2nd International Conference on Bio-based Building Materials &
1st Conference on ECOlogical valorisation of GRAnular and FIbrous materials

June 21th - 23th 2017
Clermont-Ferrand, France

AN EXPLORATORY STUDY ON EARTHEN MATERIALS STABILIZED BY ALKALINE ACTIVATOR

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Abstract

Earth is an ancient building material which has been recently the focus of scientific research because of the significant heritage of earthen buildings throughout the world. Moreover, a renaissance of earth constructions has been observed due to sustainable properties of this material. However, the disadvantage of earthen material is its low strength and its sensibility to the water content. To enhance the durability and the mechanical characteristics of earthen material, hydraulic binders are currently added (cement or lime). These hydraulic binders have high embodied energy and therefore increase the embodied energy of the stabilized earth material.In order to find an alternative binder, other components are tested. This paper presents an exploratory study which uses geopolymer as a stabilizer for earthen material. Geopolymers are inorganic binders with polymeric structure obtained by alkaline activation of raw materials containing silicon and aluminum; they are obtained by dissolution/precipitation reactions at low temperature. The present study proposes to use blast furnace slag as geopolymer raw material, which was mixed with an alkaline solution activator to obtain the stabilizer for earthen material. The furnace slag is an industrial waste and its recycling reduces the binder's environment impact. The geopolymer effects were investigated on two types of earthen material: rammed-earth (RE, soil dynamically compacted) and soil-geopolymer-concrete (soil poured with more water content). The results show that geopolymer had more effects in soil-concrete than in rammed-earth. Indeed, RE specimens stabilized by geopolymer did not present a significant improvement of compressive strength comparing to the unstabilized RE specimens. Soil-geopolymer-concrete specimens had double compressive strength comparing to soil-cement-concrete specimens. However, the results obtained on specimens stabilized by geopolymer were still relatively low (<3 MPa). The geopolymer amount, the quantity and type of clays present in the used soil could have influences on the results.

Keywords:
Rammed earth; Soil concrete; Geopolymer; Compressive strength; Earth stabilization

1 INTRODUCTION

In-situ materials which are directly available on site are used by humanity from centuries as earth (rammed earth, adobe, cob…), stone (dry stone masonry and rubble stone masonry) and wood. The construction techniques using in-situ materials are still widely used today in developing countries, thanks to their lower construction costs in comparing to conventional constructions (such as reinforced concrete or metal structures). The reason is that conventional materials are not always available in these countries and must be imported, that significantly increases the cost. In addition, the labor cost is not expensive, so the use of in-situ materials has a positive social aspect by providing works to local workers.

However, in developed countries, most of these materials were dropped consistently over the past six decades for two main reasons. First, the labor cost in these countries is high, which is not favorable for the constructions requiring important labor. Then, the current design regulations are established mainly for industrial conventional materials. There are few standards for non-industrial materials due to the lack of scientific knowledge. Nevertheless, the past few years have witnessed a renaissance of local materials in developed countries, mainly due to the urgent demands of sustainable development. Soil material gradually found its place on construction sites because it is taken and manufactured directly on site, which provides low embodied energy [Morel 2001]; walls constructed with soil material can act as a natural moisture buffering for indoor environments [Soudani 2016]. From the economic view point, using the in-situ soil as construction material is also interesting for the builder because the fee to evacuate the in-situ soil before the construction is costly [Bui 2016a].

Several traditional techniques exist today to use soil as construction material: rammed earth, compressed earth blocks, adobes, cob. The main binder in those cases is clay. For new constructions, hydraulic binders can be added (currently cement, lime) to increase the material's mechanical properties and durability [Bui 2009a]. These hydraulic binders have high embodied energy and therefore increase the embodied energy of the stabilized earth material [Reddy 2010]. In order to find an alternative binder, other components are tested. This paper presents an exploratory study which uses geopolymer as a stabilizer for earthen material.

The term "geopolymer" is used for products where amorphous three-dimensional inorganic structures are formed through the reaction of alumino-silicate precursor, with an alkaline solution activator [Davidovits 2008]. The source of alumino-silicate can be natural clays, calcined clays, industrial by-products and other natural minerals. The activators are typically sodium or potassium hydroxides or silicates, but others are also possible.

Using geopolymer technology for earth construction is interesting because the soils used for earthen construction has a significant amount of clay content and are a source of alumino-silicates such as kaolin and illite. Therefore the natural clay minerals within the soil can become an essential part of stabilizing mechanism, rather than simply being encapsulated by the stabilizer, as is the case of cement [Maskell 2014]. Compressive strength of non-calcined materials, such as kaolinite, can be increased with the addition of calcined materials including fly ash and metakaolin [Xu 2002].

There are still few studies on the stabilization of earthen materials by geopolymer but the studies of Maskell et al. [Maskell 2014] and Cristelo et al. [Cristelo 2012] can be cited. Maskell et al. [Maskell 2014] used an alkaline activator in their investigation on the geopolymer stabilization of earthen bricks. These authors tested different compositions of geopolymer (1%, 3% and 5% of sodium hydroxyde with respectively 0%, 4%, 15% and 20% of sodium hydroxyde) and investigated also the effect of curing temperature (at 20° and 105°C) on the compressive strength. However, the specimens tested were small specimens (1.8-cm-diameter and 3.6-cm-height), so the correlation with the workability at the real scale should still be investigated. Cristelo et al. [Cristelo 2012] studied the effectiveness of alkaline activation of low-calcium fly ash on rammed-earth material. Different liquid/solid ratios, alkali concentrations and Na_2O/ash ratios were tested. Effect of calcium hydroxide, sodium chloride and concrete superplasticizer was also investigated. The specimens were cured at 60 °C. Results showed that there was an optimum value for the activator/solids ratio and the alkali concentration, and that a decrease in the Na_2O/ash ratio resulted in a strength increase. No improvement was observed with the sodium chloride or the superplasticizer, while the calcium produced only an increase of early age strength.

The present study proposes to use blast furnace slag as a raw material, to be mixed with an alkaline solution activator to obtain a binder for earthen material. The furnace slag is an industrial waste and its recycling reduces the binder's environment impact. Due to its high content of calcium, silicon and aluminum, blast furnace slag presents good ability for alkaline activation and geopolymerization, which is reflected by obtaining very high mechanical performances on alkali activated blast furnace slag [Prud'homme 2016]. The geopolymer effects were investigated on two types of earthen material: rammed-earth and soil-concrete.

Rammed-earth (RE) is chosen here because this technique is largely liked in modern "green" buildings [Walker 2005]. RE is a monolithic wall which is built from several earthen layers. For each layer, the soil is poured about 15 cm thick into a formwork and then rammed by a rammer (manual or pneumatic). The soil is compacted at its optimum water content, which provides the highest dry density for the given compaction energy [Bui 2009b].The usual manufacturing water content for rammed earth is about 10-13%, in function of the material composition and the compaction energy. In developed countries, rammed earth is preferred to other earthen construction techniques (adobes, compressive earth blocks …) thanks to its esthetic and its construction rapidity, comparing to traditional earthen constructions.

The soil-concrete technique is also tested here because it is recently used in building construction, due to its rapidity comparing to other traditional earth construction (including rammed earth) because the wall is casted once, not in several layers. In order to be "poured" as a conventional concrete, more water should be added to increase the workability but this influences also on the mechanical properties of the concrete obtained.

2 SPECIMEN MANUFACTURING

2.1 Soil used

The soil used in this study was taken from a site of rammed earth construction. Table 1 presents the composition of the soil which was obtained by sieving (for elements >80 µm) and sedimentometric tests (for elements <80 µm). The methylene blue tests were carried out following French Standard [NF P 94-068] to obtain methylene blue values. The clay activity index ACB was calculated from the methylene blue values. That index enables to identify the soil's mineralogical composition (Table 2) following an abacus given by Lautrine [Lautrine 1989] which was reused by Chiappone et al. [Chiaponne 2004].

Table 3: Global composition of the soil used in this study (in weight)

	Clay	Silt	Sand	Gravel
Soil	19%	65%	16%	0%

Table 4: Clay's mineralogical composition of the soil used (in weight)

	Kaolinite	Illite	Montmorillonite
Soil	0%	65%	35%

2.2 Formulation of the geopolymer and the materials used

The geopolymer part in this study is composed of sodium silicate solution (noted SiNa, supplied by FisherScientific) with the following formula: $Na_2SiO_3.nH_2O$, a molar ratio SiO_2/Na_2O of 2.2, a density of 1.5 g.cm^{-3}, and contains 55% of water. The sodium hydroxide pellets (supplied by FisherScientific) are noted NaOH and is 99% pure. The blast slag furnace (noted BFS, density d = 2.9 g.cm^{-3}, D_{50} = 12.65 µm) is supplied by ECOCEM France. Its oxide composition is given Table 3.

Table 5. Oxide composition of BFS (weight percent).

Oxide	CaO	SiO_2	Al_2O_3	MgO	SO_3	Fe_2O_3	TiO_2	Mn_2O_3	K_2O	Na_2O
BFS	41,2	36.0	10,3	7,5	2,9	0,8	0,5	0,4	0,3	0,1

The effect of curing temperature was not investigated because the scope of this study is for an in-situ application (rammed-earth or concrete). A preliminary study on small specimens (3-cm-diameter and 6-cm-height) had been carried out to search a formula which was used for tests on standard specimens of civil engineering. Finally, the ratio of blast furnace slag: sodium silicate: sodium hydroxide was chosen based on the work of Prud'homme et al. [Prud'homme 2015]. The amount of furnace slag was chosen at 10% of the total mixture (with soil and water).

2.2.1 Rammed earth specimens

A primary study was performed that showed that the optimum water content - for the unstabilized soil and the used compaction energy - was by 11.8%, which gave the highest dry density (1.85). The representativeness of the compaction energy and the manufacturing optimum water content for RE specimens was discussed in Bui et al. [Bui 2009b]. For this exploratory study, RE specimens stabilized by geopolymer were also manufactured at this water content of unsatiblized RE. The water for the preparation of the activator (sodium silicate + sodium hydroxide) was 1.7% and other 10% (including 2% water content already present in the soil) was added directly to the soil. The detail of RE composition is presented in Table 4.

Table 6: Composition of RE specimens

Soil	Water (mixed with soil)	Geopolymer
75%	10%	10.4%

Before the adding of alkaline activator (under the form of a liquid), the soil and the furnace slag (form of powder) should be mixed to obtain a homogeneous mixture. Two processes for the mixture of the soil and the slag were tried. First, the soil and the slag were mixed at natural state (quasi-dry). But this process causes too many dusts during the mixing. That was why the second process was adopted: the soil was humidified beforehand until 10% of water content and then the slag was added and mixed (Fig.1). This enabled to avoid the dust during the mixing and the slag was better mixed with the soil and the water. Then, the alkaline activator solution (sodium silicate + sodium hydroxide + 1.8% water) was added and mixed. Two types of mold were used to manufacture geopolymer stabilized RE specimens:

- Cubic molds, 15x15x15 cm^3: each specimen has 3 earthen layers (Fig.2, at the left). These specimens will be tested in two directions: perpendicular and parallel to earthen layers.

- Cylindrical molds, 16cm-diameter x 32 cm-height: each specimen has 6 earthen layers (Fig.2, at the right). These specimens were only tested in the direction perpendicular to the layers.

Fig. 12: Soil with blast furnace slag prepared for RE specimens.

In parallel, cylindrical unstabilised RE specimens were also manufactured as reference for the comparison and so only tested in compression perpendicular to the earthen layers.

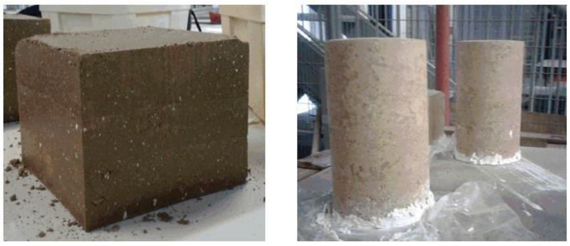

Fig. 13: Geopolymer stabilized RE specimens.

After demolding, several slag grains were still visible on the specimens, this shows that the slag was not really well mixed with soil and alkaline activator.

2.2.2 Soil-concrete specimens

For soil-geopolymer-concrete specimens, only the water amount was changed. The mixture was mixed in a concrete mixer and water was added until an acceptable workability of a plastic concrete was obtained (corresponding to a slump of about 6 cm). The total water content was 18%. With this water content, it was observed that the slag was better mixed with soil and alkaline activator than in the case of geopolymer RE specimens. The composition soil-geopolymer-concrete is presented in Table 7.

Table 7: Composition of the soil-geopolymer-concrete specimens

Soil	Water (mixed with soil)	Geopolymer
71%	16%	13%

The concrete casting was performed with cylindrical molds of 16cm-diameter and 32 cm-heigh, using a current concrete vibrator. However, after demolding, several air bulks were still observed on the specimens (Fig. *14*).

For the comparison, soil-cement-concrete specimens were also casted. A cement quantity of 8% (in weight) and 18% of water content were used. The cement amount was chosen at 8% because beyond this value, the material's embodied energy will be high and the soil-concrete will not be interesting [Reddy 2010].

Fig. 14: Soil-geopolymer-concrete specimens

3 UNIAXIAL COMPRESSION TESTS

3.1 Tests on rammed earth specimens

3.1.1 Compression tests in the perpendicular direction to earthen layers

Before the compression tests, specimens were surfaced by a lime mortar to have two plane and horizontal faces (Fig.4). The specimens were tested in force-piloted and were loaded at a rate of 0.4 kN/s.

Fig. 15: Compression in the direction perpendicular to earthen layers

After the tests, the specimens' moisture contents were measured and their dry densities were also determined. The dry density values were of 1.78 ± 0.01 and 1.85 ± 0.02 respectively for prismatic and cylindrical specimens. This result is not surprising because it has already been observed that the prismatic specimens had dry densities less than that of the cylindrical specimens. Indeed, the dynamic compaction in the corners of prismatic specimens is not easy and the results obtained on prismatic specimens are usually lower than that of cylindrical specimens [Bui 2016b].

3.1.2 Compression tests in the parallel direction to earthen layers

Cubic specimens were also tested in the direction parallel to earthen layers (Fig.5). No surfacing was needed because the upper and lower faces were plane and horizontal. The failure of specimens tested in direction parallel to earthen layers was similar to that of specimens tested in direction perpendicular to layers (Fig.5 (A)), which showed a satisfying cohesion between earthen layers.

(A) (B)

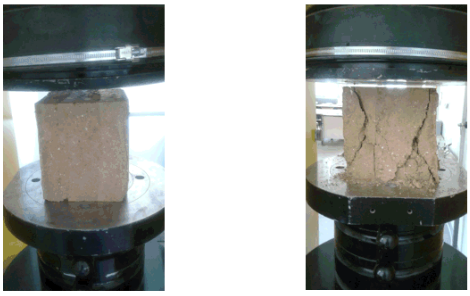

Fig. 16: Compression in the direction parallel to earthen layers, before (A) and after (B) the test.

3.2 Tests on soil –concrete specimens

Because there are not layers in soil-concrete material, cylindrical specimens were tested only in one direction. Specimens were also surfaced and tested at a rate of 0.4 kN/s. This rate is lower than that applied for ordinary concrete specimens, in order that each test takes a couple of minutes, similar to in the case of ordinary concrete specimens.

3.3 Results and discussions

A summary of the results is presented in Table 6. It is important to note that due to a small slenderness ratio of cubic specimens (height/width = 1), the frictions during the compression test, between the specimen and the upper and lower steel plateaus of the press, play a non-negligible role and the results obtained are overestimated. That is why it is well-known that results obtained on cubic specimens should be multiplied by a correction factor.

Table 8: Summary of the results obtained on different specimens.

Specimens	Dry density	Moisture content (%)	Test direction	f_c (MPa)	Age
Geopolymer RE Cube	1.78	5	Parallel to layers	1.2	2 weeks
		3		1.8	4 weeks
		5	Perpendicular to layers	1.3	2 weeks
		3		1.9	4 weeks
Geopolymer RE Cylinder	1.85	5	Perpendicular to layers	1.6	2 weeks
		3		2.4	4 weeks
Unstabilsed RE	1.85	3	Perpendicular to layers	1.8	4 weeks
Soil-geopolymer-concrete	1.64	12	NA	0.9	2 weeks
		6		1.2	4 weeks
Soil-cement concrete	1.78	4	NA	0.6	4 weeks

Following Eurocode 2 for concrete, this correction factor depends to the concrete class (strength) but is about 0.85-0.87 for mean compressive strength of low strength concrete. In absence of specific recommendations for earthen specimens, a correction factor of 0.9 was adopted here for geopolymer RE cubic specimens. The corrected results are illustrated in Fig.6.

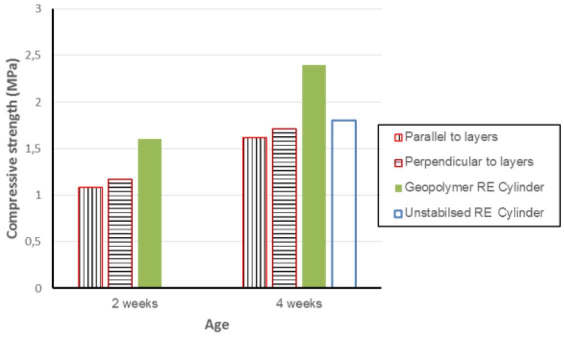

Fig. 17: Compression strengths of geopolymer RE specimens after 2 and 4 weeks. Note: a correction factor was used for cubic specimens.

As mentioned above, the dry density of prismatic specimens were less than that of the cylinders and one-scale RE walls [Bui 2016b], so the compressive strengths obtained on prismatic specimens are lower and not representative for RE walls. The tests on prismatic specimens are presented here just in order to assess the anisotropy of the geopolymer RE specimens. The results shows that the results obtained in perpendicular and parallel to earthen layers were similar (difference less than 8%). This confirms the results obtained in a previous study on unstabilized RE [Bui 2009c].

Fig. ***17*** shows that there is an improvement (50%) of the strength of geopolymer RE from 2 weeks to 4 weeks. Then, compared to cylindrical unstabilised RE specimens, the strength of cylindrical geopolymer RE specimens increased by 33%.

Fig.7 presents a comparison of compression strengths obtained on different cylindrical specimens: geopolymer RE, soil-geopolymer-concrete and soil-cement concrete. The result of soil-cement concrete (8% cement) was very low, probably due to the high quantity of water used. Indeed, with a soil containing 19% clay, a high amount water (18%) was necessary to obtain an acceptable workability. In a previous study [Bui 2016a], with a soil having a lower clay content, the water content necessary was lower and the compressive strength obtained was better.

For the soil-geopolymer-concrete specimens, an evolution of the strength in function of time was also noted. At 4 weeks, soil-geopolymer-concrete specimens had compressive strength twice of soil-cement concrete specimens. However, these results are still low comparing to geopolymer RE specimen and for construction materials in general. The high amount of water used was probably the reason of these results.

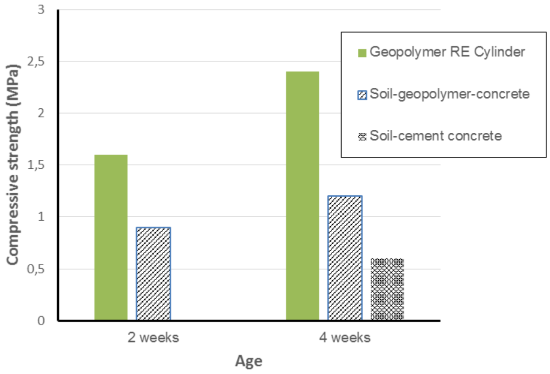

Fig.18: Compression strengths of geopolymer RE, soil-geopolymer-concrete and soil-cement concrete specimens.

4 CONCLUSIONS AND OUTLOOK

This paper presents an exploratory investigation on the use of alkaline activator to stabilize two types of earthen material: rammed earth and soil-concrete.

The results showed that geopolymer stabilization improved 33% of compressive strength of RE specimens, comparing to unstabilised RE. However, the obtained results (2.4 MPa at 4 weeks) was not as high as expected to be a material for bearing walls in the viewpoint of modern regulations. It was also observed that the slag was not well mixed with soil and alkaline activator, so if a better mixing method is found, better compressive strengths can be expected.

When more water was added (the case of soil-geopolymer-concrete), the effect of geopolymer was more positive than cement in soil-cement-concrete specimens (at 8% of cement in weight). However, due to an important amount of water, the compressive strength of the specimens was not as high as expected (1.2 MPa at 4 weeks).

The soil used in this study does not contain kaolinite. It will be interesting to study other soils which contain different quantities and types of clay.

Due to the sustainable and economic reasons, only a low amount of sodium silicate (2.5%) was used in this study. Other compositions of geopolymer will be searched to improve the compressive strength.

5 ACKNOWLEDGMENTS

The authors wish to thank Dang-Mao Nguyen, Ranime El-Nabouch from LOCIE - University Savoie Mont Blanc and Van-Huong Tran from ENTPE-Filiaterre for their help during the specimen castings.

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