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CRITICAL REVIEW ON THE MATERIAL CHARACTERIZATION OF ADOBE ELEMENTS

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ABSTRACT

Adobe is a traditional masonry made of sundried earthen bricks and mud mortar. Despite a millennial history of buildings of architectural value, adobe still connotes a so called 'not engineered' construction type. Namely, the material and structural properties of adobe are still not entirely addressed, resulting in an equally uncertain normative framework for adobe buildings design. However, over the last ten years, a large research program has been conducted in the Netherlands to qualify the material and structural properties of this sustainable building technology. In this paper, a critical analysis of the current normative body for the material characterization of adobe is addressed. Guidelines, prescriptions and requirements related to test methods, materials selection and properties contained in the available building codes for adobe around the world are assessed. A critical normative review is performed using the most recent literature produced on adobe, with particular regards to the results of experimental tests and numerical simulations performed by the authors. On the basis of these findings, some issues have been identified in relation to the knowledge currently condensed in the norms for adobe. A series of programmatic guidelines is aimed at orienting future research on adobe as well as fostering the process of updating its current normative body.

KEYWORDS

adobe; material; standardization; characterization; properties and procedures

1. INTRODUCTION

The Number 11 goal of United Nation (UN) urban agenda is concerned with making cities inclusive, safe, resilient and sustainable [1]. The introduction of the concept of sustainability in the building construction industry is urgent because of its current impact on the increasing threats inherent to natural material scarcity and global pollution [2]. The construction industry influences up to half of the total anthropogenic emissions of carbon dioxide in the atmosphere and is responsible for more than one third of the total energy and water use [3]. A significant portion of these contributions regards only the material production phase [4]. Thus, sustainable alternatives to current building practices are high priorities and research aimed at reducing the

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environmental impact of building materials while respecting performance requirements have been attempted globally. For example, biological fibres have been recently tested as sustainable alternatives to steel in reinforced concrete and natural binders or aggregates have been partially replacing Portland cement in concrete [5]. Alternatives to baking processes such as air-drying procedures are studied for baked clay bricks [6]. Most of the aforementioned practices, despite being applied to new materials, are far from being new. In particular, these belong to the tradition of adobe. In adobe masonry, bricks are made of soil mixed with natural fibres locally available in the field. Mixtures are then cast in molds and sundried without baking [7]. Fibre inclusion as well as air drying contribute to the eco-sustainability of adobe as a material [8]. Adobe is fully recyclable. It causes almost null carbon footprint and ensures a higher acoustical and thermal performance than classical modern materials. Therefore, this material has recently gained renewed attention in Europe within trends of sustainable architecture [9]. Unfortunately, the effects inherent to air drying and fiber inclusion as well as other sustainable practices tied to adobe tradition on its mechanical performance have not been addressed yet. In fact, use of adobe decayed in industrialized societies in favour of artificial building materials with higher performance and standardized production methods [10]. Progressively, adobe techniques have been applied in a rural setting by using significantly different soil and fibre properties and building techniques, according to raw material locally available and building tradition, resulting in a large heterogeneity of adobe typologies, material properties and structural performance. As a result, most of the adobe buildings in the world are currently not designed according to any standard. However, more than two billion people still live in earthen dwellings spread mainly in regions of developing countries that are prone to severe earthquakes or suffering from military conflict; notably, the building heritage of adobe can be still encountered in Europe as well [11]. Overall, in the specific case of adobe, sustainability is intertwined with other global urgencies inherent to safety and housing affordability [12]. As a result, a comprehensive characterization of earthen material is of paramount importance. Normative efforts for the material characterization of adobe were started more than fifty years ago in different areas of the world [10]. The first attempt to characterize earthen materials for construction relate to standards in Germany [13], [14] and in New Zealand [15] and the most widely used reference today is the Australian earth building handbook [16]. Other guidelines can be found in different areas of the world, including Mexico, Peru, California and Spain [17]–[19]. In codes for adobe, indications about material selection and characterization test requirements are often lacking, scarce or not consistent among the different guidelines. This occurs because adobe is a site dependent material whose properties vary based on the local resources available and building traditions, which prevent a uniform treatment of the subject. Nevertheless, it has been the lack of definite knowledge on the mechanical properties of earthen technology for building application that prevented a shared standardization process of adobe similar to modern building materials. Comprehensive studies on the mineralogical, physical and mechanical properties of adobe are still rare in literature: if this is true in statics, literature production on the dynamic performance of adobe is almost null [20]. However, research efforts toward the mechanical characterization of adobe has intensified recently for the aforementioned reasons [21]–[23]. Earthen bricks and mortar with different soil and fiber proportions have been physically as well as mechanically studied at different humidity conditions [24]. In particular, the role of fibres and water content have been experimentally studied in the dynamic regime, in ranges of strain rates which cover earthquakes and ballistic impacts [25]. These studies resulted in theories, analytical models and numerical frameworks developed to assess the material performance of adobe from statics to dynamics, including the effects of its meso-scale composition on the macro-material response [26]–[28]. In this paper, the resulting knowledge gained on the physical-mechanical performance of adobe serves to conduct a critical normative review on the material characterization of adobe. Normative guidelines, prescriptions and requirements condensed in the heterogeneous normative production currently available have been compared against the most recent physical evidences coming from literature. In this paper, a review of characterization norms is discussed in three subjects: soil selection, sample testing and material requirements. From the normative-experimental, analytical and numerical comparisons, issues and knowledge gaps have been identified in some of the existing prescriptions, requirements and procedures currently available for the material characterization of adobe. The main body of the normative review is condensed below and distinguished into a material selection criteria, material testing procedures and material properties assessment.

Final recommendations are developed to support the development of a comprehensive and homogeneous normative framework for adobe as well as to provide a perspective on future research in this field.

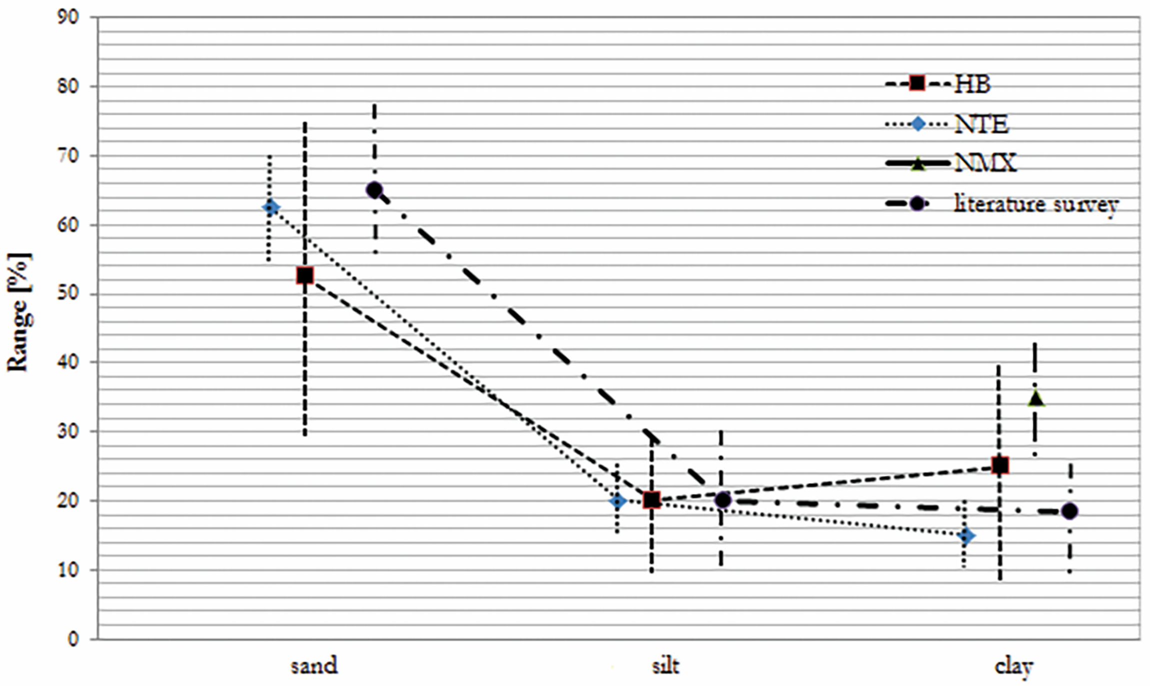
2. MATERIAL CHARACTERIZATION OF ADOBE IN THREE STEPS

Material standardization derives from a shared definition of soil selection, test methods and product performance. In the following sections, a normative review is based on the analysis of these three main subjects.

2.1 Material Selection

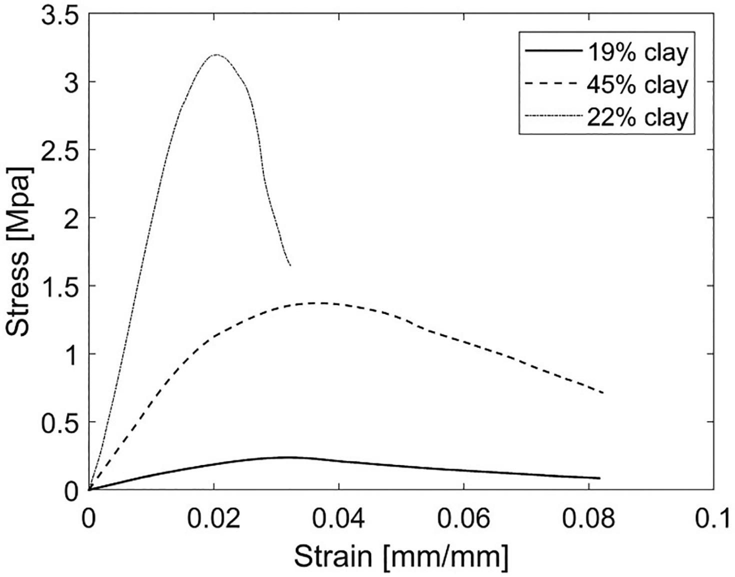
Traditional adobe bricks result from mixtures of clay, silt, sand, water and air. In most cases, bricks' soil is mixed with natural fibres while mortar contains limited or no fiber amounts. Despite scientific papers from more than thirty years ago recommending a proper characterization of the soil granulometry, plasticity and compaction properties of adobe for building purposes and the importance on the selection and identification practices of soil mixtures for earthen building applications is still not fully agreed to among the different design codes [29]. All codes for adobe currently available agree in selecting soils with no organic content and avoiding soluble salts (above 0.5–2%) [15], [16], [18]. Thus, top soil shall not be used. Potable water is recommended for mixing soil. Granulometry ranges constitute the most common recommendation contained in current building codes for adobe, as an indication on the cohesion properties of the final product [16], [18]. Guidelines mainly focus on the quantitative evaluation of the clay amount in the mixture. In fact, clay is the binder for the cohesionless granular fraction of the soil and is responsible for providing strength to the dried material [24], [30]. Codes agree that a minimum by weight of clay (10%) should be present in the mixture [16]. However, granulometry recommended ranges vary significantly around the different normative bodies, including in experimental characterization campaigns [24]. As a result, the maximum recommended clay percentages and foremost relative proportions with the larger size aggregates are still not well defined [7], [16]. For instance, the maximum aggregate size recommended can range between 5 mm to 25mm [16]–[18]. This uncertainty happens because the adopted mixture is dependent on the local availability of raw resources. An optimal clay amount is also determined by its mineralogical family and mutual proportions with the larger particles of the soil mixture. Expansive clay such as smecticte or montmorillonite are highly cohesive but also cause shrinkage cracks in the resulting adobe bricks [30]. In this regards, the use of expansive soil (i.e. "black earth") is sometimes discouraged in codes [15], but studies reveal that an optimum balance between expandable and non-expandable soil is possible and desired to ensure adequate strength to the brick [31]. Permitted ranges of soil components in the different codes are presented in Figure 1. As a result of the possible combinations available in literature, consistency in the normative assessment of the optimal ranges of soil particles for earthen building purposes is lacking. Each interpretation is true for any given soil but will vary from soil to soil. The ranges contained in the Australian standard include the best quantitative soil mixture compositions for building purposes identified by the authors for adobe from a literature survey [24].

FIGURE 1. Granulometry ranges for soil mixtures of adobe for building purposes according to Australian (HB), Peru (NTE) and New Mexico (NMX) codes compared with the results of a survey by the authors from literature.



Next to the availability of raw materials, quantity of clay as well as of other soil elements and including water in the mixture also depend on a vernacular building practice which is typical for adobe. It consists of mixing soil with natural fibres. This practice is tied to earthen architecture and dates back to ancient Egypt [10]. It's roots are in the need for limiting shrinkage cracks naturally forming in the brick during the curing process under the Sun [23]. In fact, fibres ensure better drainage systems through fiber cavities [32]. Some recommended materials in codes are e.g. rice, barley, maize, wheat and even include animal hair. Obviously, inclusion of fibres necessarily influences the initial mineralogical composition and the mixing water content, producing an impact also on the physical-mechanical behaviour of the final product. However, despite a consolidated practice, the assessment of the mixture properties after fiber inclusion is currently not regulated by characterization standards for adobe. Instead, judgment of its opportunity in soil mixtures in codes is deputized to the user and regulated often by not defined limits of not "*excessive use*" [16]. Actually, fiber inclusion in adobe guidelines is often considered as a stabilization technique of otherwise unsuitable soil compositions and suggested as an alternative to the introduction of cementitious bituminous binders recommended for highly clayey soils [15]–[17]. In this regard, fibres are suggested to improve the mechanical properties in hardness and strength, especially in tension [15]. The current interpretation on the role of fibres in many building codes for adobe is instead in contradiction with the main experimental trends recently observed for fibrous adobe in the field [24], [25]. The most common effect described in literature when adding natural fibres to soil mixtures is a decay of the initial mechanical properties of the resulting brick, namely strength and elastic modulus [23], [24]. This is valid both for flexure and compression and at different loading rates in the static and dynamic regimes [33]. In [24] higher amounts of clay were needed to partially recover the initial brick strength of a given soil mixture, if mixed with fibres, at the expenses of cracking issues after curing due to large clay amounts (Figure 2). These effects on the mechanical performance of adobe have been interpreted in [25] as the consequence of a loss of cohesion in the meso-structure of the soil mixture after fibres insertion. Particles might be separated by fibres and interaction between clay floccules to bind the cohesion less fraction of the mixture is less effective. This particularly happens for fiber amounts above 10% b.w (by weight) [24]. However, some cases in which fibres strengthen the soil mixture can be encountered in literature [34], [35]. This happens because cohesion of the brick's macro-structure results from the mineralogical properties and relative proportions of the soil and by the material, quality and quantity of the added fibres, including their mutual interactions with clay binders at the meso-scale. This interpretation suggests that an optimum mixture of fiber and soil elements capable of reducing shrinkage and enhancing the mechanical performance exists.

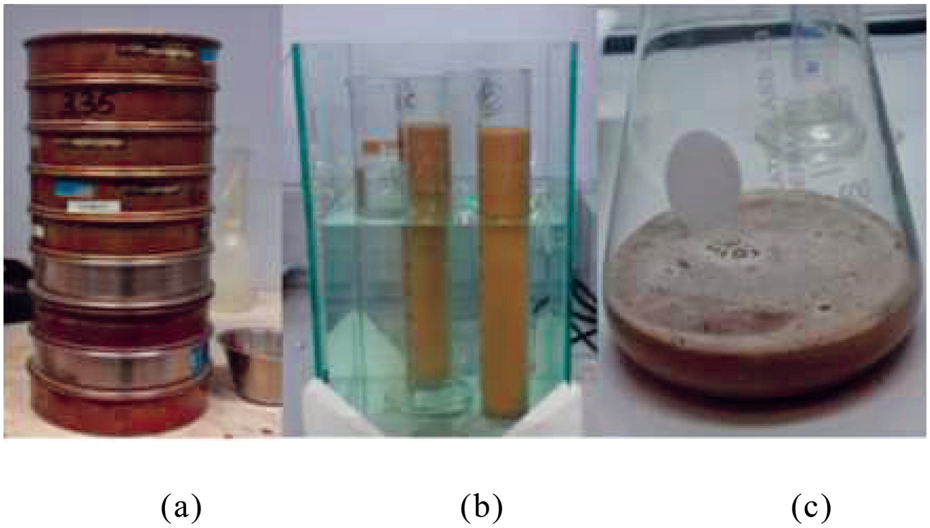
FIGURE 2. Experimental stress-strain curves for two adobe bricks containing about the same fiber content (≅30%b.w.) and different percentages in clay (≅20% and ≅45%) and one brick containing only clay (22%) tested statically (rate of 1mm/min) in compression at laboratory conditions [24].



2.2 Material Testing

Test methods and requirements inherent to the characterization of adobe components are not comprehensively neither consistently registered among the available codes [13]–[19]. A representative list of characterization tests required according to three different normative bodies on adobe is provided in Table 1. For adobe building codes, in-field tests are still considered as acceptable alternatives to more rigorous laboratory test methods. In-field tests are recommended provided the presence of the persons responsible for final construction, despite that most of earthen dwellings are still designed and fabricated by the owners themselves, often without the necessary specialist technical competences [36]. Also, the level of sophistication of the testing procedures and requirements rely on user judgement regarding the importance of the building project [15]. Some characterization tests in codes are even fully sensorial, such as the smell test to verify the presence of organic matter in soil mixtures [16]. The most widely used test to determine the grading of a soil mixture is the sedimentation bottle test, in which the shaking of a jar containing loose soil is aimed at ascertaining approximate fine and sand particles [16]. Instead, sieving and hydrometer tests are strictly recommended only in few norms [13]. In 2017, granulometry tests were performed by the authors using the BS 1377-2 norm for classification methods on soils for civil engineering purposes (Figure 3a–b) [37]. In fact, this code also includes the preliminary treatment of soil mixtures with natural fibres. Tests were performed on cured bricks of several mineralogical compositions. This implied the preliminary desegregation of the product into its original soil mixture. Later, organic content was excluded using mechanical and chemical treatments (Figure 3c). Dissolution was accomplished using hydrogen peroxide. In case of soil mixed with significant amounts and large sized fibres, this process required more cycles of chemical treatment.

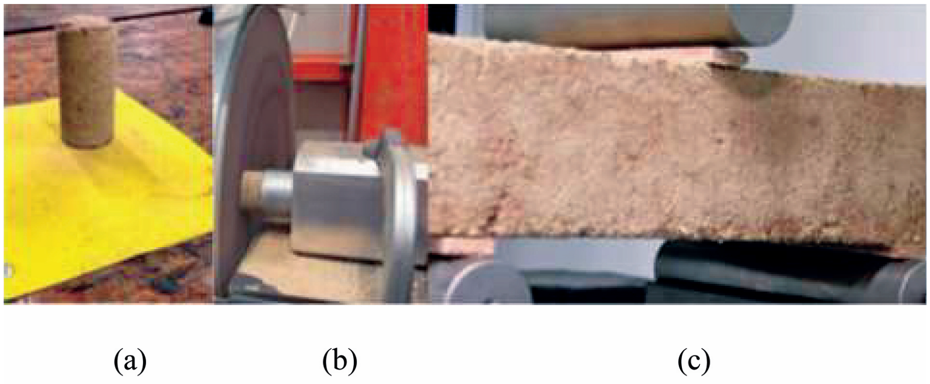
FIGURE 3. Sieving (a) and hydrometer (b) test, with preliminary chemical treatment of fibres (c) in [24].



(a) (b) (c)

Few codes currently prescribe cohesion tests for characterization purposes and they all require them to be performed only on the soil mixture before fibres insertion [16]. Moreover, operative challenges are faced when Atterberg tests are applied on organic soil [38]. Actually, for adobe, laboratory cohesion tests are recommended only in very few standards [13], [16]. In most of the cases, these imply the evaluation of Atterberg limits but only few quantitative indications are found and in broad ranges (16–30 for the plastic index and 30–50 for the liquid index) [16]. Quantitative evaluations inherent to soil plasticity as indication of soil consistency as standard but are instead more commonly related to simple in field tests such as the Ribbon test [16]. Also the mechanical characterization of adobe is not solely prescribed according to laboratory standards but in-field compressive and flexural tests are often possible and still preferred [15]–[18]. However, mechanical properties can be rigorously derived from the standard commonly used for modern materials such as concrete. Compression tests on adobe samples were performed in [24] using UNI EN 772-1 for modern masonry materials [39]. Required levels of plane parallelisms for testing purposes were achieved using mechanical rectification procedures which did not cause visible damage and achieved precisions included in standard tolerance (Figure 4 a–b). The interposition of layers of materials of significantly different properties like cement mortar is not recommended for plane parallelism purposes for adobe.

FIGURE 4. Sanding paper (a) and machine (b) used for rectification purposes and wooden strip interposition between steel rolls in a three point bending test (c) [24], [33.]



Static three point bending tests were performed by the authors according to UNI EN 12390-5 [40]. In this case, no indentation occurred when wooden stripes between adobe surfaces and steel rolls were interposed (Figure 4c). Literature studies and norms for adobe indicate that applied deformation rates above 5 mm/min may be not adequate for testing soft earthen materials. This limit is generally respected in literature studies and suggested also by the authors. Displacement controlled tests at velocities of 1–2 mm/min are suggested especially for soft adobe tested in compression and tension [24]. Higher values are discouraged also because the mechanical properties of adobe have been recently found to be sensitive to the applied loading rate [33].

If methods of investigation are uncertain, material performance requirements in codes are controversial as well. As shown in Table 1, prescribed values for important physical and mechanical properties are often lacking or incomplete. Not strictly quantitative recommendations that rely on the arbitrary judgment of the user according to the specific need and destination of the product are often encountered in codes for the assessment of many parameters [15], [16]. This is the case for instance for the smell test aforementioned or the wet/dry in-field tests. When not lacking, test limits are often not uniform among different sources. Most of the quantitative requirements normed in codes for adobe focus on the assessment of minimum strength values in compression and tension. This is a fundamental requirement especially for not engineered building technologies and thus to prevent possible heavy defects in material or production and early failures. However, there is often no agreement about the minimum required performance and the assessment of other important mechanical parameters for masonry design (like the Young's modulus or the Poisson ratio) is missing.

TABLE 1. List of main tests required for the characterization of adobe components according to the Australian (HB), New Zealand (NZS) and Mexico (NMX) codes, distinguishing in-field test (in italic) from laboratory tests and denoting with * tests without quantitative requirement limits.

Property	HB	NZS	NMX
Grading	*Bottle test* Sieving/sedimentation	*	*
Organic content	*Smell test**	*	*
Plasticity	Casagrande test *Ribbon test* *Touch test*	*	*
Durability&Erosion	*Water retention test** Water absorption test* *Spray test**	*Wet/dry test** *Spray test**	*Water retention test**
Shrinkage	*Box test*	*Box test**	*
Density	Oven drying*		*
Compression	Uniaxial test *Drop test*	Uniaxial test *Drop test*	Uniaxial test
Tension	Bending test *Flexure test*	*Flexure test**	Flexure test*

2.3 Material Performance

2.3.1 Physical Properties

Mixtures of adobe are cast in moulds and dried under the sun for a minimum of 28 days in an exterior environment before testing [15], [16]. Both literature reference and current standards for adobe recommend protecting bricks from wind and rain during drying [15]. It is known that natural fibres display their role during this phase. These fasten the draining process through cavities and prevent the formation of severe shrinkage cracks [41]. Shrinkage is abundant during drying of earthen materials and is allowed also according to codes, provided that shrinkage cracks do not jeopardize the material properties of the product [15], [17]. Caution is recommended [15] if short fine cracks spread randomly at the surface of the brick are observed. In [16], it is preferred to exclude products with crack lengths above 7 cm. See that [14] recommends quantitative limits of 2% for the property of linear shrinkage. Shrinkage cracks represent a significant issue especially in the case of high amounts of expandable clays in soil mixtures or in absence of fibres. Therefore, it can represent a threat especially for mud mortar. Characterization of mud mortar receives very little attention in codes [13], [15]. Despite its importance on the overall performance of adobe walls is recognized in literature, physical tests on mortar are usually prescribed only if different soil materials than for the bricks is used. This implies neglecting the influence of fibers during material production and wall construction and life cycle. Different shrinkage rates between bricks and mortar can be responsible for initial loss of adherence and de-cohesion issues which may soon affect structural integrity. Unfortunately, scientific studies on the material characterization of adobe mortar are also lacking and only a few references concerning the physical mechanical assessment of mud mortar have been found [24], [42]. In [24] physical tests for the determination of density and moisture content were performed on various types of bricks and mortar for the same curing conditions. This study confirmed that mortar is denser and characterized by higher shrinkage rates than fibrous bricks (Figure 5).

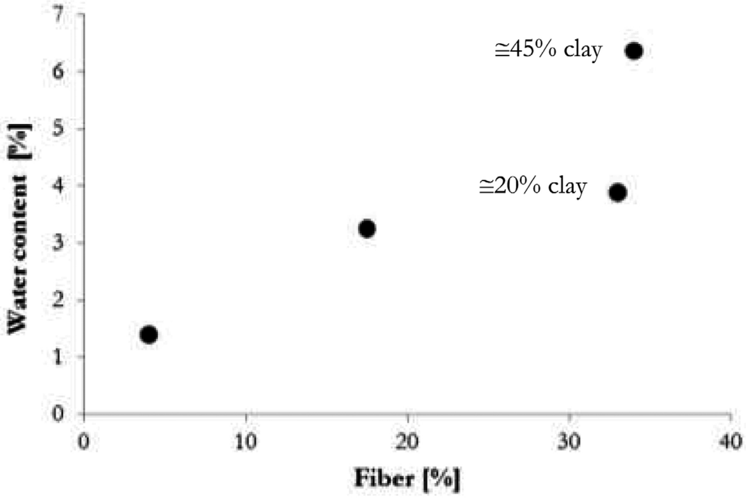
FIGURE 5. Picture of mortar just cast (a) and after five days since pouring(b): volumetric shrinkage of about 18% [26].


(a) (b)

Even if the same soil is used for bricks and mortar, the corresponding values for the property of density are different after 28 days of curing. Density in adobe is significantly influenced by fiber addition, and its inclusion in the mixture significantly reduces the density of the resulting brick. This is a common trend observed in literature and quantified in [33]. Density was determined on two types of bricks with the same mineralogical composition but with only one mixed with 18% b.w. of fibres. Tests showed that the average density of the fibrous samples was more than 30% lower than the fiber free homologous bricks. As a result of different compositions, density values among different bricks also greatly vary in literature. They usually range between 800 kg/m^3 for fibrous mixtures to 1800 kg/m^3 for clayey bricks [24], [33]. This range is close to the one recommended in standards for adobe (1200 kg/m^3–2000 kg/m^3) [16]. Tested mortar in [24] showed a density of 1400 kg/m^3 whereas the one in [42] was almost 2000 kg/m^3. In codes, durability performance of cured adobe is addressed mainly using in-field tests. The most commonly evaluated property (despite without definite limits) is erosion against water simulating raining conditions or dry/wet cycles to which adobe walls may be exposed to during its life cycle [15]–[16]. Instead, the assessment of the moisture content at 28 days of drying before wall fabrication is not required by codes. Instead, it is generally assumed that water content after curing is lower than 4% [15]. However, it counts that this assumption is not always the case and quantitatively depends on the internal composition of the product. This was experimentally inferred in [24] during a campaign aimed at testing the mechanical performance of bricks and mortar made with different clay and fiber percentages. Bricks mixed with 30%b.w. of fiber and containing 45%b.w. of clay contained more than 6% of water after 28 days of curing, whereas the same fiber amount in a mixture with half of the clay almost halved its initial moisture level for the same environmental conditions (Figure 6). This observation proves that 28 days in the sun are not always sufficient to ensure a fully dried product. Furthermore, the presence of fibres in the mixture has been found to have a relatively minor influence on the final level of water content at cured conditions of bricks [33]. In particular, for certain amounts of fibres, it has been found that water content increases significantly with the increment of the clay proportion in the mixture. This is interpreted as a consequence that the areas of the mixtures surrounding fibers are fully dried after 28 days. Thus, the final water content also depends on the spatial distribution of the fibers in the mixture, with particular regards to possible areas of clay concentrations [24]. In fact, water can still be retained by floccules of clay due to its affinity toward water: it swells in its presence and it shrinks in its absence [30].

Finally, the assessment of the material eco-efficiency in terms of physical properties such as thermal resistance are not contemplated by codes, with the exception of [16], where a typical range of the expected performance is included between 0.25–0.6 m^2K/W.

FIGURE 6. Water content at 28 days of curing for four different adobe bricks as a function of the mixing fibers: focus on the moisture content for two bricks with similar amount of fiber but different clay percentages [24].

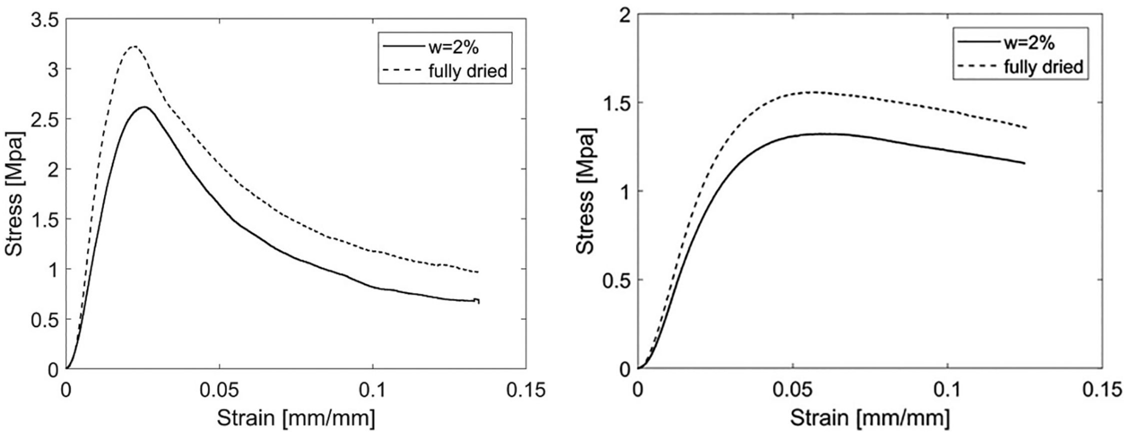


2.3.2 Mechanical Properties in Compression

For adobe, assessing the interstitial water content of earthen components prior to construction is of paramount importance. Not only is it already known that water affects the durability performance of the structure due to erosion phenomena during the life cycle of the structure [7], but it also directly influences the nominal strength of the bricks and mortar and thus of the overall walls. Guidelines consider adobe bricks as fully dried after 28 days of curing, when the water content is expected to be lower than 4% [15]. However, water levels below 2% are sufficient to determine a significant decrement in the parameters in strength, whereas a minor influence is exerted in deformation. This has been experimentally found testing various types of adobe bricks at different induced moisture levels (including oven drying the samples) [43]. Tests revealed an increment in strength for progressively lower water contents in the bricks.

This trend has been observed for all the tests performed, both in static and dynamic regimes and also when mixtures contain fibers (Figure 7).

FIGURE 7. Stress-Strain curves in compression for fiber free adobe bricks (a) and fibrous bricks (b) air dried at laboratory conditions (w@2%) and dried in the oven (reduction of about 20% in strength) [43].



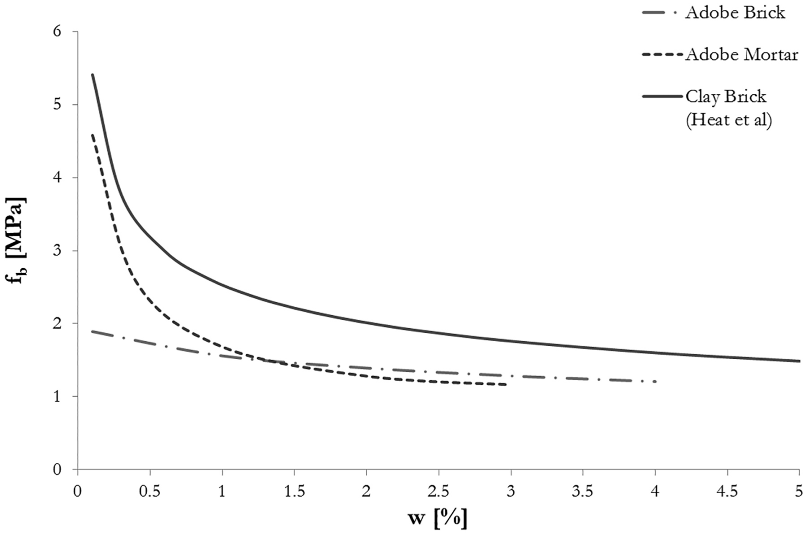
(a) (b)

However, the rate of decay of the strength of adobe due to interstitial water has been quantified in [24] as a function of the mineralogical composition of the mixture. By testing samples with different clay and fibres at certain drying conditions, it was revealed that the mineralogical composition of adobe can accelerate or decrease the loss of this mechanical property. In particular, statistical regression of experimental data on adobe resulted in eq. 1 for the prediction of strength at a given humidity condition as a function of its internal composition, namely fiber, clay and water contents [16]:

$$f_b \sim \frac{\text{clay \%}}{\text{fiber \%}} w^{\sim -\frac{\text{clay \%}}{\text{fiber \%}}} \tag{1}$$

where f_b is the compressive strength and w stands for water and variables are expressed in volumetric percentages. Examples of these laws are shown in Figure 8 for one type of brick and mortar experimentally tested. The shape of the law in eq. 1 recalls a trend derived for baked clay bricks in [6], where the rate of decay was found to increase for higher clay contents. As expected from the formulation in eq. 1, the rate of strength decay experimentally derived for adobe mortar (with low or no fiber content) is in general higher than for adobe bricks and it is found to be similar to one of the slopes determined in [6] for only clay bricks.

FIGURE 8. Compressive strength law for adobe dependent on water content. Examples of predicted trends for one type of adobe brick and one type of adobe mortar using eq. 1, compared with the law derived for clay bricks in [6].

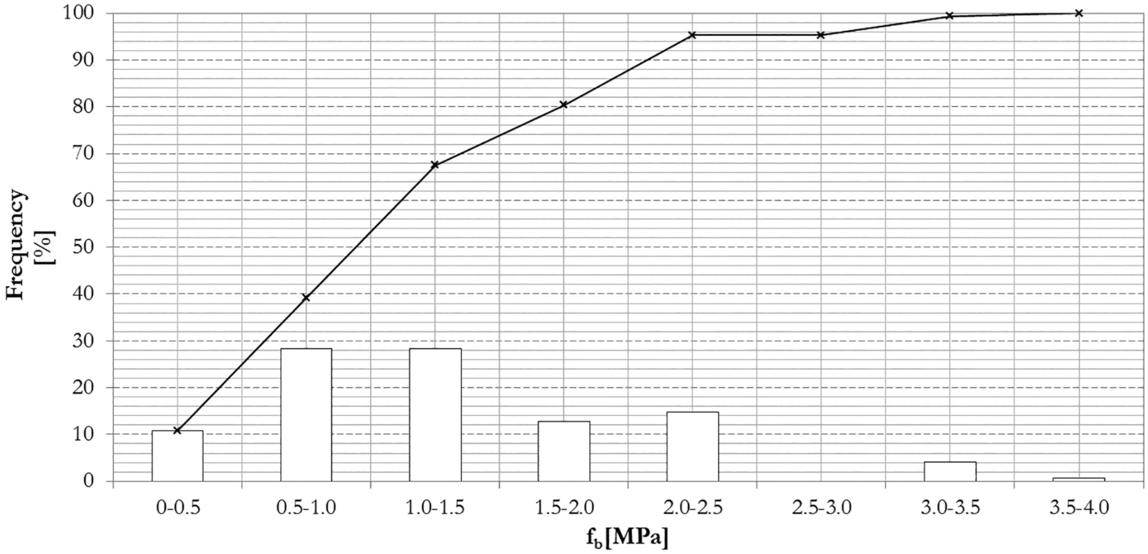


The mechanical testing procedures and prescribed values in compression of the brick after curing are covered best by current standards. Table 2 summarises the quantitative requirements in strength prescribed by four different codes for adobe. Recommendations in the different sources are not fully consistent in the prescribed test setup as well as in the required performance levels. However, the minimum values for strength prescribed by codes after aspect ratio correction are on average consistent with the values usually found for adobe bricks and mortar in literature, although lower values than prescribed requirements can also be encountered in the field [10]. Figure 9a shows the nominal strength distribution for adobe after elaboration of a database collecting more than 150 static characterization tests in the literature supplemented with the authors' data [24]. Most common values for adobe range between 0.8MPa and 2MPa. The average value of strength is found to be about 1.28 MPa, with 0.95 percentile of about 0.29 MPa. However, in almost 40% of the test cases, strength of adobe bricks was lower than 1 MPa. The unconfined values of strength are usually determined in literature using the aspect correlation factors commonly prescribed for concrete [44]. Instead, codes in [16] and [15] prescribe a more conservative law for adobe and recommend slenderness's of 3–5 as representative of the unconfined strength (Figure 10). Applying this law on the available tests in the database, the average strength is equal to 1.19 MPa, with 0.95 fractile of about 0.2 MPa.

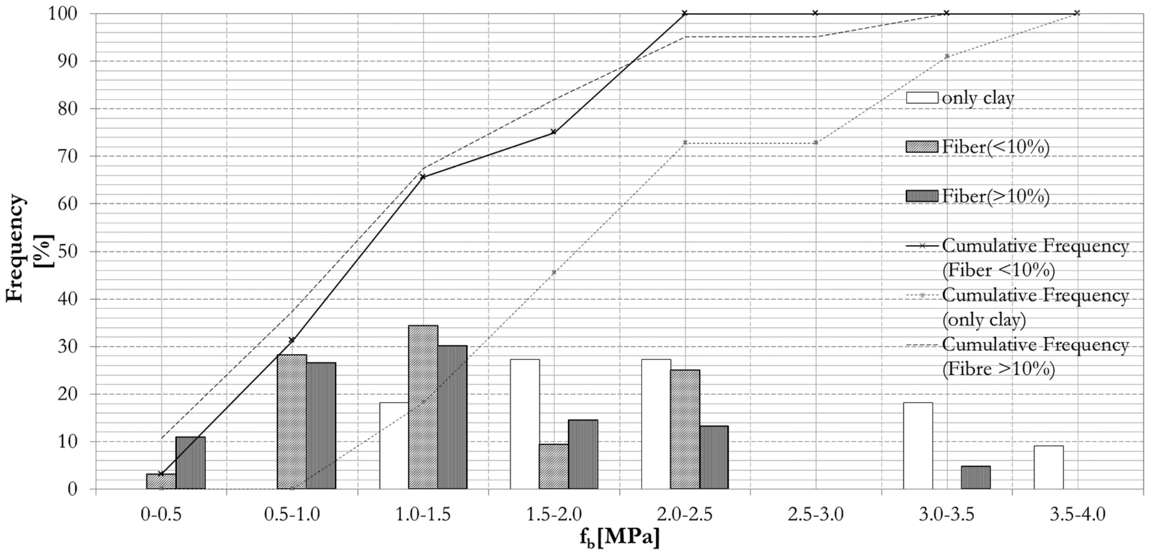
TABLE 2. Prescribed strengths (and additional indications) for four building codes on adobe.

Standard	Requirement	Indication
NZS	Minimum > 0.9 MPa	after aspect ratio correction (Figure 10)
NTE	80% fractile > 0.85 Mpa	after aspect ratio correction
NMX	Average > 2 MPa	on flat direction/no geometry info
HB	Average > 1 MPa	after aspect ratio correction (Figure 10)

FIGURE 9. Relative frequency (histogram) and cumulative frequency (line) for the unconfined strength of adobe in literature (including data from authors) considering all data (a) or disaggregating data according to fiber ratios in the mixtures (b).

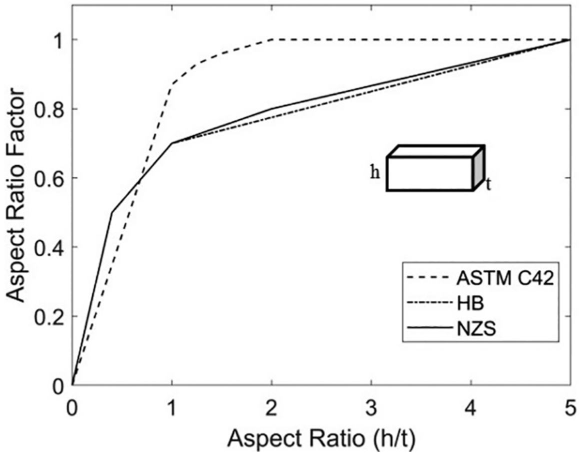


(a)



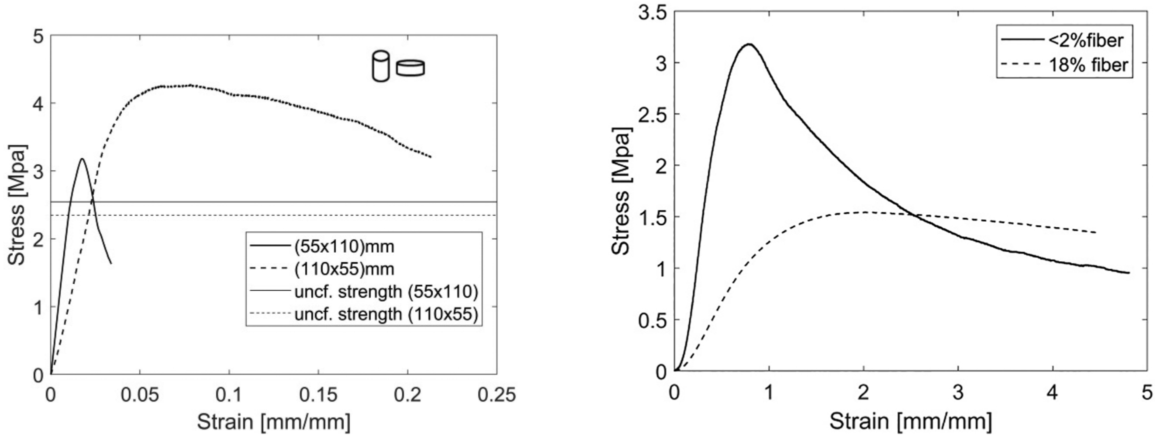
(b)

FIGURE 10. Aspect ratio correction law in strength for concrete compared with the laws proposed in the Australian and New Zealand code for adobe.



Despite the specific shape of the curves in Figure 10, there are almost no systematic studies publicly available in the literature on the size and shape dependencies of adobe [45]. Preliminary size dependence studies by the authors reveal a significant sensitivity to sample dimensions in the response to strength and deformation (Figure 11a). However, derived values for nominal strength are consistent with the aspect ratio laws depicted for adobe in Figure 10. As for shape dependence, in [45] a correlation between tests on cylinders and cubes was found with a slope of 0.94.

FIGURE 11. Stress-strain curves and unconfined strength values after aspect ratio correction in HB (Figure 10) for two adobe cylinders with same soil and fiber compositions but different slenderness (a) or with the same geometry but different fiber percentages (b) tested in uniaxial compression at laboratory conditions in [33].

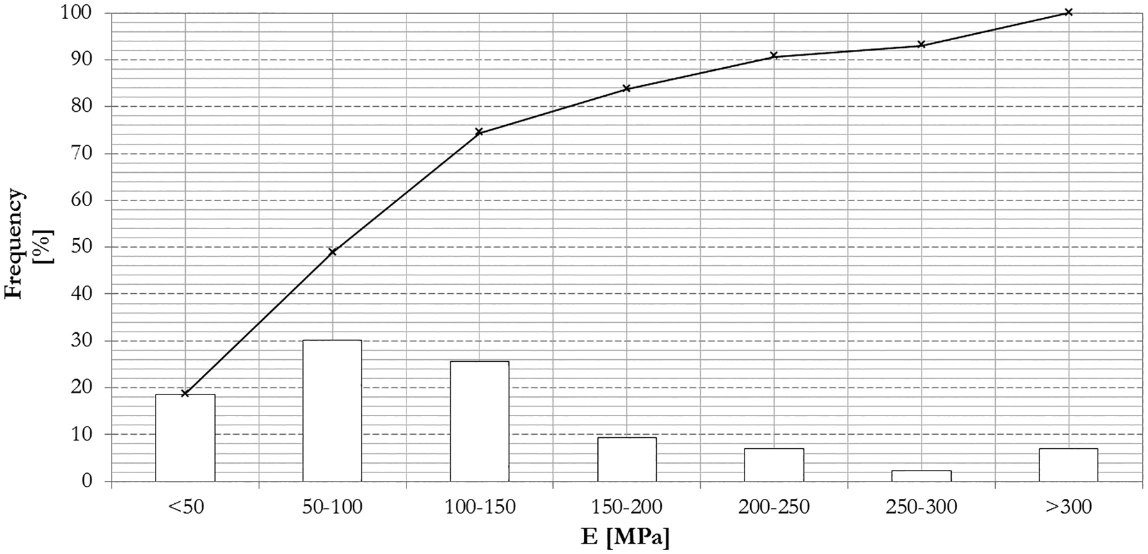


(a) (b)

Furthermore, aside from the role of water content, the mechanical characterization of adobe in standards does not address the influence of fibre content on strength, despite that most common trends in literature that relate fiber in soil mixtures to a decay of the mechanical parameters of the material (Par. 2.1). However, recognizing this role is not always easy in literature. In Figure 9b, the same data plotted in Figure 9a are aggregated according to the relative presence of fibres in the mixture, organized in three categories: fiber free (<2 b.w.%), low fiber ratio (<10% b.w.) and high fiber ratios (>10 %b.w.). From Figure 9b, fiber free samples do not possess strength values lower than 1 MPa, whereas fibrous bricks have a significant statistical incidence in the 0.5–1MPa and 1.0–1.5 MPa ranges. However, fibres can confer to bricks values of strength also higher than 3MPa. As explained in Par. 2.1, the outcome of fiber inclusion depends also on the specific characteristics of the applied fiber, original soil and resulting interactions. However, there are only few systematic studies aimed at quantitatively addressing the role of fibers in adobe bricks. Tests by the authors in [25] showed that parameters in strength and stiffness are significantly affected by fibres whereas their inclusion is always accompanied by an enhanced ductility and retarded failure (Figure 11b). The major contribution associated to the presence of fibres in the mixture on the mechanical performance of adobe is indeed related to the material ductility (Figure 2) [46]. Fibres allow the bridging of the stress through cracks, limiting their entity and holding together the vital cores of the matrix until large deformation stages [25].

Indications on the elastic stiffness (*E*) of adobe bricks are not provided in standards. Data in literature reveal a significant scatter in values, with ranges between 10 MPa and 2500 MPa. However, most common values lie between 50 MPa and 200 MPa (Figure 12). The only reference to this parameter in standards relates to the stiffness of the adobe wall, which should be designed as 300 times the corresponding strength in [15]. Calculating *E* as a ratio of the strength reduces the scatter in value associated to stiffness, since strength and stiffness are found to react in a similar manner to clay, fiber and water contents in the mixture [33]. However, the recommended value in standards is lower than the ratios commonly encountered for adobe bricks. Considering only data set in [24], E = 60–80f_b, whereas considering data in literature E = 120–180f_b [47].

FIGURE 12. Relative frequency (histogram) and cumulative frequency (line) of the elastic stiffness of adobe.



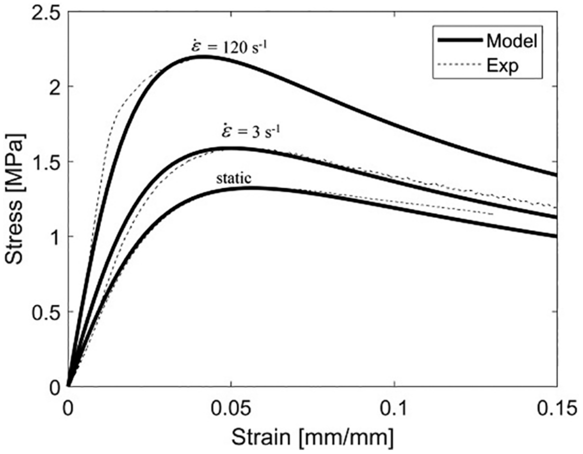
Besides the assessment of the mechanical parameters in compression, the definition of the entire curve in compression is of paramount importance for masonry materials [48]. In fact, deformation curves can be used to develop constitutive models for non-linear analyses [49]. Research has revealed that constitutive models originally developed for concrete can be used to address the curve of response of bricks and mortar of adobe [50]. In [25], a constitutive model has been developed to assess the stress-strain plots of adobe bricks made of different mineralogical composition and water content and subjected to various loading rates, from statics to dynamic impact (Figure 13a). The law recalled in eq. 2 takes its roots from the Popovics' model developed for cement geo-pastes in statics [51]. This formula properly addresses the typical non linearity observed in the curves of response of adobe in compression, characterized by microcracking processes starting in the pre-peak phase of the curve and in the final quasi-brittle softening behaviour. Parameter n in eq. 2 controls the amount of non-linearity in the uniaxial response and calibration with experimental data on adobe made this parameter a function of the fiber content in the mixtures (n ranged between 1.5 and 3.5 and decreased with increasing fiber amounts as a result of higher non linearity amount in the pre and post peak slopes). Furthermore, the model in eq. 2 modifies the original formulation in [51] in order to address the dynamic behaviour of adobe in uniaxial compression. To this end, it equips the static constitutive model with a *dynamic increase factor functions* (DIF) of strength with logarithmic shapes as in eq. 3 [25] (Figure 13b).

$$\sigma = \mathrm{DIF}\ \mathrm{E}\left(\frac{\mathrm{n}}{\mathrm{n}-1+\left(\dfrac{\varepsilon\ \mathrm{f}(\mathrm{DIF})\mathrm{E}}{\mathrm{DIF}\ \mathrm{f_b}}\right)^{\mathrm{n}}}\right)\varepsilon \tag{2}$$

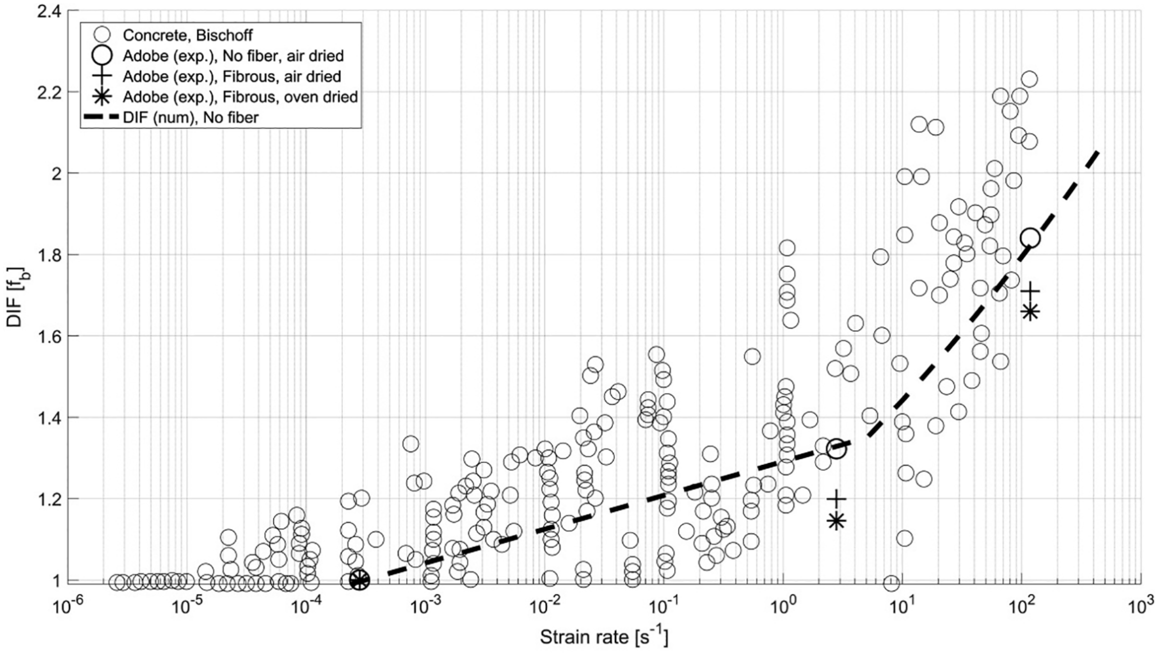
$$\mathrm{DIF} = a_0 + a_1 \log(\varepsilon) + a_2 \log(\varepsilon)^2 \tag{3}$$

where σ is the stress, ε is the corresponding strain, and a_{0-2} are material constants calibrated for adobe as in Figure 13b. In fact, as a quasi-brittle material, the mechanical performance of adobe has been found to be dependent on the applied loading rate and quantitative assessments of the rates of changes in the main mechanical properties were experimentally tested and numerically simulated [25], [27]. DIF functions in eq. 3 were addressed up to strain rates of the order of 120 s^{-1}, which were experimentally achieved using Hopkinson bar tests. The dynamic increase factors of the mechanical property of strength for the tested adobe bricks lie in the lower boundary of the cloud of data usually associated with concrete (Figure 13b). From the same figure, it is shown that if soil mixtures are provided with fibers, rate sensitivity of adobe decays. This is consistent with interpreting a reduction of cohesion after fiber inclusion. Instead, water content in the mixture enhances sensitivity to the deformation rate for a physical principle of viscosity called the Stefan effect (Figure 13b) [25].

FIGURE 13. Experimental-numerical stress strain curves in compression using eq. 2 for a fibrous adobe (n = 1.7) compressed at three different loading rates from statics to high velocity impacts (a) and dynamic increase factor functions in strength (eq. 3) calibrated (DIF) for adobe(b).



(a)



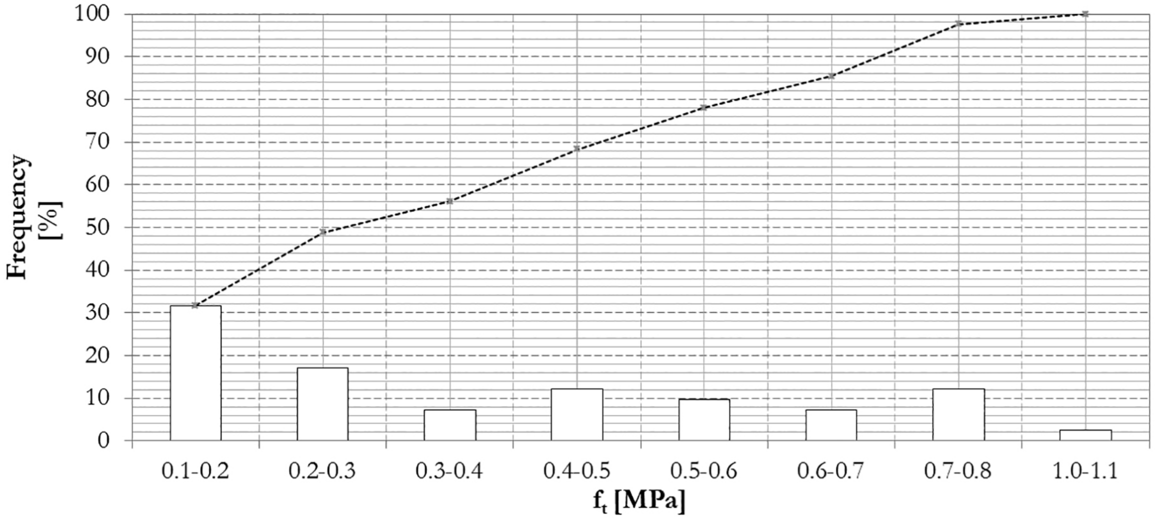
(b)

The scarcity of constitutive models describing the non-linear response in compression up to failure for adobe is reflected in the lack of numerical models for the material simulation of bricks and mortar. Constitutive models as in eq. 2 can be implemented in numerical frameworks, together with the definition of damage or plasticity surfaces. In [26], a smoothed Mohr-Coulomb damage surface implemented in a finite element isotropic damage model with exponential softening damage evolution laws was suitable for interpreting the damage process of soil-based masonry materials loaded in compression. This constitutive law has been validated against a wide range of loading conditions, including impact penetration tests on adobe walls [28].

2.3.3 Mechanical Properties in Tension

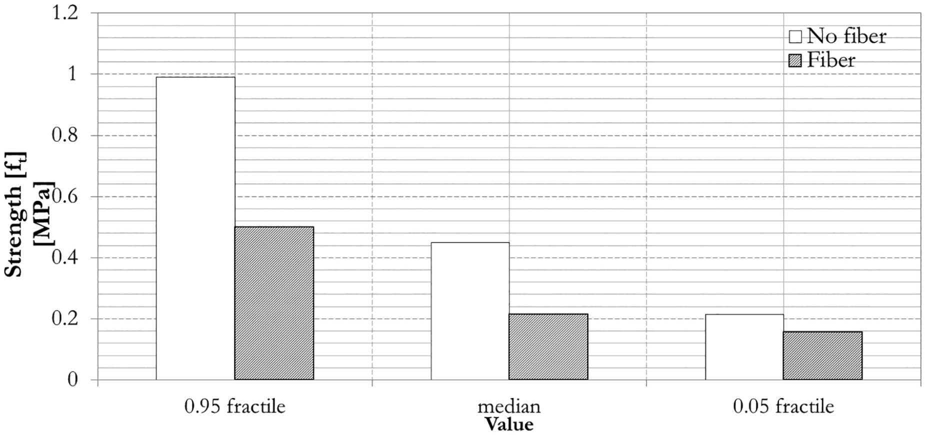
As for many quasi-brittle materials used in masonry, correctly addressing the response of adobe in tension is very important. The mechanical characterization of adobe in tension in current codes mainly concerns the evaluation of its strength parameter (f_t). Quantitative values are evaluated mainly from flexural tests, despite literature studies suggesting that splitting tests better reproduce the uniaxial tensile state [45]. Experimental data available for adobe in tension in literature and including tests in [24] is shown in Figure 14 in a similar manner with respect to Par. 2.3.1. Averages and 0.95 percentile values respectively are about 0.4 MPa and 0.15 MPa. According to codes, average values for strength of 0.34 MPa is prescribed in [17], while a minimum of 0.25 MPa is requested in [13]–[15]. This requirement is met by 65% of the experimental data for adobe in tension available in literature (Figure 14).

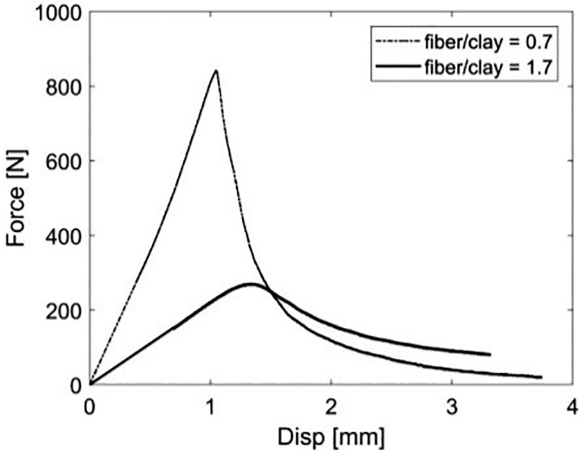
FIGURE 14. Relative frequency (histogram) and cumulative frequency (line) for the tensile strength for adobe using data in literature (including authors').



Aggregating data in tension according to the possible presence of fibres in the mixture as in Par. 2.3.1, mixing soil with fibres statistically results in a lower mean strength performance also in tension (Figure 15a). In [24], bending tests at the same laboratory conditions have revealed an enhancement of ductility in the response of adobe when fibres are added to the mixture (Figure 15b). With a value of 0.7 MPa, adobe mortar (fiber free) possessed one of the highest values of tensile strength encountered in literature for adobe.

FIGURE 15. Relative frequency for the tensile strength of adobe bricks disaggregated for fiber free and fibrous adobe samples (a) and Force–displacement plots in bending tests in [16] on two adobe bricks with different fiber proportion ratios (b).





(a) (b)

Tensile strength relates to the parameter in compression in ranges between 0.18f_b [10] and 0.4f_b [34]. In [16], this ratio ranges between 0.3f_b and 0.7f_b, with a median equal to 0.57f_b. These values are in general higher than the minimum levels suggested in [15], included between 10% and 20% of the compressive strength [15].

The failure process of adobe in tension is typically more brittle than in compression [24]. A localized failure has characterized bricks and mortar subjected to bending tests in [24], independently from water content and fiber inclusion in the mixture. Typical curves of response are characterized by an elastic phase followed by softening with exponential shape (Figure 15b). In [26], numerical simulations of bending tests on adobe using a local damage finite element model recently developed for the simulation of bricks and mortar at various loading conditions showed that the constitutive law in RILEM TC 162 [52] originally prescribed for steel fiber reinforced concrete is suitable to numerically assess the role of fibres in the localized damage failure experimentally observed in adobe in flexure (Figure 16). The adopted constitutive model in tension is linear elastic with an elastic modulus being the same as in compression until the attainment of the stress level associated to the first crack in bending, from where fibres are responsible for the amount of retardation of the softening behaviour.

FIGURE 16. Experimental crack and numerical damage localized in the middle of a brick subjected to bending test using the *adobe delta damage model* in [26], a finite element model for the simulation of adobe bricks at various loading conditions and rates.

3. FINAL RECOMMENDATIONS AND CONCLUSIONS

A review of the codes currently available for the material characterization of adobe bricks and mortar has been performed in this study. The prescriptions provided by the normative bodies for adobe globally related to test methods, soil selection and material properties have been critically addressed. They have been compared with the most recent scientific findings produced for adobe regarding the assessment and interpretation of its physical-mechanical properties. From the analysis, lack of knowledge, consistency and completeness in the current normative body stand out and a normative update effort is urged, preferably shared among the different codes around the world. An international committee is desired. Among others, two areas of improvement are deemed as a priority:

- Definition of a shared set of identifying properties for the physical-mechanical performance of adobe components, both bricks and mortar. The assessment of the drying conditions preliminary to tests on samples is a priority and the set of maximum moisture contents prior to mechanical characterization is necessary. The standardization of the influence of moisture on the mechanical performance must be integrated both at an experimental characterization and at a material design level. Moisture content dependent strength laws should be developed for the life cycle design of earthen buildings. Required properties should not solely relate to the characterization of the mechanical parameters of the resulting brick but rather to the evaluation of its original soil. If the minimum requirements in strengths by codes are generally consistent with mean experimental values found in literature, soil particle distributions tests are not sufficient to certify suitability of adobe as a building material. Assessment of fiber properties and relative amounts in the brick before mechanical characterization in codes is necessary. A comprehensive physical study on the mixture is needed, with particular reference to the plasticity and cohesive properties. These properties not only are to be determined on the raw soil, but they must also be assessed with respect to the final mixture used to produce the brick, namely including the assessment of the fiber-soil mixtures interactions at a meso and macro-material scales. At a research level, the identification of the materials, quantity and orientation of mixing fibres which ensures durability, ductility and strength to bricks and mortar of given mineralogical compositions is a priority task.

- Homogenization of test procedures, methods and requirements for each targeted property. Simplistic identification tests in the field must be preferably substituted by laboratory tests because they are often not sufficient to determine exhaustive information of fundamental properties for adobe. Standard methods can be adapted from codes for modern building materials for masonry applications. New test methods and standard for the assessment of the cohesion properties of fiber mixed soil for building applications are considered as a fundamental priority in the field of earthen constructions. Furthermore, for each property, acceptable ranges of values or minimum requirements should be carefully defined to ensure prescribed levels of safety. These values should concern the properties in strength and deformation of the brick as well as the physical properties of the mixture. Given the site dependence inherent to soil selection, prescriptions are expected in terms of ranges for the soil distribution properties and in terms of strict minimum requirements for cohesion, durability and plasticity properties of the final mixture. At a research level, new building production and construction processes capable of removing randomness in the manual production of adobe bricks can support the development of safety assessment procedures for existing constructions and the definition of new design approaches in contexts of scarcity.

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