CEBs stabilised with geopolymeric binders: mechanical performance of dry-stack masonry

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Abstract

The sustainability in the building industry is currently a sounding topic, seeking the development of more environmental friendly building materials. The incorporation of industrial wastes and the reuse of construction and demolition waste (CDW) in the production of building materials are methods being used to solve this problem. Furthermore, these methods contribute to fulfilling the targets defined by European Union for the valorisation of non-hazard waste. The construction with compressed earth blocks (CEBs) stabilised with geopolymeric binders is a solution that can contribute to this objective by incorporating both CDW (excavation soil) and industrial wastes. Despite some recent research done on this topic, it still deserves further investigation. This paper intends to contribute to the development of this topic by presenting an experimental program, continuing previous research. The experimental program is addressed to the mechanical characterisation of a dry-stack CEB (stabilised with geopolymer obtained from alkaline activation of fly ash) masonry system, and includes the evolution of the strength of the CEBs with the curing time. In general, the evolution of the strength of the CEBs cured under ambient condition was shown to be a slow process, which can have implications on the production process.

Keywords: CEB; alkaline activation; fly ash; dry-stack masonry; mechanical behaviour

1 Introduction

The development of low embodied energy building materials is a sounding topic (Pulselli et al., 2007) due to current environmental concerns. One of the approaches being used to contribute to this topic is the incorporation of non-hazard industrial wastes in the production of building materials, which also contributes to the valorisation of the several millions of tons of waste produced annually worldwide. In some cases, such materials also benefit from enhanced properties. For example, the incorporation of fly ash to substitute partially Portland cement improves the mechanical and durability properties of concrete (Berry & Malhotra, 1980). Furthermore, there is an urgent need to valorise construction and demolition waste (CDW). In the European Union, CDW constitutes approximately 25-30% of all waste generated and consists of numerous materials, including concrete, bricks, gypsum, wood, glass, metals, plastic, solvents, asbestos and excavated soil. The Waste Framework Directive (2008/98/EC) (European Union, 2008), stipulates that Member States shall take the necessary measures designed to achieve that by 2020 a minimum of 70% (by weight) of non-hazardous CDW (Art. 11.2) shall be prepared for re-use, recycled or undergo other material recovery.

Building with raw earth is a solution that presents several advantages when compared with conventional building solutions used in developed countries, namely reinforced concrete and fired brick masonry. Such advantages include not only its very low embodied energy, but also its good thermal and acoustic performances, great fire resistance and relatively low cost (Houben & Guillaud, 2008; Minke, 2006). Nevertheless, earthen materials are in general considered as non-standard, especially because they are made from soil which is a highly variable and heterogeneous material. Furthermore, there is lack of codes and standards supporting earth construction in most of countries around the world. For instance, this situation constitutes a serious impediment to earth construction in Europe, namely when the existing building codes are addressed (CEN, 2005). Traditional earth construction (eg.: adobe and rammed earth) has been successively subjected to improvement of the earthen materials and building techniques in order to overcome the aforementioned limitations. Masonry built with compressed earth blocks (CEBs) is probably the most relevant case of improvement introduced in the earth construction technology. CEBs are produced by compacting soil in a manual or hydraulic press, in a more industrialised and controlled production process than that of adobes, for instance (Doat et al., 1991). On the other hand, the production of CEBs resorts very often to chemical stabilisation of the soil (Walker & Stace, 1997), in order to promote better strength and durability properties and to decrease their dependence from the variability of the available soil. The addition of cement is in general used as universal stabilisation solution, but it results in an important increase of the embodied energy and cost of earthen materials (Dahmen, 2015), making this solution less attractive.

On the other hand, the production of CEBs is a technique that may benefit from the advantages of geopolymeric binders (Pacheco-Torgal et al., 2007) used for soil stabilisation purposes (Cristelo et al., 2012). Geopolymeric binders present as main advantages the enhanced mechanical behaviour and durability over those manufactured with Portland cement. Furthermore, geopolymeric binders present enhanced environmental impact, since they can be manufactured from alkaline activation of industrial wastes rich in alumina-silicate. Therefore, the production of CEBs may contribute for the valorisation of waste by incorporating CDW excavated soil and industrial waste as source of alumina-silicate, and thus contribute to fulfil the European objectives proposed in the Waste Framework Directive (2008/98/EC) (European Union, 2008). Exploratory research regarding the production of CEBs stabilised by means of alkaline activation of fly ash was initiated very recently (Silva et al., 2015). Nevertheless, further research is required in order to validate the use of geopolymer binders in the production of CEBs. Taking this into account, a new experimental program was carried out based on that presented by Silva et al. (2015). Both experimental programs were addressed to the mechanical characterisation of a dry-stack CEB masonry system, but the curing time is addressed in this case.

2 Experimental program

2.1 *Production of the CEBs*

The soil used in the manufacturing of the CEBs was collected from Guimarães (northern Portugal) and its geotechnical properties were characterized in terms of particle size distribution (PSD), Atterberg limits and Proctor compaction parameters, as described in Silva et al. (2015). The clay content of the soil was shown to be insufficient to produce CEBs, and furthermore its compressive strength was shown to be insufficient to be used without stabilisation (Silva et al., 2013). Therefore, the CEBs tested in the experimental program were produced with stabilisation by means of addition of a geopolymeric binder obtained by alkaline activation of fly ash. The mixture used was composed by 85% of air dry soil and 15% of fly ash. The fly ash (type F) was obtained from a Portuguese thermo-electric power plant (PEGOP) and is characterised by a mass of silica and alumina of about 71%. The activator was constituted by a solution of sodium hydroxide and a solution of sodium silicate in ratio 2:1, respectively. The sodium hydroxide solution presented a concentration of 12.5 molal, while the sodium silicate solution presented a sodium oxide (Na_2O) content of 13% and a SiO_2:Na_2O ratio of about 2. The ratio activator/solids was established as 13.7%. It should be noted that this mixture corresponds to mixture SFA15 presented by Silva et al. (2015). The geometry of the CEBs produced consists in a hollow block, which allows to build single- and double-leaf walls (Figure 1). The masonry built with these CEBs consists in a dry-stack interlocking system, relying on a docking mechanical connection (indentation) between CEBs, which does not require the use of mortared joints (Sturm et al., 2014; Silva et al., 2015). The CEBs were manufactured using a Terstaram manual press. Production control was made in terms of weight of mixture required to perform each CEB. After compaction, the CEBs were left to cure on the floor for about 7 days and then were packed until testing. The curing of the CEBs occurred under laboratory conditions at an average temperature of about 18ºC and relative humidity of about 52%.

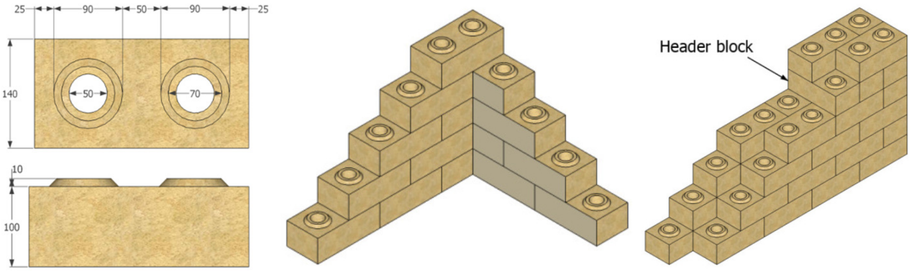


Figure 1. Dry-stack interlocking CEBs masonry system (Sturm et al., 2014).

2.2 *Testing procedures*

The experimental program included the testing of single CEBs, single-leaf dry-stack prisms and wallets. The compression tests of single CEBs were carried out according to EN 772-1 (CEN, 2011), but the load was applied under displacement control at a rate of about 4 µm/s. A set of three CEBs were tested at different curing ages, namely 7, 14, 21, 28, 42, 56, 70, 120, 150 and 180 days.

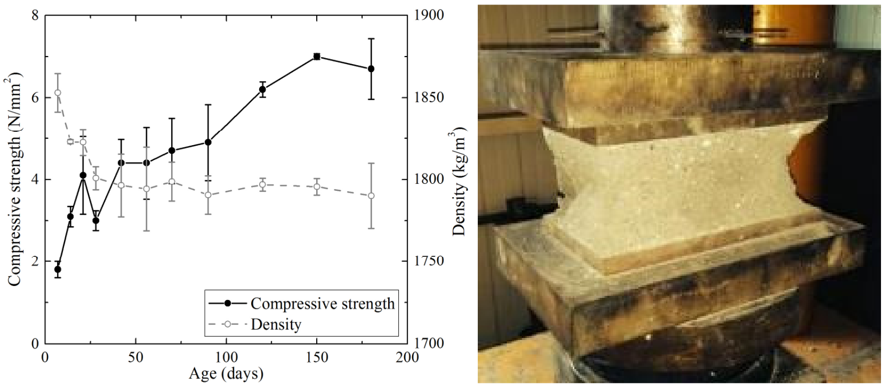
The compressive behaviour of the single-leaf masonry system was tested by means of compression tests on three dry-stack prisms of five blocks, with dimensions of about 280 x 140 x 500 mm^3 (width x thickness x height), and on three wallets with nine courses, with dimensions of about 840 x 140 x 900 mm^3. The CEBs constituting both types of specimens cured for a period between 100 and 120 days. The tests of the prisms were carried out according to ASTM C1314-03b (ASTM, 2003), but the load was applied under displacement control at a rate of about 5 µm/s. The tests of the wallets were carried out according EN 1052-1 (CEN, 1999), but under displacement control at a rate of about 13 µm/s. The vertical displacements were measured between the third and the seventh course by means of two LVDTs placed on each face of the wallets. The horizontal displacements were also measured by means of an LVDT placed on the fifth course of each face and measuring between two vertical joints.

The shear behaviour of the CEB masonry of both mixtures was assessed by means of shear tests on dry-stack prisms of three CEBs, with average dimensions of about 280 x 140x 300 mm^3. The tests were carried out according to EN 1052-3 (CEN, 2002), using three levels of pre-compression stress, namely 0.10 N/mm^2, 0.30 N/mm^2 and 0.50 N/mm^2. The shear load was applied by means of an actuator parallel to the joints under displacement control at a rate of about 10 µm/s. The relative shear displacement of the middle block was measured by means of two LVDTs, while the axial displacements between the top and bottom blocks were measured by means of two LVDTs attached on each face of the prism. Three prisms were tested for each level of pre-compression stress.

3 Results and discussion

3.1 Compressive strength of the CEBs

The evolution of the density and compressive strength of the CEBs with the age is presented in Figure 2a. The density is shown to decrease with the age of the specimens, as a consequence of the evaporation of the water incorporated in the activator. The compressive strength shows a fast increase in the first 21 days, after which, there is a sudden decrease at 28 days. This decrease is probably related with the geopolymerization process and was already observed in previous studies (Silva et al., 2014). At 42 days of age, the strength returns to values similar to that of 21 days of age and increases at slow rate until the 90 days, in what seems to be a latent phase. Then, the strength has fast increase until the 150 days, after which it seems to stabilise. This evolution shows that, under ambient curing conditions, the CEBs are distant from achieving their full strength potential for the typical reference age of 28 days. On the other hand, thermal curing could be used to increase the hardening rate, but this process would increase the embodied energy. At 120 days the CEBs are close to their maximum, seaming that this age would constitute a better reference age for this type of material (if storage costs are not taken into account). Nevertheless, the CEBs at 28 days of age exceed a compressive strength of 2.0 N/mm^2, which is a minimum value typically recognized for earthen materials (Houben & Guillaud, 2008). The failure mode of the CEBs was characterised by the formation of a pyramidal-trunk (Figure 2b)



(a) (b)

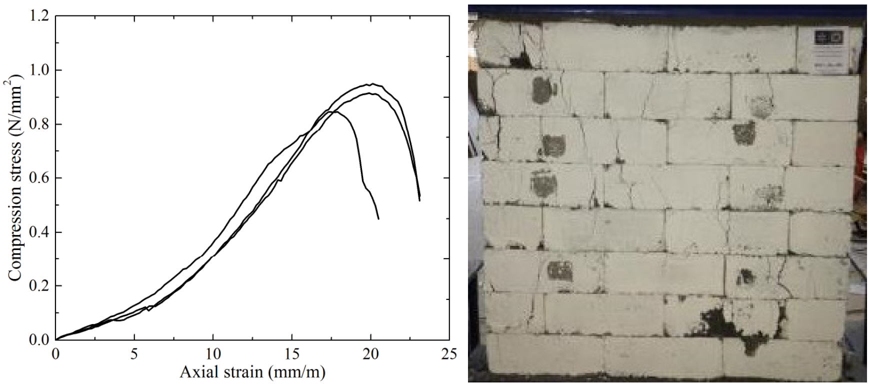
Figure 2. Results of the compression tests on single CEBs: (a) evolution of the compressive strength; (b) typical failure mode.

3.2 Compressive behaviour of the masonry

The results of the compression tests on the masonry specimens are presented in Table 1, in terms of average compressive strength of the prisms ($f_{c,p}$), compressive strength of the wallets ($f_{c,w}$) and Young modulus of the wallets computed between 30% and 60% of the compressive strength ($E_{30\text{-}60,w}$). The compressive strength of both type of specimens presented a strong reduction comparatively to that of the CEBs, namely 0.26 and 0.16 times for the case of the prisms and wallets, respectively. It should be noted that these ratios were defined with basis on the interpolated value of the compressive strength of the CEBs for 110 day of age (5.8 N/mm^2). This situation results from the assemblage of the CEBs in masonry and is expected to be amplified by the fact that the joints are dry-stack, as discussed by Silva et al. (2015). Furthermore, the decrease in strength of 0.6 times from the prisms to the wallets, shows that testing prisms may not provide reliable and representative results for this masonry system. The value obtained for $E_{30\text{-}60,w}$ is also show to be substantially low, which is a consequence of the large deformations mainly occurring at the dry joints. The compression stress-axial strain curves of the wallets are presented in Figure 3a. The curves show an initial adjustment phase, which is related with the accommodation between CEBs at the dry joints. The failure mode is characterised by distributed cracking, as shown in Figure 3b. The first cracks appeared very early (10% of $f_{c,w}$) and develop continuously from a block to block, without showing relative displacements at the dry-stack joints.

Table 1. Results of the compression test on the masonry prisms and wallets (coefficient of variation in brackets).

$f_{c,p}$ (N/mm^2)	**$f_{c,w}$ (N/mm^2)**	**$E_{30\text{-}60,w}$ (N/mm^2)**	**$f_{c,w}$ / $f_{c,p}$**
1.5 (3%)	0.9 (6%)	98 (16%)	0.60

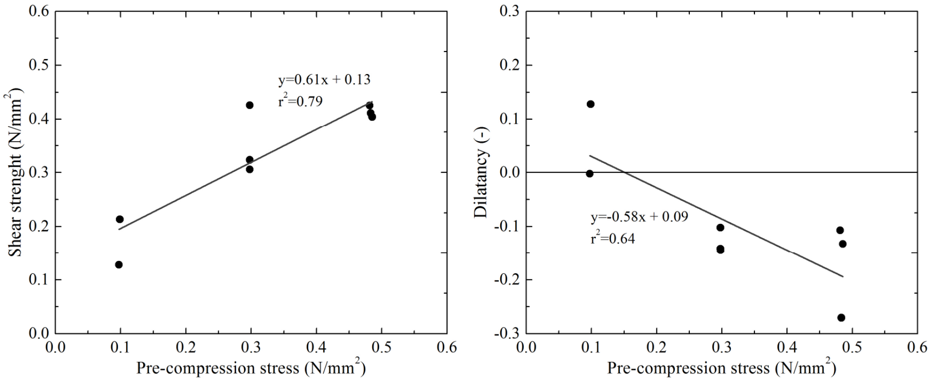


(a) (b)

Figure 3. Results of the compression tests on the wallets: (a) compression stress-axial strain curves; (b) typical failure mode.

3.3 Shear behaviour of the masonry

The relationship between shear strength and pre-compression level is depicted in Figure 4a. The linear regression applied to the points of the graph shows an initial shear strength of about 0.13 N/mm^2. This non-zero strength value represents the contribution of the interlocking system for the shear strength of the masonry. The friction coefficient (tanϕ) was of about 0.61, which is significantly higher than 0.4, as proposed in Eurocode 6 (CEN, 2006), which is probably a consequence of the very rough and apparently hard contact surfaces of the blocks and of the progressive failure of the interlocking system. Figure 4b presents the relationship between dilatancy and pre-compression level, where the positive values of the lowest level mean that the pre-compression stress was insufficient to overcome the “ramp effect” introduced by the indentations. The negative values mean that this effect is overcome and the dry joint is worn and crushed with the test.



(a) (b)

Figure 4. Results of the shear tests: (a) relationship between shear strength and pre-compression stress; (b) relationship between dilatancy and pre-compression stress.

4 Conclusions

This paper presents an experimental program, where the evolution of the compressive strength of CEBs stabilised with alkaline activation of fly ash was the main focus, in addition to the mechanical characterisation of the masonry system. The evolution of the strength of the CEBs cured under ambient condition was shown to be a slow process. Furthermore, the strength at the typical reference of 28 days of age was show to be distant from achieving the full strength potential of the CEBs. Despite that, the CEBs tested at this age seem to deem with minimum strength requirements for earthen materials.

The compression tests on the masonry specimens seem to show an important strength reduction relative to the strength of the CEBs, which seems to be a consequence of the dry joint system. Furthermore, it was shown that the testing of masonry prisms may not provide reliable results of the masonry system.

Finally, the shear tests seem to show that the indentation of the CEBs have participation on the shear behaviour of the masonry, namely with respect to the initial shear strength.

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