect of the physical properties of the mixture (such as fiber and clay percentages or moisture content) on the mechanical parameters of the resulting bricks and mortar. This paper proposes new predictive formulations of the most relevant material parameters in strength and deformation, such as compressive strength, deformation at peak stress and ultimate displacement for both adobe bricks and mortar. They quantify the influence that water content, clay percentage and fiber reinforcement produce on the mechanical performance of the tested adobe components. This was made possible by means of multivariate statistical analyses on the mechanical parameters derived from all the tested samples.

KEYWORDS

adobe, masonry, brick, mortar, standard, characterization, compression, flexure, strength, deformation, clay, soil, fiber, moisture

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1. INTRODUCTION

Traditional adobe, literally "sun-dried brick" according to the Arabic Al Tob [1], defines one of the most ancient forms of masonry on earth, constituted by unpressed sun dried bricks joined together by mud mortar. Despite its history [2] characterized by buildings of architectural value [3], its spread in European countries in the modern age is limited as a consequence of the introduction of modern building materials during the Industrial Revolution [4]. As a result, the assessment of the physical-mechanical properties of this traditional masonry was not a priority of the scientific community until recently.

Only recently adobe has started gaining significant attention [4, 5]. Two main world socio-economic trends are at the basis of the renewed interest towards this masonry typology. On one hand, governments of developing and third world countries in the recent past have not met their housing targets, leading people to build houses by themselves within an informal settlement [6]. As a result, more than one third of the world population still lives in earthen dwellings, which often exist in areas characterized by seismic risk or involved in military operations, with dramatic loss of human lives and cultural heritage [7]. In fact, adobe dwellings erected by local farmers without proper knowledge of structural systems and awareness of the suitability of the applied soil for building purposes, result in an intrinsic vulnerability to dynamic loadings [8–10]. By contrast, developed countries, with goals of energy efficiency and pollution reduction, are promoting adobe because of its favourable acoustic and thermal properties and the related minimal environmental impact [11, 12]. However, knowledge about adobe is still scarce at both a material and structural level [13]. The number of characterization campaigns on adobe bricks is still limited and in the case of mortar even rare [14]. The current stage of production regarding its material properties and their influencing factors is discussed in the following section. From its analysis, it is inferred that different or opposite trends can be found in the literature in terms of the influence of the adopted soil mixture on the resulting mechanical performance. This happens because mechanical values are compared using bricks made with various soil mineralogy, different reinforcement materials and methods of construction. Brick composition varies significantly according to building traditions and the local availability of materials, which affects the resulting performance of the material [15]. As a result, there is often no homogeneity in the prescriptions and formulations contained in the few building codes currently available for adobe. European standards for the production, testing and design of adobe do not exist yet. In this study, the comparison of the effects of soil mixture on the static performance of both bricks and mortar have been investigated at both a qualitative and quantitative level. In fact, the paper presents the results of a physical-mechanical characterization campaign performed in 2016 by the authors on three different types of bricks and mortar made of the same mineralogical family and the same building process. Furthermore, the same bricks were subjected to two different drying conditions (namely air drying and oven drying), consistent with the traditions of different geographic regions of interest [16]. No study on the influence of moisture content on the performance of adobe components was found in literature so far. Therefore, the analysis and data elaboration resulted from an extended dataset. The statistical analysis revealed relationships between the mechanical performance of the components and their mineralogical composition with the drying process. A novel assessment of the compressive strength parameter of adobe was carried out, which could be defined adapting a law originally developed for predicting the strength of unbaked modern clay bricks according to its internal moisture content. It consists of an exponential function of moisture content multiplied with a fully dried compressive strength value, which is dependent on the percentage of clay and fiber reinforcement. The reinforcement was confirmed to largely determine the deformation capacity of adobe. The found relations in strength and deformation, calibrated according to data on tested bricks, could be used to predict the performance of mortar. These findings link the material class of mortar and bricks in case of adobe masonry. Overall, this study aims at sharing an experimental dataset already used in other research on the dynamic properties of adobe masonry [17, 59]. But in general, it provides a clear indication of the mechanical material performance assessment of adobe according to its physical properties. That was made possible by conducting tests according to standards developed for modern materials and adapting them to adobe. After the introductory section, this paper presents the characterization campaigns, detailing both the standards and setup adopted and the related results. Next, the mechanical performance is investigated in Section 4 according to the physical characterization.

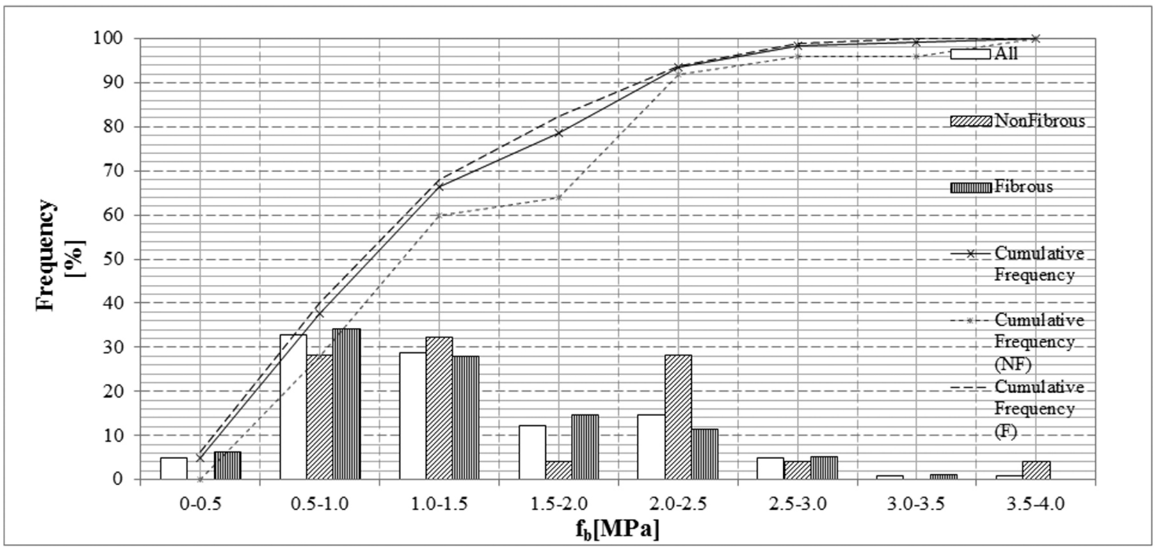
2. CURRENT KNOWLEDGE ON THE INFLUENCING FACTORS ON ADOBE BRICKS AND MORTAR PERFORMANCE

Sun-dried adobe bricks contain mixtures of clay, silt, sand, water and possibly straw [19]. Mortar is usually made of the same or similar mixture as the bricks, although it is often free of straw [20]. Only one recent study was found in which a characterization campaign on the response of adobe mortar was performed [14]. According to published studies, typical ranges of element proportions in soils suitable for brick production are as follows: 12–25% clay, 55–75% sand, 10–30% silt ([2]–[13]).

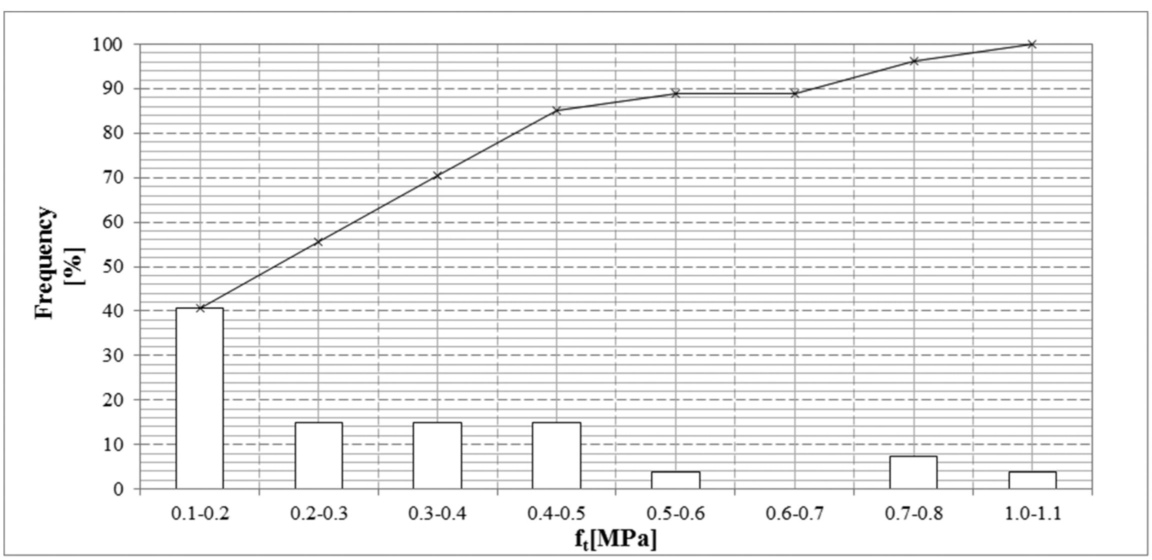
Clay and silt, cohesive elements in nature, form a matrix in which the sand particles are enclosed, acting as a binder for the cohesionless granular fraction of the soil [2]. Thus, clay is supposed to provide strength to the dried material, although it is also the main cause for shrinkage cracks, which occurs during the drying process of the bricks due to its affinity towards water [2, 32]. Therefore, it is often recommended to set an upper bound to its volume in the mixture, usually around 20% according to literature [33, 22]. Spectroscopic investigations have revealed that it is not only the relative content in the mixture, but also that the clay mineralogical family plays a significant role regarding the performance of the product [34]. A correct balance between expandable clay minerals (i.e. smectite), that provide strength but are responsible for undesirable cracks, and non-expandable clay minerals (i.e. kaolinite), responsible for less shrinkage problems and cohesion, is often required [19, 2, 25].

Adobe bricks can consist of only soil elements, or also include natural fibers [19]. Actually, the addition of straw into the soil mixture is common practice according to many building traditions [35, 36]. This insertion can significantly influence the resulting properties of adobe components. First of all, fibre is often associated with a reduction of shrinkage rates in the drying material, limiting the formation of cracks as a consequence of a more efficient drainage system [22, 37]. Straw also lightens the weight of the resulting brick and it boosts the thermal properties of the material [38]. However, an excessive amount of fiber can result in a too fast drying process and thus in an intrinsic brittleness of the product [24]. Also, with reference to the fiber content percentage, upper bounds are suggested in the literature [5, 36, 39]. In fact, besides the influence of fibers on the drying process, its contribution to strength and deformation performance of the dried brick is more controversial. This happens because a common approach in the literature is to quantitatively compare results obtained from different types of bricks from different regions, resulting in a lack of definite assessment (Figure 1). A fiber-free earthen brick under compression is generally characterized by quasi-brittle failure similar to unconfined concrete, while a straw reinforced brick more often shows the development of an increased number of micro-cracks accompanied by more ductile behaviour [22, 24, 13]. From a physical point of view, this can be due to the redistribution of forces within the soil matrix due to the fibers that can hold together parts of the soil matrix at large deformations [13]. However, the presence of straw is often associated with a decrease in strength and elasticity with respect to unreinforced bricks [24]. The observed trend may be a consequence of adherence problems between the fibers and the soil matrix that is likely influenced by the type and geometry of the adopted fiber reinforcement [40]-[43]. These weakening effects on bricks are not always noticeable; for instance, they seem to be inverted in cases of highly sandy mixtures [22].

FIGURE 1. Relative and cumulative frequency for compression strength (a), tensile strength (b), elastic modulus (c) of adobe bricks according to statistical analysis on data from experimental tests in [17–27].

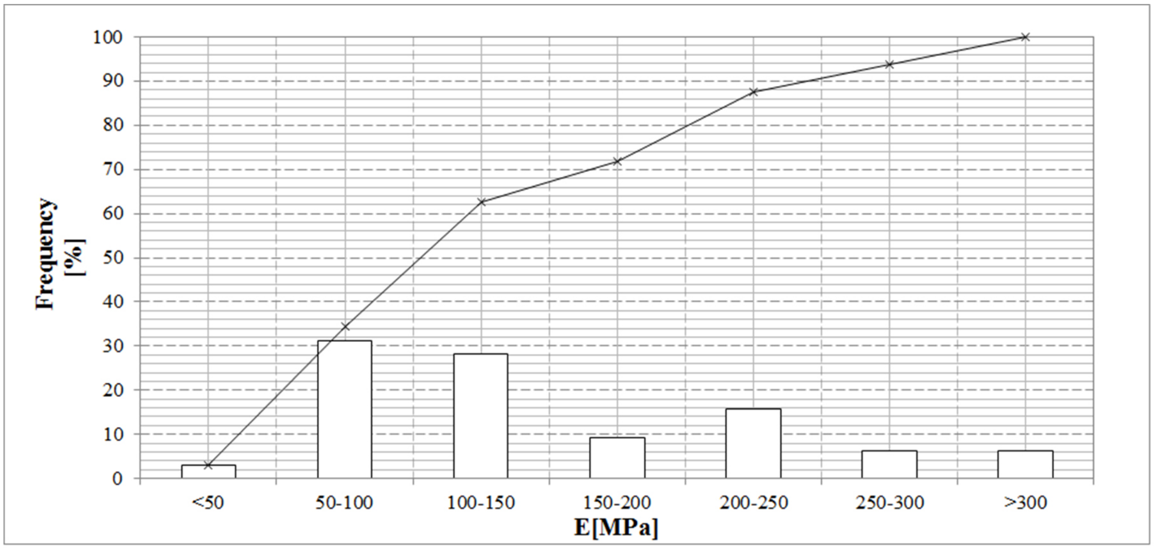


(a)



(b)

FIGURE 1. *(Cont.)*



(c)

Similar controversies exist regarding fiber reinforcement and performance under tensile loading of reinforced adobe [20, 24]. Recent elaborations on a heterogeneous dataset relate strength with the dry density of bricks [20]. It is known that the amount of water required for mixing the soil elements depends on their relative percentage and inherent mutual interactions, especially in the case of a fiber reinforced mixture [2]. Usually, as the fibers or the clay content increases, the water fraction needs to be increased as well [24]. On the other hand, an excessive increase of water with respect to the amount strictly necessary to obtain acceptable workability of the mixture can compromise the unit weight and the strength of the specimen [24, 35]. High moisture content is a prominent risk for the strength and the durability of adobe structures during their entire life cycle [19]. The preservation of the mechanical performance of adobe seems to be mainly governed by the capability of keeping the structures dry [2].

Finally, it is worth stressing that the absence of production chains and quality control which is common practice for adobe buildings erected by local farmers make the mechanical properties of the resulting products extremely difficult to be assessed independently from the contribution of the applied mixture. Despite the method of production and construction affecting the material behaviour of adobe [15, 37], their influences are not addressed within the present work.

3. THE CHARACTERIZATION CAMPAIGN

A characterization campaign was performed on the components already used to assemble adobe walls in previous studies [44]. To this end, three pallets of bricks with different mixture proportions but from the same mineralogical family were ordered from the same supplier, together with two bags of mortar (Figure 2). The characterization campaign consisted of physical and mechanical tests. Static tests were performed at the Military Engineering Laboratory of the Netherlands (NLDA), while the physical characterization was performed at the laboratory of Geoscience and Engineering of Delft University of Technology, also in the Netherlands. The physical characterization consisted of density, moisture content and granulometric tests, while mechanical tests consisted of uniaxial compressive tests and three point bending tests. All tests were conducted adopting European standards developed for modern building materials adapted to the nature of the material if necessary. In fact, a European normative framework is still lacking for adobe. A preliminary study of the few existing technical codes for adobe was conducted [45]–[48] and the set up applied in previous research was acknowledged [4]. As a result, the application of each adopted standard possibly resulted in modifications in the setup. The adopted standards and the complete list of precautions are presented in Table 1 in order to provide a characterization reference on adobe. All tests were performed after 28 days of air drying at controlled laboratory conditions. For the mortar samples, this curing period was preceded by the casting process, which elapsed twenty-one days hardening within moulds and fourteen days of air curing. Tests in compression were performed on both air dried and oven dried samples in order to also address the behaviour of burnt adobe [16]. In this case, after laboratory conditioning, samples were oven dried until a constant mass was achieved (approximately after three days) and tested after having cooled down to room temperature [52]. In the following paragraphs, bricks are identified as: Type A, Type B, and Type C, according to the different soil mixture and the mortar is denoted with Type M. Each tested sample in the following paragraphs is indicated by a set of letters representing the type of bricks and the type of test (C for compressive and T for tensile), followed by numbers representing the specific sample extracted. For compressive tests, a further number distinguishes between air dried (1) or oven dried (2) samples. In the following sections, the physical and mechanical characterization of adobe are described.

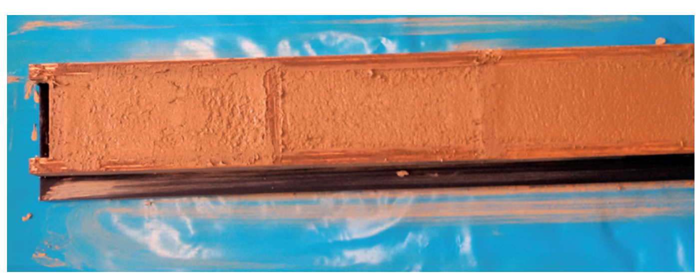
3.1 Physical characterization

3.1.1. Granulometric test

Standard, Set up and Testing Procedures. Three samples per type, extracted from randomly chosen bricks were pulverized and subjected to granulometric tests. Tests were performed according to standard BS 1377-2 [50]. However, the direct insertion of hydrogen peroxide in the solution before the hydrometer tests, as the procedure prescribes for a soil with organic content, was not a plausible option for adobe. In fact, it appeared that a significant amount of fibers in the bricks causes unstable chemical exothermal reactions characterized by solution leakage. Thus, it was decided to apply a preliminary mechanical separation of the largest part of the organic content by means of 2mm sieving. The subsequent chemical treatment was repeated three times in two days until no further reaction was noticed. The total loss in weight was registered.

FIGURE 2. Bricks from "Type B"-pallet (a) and mortar cast (b) in laboratory.

(a)



(b)

TABLE 1. List of test standards and initial setup.

Test	no. Tests per Type	Standard	Precautions
Granulometry	3	BS 1377-2	Preliminary sieving
			Repeated hydrogen peroxide treatment
Density	6	NT Build 333	Temperature at 85°C
Moisture content	6	NT Build 333	Temperature at 85°C
Uniaxial compression	>7 (oven dried)	UNI EN 772-1	Rectification
	>7 (air dried)		Def. rate 2 mm/min
Three point bending	4 (air dried)	UNI EN 12390-5	Rectification
			Def. rate 1 mm/min
			Interposition of wood strip

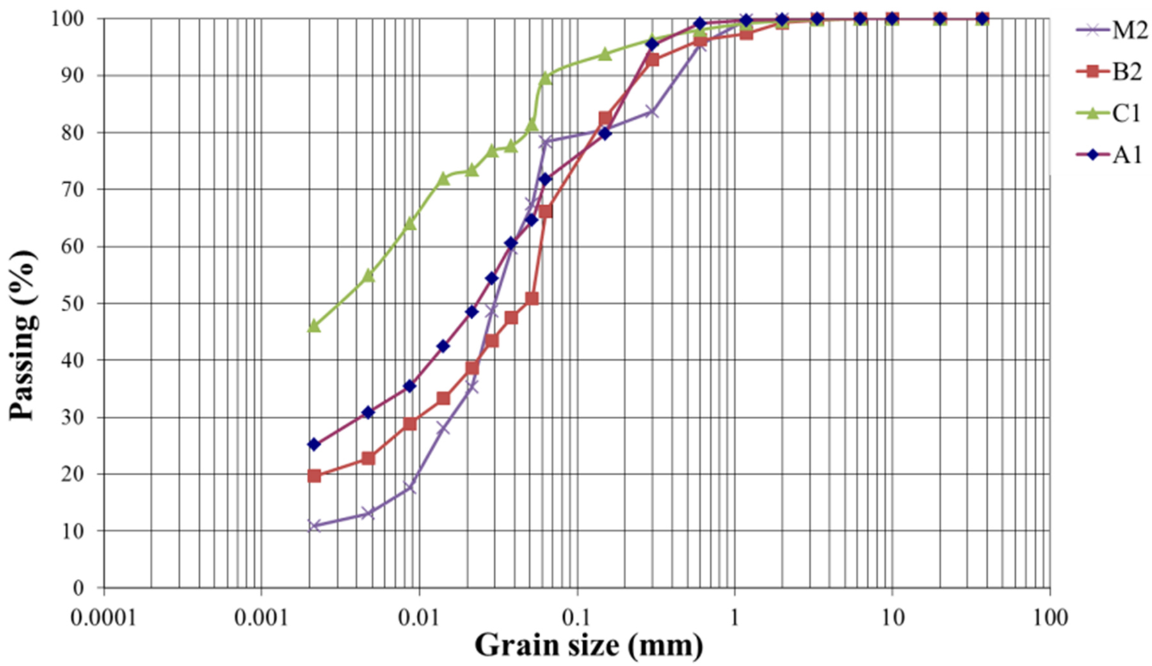
Observations and Results. For each test, the percentages of sand, silt and clay of the soil mixture were derived from the MIT classification system [51]. Also the relative amount of fiber by weight was calculated. The tests revealed the presence of a large variety of reinforcement materials in the same mixture, from straw to chopped wood. Therefore, in the following the term fiber refers to whatever organic content is present in the mixture. The results are reported in Table 2 and expressed as ranges of values for each type [13]. Furthermore, a graphical comparison of typical granulometric curves for each type of sample is reported (Figure 3).

Brick mixtures are characterized by high fiber content. In particular, Type B and Type C display similar reinforcement percentages but they significantly differ in soil composition. The soil of Type A and B is defined as a clayey sandy silt according to the MIT system, while Type C is a clay and silt with some sand. The amount of clay is similar for Type A and B, but it is less than half its percentage presence in Type C. All brick mixtures show similar values in terms of silt percentage, which is generally the dominant component of the mixture. Mortar samples contain a low percentage of fiber reinforcement with respect to bricks, and a mixture composition which is characterized by a high level of silt and a modest percentage of clay (sandy silt with some clay).

3.1.2. Dry density and moisture content tests

Standard, Set up and Testing Procedures. Moisture content at laboratory conditions and density were determined according to NT Build 333 [52]. Six samples of each type were analysed. It is worth mentioning that because of the unbaked nature of the bricks and mortar, the temperature of the oven was set at 85 degrees Celsius instead of the prescribed value of 105 degrees Celsius.
Observations and Results. The density and moisture content results obtained from the tests are summarized in Table 3 in terms of mean values and related standard deviations. Type B and C bricks have similar values of dry density, although the latter are characterized by higher uncertainty. Type A has higher values while mortar samples are more dense than the tested types of bricks.

FIGURE 3. Examples of comparison in granulometric distribution for different types of mixtures.



At laboratory conditions, Type M is also characterized by the lowest moisture content values, while for Type C the mean moisture content is almost twice the values associated for all other bricks. At the same conditions, the highest moisture content per dry mass is associated with the mixture with the highest clay content percentage (Type C). This was already observed in previous research on clay samples [53]. Type A and B bricks and the mortar may be classified as "dried" according to NZS standard [54] that assumes a range of 3–5% in terms of moisture content level for sun dried samples after 28 days of air curing.

3.2 Mechanical characterization

3.2.1 Uniaxial compression test

Standard, Set up and Testing Procedures. Uniaxial compression tests were performed according to UNI EN 772-1 and the Australian code [48, 55]. Sample dimensions were decided after

TABLE 2. Percentages of soil elements and fiber content by weight.

	Clay	Silt	Sand	Fibre
Type	%	%	%	%b.w.
A	24–25	47–48	27–28	17–18
B	18–19	43–46	30–33	32–37
C	46–50	40–43	7–10	32–33
M	11–12	66–68	21–22	3–5

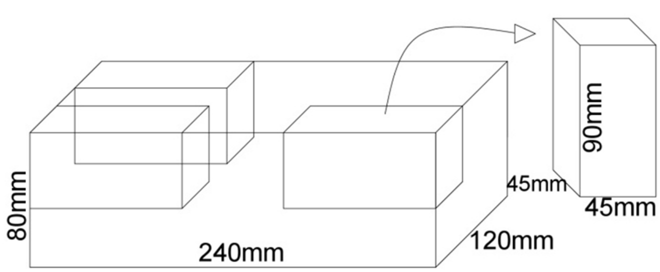
TABLE 3. Mean values and corresponding standard deviations (in brackets) of dry density and moisture content at laboratory conditions for each type.

	Density	Moisture Content
Type	kg/m^3	%
A	1233.9 (24.12)	3.25 (0.10)
B	799.3 (29.6)	3.89 (0.17)
C	821.5 (45.33)	6.36 (0.34)
M	1414.0 (25.1)	1.39 (0.04)

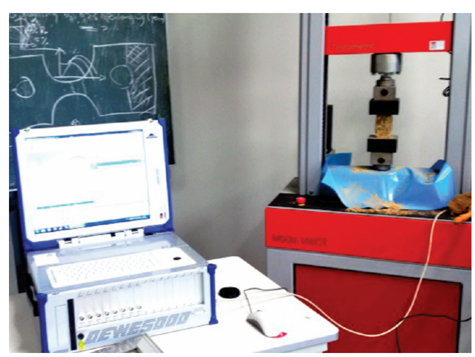
review of compression test standards for masonry materials in the literature, since the plate dimensions were not compatible with the initial geometry of the entire bricks. Samples with a height of 90 mm and slenderness ratio equal to two were tested. Prismatic samples were sawn from the corners of rectified entire bricks and surfaces in direct contact with the steel plates of a Universal machine were further rectified to ensure plane parallelism (Figure 4). In order to analyse the mechanical response of adobe according to the drying process, half of the samples were oven dried at 85 Celsius degrees. Samples which were heavily damaged after the cutting process were not tested (the majority from Type B). Displacement controlled tests were performed. Deformation was recorded from the relative displacement of the steel plate, which was prescribed to descend at a speed rate of 2 mm/min. In the following paragraphs test results are reported for the different sample types and drying conditions in terms of cracking pattern and resulting force-displacement plots. Since the mechanical characterization is the ultimate goal of this paper, an entire section is devoted to this end, while the raw data and visual observations are reported in the next paragraphs.

Observations and Results. For each test, the failure patterns were observed and the corresponding force (F) – displacement (d) diagram were recorded. They are reported in Figure 5 for each material type and drying condition. Most of the tests revealed four different regions in the force-displacement curve, independently from type and drying condition (Figure 6).

FIGURE 4. Mean geometrical dimensions of tested samples (a), and Universal testing machine (b).



(a)



(b)

FIGURE 5. F-d curves for air dried (left) and oven dried (right) samples of Type A (a–b), B (c–d), C (e–f), M (g).

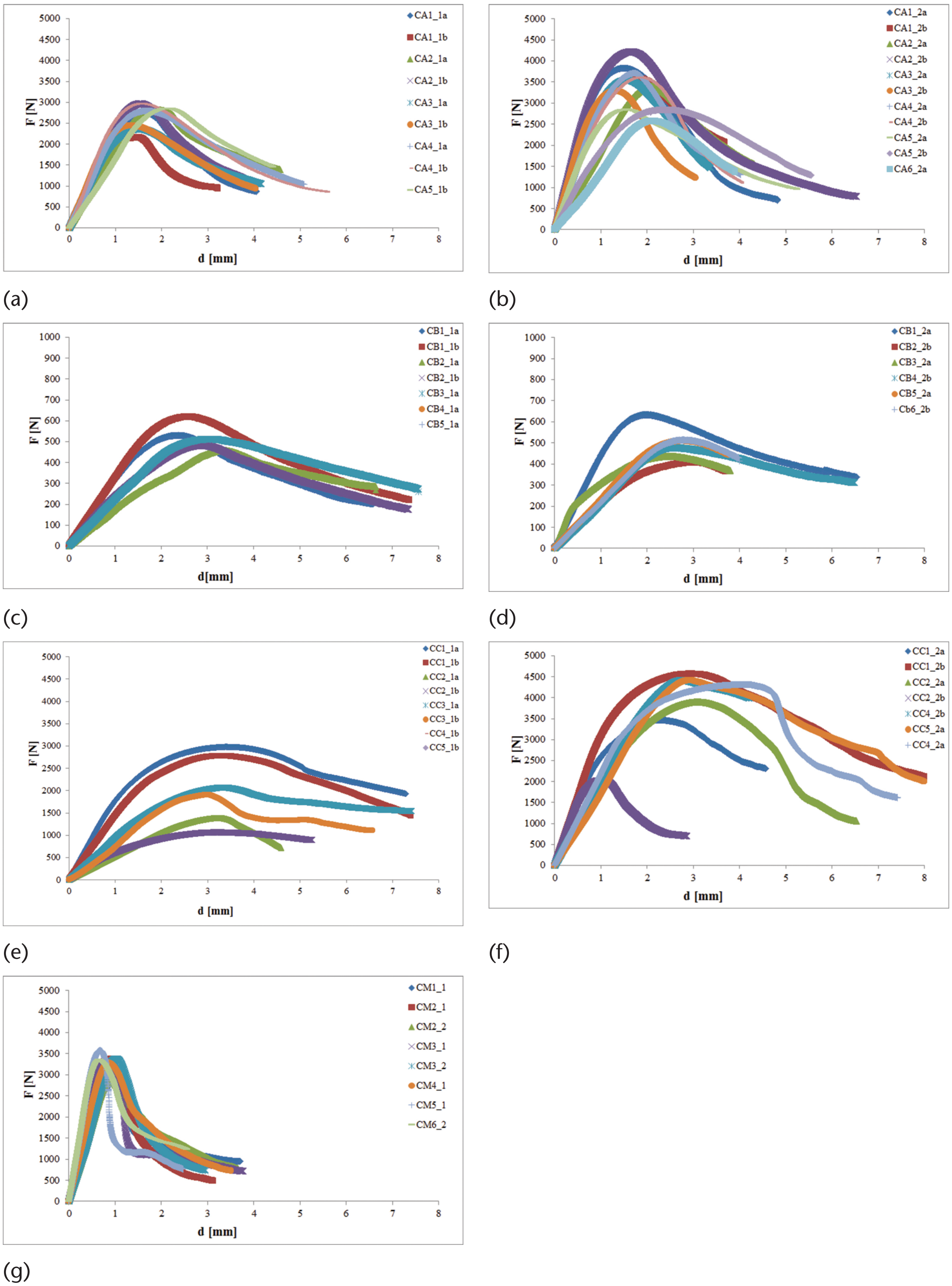
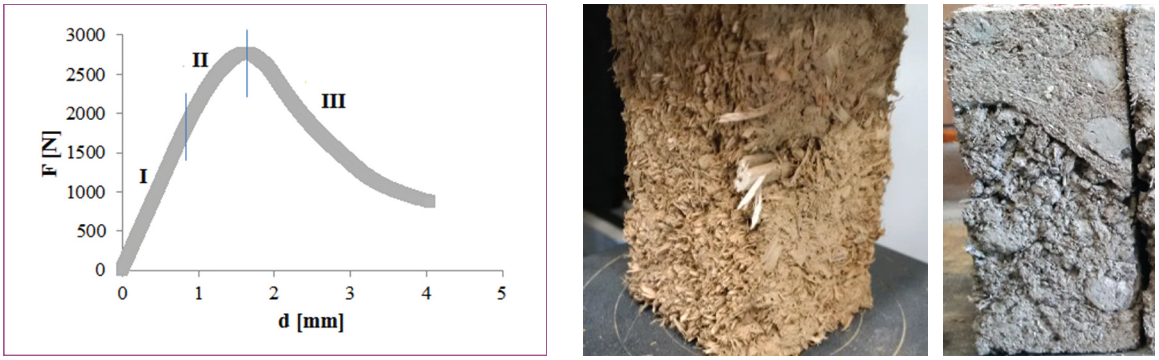


FIGURE 6. Typical F-d regions in compression (a), Type B-sample with visible piece of wood (b-left) and Type C sample with large voids (b-right).



(a) (b)

After an initial nonlinear phase, due to plate-top surface setting (not shown in Figure 6(a)), a linear elastic branch (I) is followed by a non-linear hardening phase (II) until the attainment of the peak load, which is followed by softening behaviour and collapse (III). Exceptions to the depicted F-d are ascribable to (few) samples with pronounced irregularities such as visible reinforcement concentration (Type B) or clay agglomeration (Type C) as shown in Figure 6(b).

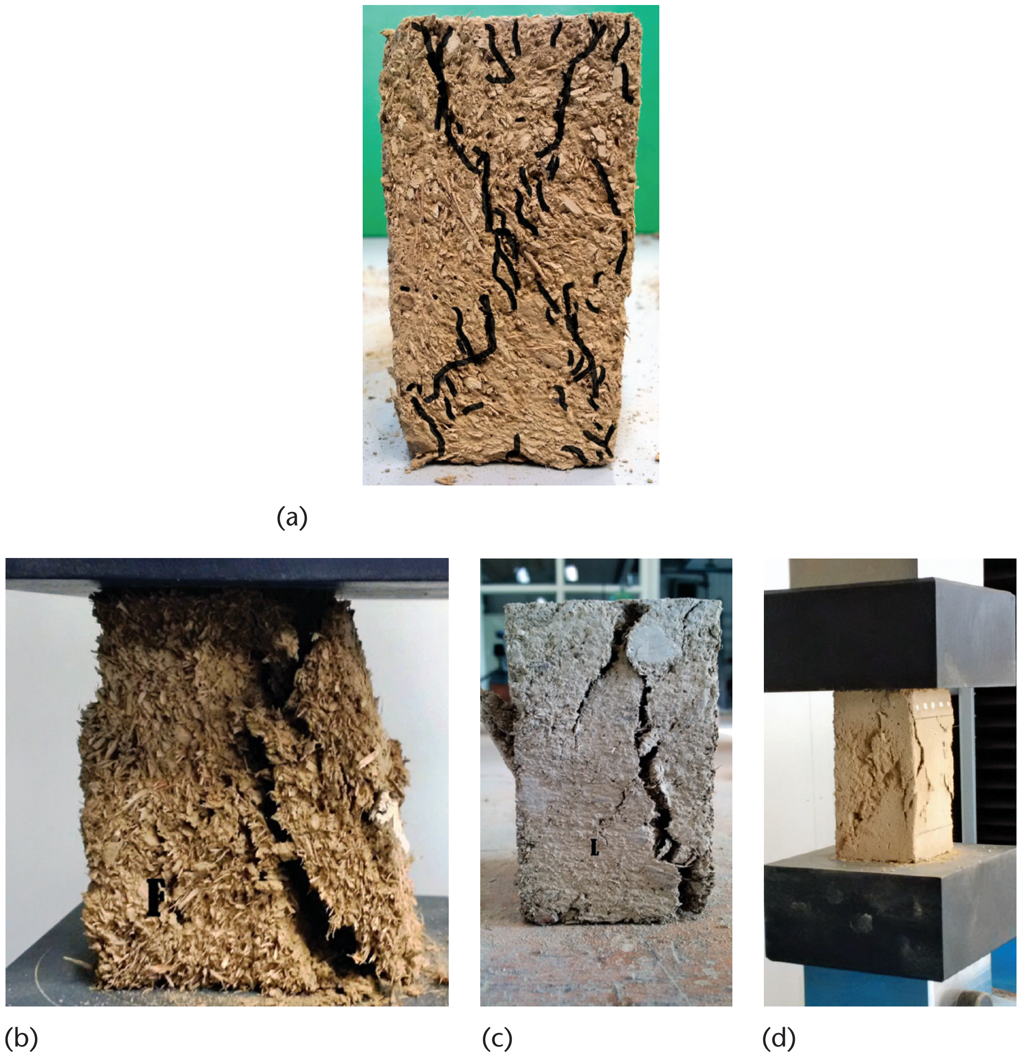
Also, a dominant cracking pattern was observed. In fact, the failure mechanism of the majority of air and oven dried samples was characterized by diagonal cracking (Figure 7(a)). A first crack appeared nearby the opposite edges of both the frontal or lateral surfaces after the attainment of the peak load and cracks progressively spread in at least three surfaces of the sample. Almost all Type A specimens were characterized by this failure pattern. A similar mechanism was recognized in the majority of tests of Type M, which were also often characterized by exfoliation of the external layers of mortar (Figure 7(d)). Furthermore, in a not negligible number of samples from Type B (and sometimes in Type C), a main crack starting from the edges of opposite faces propagated all along the total height of the sample causing collapse by spalling (Figure 7(b–c)).

The main mechanical parameters characterizing the material in compression were derived from each force-displacement curve, for both air dried (Table 4) and oven dried (Table 5) samples. The compressive strength f_b was calculated, normalizing the peak load of each curve with respect to the geometrical dimensions of the sample. Furthermore, the unconfined compressive strength f_{bu} is calculated according to the Australian standard HB195 [48]. The Young modulus E was calculated both as the secant modulus between strains at 5% and 33% of the peak strength $E_{5\text{-}33}$ [56, 57] and as chord modulus at 60% of the peak strength E_{60} [57]. In deformation, the strain at peak strength ε_{fb} and a ductility parameter d_u, defined as the ratio between displacements at 80% of the strength in the post peak regime and peak load, were derived. These values are reported in the following Tables (4–5).

3.2.2 Three point bending tests

Standard and testing procedures. Three point bending tests were performed according to UNI EN 12390-5 [58] on entire air-dried bricks. The horizontal surfaces were rectified in order to ensure plane parallel surfaces. Two further corrections were applied in the test setup. The bottom and

FIGURE 7. Typical cracking pattern in compression (a) and examples of different failure modes for Type B (b), C (c) and mortar D (d) samples.



upper 3 cm diameter steel rolls were interposed by 5 mm thick ply wooden strips approximately 16 mm long, equal to the maximum thickness of the samples (Figure 8). The strips were added in order to avoid possible indentation on adobe due to the large difference in stiffness between the steel rolls and adobe. At the end of the tests, the wooden strips were slightly concave, but no sample showed indentation. The span (s) in each test follows the prescriptions of the adopted standard. Furthermore, a low displacement rate of 1mm/min was applied in order to avoid dynamic effects during the test.

Observations and Results. For each test, the failure mechanism was observed and the corresponding force (F) – displacement (d) diagram was recorded. They are shown in Figure 9 according to each type. In all tests, the plot revealed two distinct regions. An elastic phase until peak load, characterized by a dominant linear branch with possible slight pre-peak damage (Type B), and a post-peak softening response of exponential shape. In samples M, the attainment of the peak load corresponds to a sudden stop of machine records, which refers to possible snap back behaviour, followed by a residual strength tail (Figure 9(d)).

TABLE 4. Summary of results for air dried adobe bricks and mortar's mechanical properties in compression.

	f_b	f_{bu}	E_{5-33}	E_{60}	ε_{fB}	d_u
Type	MPa	MPa	MPa	MPa	%	—
A	1.33 (0.13)	1.06 (0.13)	101.5 (16.1)	104.0 (16.8)	1.9 (0.3)	1.4 (0.2)
B	0.24 (0.03)	0.19 (0.02)	11.5 (2.3)	11.2 (2.5)	3.1 (0.3)	1.5 (0.1)
C	1.14 (0.40)	0.91 (0.33)	50.0 (23.0)	50.5 (23.8)	3.4 (0.4)	1.5 (0.2)
M	1.61 (0.11)	1.29 (0.09)	205.8 (56.0)	204.9 (52.6)	0.9 (0.2)	1.4 (0.1)
All	1.1	0.9	92.2	92.6	2.3	1.5
All (except mortar)	0.9	0.7	54.3	55.2	2.8	1.5

TABLE 5. Summary of results for oven dried adobe bricks and mortar's mechanical properties in compression.

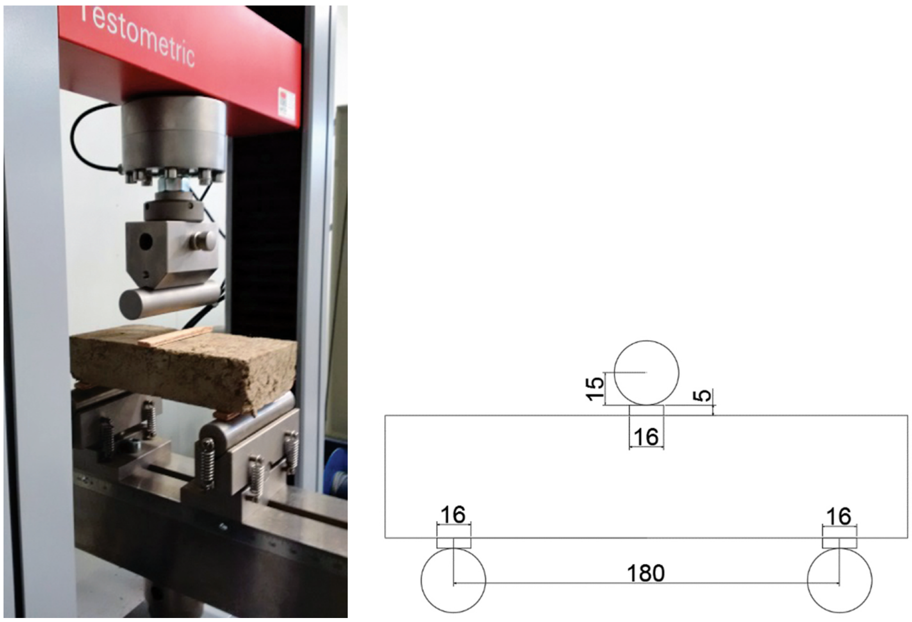
	f_b	f_{bu}	E_{5-33}	E_{60}	ε_{fB}	d_u
Type	MPa	MPa	MPa	MPa	%	—
A	1.71 (0.20)	1.38 (0.16)	141.5 (35.0)	140.3 (34.9)	1.9 (0.3)	1.5 (0.1)
B	0.25 (0.04)	0.20 (0.03)	14.0 (6.4)	13.8 (4.4)	2.9 (0.3)	1.6 (0.2)
C	1.91 (0.44)	1.53 (0.35)	109.6 (29.3)	108.5 (26.9)	3.0 (0.9)	1.5 (0.4)
All (except mortar)	1.3	1.0	88.2	87.6	2.6	1.5

Failure was characterized by the formation and propagation of a single crack. It appeared at the bottom side of the front and rear faces, corresponding to the loading upper roll (Figure 10), and it very quickly propagated through the thickness. As exceptions to this trend, in two tests of type C, two different cracks were formed at the bottom of the front and rear faces of the bricks, not aligned with the vertical of the upper roll, without coalescence in the middle of the bottom face (sample 2 and 3 in Figure 10(c)).

The main mechanical parameters characterizing the material in tension were derived from each force displacement curve. The tensile strength (f_t) and the flexural modulus (E_t) were calculated according to elastic material hypothesis, which is considered an acceptable approximation. The parameters are calculated according to the following equations:

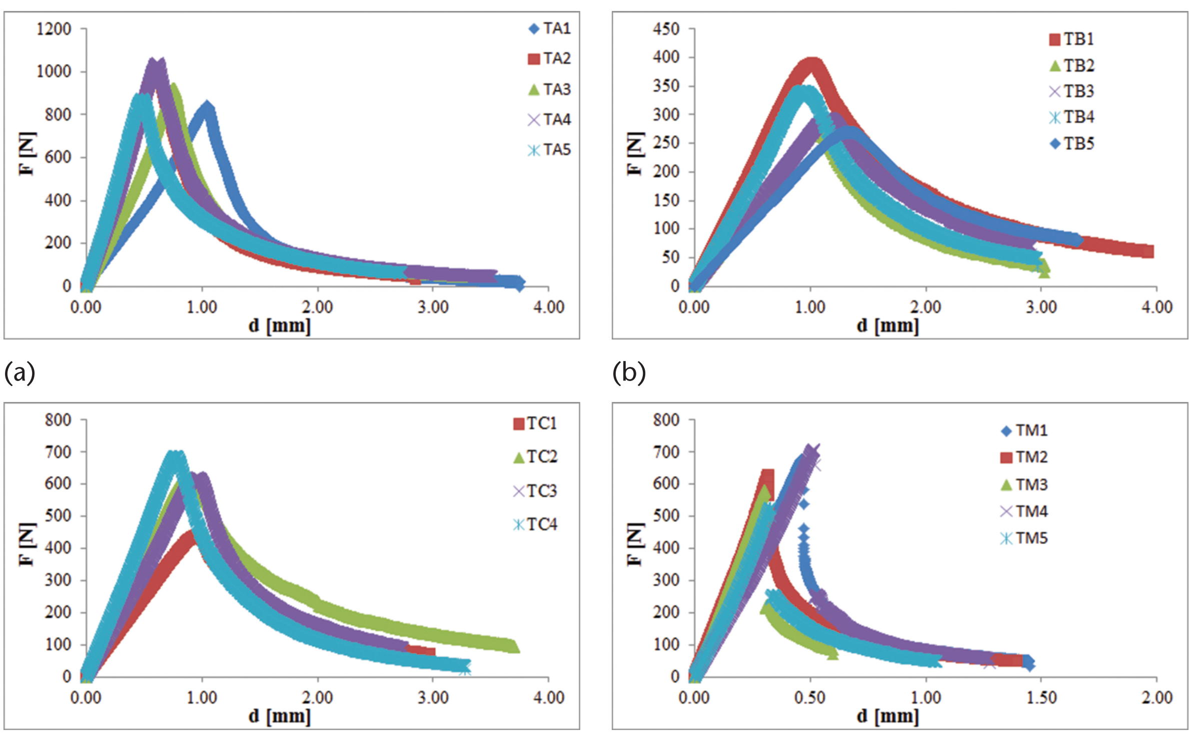
$$\begin{cases} f_t = \dfrac{3sF_{\max}}{2th^2} \\ E_t = \dfrac{3s^3F_{\max}}{4th^3d_{F_{\max}}} \end{cases} \tag{1}$$

FIGURE 8. Three point bending test setup (a) with indication of geometrical dimensions in mm (b).



(a) (b)

FIGURE 9. F–d curves for air dried Type A(a), B (b), C(c), M(d).



(a) (b) (c) (d)

FIGURE 10. Failure mode in bending for air dried Type A(a), B(b), C(c), M(d) (bottom view).

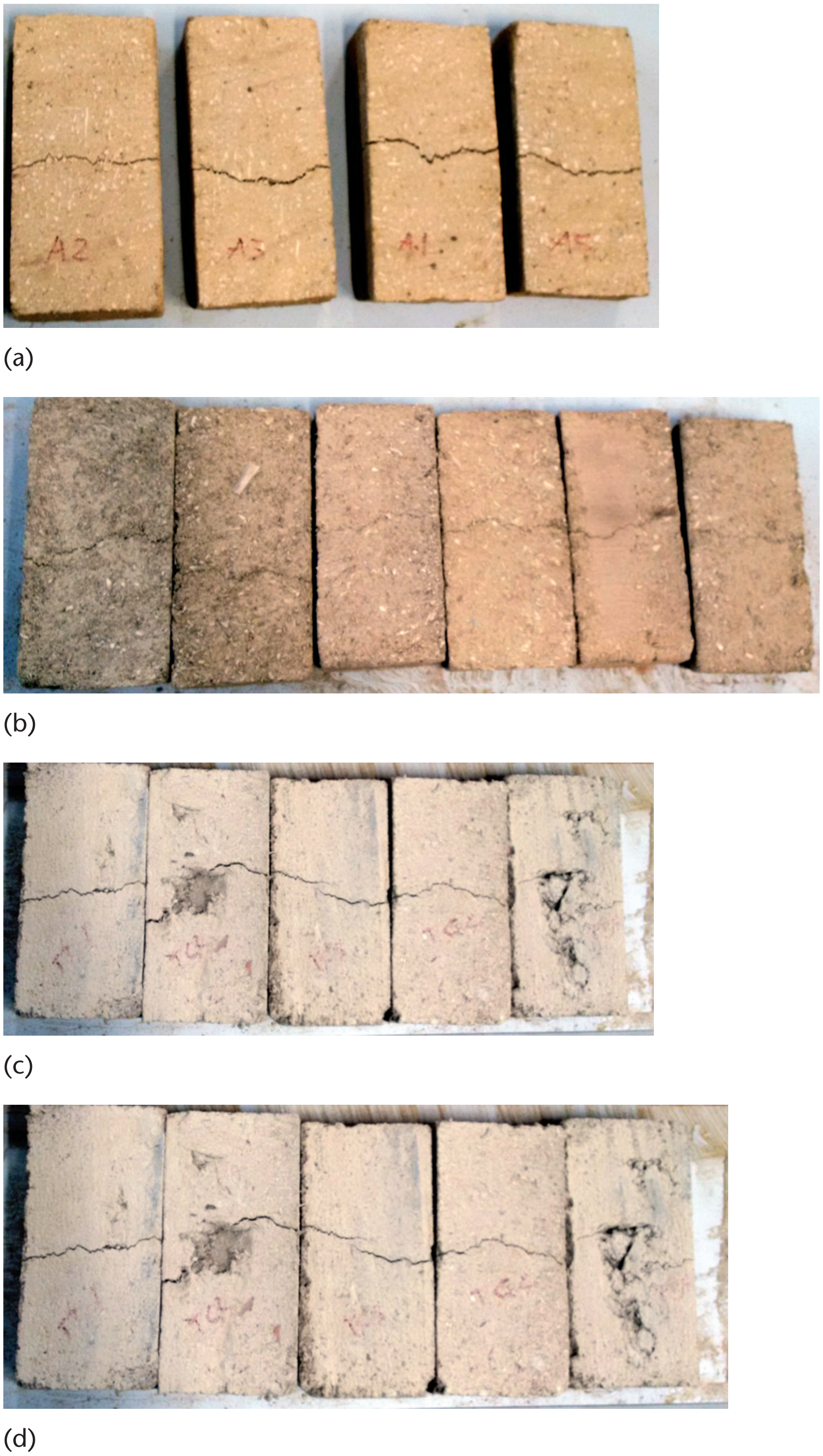


TABLE 6. Summary of results for air dried adobe bricks and mortar's mechanical properties in tension.

	l	t	h	$F_{\max}$	$d_{F_{\max}}$	f_t	E_t
Type	mm	mm	N	mm	MPa	MPa	
A	244	115	57	958 (64)	0.60 (0.10)	0.69 (0.05)	108.2 (16.0)
B	256	122	55	314 (46)	1.10 (0.13)	0.23 (0.03)	20.9 (4.3)
C	230	110	51	592 (91)	0.90 (0.10)	0.59 (0.12)	72.9 (17.7)
M	233	91	52	624 (65)	0.40 (0.10)	0.70 (0.10)	192.2 (23.4)

where the peak load ($F_{\max}$) and the displacement at peak load ($d_{F\max}$) with the geometrical dimensions in thickness (t) and height (h) were input. The mean values are reported in Table 6 together with the resulting mean mechanical parameters calculated.

4. THE MECHANICAL PERFORMANCE OF ADOBE ACCORDING TO THE PHYSICAL PROPERTIES OF ITS MIXTURE

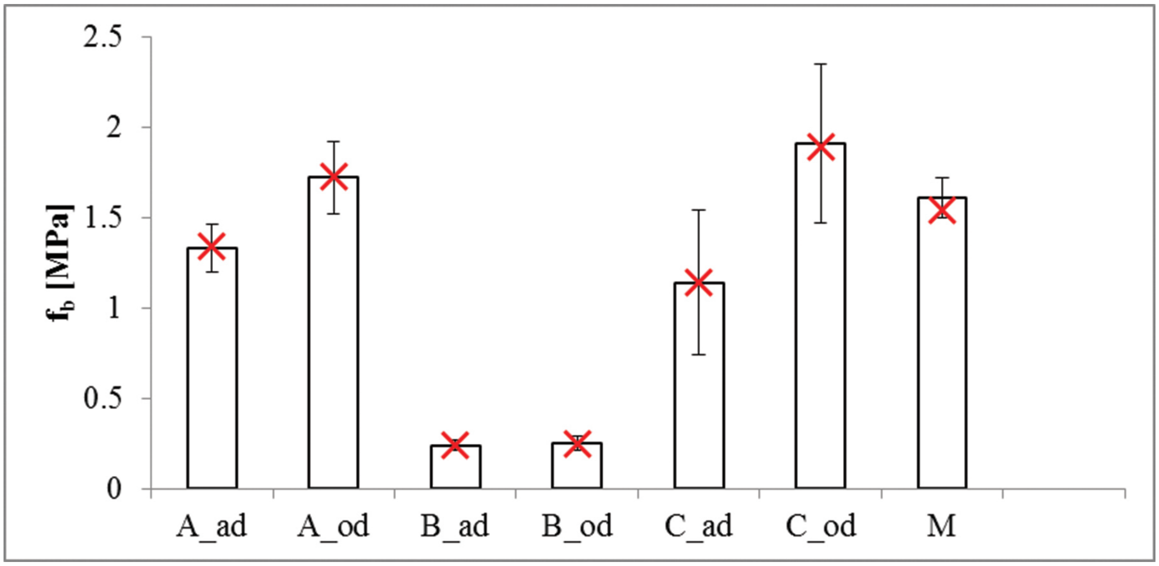
The previous section resumed the results of the mechanical characterization campaign on adobe samples made with different soil element composition at different drying conditions. The information contained has been already used for research on the mechanical performance of adobe [59, 17]. This section is meant to deepen the analysis in order to quantify the influence of the physical properties of the mixture on the mechanical performance in compression of the resulting adobe components. Moreover, as for masonry materials, the relationships between strength and Young's modulus in compression and the corresponding parameters in tension were also investigated. Statistical analyses were used to this end. The results are presented below and subdivided for compression and tension.

4.1 Parameters in compression

Considering all tests, the compressive strength ranges between 0.21MPa (CB22b) and 2.26 MPa (CC12b). The mean mechanical parameters corresponding to each type and drying condition reported in Tables 4–5 are shown in graphical form in Figure 11.

Considering air dried samples, strength significantly differs for the four types of constituent proportions. Mortar has the highest values in terms of compressive strength while samples belonging to Type B show the lowest performance. In particular, the mean compressive strength for Type B is not within the range indicated in the Australian earthen building book for adobe elements (1–5 MPa) [48], and it does not meet the lower threshold for unconfined strength requirement as prescribed by the New Zealand standard for adobe bricks (the least unconfined strength value out of five tests above 0.9 MPa) [60, 45]. Comparing the strength values from Table 4 and Table 5, the effect of curing conditions is also immediately recognizable. For all types, the mean compressive strength of oven dried bricks is higher than the corresponding air dried ones, but the proportion of increment varies among mixtures (Figure 11). Possible systematic relations between these physical factors and the resulting compressive strength for adobe

FIGURE 11. Experimental mean values and standard deviations for air dried (ad) and oven dried (od) bricks and mortar's compressive strength and predicted values of strength (red cross "x") determined according to eq. 2.3.



components were statistically investigated. To this end, it was decided to test a law recently proposed to address the influence of moisture content on the strength of modern unfired clay bricks [61, 62]. The compressive strength at a given moisture content is given by eq. (2) [61]:

$$f_{ba} = Aw^{-b} \tag{2}$$

where f_{ba} is the air-dried strength (MPa), w is the moisture content (%), B is a unit-less positive constant and A is a stress dependent term (MPa) depending on the type of soil particle in the mixture and increasing with clay amount [61]. In the present analysis, it was decided to link the stress unit term A to the compressive strength f_{bo}, which is in turn investigated according to the granulometry proportions of each type. Considering the mean values in terms of relative moisture content and strength for each type of brick (Section 3), multivariate statistical analysis resulted in best fit formulation for the oven dried strength f_{bo} and for the material coefficient b, both as functions of mixture elements percentages according to eq. (3):

$$\begin{cases} A(\cong f_{bo}) = 1.8\left(\dfrac{\text{clay}(\%)}{1+\text{fiber}(\%)}\right) - 0.7 \\ b = 0.008e^{2.5\left(\frac{\text{clay}(\%)}{1+\text{fiber}(\%)}\right)} \end{cases} \tag{3}$$

According to eq. (3), the stress term f_{bo} increases with the amount of clay as shown in [61]; however, in case of adobe, it appears to also be dependent on the fiber percentage, which weakens the overall strength. For the tested adobe, this finding is interpreted as the consequence of a lack of adherence between clay, soil matrix and fiber reinforcement.

The theoretical trends of compressive strength as a function of moisture content according to eq. (2.3) are plotted for each type of adobe brick in Figure 12, together with the mean experimental values of the air-dried and oven-dried compressive strengths values associated with each type and drying condition. The theoretical air-dried and oven-dried compressive strength values calculated according to eq. 3 are plotted as red crosses in Figure 11 for each type and corresponding moisture contents (Table 3).

Furthermore, as a final validation a blind prediction was performed. The formulation in eq. (2.3), which was calibrated only with respect to bricks in eq. (3), was used to predict the compressive strength at laboratory condition of Adobe mortar. The theoretical trend is also plotted in Figure 12 together with the ones associated to adobe bricks. The resulting compressive strength value of 1.53 MPa at 1.4% moisture content reported in Figure 11 is very similar to the average experimental one, and it lies within the standard deviation associated to Type M.

Considering all tests, elastic stiffness ranged between 7.7 MPa (CB21a) and 289 MPa (CM51) (Tables 4–5). Values show little discrepancy considering the two different formulations proposed to calculate the elastic stiffness (E_{60} and $E_{5\text{-}33}$ in Tables 4–5). Therefore, in the following, only the latter column is analysed and it is simply referred to as E (Figure 13).

The same influence in terms of drying conditions and mixture proportions on strength is observed in terms of stiffness (Figure 13). The Young's modulus was investigated according to the following relationship for unreinforced masonry [63,64]:

$$E = kf_b \tag{4}$$

where k is a coefficient that can significantly vary in the literature [64]. Within the performed tests on adobe, a different slope is revealed considering mortar or bricks. Considering all bricks,

FIGURE 12. Predicted compressive strength laws for each type as a function of water content using eq. (2) calibrated in eq (3) and comparison with experimental values for each type and drying conditions.

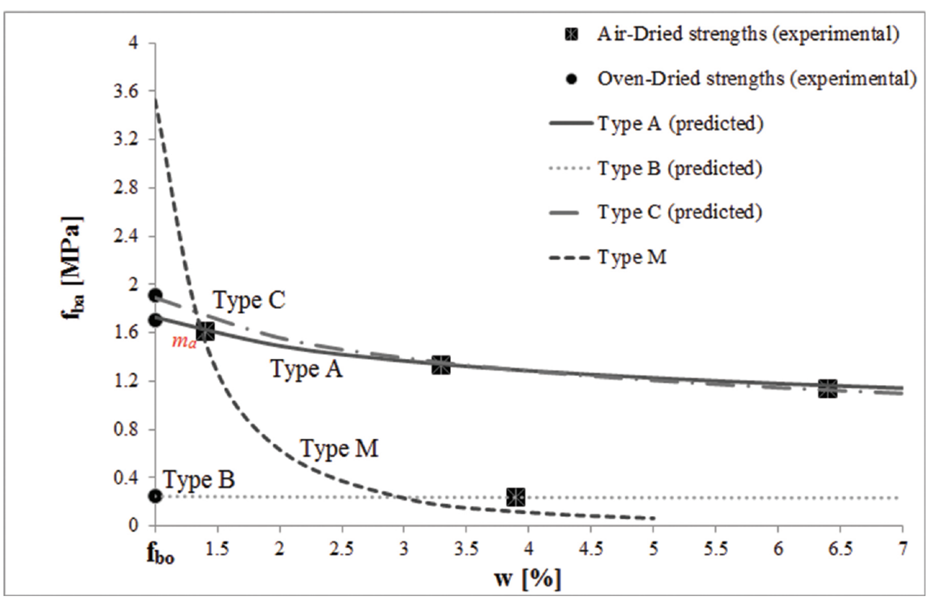
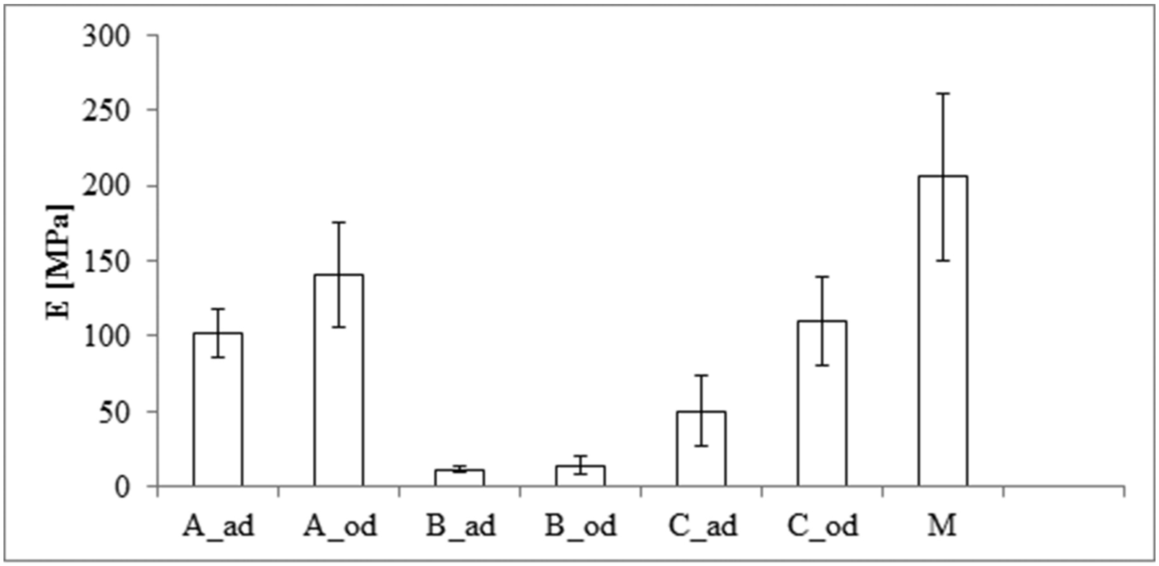


FIGURE 13. Experimental mean values and standard deviations for air dried (ad) and oven dried (od) bricks and mortar's elastic stiffness.



both air-dried and oven-dried tests, an average slope of k = 66 is found with a discrete correlation factor and a minor difference between the oven-dried and the air-dried bricks (Figure 14(a)). By contrast, also including the mortar in the analysis, the best fit of the slope increases to k = 79, with a decrease in the correlation factor r^2 = 0.55 (Figure 14b). In both cases, the slope is significantly lower than the ratio between strength and elasticity modulus prescribed by codes for adobe walls (k=300) [60].

Considering all tests, the deformation at peak stress ranged between 0.7% (CM62) and 4.5% (CC42) mm/mm (Tables 4–5). An analysis of strain capacity revealed no significant differences between air-dried and oven-dried samples, especially considering the high scatter that characterizes Type C (Figure 15a). Instead, the mean strain at peak stress was significantly different among types, with the highest performance associated to both Type B and Type C and with the lowest for mortar.

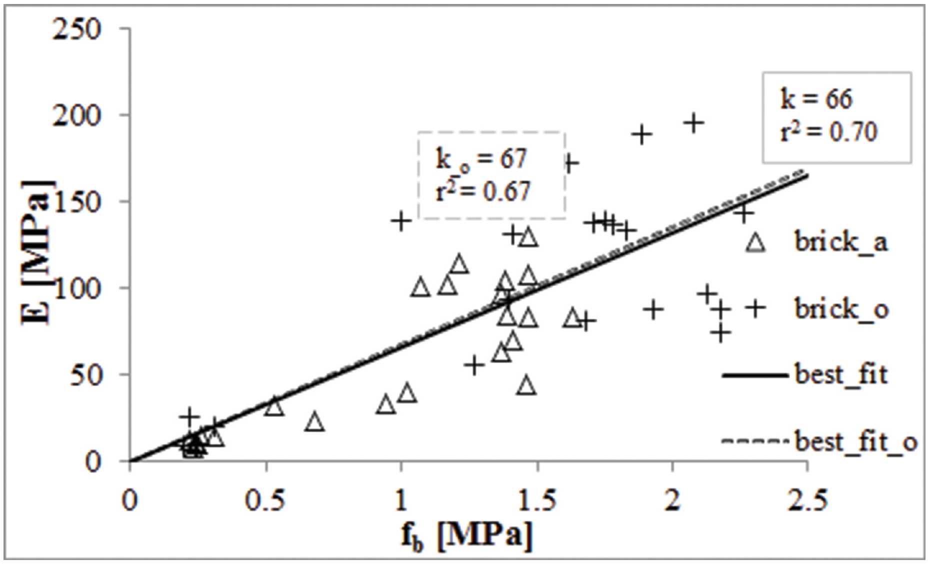
The dependency of this mechanical parameter with respect to the soil mixture composition was statistically investigated. This leads to a best fit formulation of ε_{fb} dependent only on fiber content. Calibrated with respect to oven dried values (only bricks), it resulted in the relation given in eq. (5):

$$\varepsilon_{fb} = 0.07 \text{ fiber } (\%) + 0.7 \tag{5}$$

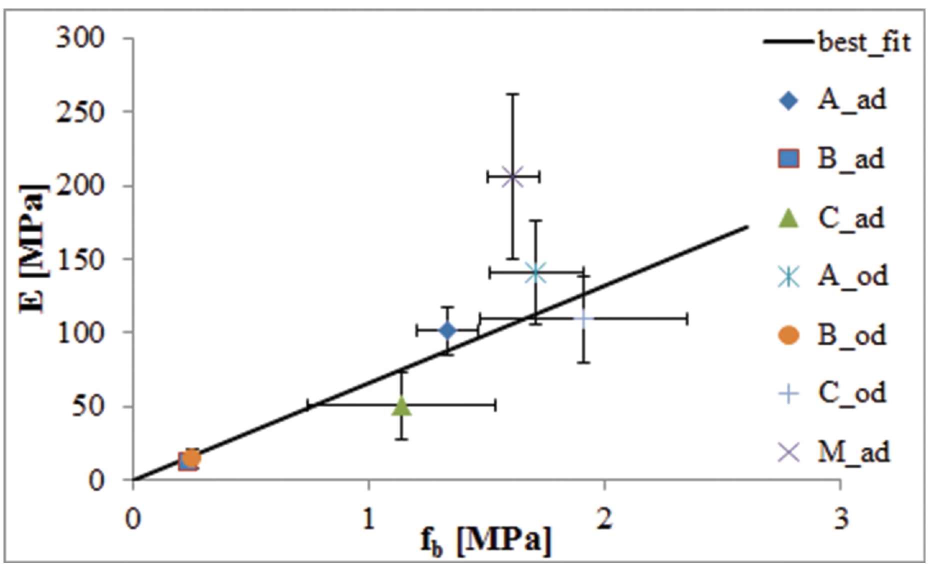
The formulation provides a good correlation with respect to bricks performance (Figure 16). Also, in this case, a blind prediction was performed using eq. (5) for mortar and a good match was obtained (Figure 15(a)).

Eq. (5) appears to be dependent only on the percentage of fiber in the mixture and independent of its water content. A possible interpretation of this finding relates to the drying status of fibers in the mixture. The similar performance in deformation for air dried and fully dried

FIGURE 14. Elastic stiffness-compressive strength experimental values considering only bricks (a) and mean E-f_b values including standard deviations associated to each type, including mortar (b).



(a)



(b)

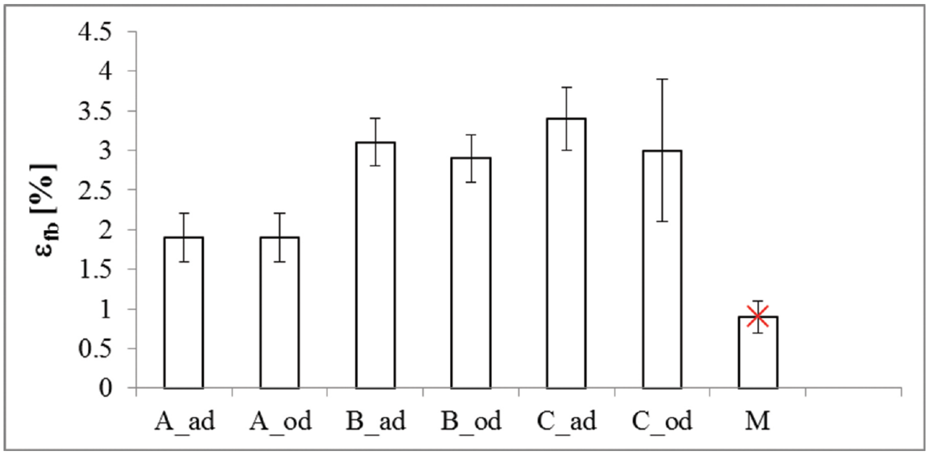
adobe suggests that fibers are already in a dry state after 28 days, while moisture is supposed to be contained mainly in the soil mixture.

Ductility, as defined in Sec. 3.2, was almost a constant parameter among all tests, independent of drying conditions and mineralogical compositions, and ranging between 1.4 and 1.6 (Figure 15(b)).

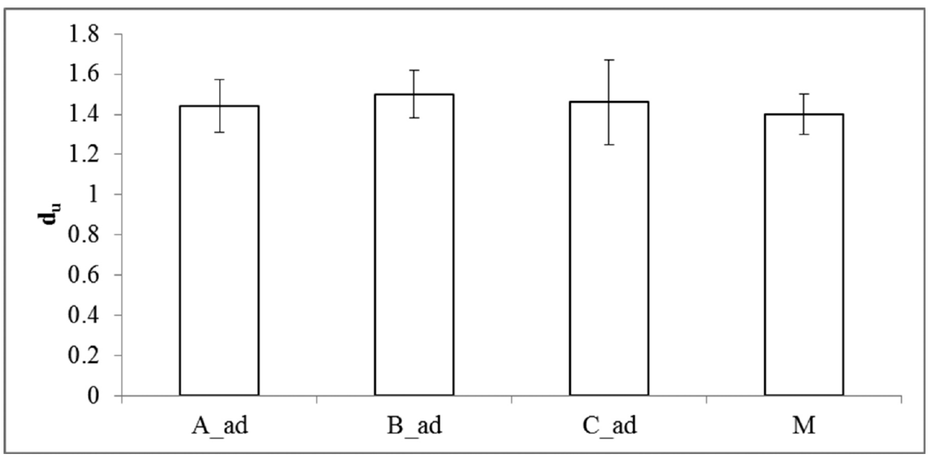
4.2 Parameters in tension

Only air-dried samples were subjected to three point bending tests. Considering all tests, the flexural strength ranged between 0.2 (TB2) and 0.8 (TM4) MPa. The mean values for each

FIGURE 15. Experimental mean values and standard deviations for air dried (ad) and oven dried (od) bricks and mortar's deformation at peak stress and predicted values (red cross "x") determined according to eq. 5 (a) and Experimental mean values and standard deviations for air dried (ad) bricks and mortar's ductility (b).



(a)



(b)

material components in Figure 17(a). All mean values are in the typical range for bending strength required for adobe (0.1–0.5 MPa) in the Australian standard [48]. Only Type B did not meet the requirement for adobe bricks provided by the New Zealand Code in tension (minimum value of strength from individual flexural tests above 0.25 MPa) [60]. The flexural stiffness ranged between 14.7 (TB5) and 226 (TM2) MPa (Figure 17(b)).

Also in tension, a relationship between strength and elasticity was investigated in the form of eq. (4). A slope of k =138 was found considering all bricks while the introduction of mortar in the analysis increases the slope to k = 191 with a decay of accuracy (Figure 18).

As in compression, strength and stiffness varied significantly with soil mixture proportions (Table 6). Plotting for each type, the mean strength in tension vs the corresponding unconfined strength in compression, the best fit slope considering all the tests was approximately 0.6. This value slightly increased to 0.64 if mortar was excluded from the analysis, with an increase in

FIGURE 16. Deformation at peak stress as a function of fiber reinforcement for bricks and mortar: experimental values and analytical formulation (eq.5).

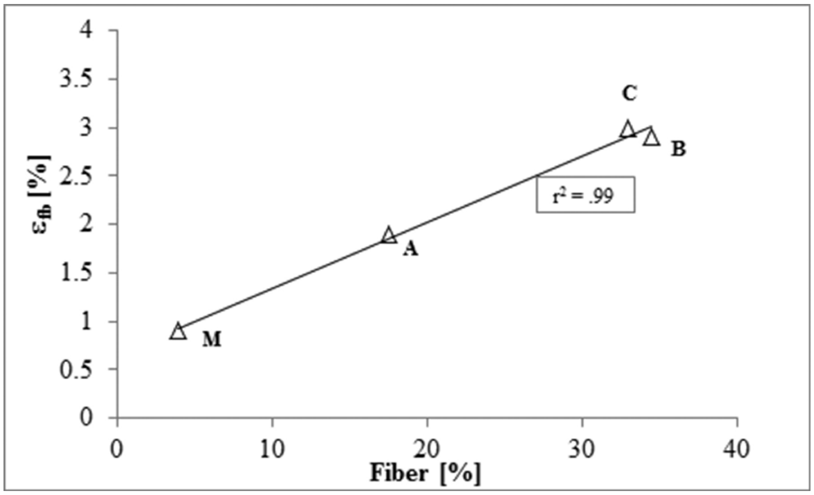
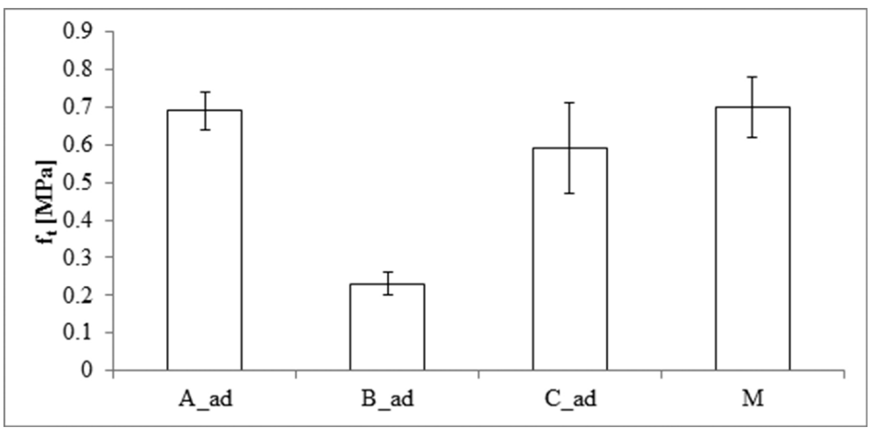
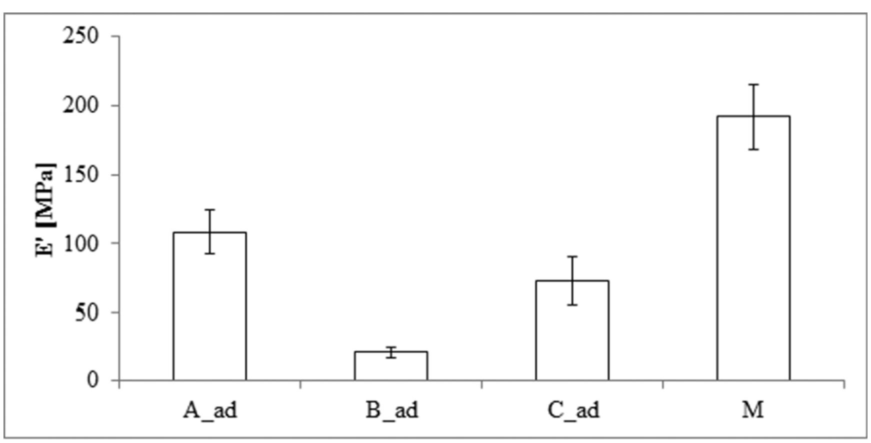


FIGURE 17. Experimental mean values and standard deviations for air dried (ad) brick's and mortar's tensile strength (a) and flexural stiffness (b).

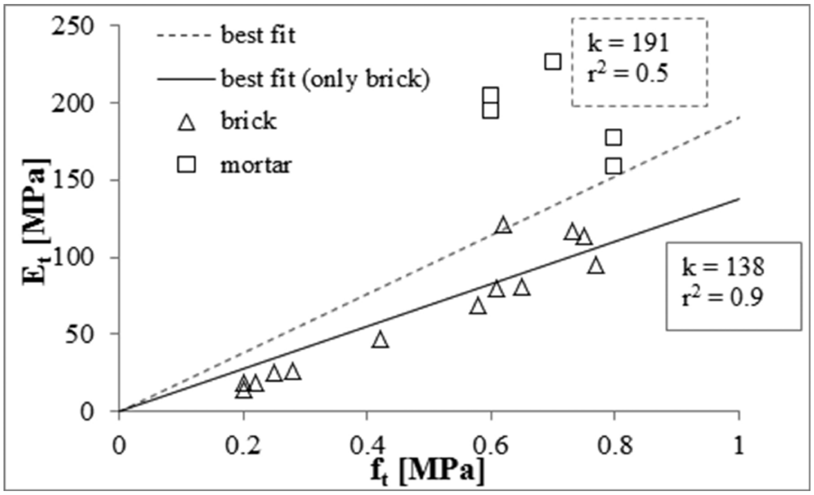


(a)



(b)

FIGURE 18. Experimental flexural stiffness-strength values considering all tests and only bricks.



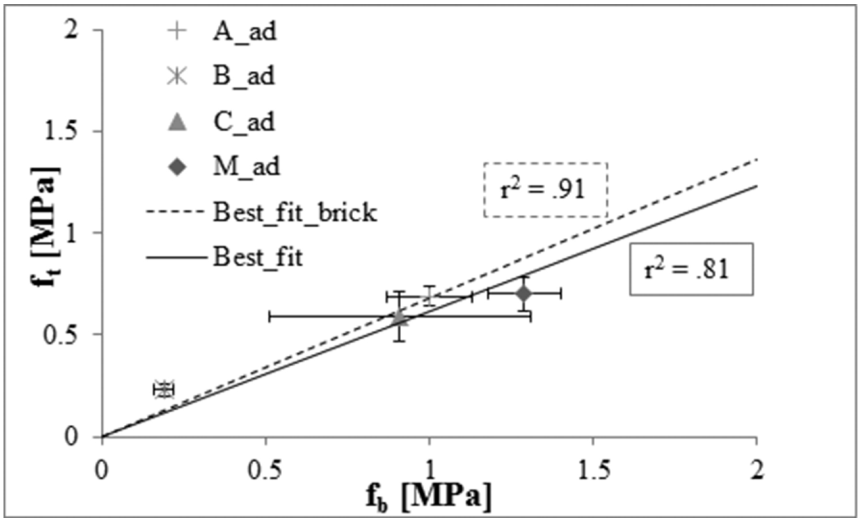
correlation factor (Figure 18(a)). In both cases, the found slope was higher than the typical range indicated for adobe in the New Zealand Standard, where flexural strength lies between 10% and 20% of the compressive strength [60]. Finally, proceeding with a similar approach as for elastic moduli, a clear correlation was found within the tested samples, with an almost unitary slope (k = 0.98) (Figure 18(b)).

5. CONCLUSIONS AND FUTURE PERSPECTIVES

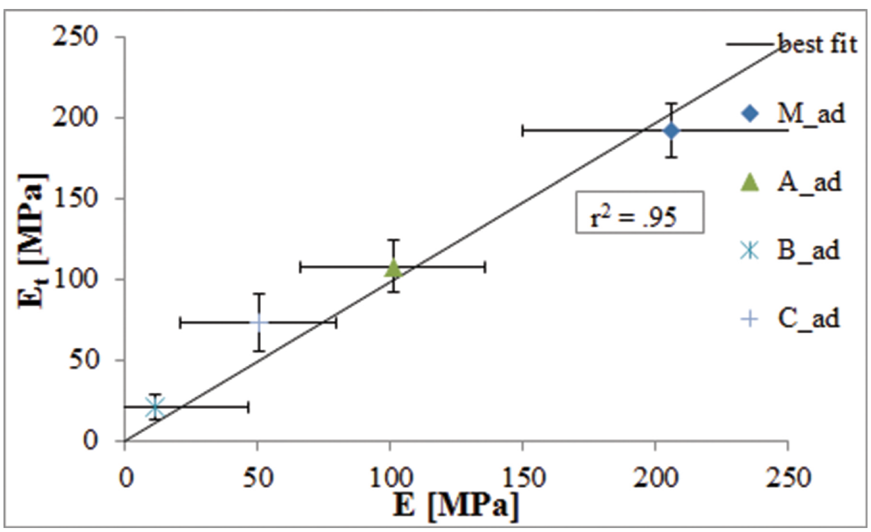
An experimental characterization campaign was conducted on three types of bricks and one mortar with different mixture components proportions from the same mineralogical family, produced in Europe with the same production process. The resulting mechanical properties were statistically investigated in order to determine possible relations with respect to the physical properties of the mixture. The research revealed the important influence that its physical state has on the mechanical performance of the resulting adobe component, leading to the definition of predictive formulations in strength and deformation. The compressive strength of adobe components at a given moisture content was predicted adapting a law used for unbaked clay bricks. According to the formulation, the air-dried compressive strength is inversely related to the water content of the mixture and directly proportional to the fully dried compressive strength value. Furthermore, the compressive strength of adobe improved increasing the ratio between clay and fiber reinforcement percentages. Although the inclusion of fiber within the soil mixture resulted in a reduction of the strength of adobe, it enhanced the deformability of the material. A predictive formulation for the compressive strain at peak stress was found dependent only on fiber percentages in the mixture and independent of its water content.

It is worth noting that the found laws are strictly valid for the tested types of adobe and their general applicability should be confirmed experimentally through further investigations accounting for different types of mineralogical families, reinforcement typologies, and soil and fiber elements' proportions.

FIGURE 19. Mean flexural-compressive strength considering only air-dried bricks or also mortar (a) and mean flexural-compressive stiffness considering all air dried types (b)



(a)



(b)

However, the formulations for strength and strain in compression proposed in this study, calibrated according to results on bricks, were determined to be valid also for assessing the mechanical performance of one type of mortar tested, which shared similar failure modes and force-displacement slopes. These trends reveal that in the case of adobe, the feature of structural heterogeneity typical of modern masonry is no longer valid. Both bricks and mortar of this traditional masonry belong to the same material class, and they share the same general properties. These are only determined by the mineralogical composition and granulometry proportions of the adopted mixture.

Among the tested samples, Type A assured the best compromise in terms of strength and ductility performance. This resulted from a better proportion between clay and fiber percentage. In general, the research demonstrates that an optimal combination of soil element proportions and fiber reinforcement capable of providing both adequate levels of strength and deformation capacity can exist and be determined. This does not necessarily comply with the recommendations in terms of soil mixture proportions contained in standards developed in different countries, which are based on the results of specific types of soil and production methods.

In Europe, designing codes are urgently needed for the rehabilitation of existing structures of adobe (present in many countries including Germany, Italy, France and Portugal) but also for the design of new buildings according to the growing principles of "sustainable architecture." The normative effort should start from the study and evaluation of standards for the execution and interpretation of granulometry tests on adobe soil with respect to the resulting mechanical parameters. This issue is still not sufficiently addressed within the existing legislative tools, and it is often neglected in scientific research.

REFERENCES

[1] A. Costa, J. M. Guedes, H. Varum, Structural Rehabilitation of Old Buildings, Buildings Pathology and Rehabilitation (2014) 350arXiv:arXiv: 1011.1669v3, doi:10.1007/978-3-642-39686-1.

[2] P. W. Brown, J. R. Clifton, The properties of Adobe, International Institute for Conservation of Historic and Artistic Works, Taylor & Francis, Ltd. 23 (1978) 139{146}.

[3] Alberti, De Re Aedificatoria, 1443.

[4] D. Silveira et al., Mechanical properties of adobe bricks in ancient constructions,Construction and Building Materials 28 (1) (2012) 36–44 doi:10.1016/j.conbuildmat.2011.08.046. URL http://dx.doi.org/10.1016/j.conbuildmat.2011.08.046

[5] H. Danso, D. Martinson, M. Ali, J. Williams, Physical, Mechanical, Durability Properties of soil building blocks reinforced with natural fibres, Construction and Building Materials (1) (2015) 797–809

[6] A. Agarwal, Mud as a Traditional Building Material, The Changing Rural Habitat; edited by Brian Brace Taylor. Singapore: Concept Media/Aga Khan Award for Architecture 1 (1975) 137–146.

[7] L. E. Yamin, C. A. Phillips, J. C. Reyes, D. M. Ruiz, Seismic Behavior and Rehabilitation Alternatives for Adobe and Rammed Earth Buildings, 13th World Conference on Earthquake Engineering (2004).

[8] D. Silveira, H. Varum, A. Costa, Infuence of the testing procedures in the mechanical characterization of adobe bricks, Construction and Building Materials 40 (March) (2013) 719–728. doi:10.1016/j.conbuildmat.2012.11.058.

[9] A. Anand, Non-Engineered Construction in Developing Countries an, in: 12 Wcee Conference, Vol. 91, 2000, pp. 1–22.

[10] A. Arya, T. Boen, Y. Ishiyama, Guidelines for earthquake resistant non-engineered construction, no. iv, UNESCO, 1986.

[11] G. Minke, Building with earth: Design and Technology of a sustainable architecture, Birkhauserar Xiv:arXiv:1011.1669v3, doi:10.1017/ CBO9781107415324.004.

[12] F. Champire, A. Fabbri, J. C. Morel, H. Wong, F. McGregor, Impact of relative humidity on the mechanical behavior of compacted earth as a building material, Construction and Building Materials 110 (2016) 70–78, doi:10.1016/j.conbuildmat.2016.01.027.

[13] R. Illampas, I. Ioannou, D. C. Charmpis, Adobe bricks under compression: Experimental investigation and derivation of stress strain equation, Construction and Building Materials 53 (2014) 83–90. doi:10.1016/j.conbuildmat.2013.11.103. URL http://dx.doi.org/10.1016/j.conbuildmat.2013.11.103

[14] R. Aguilar, M. Montesinos, S. Uceda, Mechanical characterization of the structural components of Pre-Columbian earthen monuments: Analysis of bricks and mortar from Huaca de la Luna in Peru, Case Studies in Construction Materials 6 (2017) 16–28. doi:10.1016/j.cscm.2016.11.003. URL http://dx.doi.org/10.1016/j.cscm.2016.11.003

[15] E. W. Smith, Adobe bricks in New Mexico, Circular 188, New Mexico Bureau of Mines and Mineral Resources (1982).
[16] M. Larcher, M. Peroni, G. Solomos, N. Gebbeken, P. Bieber, J. Wandelt, N. T. Tran, Dynamic Increase Factor of Masonry Materials: Experimental Investigations, ISIEMS/ICPS 2013, Potsdam, Germany (2013).
[17] T. Li Piani, L. Koene, J. Weerheijm, L. J. Sluys, The Ballistic Resistance of Adobe Masonry: An analytical model for penetration in soil bricks and mortar, International Symposium on Ballistics Impacts on Structures (17th ISIEMS), Bad Neuenahr, Germany, (2017).
[18] A. Heine, M. Wickert, Scale-independent description of the rigid-body penetration of spherical projectiles into semi-infinite adobe targets, International Journal of Impact Engineering 75 (2015) 27–29. doi:10.1016/j.ijimpeng.2014.07.009. URL http://dx.doi.org/10.1016/j.ijimpeng.2014.07.009
[19] G. Austin, Adobe as a building material, New Mexico Bureau of Mines and Mineral Resources, Socorro (1984) 69–71.
[20] A. Caporale, F. Parisi, D. Asprone, R. Luciano, A. Prota, Comparative micromechanical assessment of adobe and clay brick masonry assemblages based on experimental data sets, Composite Structures 120 (2015) 208–220. doi:10.1016/j.compstruct.2014.09.046. URL http://dx.doi.org/10.1016/j.compstruct.2014.09.046
[21] J. W. Garrison, E. F. Ruffner, Adobe, practical & technical aspects of adobe conservation, The Journal of Arizona History 25 (1983) 448–450.
[22] E. Quagliarini, S. Lenci, The inuence of natural stabilizers and natural fibres on the mechanical properties of ancient Roman adobe bricks, Journal of Cultural Heritage 11 (3) (2010) 309–314. doi:10.1016/j.culher.2009.11.012.
[23] E. Adorni, E. Coisson, D. Ferretti, In situ characterization of archaeological adobe bricks, Construction & Building Materials 40 (2013) 1–9. doi:10. 1016/j.conbuildmat.2012.11.004. URL http://dx.doi.org/10.1016/j.conbuildmat.2012.11.004
[24] S. Yetgin, O. Cavdar, A. Cavdar, The effects of the fiber contents on the mechanic properties of the adobes, Construction and Building Materials 22 (222–227). doi:10.1016/j.conbuildmat.2006.08.022.
[25] E. Baglioni, F. Fratini, L. Rovero, the Materials Utilised in the Earthen Buildings Sited in the Draa Valley (Morocco): Mineralogical and Mechanical Characteristics, IX Seminario Iberoamericano de Construccion con Tierra (9 SIACOT), (May 2016).
[26] D. Liberatore, G. Spera, M. Mucciarelli, M. R. Gallipoli, D. Santarsiero, C. Tancredi, Typological and Experimental Investigation on the Adobe Buildings of Aliano (Basilicata, Italy), Structural Analysis of Historical Constructions Constructions (January) (2006) 851–858.
[27] C. Galan-martin, C. Rivera-gomez, J. Petric, Clay-based composite stabilized with natural polymer and fibre, Construction and Building Materials 24 (8) (2010) 1462–1468. doi:10.1016/j.conbuildmat.2010.01.008. URL http://dx.doi.org/10.1016/j.conbuildmat.2010.01.008
[28] F. Wu, G. Li, Strength and stress strain characteristics of traditional adobe block and masonry, Materials and Structures 46 (2013) 1449–1457. doi:10.1617/s11527-012-9987-y.
[29] D. Silveira, H. Varum, A. Costa, Influence of the testing procedures in the mechanical characterization of adobe bricks, Construction and Building Materials 40 (March) (2013) 719{728. doi:10.1016/j.conbuildmat.2012.11.058.
[30] F. Fratini, E. Pecchioni, L. Rovero, U. Tonietti, The earth in the architecture of the historical centre of Lamezia Terme (Italy): Characterization for restoration, Applied Clay Science 53 (3) (2011) 509–516.doi:10.1016/j.clay.2010.11.007.
[31] F. Parisi, D. Asprone, L. Fenu, A. Prota, Experimental characterization of Italian composite adobe bricks reinforced with straw fibers, Composite Structures 122 (July) (2015) 300–307. doi:10.1016/j.compstruct.2014.11.060.
[32] F. Fratini, E. Pecchioni, L. Rovero, U. Tonietti, The earth in the architecture of the historical centre of Lamezia Terme (Italy): Characterization for restoration, Applied Clay Science 53 (3) (2011) 509–516.doi:10.1016/j.clay.2010.11.007.
[33] C. H. Kouakou, J. C. Morel, Strength and elasto-plastic properties of nonindustrial building materials manufactured with clay as a natural binder, Applied Clay Science 44 (1–2) (2009) 27–34. doi:10.1016/j.clay.2008. 12.019. URL http://dx.doi.org/10.1016/j.clay.2008.12.019
[34] Y. Millogo, M. Hajjaji, R. Ouedraogo, Microstructure and physical properties of lime-clayey adobe bricks, Construction and Building Materials. 22.

[35] A. A. Hammond, Prolonging the life of earth buildings in the tropics, Building Research and Practice 1 (3) (1973) 154–163. doi:10.1080/ 09613217308550234.
[36] H. Binici, Investigation of fibre reinforced mud brick as a building material, Construction and Building Materials 19 (2005) 313–318. doi:10.1016/j. conbuildmat.2004.07.013.
[37] J. Vargas, J. Bariola, M. Blondet, P. K. Mehta, Seismic strength of adobe masonry, Materials and Structures 19 (4) (1986) 253–258. doi:10.1007/ BF02472107.
[38] H. Binici, O. Aksogan, M. N. Bodur, E. Akca, S. Kapur, Thermal isolation and mechanical properties of fibre reinforced mud bricks as wall materials, Construction and Building Materials 21 (4) (2007) 901–906. doi:10.1016/ j.conbuildmat.2005.11.004.
[39] M. Bouhicha, F. Aouissi, S. Kenai, Performance of composite soil reinforced with barley straw, Cement & Concrete Composites 27 (2005) 617–621. doi:10.1016/j.cemconcomp.2004.09.013.
[40] H. Danso, B. Martinson, M. Ali, J. Williams, Effect of fibre aspect ratio on mechanical properties of soil building blocks, Construction & Building Materials 83 (2015) 314–319.
[41] M. M. S. Islam, K. Iwashita, Seismic Response of Fiber-Reinforced and Stabilized Adobe Structures, Proceedings of the Getty Seismic Adobe Project 2006 Colloquium 11 (3) (2006) 13.
[42] Y. Millogo, J. C. Morel, J. E. Aubert, K. Ghavami, Experimental analysis of Pressed Adobe Blocks reinforced with Hibiscus cannabinus fibers, Construction and Building Materials 52 (January) (2014) 71–78. doi: 10.1016/j.conbuildmat.2013.10.094.
[43] A. Vatani Oskouei, M. Afzali, M. Madadipour, Experimental investigation on mud bricks reinforced with natural additives under compressive and tensile tests, Construction and Building Materials 142 (2017) 137–147. doi:10.1016/j.conbuildmat.2017.03.065. URL http://dx.doi.org/10.1016/j.conbuildmat.2017.03.065
[44] Resultaten miniMOUT: effect van veroudering op ballistische weerstand van adobe muren met twee steen-sterkten, TNO Report, Tech. rep., TNO(2013).
[45] California Code of Regulations for Adobe in New Constructions (2011).
[46] New Mexico Earthen Building Materials Code—Title 14, Chapter 7 (Part 4),2004.
[47] NZS 4298 (1998): Materials and workmanship for earth buildings [Building Code Compliance Document E2 (AS2)] (1998).
[48] HB 195-2002 The Australian earth building handbook-Standards Australia International, NSW 2001 (2001).
[49] UNI EN 772-16: Metodi di prova per elementi di muratura. Parte 16: Determinazione delle dimensioni (2005).
[50] BS 1377-2:1990 Methods of test for soils for civil engineering purposes. Classification tests.
[51] D. Shah, A. Shroff, Soil Mechanics and Geotechnical Engineering, CRC Press, 2003.
[52] NT Build 333: Bricks and masonry blocks: Moisture content (1988).
[53] S. K. Vanapalli, D. G. Fredlund, D. E. Pufahl, The influence of soil structure and stress history on the soil-water characteristic of a compacted till, Geotechnique 49 (2) (1999) 143–159.
[54] NZS 4298, NZS 4298 (1998): Materials and workmanship for earth buildings, New Zealand Technical Committee 4298 (1998) 91.
[55] UNI EN 772-1:2015 Metodi di prova per elementi per muratura—Parte 1: Determinazione della resistenza a compressione.
[56] R. Drysdale, A. Hamid, L. Baker, Masonry Structures: behaviour and design, The Masonry Society, Boulder, Colorado, United States, Boulder, Colorado, 1999.
[57] EN 1052-1:2002 Methods of test for masonry—Part 1: determination of compressive strength. Brussels: European Committee for Standardization (CEN), 2002.
[58] NEN-EN 12390-5 Testing hardened concrete Part 5:Flexural Strength of test specimens (2009).
[59] T. Li Piani., J. Weerheijm., L. Koene, L.J. Sluys, The Adobe delta damage model, Computational Modelling of Concrete Structures (EURO-C 2018), CRC Press, 2018.
[60] New Zeland Standards, NZS 4297 (1998): Engineering design of earth buildings NZS 4297 (1998) 63.
[61] A. Heath, P. Walker, C. Fourie, M. Lawrence, Compressive strength of extruded unfired clay masonry units, Proceedings of the Institute of Civil Engineers Construction Materials 162 3 162 (3) (2009) 105 URL http://dx.doi.org/10.1680/coma.2009.162.3.105
[62] E. J. d. P. Hansen, K. Kielsgaard Hansen, Unfired clay bricks—moisture properties and compressive strength, in: A. Gustavsen, J. V. Thue (Eds.), Proceedings of the 6th Symposium on Building Physics in the Nordic Countries, Vol. 2, Norwegian University of Science and Technology, 2002, pp. 453–460.

[63] European Committee for Standardization (CEN), "Eurocode 6:Design of masonry structures-Part1-1: General rules for unreinforced and reinforced masonry structures," 2005.
[64] R. Lumantarna, D. T. Biggs, J. M. Ingham, D. M. Asce, J. M. Ingham, M. Asce, Uniaxial Compressive Strength and Stiffness of Field-Extracted and Laboratory-Constructed Masonry Prisms, Journal of Materials in Civil Engineering 26 (4) (2014) 567{575. doi:10.1061/(ASCE)MT.1943-5533.0000731.