MECHANICAL ENHANCEMENT OF CASTED AND COMPACTED EARTH-BASED MATERIALS BY SAND, FLAX FIBER AND WOVEN FABRIC OF FLAX

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Abstract

Earth-based materials are commonly reinforced with bio-based materials such as straw. In this study, we use high performance bio-based flax fibers and fabrics. The aim of this work is to find reinforcements that are able to improve the mechanical strengths and the ductility of an earth-based matrix. We also try to describe the reinforcement mechanisms are also described. In a first step, a kaolinite-based clay soil is mixed with sand to design earth-based mortars with the highest density at the dry state. The sand dosage is found using mix-design method commonly used for concrete. We show that, at the same water content, the compressive strength at the dry state only depends on the dry density of the sample (and does not depend on forming process and use of dispersant). In a second strep, the mix-designs exhibiting the highest compressive strengths are chosen for both casting and compaction. Then, different amounts of fibers or fabrics are used to reinforce the studied mortars. We found that those reinforcements significantly increase the compressive strength of all tested samples. This result is very interesting because this is not always the case for other mineral matrix such as mortar and concrete. Such comparison with concrete helps us to understand the reinforcement mechanisms for fibers. This study shows that concrete mix-design methods are very helpful to increase the density at the dry state and the mechanical strength of earth-based materials. It also highlights that natural fibers and woven fabrics really enhance the mechanical behavior of earth even for compressive load.

Keywords:

Earth-based materials, flax fibers, woven fabric of flax.

1 INTRODUCTION

Earthen construction has recently regained much attention in the building industry due to its low environmental impact and recyclability (Azeredo et al. 2008; Bui et al. 2009; Aubert et al. 2015; Moevus et al. 2015). The development of earthen construction is still limited because of the time required by the material to harden and by the difficulty to achieve a mix-design that allows for both fast casting and sufficient strength in the dry state. In order to answer both problems and to improve mix-design of earth-based materials, a recent trend has been to apply scientific knowledge and expertise, developed by the concrete industry, to earthen construction (Gnanli et al. 2014; Moevus et al. 2015; Ouellet-Plamondon and Habert 2016).

One of the options adopted from concrete technology is the optimization of the granular skeleton (Moevus et al. 2015) which increases the dry density of earth material and thus its mechanical strength. Another option is to use a coagulant or a hydraulic binder in order to shorten the material's hardening stage (Walker and Stace 1997; Venkatarama Reddy and Prasanna Kumar 2011a; Venkatarama Reddy and Prasanna Kumar 2011b; Khelifi et al. 2013; Tripura and Singh 2014; Gnanli et al. 2014; Khelifi et al. 2015; Miccoli et al. 2015). This last option, emanating from concrete mix design, is to improve the earth material's workability to enable the possibility of making an extrudable, flowable and even castable earth material (Gnanli et al. 2014; Moevus et al. 2015). For this last option, the objective is to deflocculate the micro-sized clay-based structures in order to reduce the interaction force between clay particles. The deflocculation can be obtained by using a dispersant which acts just like a superplasticizer on cement particles in concrete (Flatt 2004; Kjeldsen et al. 2006; Zingg et al. 2008; Roussel et al. 2010; Perrot et al. 2012; Perrot et al. 2016). This option is also expected to lead to a reduction of the material porosity and therefore improve material strength and durability (Moevus et al. 2015).

In this work, the first option is used to obtain a material with a continuous particle size distribution leading to a dense matrix by adding fine and coarse sand. This earth-based mortar can be either compacted or also casted by adding hexametaphosphate as a dispersant making the mortar flowable.

Different water to powders mass ratios are tested to find the optimal value providing the highest mortar densities. An interesting result show that the compressive strengths of the dry samples do not depend on the forming process but only on the dry density of the product.

After this powder mix-design step, reinforcement strategies are tested using dispersed flax fibers and woven fabrics made of flax fibers. We here show that those reinforcements helps to increase the compressive strength the earth-based mortars.

2 MATERIALS AND METHODS

The kaolin clay used was provided by Imerys and came from the "Kaolins de Bretagne" quarry at Ploemeur, France. The kaolin clay had a speciific gravity of 2.65 and a specific surface area 10 m²/g. The largest clay grain size was approximately 10 μm and the mean mass kaolin grain size approximately 4 μm. The particle size was measured in ethanol using a laser particle size analyzer and is set out in figure 1. The paste used in the tests consisted of a mixture of kaolin clay powder and water.

The clay is mixed with two different sands, a fine one with grain size ranging from 63 to 200 μm, and a coarser one with grain size ranging from 0 to 4 mm. The grain size distributions of the materials are plotted in figure 1.

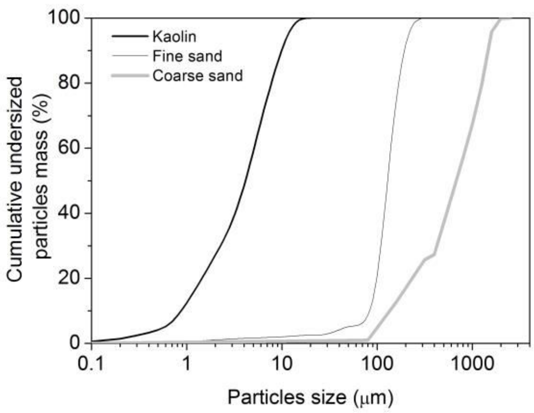

Fig. 1: Particles size distribution of the powders

Hexametaphiosphate (HMP) is used as a dispersant in this study to make the mortar flowable. Dosages of 0.25 % of the kaolin clay content is tested based on previously obtained results on the effect of dispersant on the rheological behavior of clay pastes (Perrot et al. 2016).

Dispersed flax fibers and woven fabric of flax fibers are tested as reinforcements (Figure 2).

Fig. 2: Dispersed flax fibers and woven fabric of flax fibers.

The dispersed flax fibre (Marylin variety) used in this study was supplied by the CTLN® Company (Le Neubourg, France). The fibres were scutched, carded and cut into 4 mm lengths. These flax fibres were the same as those used in the study by Bourmaud et al. [18].

The woven fabric of flax fibers is isotropic with a mesh size of 4 mm. The specific mass of the fabric is 500g/m² of textile.

Cylindrical samples of 50 mm in diameter and height were compacted using static compression with a 200 kN loading frame at a maximum vertical stress of 45 MPa. Proctor-like dynamic compaction was also used to make 150 mm and 150 mm in diameter and height samples to compare the effect of the compaction technique. Samples were compacted in CBR mold, in five layers with 56 strokes of CBR ram for each layer.

For cast samples, cement mortar 40x40x160 mm^3 moulds were used.

Because all the compressive tests were carried out with samples of aspect ratio 1 (sample height over sample diameter for cylindrical samples or sample side length for prismatic samples), we have considered that mechanical measurments can be compared even if their forms are different.

Samples are then conserved in a 40°C temperature controlled storage until weight stabilization. Such a temperature allows a relatively fast drying and ensures that only free water is leaving the sample. Once the mass reaches its final value, the compressive strength of the sample is measured using a 50 kN loading frame. The test is carried out at a constant velocity of 1 mm/min which is in agreement the French national standard recommendation for soils testing XP CEN ISO TS 17892-7 (test duration ranging between 2 and 15 minutes, maximum strain rate of 2% per minute). After this curing step, we consider that the samples are dry.

3 OPTIMIZING THE PARTICLES SIZE DISTRIBUTION

The particle size distribution of the mortar is designed to obtain the highest density once placed. Concepts of concrete mix-design are used in order to obtain the densest packing. It is also important to note that the binder content (here the kaolin clay) must be kept higher than a critical value that ensures sufficient cohesion within the sample.

In order to optimize the particle size distribution (PSD), the method proposed by Dreux and Gorisse (Dreux and Festa 1998) to determine the optimized ratio of sand to gravel is used to obtain the densest aggregates packing. As we have three different particles type, a two steps computation is performed. In a first step, the kaolin clay and the fine sand PSD are used to obtain the optimized PSD of the clay/fine sand mix. Then, the optimized PSD of the binary mix is used together with the PSD of the coarse sand to find the optimized PSD of the ternary mix of clay/fine sand/coarse sand.

It is interesting to note that using this method, the amount of binder is equal to 17% of the total mass of powder. This value can be considered as low dealing with clay content commonly find in earth construction.

The final PSD of the ternary mix of powder is plotted in figure 3. It is composed in mass (and volume, as all particles have almost the same density) of 17% kaolin, 23% fine sand and 60% coarse sand. We can observe a plateau on the PSD between 10 and 60 μm, because neither the kaolin nor sand have those particle sizes.

In order to highlight that this step of PSD optimization is paramount we have prepared samples of clay, of binary mixes (fine sand + kaolin) and of ternary mixes (coarse sand + fine sand + kaolin) at different water content with using a CBR mould compacted in 5 layers using 56 strokes. Those samples were weighted after drying and mechanically tested to measure their compressive strength.

The compressive strength is plotted as a function of the dry density of the samples (Figure 4). Results show that the widening of a continuous particle size distribution increases dry density of the samples and therefore their compressive strength, as commonly observed (Morel et al. 2007; Bruno et al. 2015).

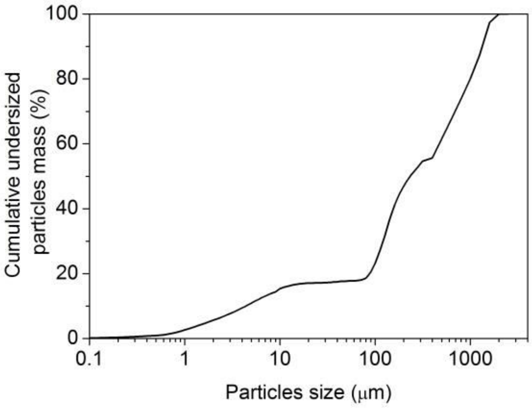

Fig. 3: Particles size distribution of the powders

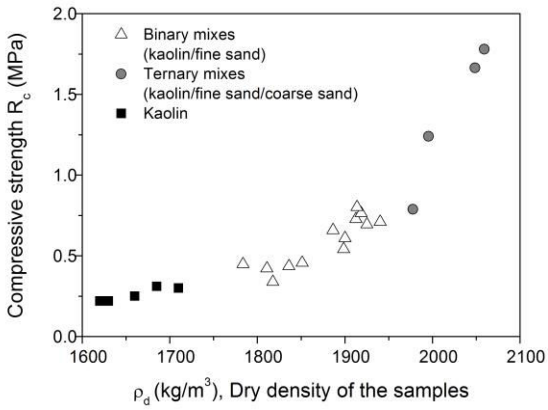

Fig. 4: Compressive strength as a function of dry density for kaolin, binary mix (fine sand+kaolin) and ternary mix (coarse sand+fine sand+kaolin)

In the following parts of this paper, only the ternary mix is used.

It is interesting to note that we have attempted to add a limestone filler with a particle size distribution ranging from 10 to 63 μm (ie in the range of the size not present in the PSD depicted in figure 3). Using this fourth material, optimized PSD provides kaolin volume fraction of around 10% which was not sufficient to obtain cohesive product after casting or compaction. Such result is in agreement with what can be found in the literature suggesting that a minimal content of clay is needed to make earth-based materials for construction.

4 INFLUENCE OF THE FORMING PROCESS

In Figure 5 is plotted the evolution of the dry density of casted or compacted samples with initial water content. The plotted curves show that the optimal water content for obtaining the densest material depends on the forming process. Dynamic compaction requires the smallest water content, here 5.5% of the dry particles mass while casting requires more water 14% to obtain the densest material, and therefore the material with the best mechanical properties. Between those two forming process, static compaction shows a maximal dry density for an initial water content of 10%. This means that the rheology (or the consistency) of the wet material must be optimized regarding the forming process. It is also interesting to note that the maximal density obtained for each forming process stands in the same range (between 2060 and 2080 kg/m^3).

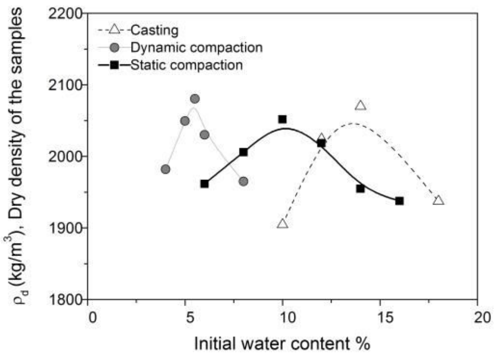

Fig. 5: Influence of the initial water content (water added during mixing) on the dry density of the samples for the 3 tested forming process. The static compaction was performed at a maximum load of 25 MPa.

We have also observed (not plotted on the figure) that for the static compaction process, the final dry density depends on the level of loading. An increase of the vertical stress from 25 to 45 MPa leads to an increase of the dry density from 2060 to 2100 kg/m^3.

In figure 6 is plotted the curve of the compressive strength versus the dry density.

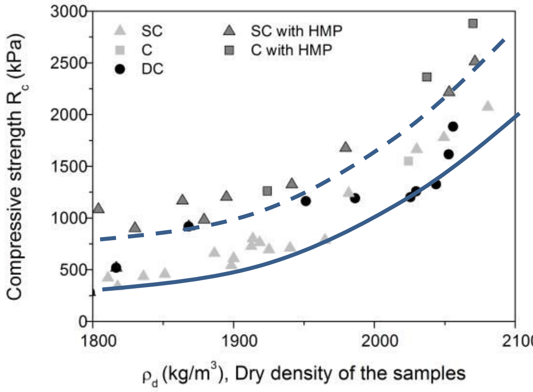

Fig. 6: Evolution of the compressive strength of the sample after drying versus the dry density for the different forming processes and possible use of HMP.

All the results are grouped around two lines, the first one for the mix containing HMP and the other for the mix without HMP. For a same density, mixes with HMP present a higher mechanical strength. This can be due to a better dispersion of the clay particles, as shown by

(Perrot et al. 2016) that improves the mechanical properties of the dry materials.

The compressive strengths of the dry samples increase from 0.5 MPa to 2.5 MPa for mixes without HMP and from 0.8 MPa to 2.8 MPa for mixes containing HMP when the dry density increases from 1800 to 2080 kg/m^3.

It is also worth to note that the forming process does not influence the mechanical strength. Two samples made with different forming processes but exhibiting the same dry density will present the same compressive strength.

5 REINFORCEMENT STRATEGIES

5.1 Woven fabrics

The woven fabrics of flax are deposited between layers of earth-based materials compacted or cast in the surface transverse to the direction of loading during compressive strength measurements. All tested samples present an aspect ratio of 1. A number of woven fabrics ranging from 1 to 4 have been tested in the frame of this study. Sample containing one woven fabric present two layers of material with a dimensionless height of 0.5 (ratio of the layer height over the total sample height). In a general way, the height of casted and compacted earth-based materials is equal to 1/(n+1) where n is the number of woven fabrics. It is worth noting that we try to have layers with equal height by computing a targeted value of the mass of the layer height assuming the density obtained with no woven fabric.

In Figure 7, the dimensionless compressive strengths of samples with woven fabrics (i.e. the ratio of the compressive strength vs. the compressive strength of the samples without fabric) are plotted versus the dimensionless height of earth-based materials layer.

For the tested material, it appears that there is an obvious relationship between the reinforcement effect of the woven fabrics and the height of an elementary layer of earth-based materials located between woven fabrics. Those results are in agreement with results previously obtained in the work of P'kla (P'Kla 2002; Pkla et al. 2003) and more generally with works on the reinforcement of soils by geotextiles and geomembranes (Guido et al. 1986; Lawrence 2014).

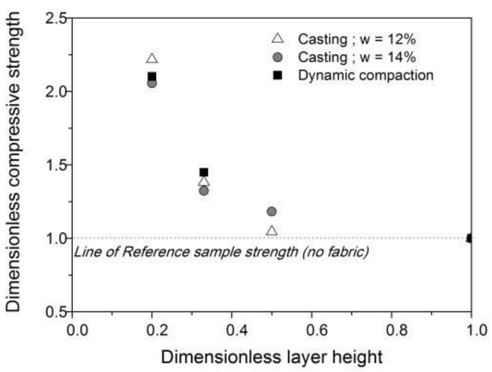

Fig. 7: Dimensionless compressive strength of fabric reinforced samples versus the dimensionless height of layers of earth-based materials.

In Figure 8, a fabric reinforced sample is shown before and after a compressive strength measurement. Fractures occur at the fabric interface. This means that shear happens at this interface. Moreover, the vertical fractures do not always cross fabric interface from one layer to the other showing that the sample behaves as a vertical assembly of partially independent layers of earth-based materials. As those elementary layers presents lower aspect ratio, the compressive strength of the sample increases as the height of the elementary layer.

Fig. 8: Observation of the dynamically compacted samples with 4 woven fabrics before and after the compressive strength measurement.

It seems that the reinforcement effect of woven fabric does not depend on the forming process. To conclude, it is interesting to note that the maximal compressive strengths of the sample is obtained with 4 woven fabrics (maximum numbers of tested fabric) and are 4.5 MPa for casted sample and 4.35 MPa for compacted samples. Another benefit brought by woven fabric is that the large increase in compressive strength is accompanied by a decrease in dry density of the sample for earth which is known to make heavy structures(from 2080 to 2050 kg/m^3 in the case of compacted samples and from 2070 to 1930 kg/m^3 in the case of casting).

5.2 Flax Fibers

Flax fibers are mixed with the dry powder before adding water. Volume fractions ranging from 1 to 4% are tested in the scope of the present study. In figure 9, we have plotted the evolution of the dimensionless compressive strength of the sample versus the fiber volume fraction added to the earth-based materials. We can see that the increase of the compressive strength does not depend on the forming process but are directly linked to the fiber content. The higher the fiber content is, the higher is the compressive strength. This observation is true for the tested materials as long as fibers do not bring workability issues as commonly observed in fiber-reinforced concrete rheology (Perrot et al. 2013).

The increase of compressive strength with fiber content is quite surprising because it is not observed with cement-stabilized clay or concrete (Khelifi et al. 2015). However in our study, the tested mineral matrix presents a lower mechanical strength and the mechanical contribution brought by the friction/shear at the fiber/matrix interface between no longer negligible in compressive strength.

For the statically compacted samples with 4% volume content of flax fiber, the compressive strength reached is 5.6 MPa which is more than two times the compressive strength obtained without fibers.

Moreover, it is important to note that the dry density of this sample drop down from 2070 to 1920 kg/m^3.

In further study it could be very interesting to use a combination of both types of reinforcements that works differently and could bring additional reinforcement to earth-based materials.

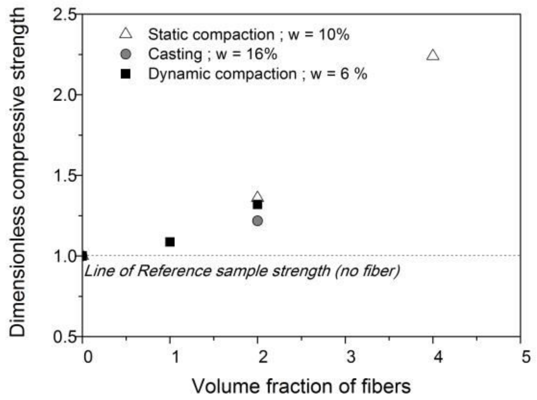

Fig. 9: Dimensionless compressive strength of fiber reinforced samples versus the volume fraction of fibers contained in earth-based materials.

6 CONCLUSIONS

In this paper we have investigated the best ways to improve the compressive strength of kaolinite clay using different strategies to make raw earth-based materials. We have firstly optimized the particle size distribution of the material with two types of sand to make the densest assembly of particles containing a sufficient amount of clay to make cohesive samples using concrete mix-design tools. The best result was obtained with a mix of 16% kaolin clay, 24% fine sand and 60% coarse sand.

Then we have tested different forming processes to check the influence of processing on the mechanical behavior of the dry earth-based materials. We have shown that the compressive strength of the samples does not depend on the forming process (casting, static or dynamic compaction) but on the final dry density of the raw earth. It has also been shown that a dispersant (here hexametaphosphate) allows increasing the compressive strength of the dry material. In the best case, we have obtained a mechanical strength of 2.5 MPa with a density of 2080 kg/m^3.

In a final part, we have examined two ways of reinforcement of the material using woven fabric of flax and flax fibers. Both strategies show that the reinforcement effects depend on the amount of reinforcements. We have shown than the intercalation of four fabrics in a sample of aspect ratio 1 is able to more than double the compressive strength while the addition of 4% fibers in volume is able to multiply by 2.25 the compressive strength.

In further work, it can be fruitful to simultaneously used both ways of reinforcements as their mechanisms of action are different: fibers/matric interface shearing increases the cohesiveness of the material while fabrics decreases the apparent aspect ratio of the samples.

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