Construction and Building Materials 75 (2015) 349–358

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Mechanical characterisation of dry-stack masonry made of CEBs stabilised with alkaline activation

Rui A. Silva [a,*], Edgar Soares [a], Daniel V. Oliveira [a], Tiago Miranda [a], Nuno M. Cristelo [b], Dinis Leitão [c]

[a] ISISE, University of Minho, Department of Civil Engineering, Guimarães, Portugal
[b] C-MADE, University of Trás-os-Montes e Alto Douro, School of Sciences and Technology, Vila Real, Portugal
[c] C-TAC, University of Minho, Department of Civil Engineering, Guimarães, Portugal

HIGHLIGHTS

- Manufacturing of CEBs with granitic residual soil requires chemical stabilisation.
- The alkali activation of fly ash was tested as a stabilisation technique.
- The alkali activation improves substantially the strength of the CEBs.
- The stabilisation of CEBs by alkaline activation can be further optimised.

ARTICLE INFO

Article history:
Received 21 July 2014
Received in revised form 7 October 2014
Accepted 12 November 2014

Keywords:
CEB
Granitic residual soil
Mechanical characterisation
Sustainability
Alkaline activation
Fly ash

ABSTRACT

The increasing interest on earth construction as a sustainable building solution led to the development of modern earth construction techniques, in particular of masonry made of compressed earth blocks (CEBs). The traditional chemical stabilisation of the soil is a frequently used improvement process. However, such process increases significantly the embodied energy of the CEBs. This paper presents an alternative technique for the stabilisation of CEBs, based on alkali activation of fly ash. The mechanical behaviour of the CEBs and of the respective dry stack masonry is comprehensively investigated through an experimental program, during which this technique proved to be highly effective.

1. Introduction

Raw earth has been used to build sheltering since ancient times [1]. Nowadays, building with earth continues to be a popular solution in many developing countries, such as Peru, Angola, Mozambique, Yemen, Iran, India and China. In fact, this building material constitutes the only feasible alternative in many situations. On the other hand, the use of earth construction fell into disuse during the past century in many developed countries, such as Portugal, Spain, France and Germany. Earth construction has been continuously replaced by modern constructions integrating stronger materials, as reinforced concrete and fired brick, but whose CO_2 emissions are also much higher. Despite that, the current importance of earth construction in the World is still very high, as about one fourth of the World's population is estimated to live in earthen dwellings [2]. Furthermore, earth constructions are usually associated to vernacular architecture, since local soils are typically used by local populations. This means that a large diversity of traditional building techniques exist and reflect several features, such as differences between soils, and social, cultural and economic backgrounds of the populations. Among the traditional building techniques, adobe and rammed earth are the most popular ones [1].

Earth construction is a sounding topic nowadays, with growing interest due to the high sustainability (low CO_2 emissions and capacity to return the earthen materials back to nature after their life-cycle), thermal and acoustic performance, fire resistance and cost of the raw material (soil) [3]. In fact, earth construction can constitute a feasible solution for a more sustainable construction industry in developed countries. However, the major drawback is that traditional earthen materials are typically considered as

* Corresponding author at: Department of Civil Engineering, University of Minho, Azurém, 4800-058 Guimarães, Portugal. Tel.: +351 253 510 200; fax: +351 253 510 217.

E-mail address: ruisilva@civil.uminho.pt (R.A. Silva).

http://dx.doi.org/10.1016/j.conbuildmat.2014.11.038
0950-0618/

non-standard. The great variability and heterogeneity of the properties of the available soils, the lack of quality control in the manufacturing of the earthen materials and in the construction process can be pointed out as the main reasons behind this situation. Furthermore, only few countries issued standards and recommendations supporting earth construction (e.g.: NZS 4297 [4], NZS 4298 [5], NZS 4299 [6], UNE 41410 [7], HB 195 [8], E.080 [9]), discouraging the design of earth construction by the technical community in countries where these documents are absent. As a consequence, earthen materials are usually associated with poor mechanical properties, low seismic performance and poor durability against water. These materials are also associated to poverty and to the subsistence construction usually found in developing countries. These aspects lead to little acceptance of earth construction by potential owners in developed countries.

Traditional earth construction 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, as these blocks can be seen as an upgrade of the adobes. CEBs are manufactured resorting to specific presses, where the moistened earth is statically compacted in a mould to form the block, which is immediately demoulded and put to dry. This technique was introduced in the nineteen fifties with the development of a specific manual press, which became worldwide known as CINVA-RAM [10]. This procedure allows the strict control of the geometrical features of the CEBs and a significant improvement of the mechanical properties. Nowadays, hydraulic presses can be used instead [11], allowing higher compaction pressure and thus increased mechanical properties [12].

The chemical stabilisation of the soil by addition of cement and lime is often used in the manufacturing of CEBs to increase the mechanical properties of the CEBs and their resistance to water. This procedure is particularly interesting in the cases where the available soil does not meet adequate properties. Nevertheless, the chemical stabilisation is systematically used, even in soils with adequate properties [1]. On the other hand, the addition of cement and lime increases substantially the cost and the embodied energy of the CEBs, making this solution less competitive [13,14]. The use of geopolymeric binders obtained from alkaline activation has shown lower CO_2 emissions than cement based binders, without compromising properties such as strength and durability [15]. A similar result is expected when applying this technique in the stabilisation of soils. Roughly speaking, the stabilisation process consists in the mixing of the soil with a geopolymer binder, which hardens and forms a matrix that involves and binds the particles in a soil-binder interface that usually delivers strength levels higher than the soil alone. The alkaline activation process consists in a reaction between alumina-silicate materials and alkali or alkali earth substances (constituting the alkaline activator), namely: ROH, $R(OH)_2$, R_2CO_3, R_2S, Na_2SO_4, $CaSO_4{\cdot}2H_2O$, $R_2(n)SiO_2$, in which R represents an alkaline metal like sodium (Na^+) or potassium (K^+), or an alkaline earth metal like calcium (Ca^{2+}). This reaction is followed by a polycondensation process, in which the silica (SiO_2) and alumina (AlO_4) tetrahedra interconnect and share the oxygen ions. The resulting polymer structure of Al–O–Si bonds constitutes the main structure of the hardened geopolymer matrix, which is very similar at a molecular level to natural rocks, sharing their stiffness, durability and strength. Fly ash is probably the most popular alumina-silicate raw source used in alkaline activation, but others can be mentioned such as high-furnace slag and metakaolin [16]. The first two are industrial by-products, meaning that they produce zero CO_2 emissions and their use is a way to valorise them in the building industry. Therefore, most of the environmental impact of the alkaline activation technique resides in the production of the alkaline activator compounds, namely sodium hydroxide and sodium silicate [17].

The chemical stabilisation of soils with alkaline activation of fly ash is a topic being studied recently in geotechnical applications [18,19] and in rammed earth construction [20]. The mentioned studies have been able to demonstrate that the stabilisation of soils with this technique can deliver similar or higher mechanical performance than that obtained from the addition of lime or cement [19]. Therefore, the integration of the alkaline activation of fly ash in the production of CEBs contributes for the mitigation of the environmental impact associated with more traditional chemical stabilisation (usually achieved with cement), while maintaining the mechanical performance standards. In practical terms, this means that the use of this industrial by-product associated to a control of the incorporated alkaline activator compounds is expected to result in CEBs with lower embodied energy. For instance, Cristelo et al. [21] show that the use of alkaline activation of fly ash in grouts for jet mix columns produces only 77% of CO_2 of the equivalent solution with a cement-based grout.

This paper presents an experimental program where the mechanical behaviour of dry-stack masonry made of CEBs stabilised with alkaline activation of fly ash is assessed in detail. The CEBs were manufactured with granitic residual soil (GRS), typical from northern Portugal, and using two different percentages of fly ash (10% and 15%). The individual CEBs were tested under compression and three-point bending (in dry and saturated conditions). The respective masonry was additionally tested for compression and shear behaviour.

2. Experimental program

2.1. Geometry of the CEBs and masonry system

The geometry of the CEBs and the respective building system was based on an output from a previous partnership between the University of Minho and the company Mota-Engil SA. The aim of the project was the development of a simple and innovative solution for the construction of sustainable buildings in seismic countries, which took Malawi as a case study [22]. The geometry of the CEBs consists in a hollow block, see Fig. 1, which allows to build single- and double-leaf walls. According to Minke [23] and the Auroville Earth Institute [24], this type of CEB is recommended for regions with non-negligible seismic hazard, because the holes allow the introduction of vertical reinforcement and to decrease the self-weight of the blocks. 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. This last feature allows a simpler building process, which promotes faster building processes and lower building costs. Further information on the constructive system is addressed in Ramos et al. [22].

2.2. Materials

2.2.1. Soil

The soil used in the manufacturing of the CEBs was collected in Guimarães (northern Portugal) and its geotechnical properties were characterised in terms of particle size distribution (PSD) [26], Atterberg limits [27] and Proctor compaction parameters, namely maximum dry density and optimum water content [28]. These properties were then compared with some international documents (standards and recommendations) regulating earth construction in order to conclude about the suitability of the soil for manufacturing unstabilised CEBs [1,7,8,11]. It should be noted that Portugal has not issued any standard regarding earth construction so far.

Fig. 2 presents the PSD curve of the soil and compares it with the envelope provided by Viana da Fonseca [29], regarding GRS from Porto, also located in northern Portugal. In general, the PSD curve of the soil fits within the envelope, meaning that both soils are similar.

In Fig. 3, the obtained PSD curve is plotted against envelopes relative to the manufacturing of CEBs, recommended by Houben and Guillaud [1] and by the standard UNE 41410 [7]. In both cases the low fines' content is highlighted, particularly its clay fraction of 4% ($\leqslant$0.002 mm). The clay content of the soil is clearly inferior to the minimum values recommended by most of the documents regulating CEB construction. For instance, the HB 195 [8] recommends a soil with a minimum clay percentage of about 10% in order to manufacture unstabilised CEBs. The UNE 41410 [7] requires the same minimum percentage, but a more restrictive criterion is given by discarding the use of any soil with inferior clay percentage. Even in the case of