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Further development of a laboratory procedure to assess the mechanical performance of cob

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Abstract

Cob is a vernacular earth building technique, which has encountered renewed interest for its low environmental impact compared to conventional construction materials. Relevant mechanical characterisation is essential for cob building structure design and calculation. This article presents an improved laboratory procedure to better the characterisation of representative cob samples. Samples prepared by four different methods were compared to representative cob wall elements, by measuring shrinkage ratio, pore size distribution, uniaxial compressive strength and Young's modulus. The preliminary laboratory testing provides satisfactory results but needs to be validated with other cob mixtures.

Keywords

Building, structure & design; Fibre-reinforcement; Strength & testing of materials

Introduction

Cob is a vernacular earth building technique, which involves forming clods of earth in a plastic state (i.e. $W_P < W < W_L$), and stacking them wet to build a monolithic and load-bearing or freestanding wall (Hamard, Cazacliu, Razakamanantsoa, & Morel, 2016). Europe, Africa and Asia possess a significant cob heritage which requires appropriate maintenance and characterisation (Hamard et al., 2016; L. Keefe, Watson, & Griffiths, 2001; Laurence Keefe, 2005; Saxton, 1995). Moreover, like other earth building techniques, cob has encountered renewed interest from modern sustainable building for its low environmental impact compared to conventional construction materials (Griffiths & Goodhew, 2017; Hamard et al., 2016; King, 2010; Morel, Mesbah, Oggero, & Walker, 2001).

Cob construction is carried out with highly wetted soil material, kneaded by foot and piled on the wall in a plastic state. These mixing and compaction methods generate irregular kneading and are unusual in the context of soil mechanics. This particularity of cob wall material requires the development of suitable laboratory testing procedures to assess its mechanical performance.

Cob specimens production procedures to determine Uniaxial Compressive Strength and Young's modulus refer to cylindrical test specimens with a slenderness ratio of 2:1 in order to reduce the frictional forces due to the confinement caused by testing machine plates (Addison Greer, 1996; Coventry, 2004; Harries, Saxton, & Coventry, 1995; Laurence Keefe, 2005; Pullen & Scholz, 2011; Saxton, 1995). Specimen sizes are either 100×200 mm or 150×300 mm since smaller size specimens are judged unrepresentative and larger ones are too heavy to be handled conveniently (Coventry, 2004; Harries et al., 1995; Laurence Keefe, 2005; Saxton, 1995). Cob mixture was introduced into cylinder moulds in several layers and compacted either under dynamic load using a Proctor compaction device (Coventry, 2004; Harries et al., 1995; Laurence Keefe, 2005; Saxton, 1995) or by hand (Pullen & Scholz, 2011). Cob mixture was also introduced into cylinder moulds by compaction under static load using a machine (Addison Greer, 1996). The aim during compaction was to produce specimens that did not contain noticeable air voids. As the cob mixture is in a soft state, over-compaction would have little additional effect on density (Saxton, 1995).

Specimens are either air-dried (Laurence Keefe, 2005), dried in a humidity and temperature-controlled chamber (25°C and 75% relative humidity) (Coventry, 2004; Harries et al., 1995; Saxton, 1995) or oven-dried (75°C) (Pullen & Scholz, 2011). Usual recommendations require a drying temperature lower than 60°C. In addition, the mechanical strength of earth materials depends on the water content of the specimens: the higher the moisture content, the lower the compressive strength (Champiré, Fabbri, Morel, Wong, & McGregor, 2016; Gallipoli, Bruno, Perlot, & Salmon, 2014; Saxton, 1995). A typical cob mechanical test description was proposed by Addison Greer (1996) and Miccoli, Müller, & Fontana (2014). In both cases, a linear stress/strain response was followed by a ductile failure, induced by fibres (Coventry, 2004; Miccoli et al., 2014).

Tangent Young's moduli values proposed in the literature were calculated according to the total strain of test specimens, i.e. by measuring the displacement of testing machine plates (Addison Greer, 1996; Coventry, 2004; Pullen & Scholz, 2011). However, earth materials have an elasto-plastic behaviour (Champiré et al., 2016). As a consequence, in order to measure the elastic contribution only, secant moduli of repeated loading cycles should be considered. Furthermore, it has been demonstrated that frictional forces caused by confinement of testing machine plates have a high impact on the mechanical behaviour of earth materials (J.-E. Aubert, Fabbri, Morel, & Maillard, 2013; J. E. Aubert, Maillard, Morel, & Al Rafii, 2016; Bui, 2008; Laborel-Préneron, Aubert, Magniont, Tribout, & Bertron, 2016). Strain measurement for Young's modulus calculation should only

concern the central third part of cylindrical specimens. Most cob data available in the literature were obtained without regard to these requirements.

Little literature exists concerning cob's mechanical behaviour, and each author has developed their own testing protocol. This makes data comparison difficult and highlights a need to standardise mechanical testing procedures (Jiménez Delgado & Guerrero, 2007; Laborel-Préneron et al., 2016; Miccoli et al., 2014).

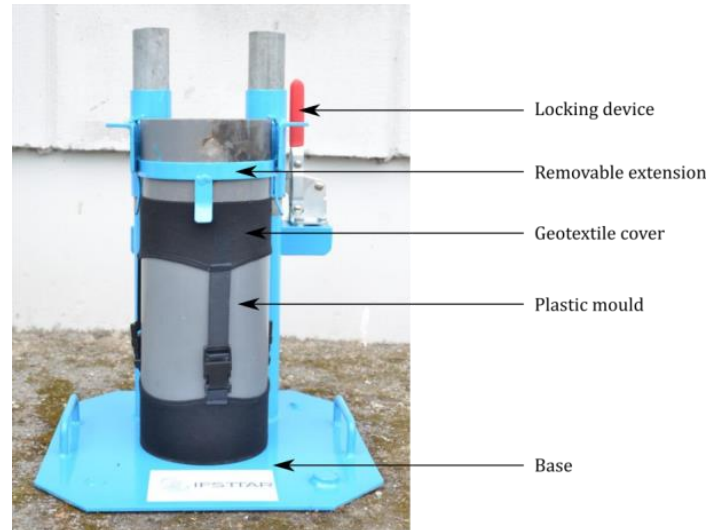


Figure 1. Device for cob specimen production.

In this paper, an improved laboratory procedure to assess the mechanical performance of cob walls is proposed. An elastic geotextile cover is placed on the inner face of a cylinder mould wall (diameter 150 mm, height 300 mm) to reduce friction and adherence with the earth material (Figure 1). The top and bottom of the cylinder are open and the bottom lean on a filter paper so that material can dry from both sides. Cob wall elements were used as a reference in this study. A comparative study of the mechanical performance obtained with different specimen preparation protocols was carried out based on the cob wall elements' behaviour. The comparisons focuses on uniaxial compressive strength, Young's modulus, shrinkage ratio, bulk density and pore size distributions obtained using 2 plant fibre lengths and 2 drying methods.

1 Materials and methods

1.1 Earth material source and geotechnical identification

The earth material employed for these series of experiments comes from a stock pile of earth from the town of Saint Sulpice-la-Forêt (Brittany, France). This stock pile was selected since this city possesses an important cob heritage and this earth has been employed with success by several skilled craftsmen for cob wall construction.

Table 1. Identification of the earth of Saint Sulpice-la-Forêt (Brittany, France) employed for specimen production.

<i>Clay</i> (0 - 2 μm) (%)	<i>Silt</i> (2 - 50 μm) (%)	<i>Sand</i> (50 μm - 2 mm) (%)	<i>Gravel</i> (> 2 mm) (%)	<i>Methylen Blue</i> <i>Value</i> (g/100g)
3	18	42	37	1.01
<i>W_P</i> (%)	<i>I_P</i>	<i>W_{OPN}</i> (%)	<i>Y_{OPN}</i> (g.cm ⁻³)	<i>Soil classification</i> (ASTM)
29.1	15.7	20.1	1.67	Clayey sand (SC)

The identification of the material consisted of determining: (1) particle size distribution obtained by dry sieving for the coarse fraction (above 80 μm), according to French standard NF P 94-056 (AFNOR, 1996) and by the hydrometer method for the fine fraction (below 80 μm), according to French standard NF P 94-057 (AFNOR, 1992); (2) methylene blue absorption capacity value according to French standard NF P 94-068 (AFNOR, 1998); (3) plastic limit (W_P), liquid limit and plastic index (I_P) according to French standard NF P 94-051 (AFNOR, 1993); (4) normal Proctor water content (W_{OPN}) and density (Y_{OPN}) according to French standard NF P 94-093 (AFNOR, 2014); (5) specific gravity of specimens according to French standard NF

P 94-054 (AFNOR, 1991). Water content of specimens following mechanical tests was determined after drying at 105°C, according to French standard NFP 94-050 (AFNOR, 1995). Soil classification was stated according to ASTM standard (ASTM D2487-11, 2011). Results of material identification are presented in Table 1.

1.2 Specimen production

Cob was mixed by foot treading, according to Brittany’s vernacular cob process (case (a) of the classification proposed by Hamard et al. (2016)), with a straw fibre content of 0.9 % by mass, at a plastic consistency. Fibre content is in accordance with fibre content of vernacular cob techniques, usually between 1 and 2 % by mass (Hamard et al., 2016).

Four fibred cob wall elements (600 mm long, 600 mm high and 300 mm thick) were manufactured according to Brittany’s vernacular cob process (case (a) of the classification proposed by Hamard et al. (2016)). Average fibre length was 150 mm. Walls were dried under natural conditions inside a laboratory. Their weight was monitored and they were considered dry when their weights were stabilised, in this case after 60 days.

Table 2. Nomenclature of studied protocols.

<i>Mould</i>		<i>Fibre length</i>		<i>Drying</i>		<i>Protocol</i>
Cardboard (160 × 320 mm)	Plastic with Sock (150 × 300 mm)	Equal to diameter (150 mm)	Equal to radius (75 mm)	Oven (40°C)	Air (15 - 30°C)	
C	S	D	R	O	A	
						<i>CDA</i>
						<i>SRO</i>
						<i>SDA</i>
						<i>SDO</i>
<i>not applicable</i>						<i>Wall</i>

Three criteria were studied in order to propose a laboratory procedure to produce cob specimens: the mould type, the fibre length and the drying conditions. Four different cob specimen protocols were defined, and named according to these criteria, as shown in Table 2. For each protocol, four specimens were produced. Standard deviations of specimens’ test results are compared to standard deviation of wall elements’ test results to discuss the representativeness of this series of tests.

Two different cylindrical mould types, with a 2:1 slenderness ratio (Coventry, 2004; Saxton, 1995) were employed: concrete cardboard moulds (160 mm diameter, 320 mm height) and plastic moulds (150 mm diameter, 300 mm height) with the inner face covered with an elastic geotextile (Figure 1). Specimens were carried out in 8 layers and compacted according to the normal Proctor protocol (AFNOR, 2014).

Fibre length for wall elements and specimens CDA, SDA and SDO (Table 2) was set to 150 mm. In order to evaluate fibre length effect, a second fibre size was employed for SRA specimens (Table 2), with a size equal to the radius of the specimen, i.e. 75 mm.

Drying of cob walls and CDA and SDA specimens (Table 2) was conducted under natural conditions, i.e. air dried. In order to assess drying effect, SRO and SDO specimens (Table 2) were oven-dried at 40°C. After drying, oven-dried specimens were conditioned in a temperature controlled laboratory, set to 20°C, for 2 weeks prior to mechanical tests.

1.3 Mechanical and microstructural characterisation of specimens

After drying, specimens were weighed and their volumetric changes measured using a vernier calliper. Bulk densities and average vertical shrinkage divided by horizontal shrinkage (V/H) were calculated. Pore size distributions were determined using Mercury Intrusion Porosimetry.



Figure 2. Mechanical tests of cylindrical cob specimens (a) and cob walls (b). 3 loading cycles were applied to the specimens and strain was measured in the central third of the specimen using an extensometer composed of 3 displacement sensors (a) or an optical extensometer for two couples of two targets located in the central third of the wall elements (b).

Uniaxial Compressive Strength (UCS) tests were controlled in displacement at a speed of $1 \text{ mm}\cdot\text{min}^{-1}$. Tests for cylindrical specimens were conducted on an electromechanical press with a 100 kN load cell and for wall elements on a hydraulic press with a 2500 kN load cell. UCS was defined as the maximum strength of the specimen. Young's moduli were determined by 3 loading cycle and deformations measured in the central third of specimens, using extensometers for cylindrical specimens (Figure 2a) and using optical extensometer for two couples of two targets on the back face of the wall elements (Figure 2b). For each loading cycle the secant moduli was calculated. The average secant moduli are reported.

2 Results and discussion

2.1 Influence of implementation method on specimen quality

As they shrunk during drying, the specimens made with plastic moulds covered with an elastic geotextile (SRO, SDA and SDO) could be removed from the plastic moulds and elastic geotextile cover after a drying period of only 24 h. Because of shrinkage, the upper faces of these specimens were irregular and had to be cut, using a block saw, in order to provide a flat load-bearing surface for mechanical tests.

Specimens made in concrete cardboard cylinders (CDA) stuck to the sides of the moulds creating poor surface quality. Moreover, concrete moulds are impermeable and the bottoms of the specimens could not dry, creating a high water content contrast between the dry upper face and the wet lower face of specimens. These specimens were therefore very difficult to remove from moulds. Another consequence of water stagnation was rust growth at the bottom of moulds that stuck to the lower face of specimens and caused poor surface condition.

Compared to plastic moulds with elastic geotextile covers (Figure 1), concrete cylinder cardboard moulds are a simpler device, but they are not adapted to cob drying and produced cob specimens of poor quality. Nonetheless, the discussion on the selection of a protocol has to be based on the physical representativeness of the cob specimens with regard to the wall elements.

2.2 Comparison of shrinkage ratio

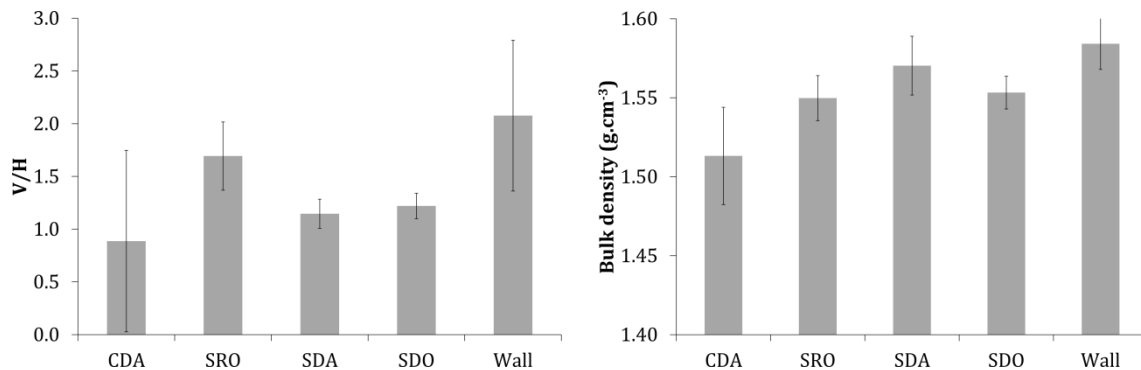


Figure 3. Comparison of average ratio of vertical by horizontal shrinkage (V/H), left, and average bulk density, right.

For cob, the dry density of the material is the result of shrinkage drying (Hamard et al., 2016). The mechanical behaviour of cob depends on density and therefore on shrinkage rate. Vertical shrinkage divided by horizontal shrinkage (V/H) is around 2 for wall elements, around 1.7 for SRO, around 1 for SDA and SDO and less than 1, with a high scattering, for CDA specimens (Figure 3).

The stress state of the wall elements during drying is only governed by dead load. Under this condition, vertical shrinkage is higher than horizontal shrinkage. The mass of the cylinder specimens is about 40 times less than that of the wall elements. The effect of dead load is thus less pronounced in cylinder specimens and their V/H shrinkage values are therefore lower (Figure 3).

The high scattering of V/H results of CDA specimens highlights the operator dependency and the difficulty of making cob specimens of satisfactory repeatability with this protocol (Figure 3).

Specimens with radius-length fibres (fibre length equal to the specimen radius, SRO) have a higher V/H shrinkage ratio than those made with diameter-length fibres (SDA, SDO) (Figure 3). Diameter-length fibres do not easily fit inside moulds and so have to bend more than radius-length fibres. Hence, radius-length fibres are mainly horizontally-orientated whereas diameter-length fibres have a more random distribution. Horizontal shrinkage is thus more restrained in specimens with radius-length fibres (SRO) than in those with diameter-length fibres (SDA, SDO). In the wall elements, fibres are mainly horizontally-orientated, reinforcing the contrast between horizontal and vertical shrinkage.

2.3 Comparison of bulk densities

Bulk densities of CDA specimens are lower than those of wall elements and exhibit a high scattering (Figure 3). Once again, the high scattering of CDA specimens highlights the operator dependency and poor repeatability of this protocol.

Bulk densities of SRO, SDA and SDO specimens do not exhibit significant differences (Figure 3). The SRO-SDA-SDO average bulk density is $1.56 \pm 0.02 \text{ g.cm}^{-3}$. Apart from CDA specimens all bulk density results are in agreement with the bulk density of wall elements ($1.58 \pm 0.02 \text{ g.cm}^{-3}$).

2.4 Influence of production method on the microstructure of specimens

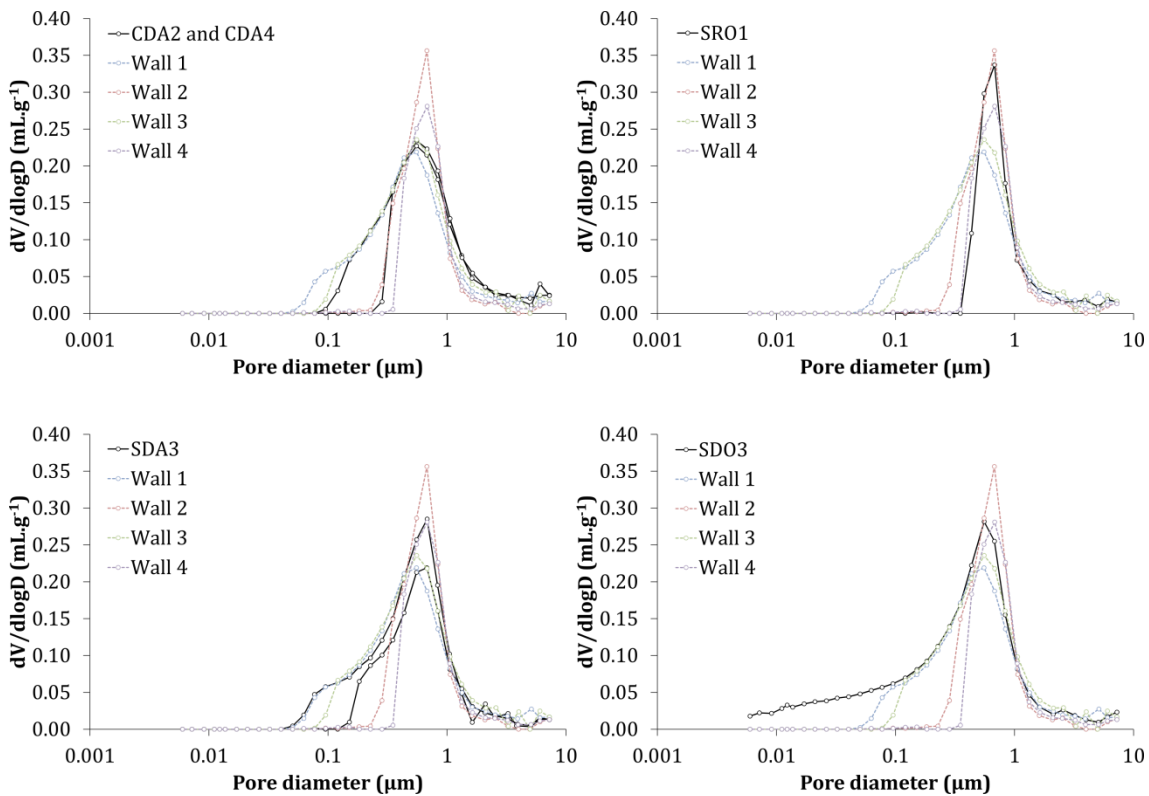


Figure 4. Comparison of pore size distribution obtained by mercury intrusion porosimetry.

Pore size distribution of all specimens exhibit a similar 1 μm peak (Figure 4). This microporosity results from material humidification (Casini, Vaunat, Romero, & Desideri, 2012; Romero & Simms, 2009) and, in the present study, is less affected by compaction. These results underline the homogeneity of cob mixture used to produce specimens.

Nevertheless, the higher mesoporosity (10-100 μm) of CDA specimens (Figure 4) highlights the presence of cracks and a less effective compaction. This can be attributed to the adherence between the cob mixture and the wall of the concrete cylinder cardboard moulds. This effect is less pronounced with plastic cylinder moulds covered with an elastic geotextile, due to the elasticity of the geotextile, which can accommodate the strain of cob wall material under compaction. Mesoporosity of these specimens is therefore in good agreement with that of the wall elements (Figure 4).

2.5 Comparison of compressive strength and Young Modulus of cob specimens

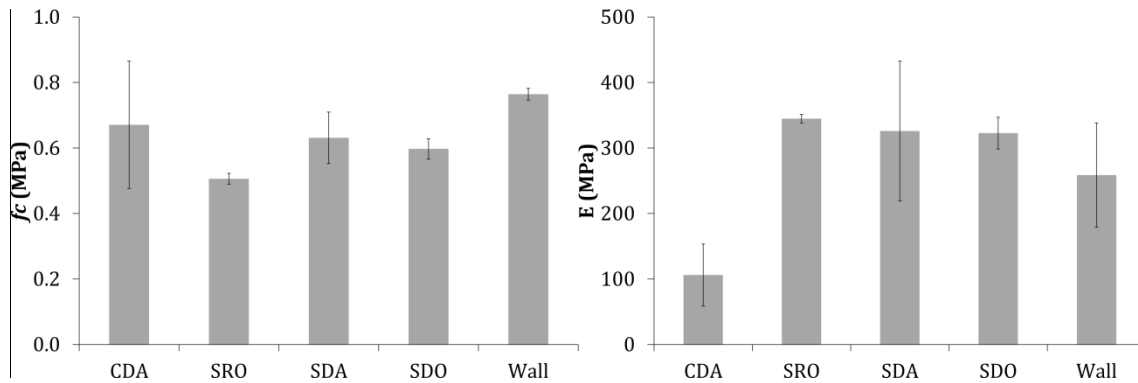


Figure 5. Comparison of average compressive strength (f_c , left) and average Young's moduli (E , right) for the four cob specimen protocols and cob walls.

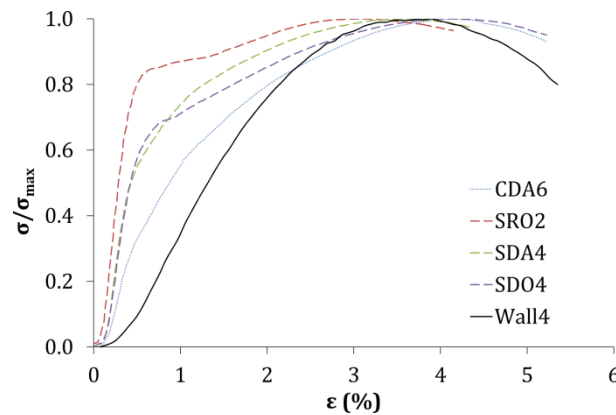


Figure 6. Normalized stress (σ/σ_{max}) strain (ϵ) curve of one specimen of the four cob protocols and cob walls.

Orders of magnitude of Uniaxial Compressive Strength (UCS) and Young's modulus (E) of cob wall elements (Figure 5) are in agreement with Coventry (2004), Keefe (2005), Pullen & Scholz (2011), Saxton (1995) and Ziegert (2008) but two times lower than these of Miccoli et al. (2014). Stress-strain curves of cob wall elements (Figure 6) are in agreement with the 3 stages described by Addison Greer (1996): (1) initial compaction, (2) linear stress/strain response and (3) initiation and propagation of cracks. Cob wall-elements mechanical results are thus in good agreement with existing studies.

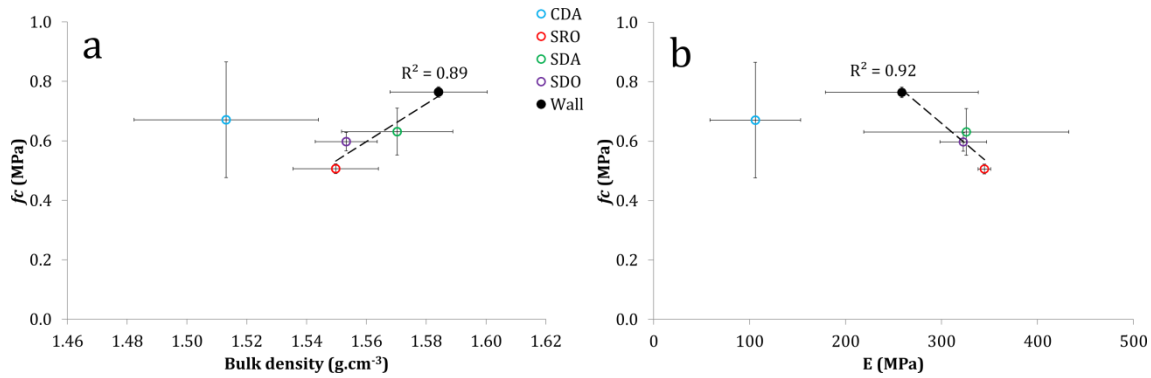


Figure 7. Average compressive strength (f_c) with respect to bulk density (a) and average compressive strength (f_c) with respect to Young's modulus (E) (b).

Young's moduli of CDA specimens are very low compared to the Young's moduli of wall elements (Figure 5 and Figure 7). Indeed, the behaviour of CDA specimens is elasto-plastic and no elastic domain can be identified (Figure 6). Moreover, CDA results are outside the trends drawn for all other specimens (Figure 7). Hence, the mechanical behaviour of CDA specimens cannot be regarded as representative of the cob wall elements. This difference is attributed to the wall effect of concrete moulds, reducing the bulk density of CDA specimens (Figure 3).

Average UCSs of cob specimens made according to the new specimen preparation procedure are lower than those of cob wall elements (Figure 5). This difference is attributed to a different compaction mode: wall elements were self-compacted under dead-load whereas cob specimens were compacted according to Proctor testing protocol. However, a trend can be drawn between bulk density and UCS, the higher the density, the higher the UCS (Figure 7). This tendency can be used to estimate the UCS of a cob wall of known bulk density, using cob test specimens made during wall construction and tested according to the proposed laboratory procedure.

Except for CDA, a linear correlation can be drawn between Young's modulus and UCS of all specimens, indicating that the higher the stiffness, the lower the mechanical resistance (Figure 7). This tendency is in contradiction with the results of Champiré et al. (2016) obtained with rammed earth specimens, Chan (2011) obtained with cement-stabilized adobe reinforced with fibres and Salgado (2009) obtained with unfibred pressed adobe block specimens, who found a positive strength-to-stiffness ratio. Nonetheless, a negative correlation between Young's modulus and UCS has been found by Piattoni, Quagliarini, & Lenci (2011) for Compressed Earth Blocks reinforced by straw fibres. This trend (Figure 7) can be attributed to a more fragile (high Young's modulus) or a more ductile (low Young's modulus) mechanical behaviour of cob. For the more ductile behaviour, due to fibres, cracks and failures were distributed over a larger volume of cob wall material which enhanced their ability to bear higher strains (Laborel-Préneron et al., 2016). This tendency can be used to estimate the Young's modulus of cob walls of known UCS.

2.6 Comparative study of testing devices

The CDA protocol (Table 2), using concrete cardboard cylinders, is easy to use, but presents several limitations: (1) the wall effect is strong and compaction is not efficient enough (Figure 4); (2) concrete moulds are impermeable, drying is therefore not homogeneous and drying times are very long; (3) earth material sticks to the inner face of the mould which results in a poor quality surface for the specimen; (4) the high scattering of CDA results highlights the operator dependency of this protocol (Figure 3 and Figure 5). In contrast, standard deviations of the results of the other protocols (SRO, SDA and SDO) are in the region of standard deviations of the results of the wall elements. This highlights the representativeness of the preparation protocols and of the series of tests.

The new preparation procedure proposed here (Figure 1) offers several advantages: (1) the elasticity of the geotextile cover reduces the wall effect of the cylinder and reduces the adhesion of earth to the inner face of the cylinder (Figure 4); (2) it provides specimens with a good surface condition; (3) due to horizontal shrinkage, specimens can be unmoled after only 24 h drying time.

2.7 Influence of fibre length and orientation

Radius-length fibre specimens (SRO) have a fibre orientation and a Vertical/Horizontal (V/H) shrinkage ratio close to that of cob wall elements (Figure 3). However, the mechanical behaviour of diameter-length fibre specimens is more representative of the mechanical behaviour of cob wall elements (Figure 5, Figure 6 and Figure 7). Fibre aspect ratio emerges as a key parameter in comparison to fibre orientation (Danso, Martinson, Ali, & Williams, 2015). The use of fibre length close to that of the cob wall is therefore recommended.

Two modes of fibre length were identified for cob (Hamard et al., 2016): small fibres (10-20 cm), and long fibres (40-60 cm). The diameter-length fibre specimens have the same fibre length as cob with short fibres. In the case of cob with long fibres, fibres are too long to fit inside the cob specimen and should be cut.

2.8 Influence of drying method

Drying conditions affect specimen shrinkage and therefore have an impact on mechanical behaviour. No significant difference occurs between air-dried (SDA) and oven-dried (SDO) cob specimens, for specimen's characteristics (Figure 3 and Figure 4) and mechanical behaviours (Figure 5, Figure 6 and Figure 7). The accelerated oven-drying can be regarded as representative of on-site drying conditions.

3 Conclusion

The results of this preliminary study demonstrate that the protocol using concrete cardboard cylinders (CDA, Table 2) is unsatisfactory for producing cob specimens. In contrast, the improved specimen preparation procedure proposed here, using plastic cylinders with the inner face covered with a geotextile produces cob specimens with bulk density and pore size distribution similar to that of wall elements. The procedure succeeds in reproducing the irregular kneading effect of cob. Moreover, the laboratory procedure permits the estimation of Uniaxial Compressive Strength and the Young's modulus of a cob wall of known bulk density. This laboratory procedure offers the advantage of being usable either on-site, under air-drying and weather conditions, or in the laboratory, under oven-drying conditions. Nonetheless, further investigations are needed to validate this improved laboratory procedure with other cob mixtures.

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