Strategies for optimizing the mechanical strengths of raw earth-based mortars

A. Perrot, Damien Rangeard, F. Menasria, S. Guiheneuf

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Abstract Earth-based mortars are commonly reinforced with bio-based materials such as straw or biopolymers. The aim of this work is to identify reinforcements that are able to improve the mechanical strengths and the ductility of an earth-based matrix. We have also attempted to describe the mechanisms of reinforcement involved in such materials. Firstly, a kaolinite-based clay soil was mixed with sand to achieve earth-based mortars with the highest density at the dry state. For this material (kaolinite-based mortar), we have shown that, at the same water content, the compressive strength at the dry state only depends on the dry density of the sample whatever the forming process. Various quantities of fibers, fabrics and alginate were then used to reinforce the studied mortars (a kaolinite based mortar and a natural soil containing swelling clay sieved at 4 mm). We found that these reinforcements significantly increase the compressive strength of all tested samples containing kaolinite. A comparison between the two materials helps us to understand the reinforcement mechanisms for various fibers; it also demonstrates that natural fibers and woven fabrics enhance the mechanical behavior of earth mortars notably under a compressive load.

Keywords: Earth-based materials, flax fibers, woven flax fabric, alginate.

I Introduction

Earthen construction has recently regained much attention in the building industry due to its low environmental impact and recyclability [1–4]. The development of earthen construction is still limited because of the time required for 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 address both problems and to improve mix-design of earth-based mortars, a recent trend has been to apply scientific knowledge and expertise, developed by the concrete industry, to earthen construction[4–8].

One of the options adopted from concrete technology is the optimization of the granular skeleton [4] which increases the dry density of earth mortars and thus its mechanical strength. Another option is to use a coagulant, a biopolymer or a hydraulic binder in order to shorten the material's hardening stage [9–18]. Another solution, emanating from concrete mix design, is to improve the earth mortar's workability to enable the possibility of making an extrudable, flowable and even castable earth mortar [4–6]. The objective of using a dispersant is to deflocculate the micro-sized clay-based structures in order to reduce the interaction force between clay particles. Deflocculation can be obtained by using a dispersant which acts just like a superplasticizer on cement particles in concrete [6, 19–23]. This option is also expected to lead to a reduction of the material porosity and therefore improve material strength and durability [4].

In this study, the first option was used to obtain a material with a continuous particle size distribution, leading to a dense matrix, by adding fine and coarse sand. Two materials were used, a commercial kaolin powder mixed with sand and an earth-based material which is known to be suitable for cob construction. The earth-based mortar can be either compacted or cast by adding a dispersant hexametaphosphate (HMP) thus making the mortar flowable. In this study, HMP was used as a dispersant because it has been shown to be more efficient than cement superplasticizer for reducing the yield stress of kaolin mortar [6]. Finally, alginate was also added in order to obtain a rapid strength gain of the earth. The effects of alginate and dispersant on the compressive strength of the materials were also tested.

Various water to dry material mass ratios were tested to find an optimal value that gave the highest mortar densities for different forming process. An assessment of the material behavior was also made to see if it was influenced by the forming process.

Following the powder mix-design, reinforcement strategies were tested using dispersed flax fibers and woven fabrics made of flax fibers. These different reinforcement strategies were tested within the framework of this study. Following a description of the materials and methods, the following evaluations were carried out on the earth-based mortars; the effects of particle size distribution optimization; the influence of processing and bio-based reinforcements (alginate or flax individual fibers or woven fabrics) on ductility, compressive and flexural strength of earth-based mortars. Finally, the combined effects of the different reinforcement types were assessed.

II Materials and methods

II.1 Materials

The kaolin clay used was provided by Imerys and came from the "Kaolins de Bretagne" quarry at Ploemeur, France. The kaolin clay had a specific gravity of 2.65 and a specific surface area of 10 m²/g (data provided by the supplier). The largest clay grain size was approximately 10 μm and the mean kaolin grain size approximately 4 μm. The particle size was measured using a laser particle size analyzer and is set out in figure 1. Before measurement, the sample was dispersed in a suspension of distilled water with a deflocculant agent (sodium hexametaphosphate Na-HMP) at 2,500 rpm stirrer speed. The suspension was placed in the measurement cell, and an ultrasonic stimulation was carried out for 30 seconds before measurement.

The mortar used in the tests consisted of a mixture of kaolin clay powder, sand and water. The clay was mixed with two different sands: fine sand, with grain size ranging from 63 to 200 μm, and coarser sand with grain size ranging from 0 to 4 mm. The grain size distributions of the sands are also plotted in figure 1. The fine sand particle size distribution was obtained by laser diffraction and the coarse sand distribution was obtained by sieving.

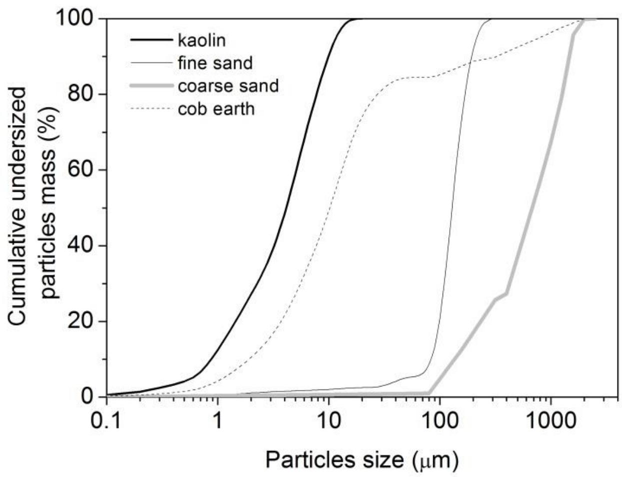

Fig. 1: Particle size distribution of the powders and Saint-Sulpice-La-Forêt soil (cob earth)

In order to optimize the particle size distribution (PSD) of the kaolin-based mix, the method proposed by Dreux and Gorisse [24] to determine the optimized ratio of sand to gravel was used to obtain the densest aggregates packing. As three different particle types were used, a two steps computation was performed. Firstly, the kaolin clay and the fine sand PSD were used to obtain the optimized PSD of the clay/fine sand mix (binary mix). The optimized PSD of the binary mix was then used together with the PSD of the coarse sand to find the optimized PSD of the ternary mix of clay/fine sand/coarse sand.

The final PSD of the ternary mix of dry particles was optimized using Dreux and Gorisse method [24] which is plotted in figure 2. This composition allows for the best mechanical strength with this ternary mix (see next section and in [25]). The mix was composed by mass (and volume, as all particles have almost the same density) as follows 17% kaolin, 23% fine sand and 60% coarse sand. A plateau in the PSD can be seen between 10 and 60 μm, as neither the kaolin nor the sand have those particle sizes.

The second material tested was a cob earth from Saint-Sulpice-La-Forêt (Ille et Vilaine, France). It was a fine soil with 70% of particles finer than 10 μm (the PSD is plotted on figure 1 and was obtained in the same way as the kaolin PSD). The soil particles were a mix of quartz, and various types of clay: kaolinite, illite and smectite; this being determined by XRD analysis before and after thermolysis at 550°C. The Plasticity Index of this soil was 21 with a liquid limit of 48% and a plastic limit of 27%.

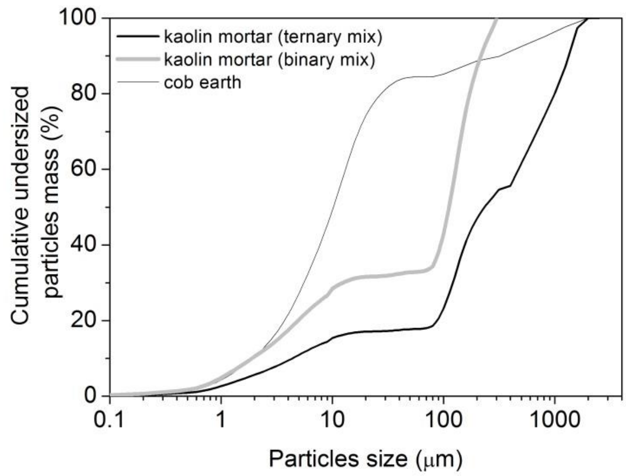

Fig. 2: Particle size distribution of the kaolin mortars (binary and ternary mixes) and Saint-Sulpice-La-Forêt soil (cob earth)

The alginate used in the study was a white powder of alginic salt Cimalgin HS3® provided by Cimaprem (Redon, France). It is designed to make high strength gel for arts and molding applications. Dosage rates used ranged from 1% to 5% of particles smaller than 10 µm. The HS3 product is mostly composed of alginate salt with an "on demand" calcium release agent that allows the monitoring of the duration of the alginate gel network creation. Alginate can form a cross-linked isotropic insoluble gel when a soluble form of alginate nucleates with divalent metal cations, like Ca^{2+}, which can be found in earth-based materials. Chains of alginate make junctions by intercalating divalent cations creating a sort of egg-box connection [26]. In order to aid the dispersion of alginate within the earth material, the HS3 powder is firstly mixed with an equal mass of water.

Hexametaphosphate (HMP) was used in this study as a dispersant to make a mortar flowable. For the kaolin mortar, a dosage of 0.25 % of the kaolin clay content was tested, this being based on previously obtained results on the effect of dispersant on the rheological behavior of clay pastes [6]. For the cob earth from Saint-Sulpice-La-Forêt, the mass ratio of HMP was 0.3% of the dry material. The choice of this dosage was made using the same methodology as that used for the kaolin mortar in [6].

The dispersed flax fibers (Marylin variety) used in this study was supplied by the CTLN® Company (Le Neubourg, France). The fibers, shown on Figure 3, were scutched, carded and cut into 4 mm lengths. These flax fibers were the same as those used in the study by Bourmaud et al. [27]. The volume fraction of fibers ranging from 1 to 4% was used in the present study. The woven fabric of flax fibers was isotropic with a mesh size of 4 mm. The mass per unit area of the fabric textile was 500g/m².

Dispersed flax fibers and woven fabric of flax fibers were tested as reinforcements (Figure 3).

Fig. 3: Dispersed flax fibers and woven flax fiber fabric.

II.2 Methods

The earth samples were prepared using high capacity Hobart mixer. Dry powder was firstly introduced into the bowl. When using fiber reinforced material, dry fibers were mixed with the dry powder by hand until a homogeneous material with well dispersed fibers was obtained. Water was then added, the quantity being that necessary to attain the targeted water content. The mixing procedure consisted of a 4 minutes low velocity mixing stage, followed by a high velocity mixing stage of 5 minutes. Between these two stages, the bowl was scraped in order to ensure that no unmixed material remained adhered to the bowl. After mixing, the material was placed in a closed container for 24 hours to allow homogenization.

The alginate solution was prepared just before casting and/or compaction and was mixed with the wet earth using a mortar hand mixer for 4 minutes.

Cylindrical samples of 50 mm diameter and height were compacted using static compression with a 200 kN loading frame at a maximum vertical stress of 45 MPa. To compare the effect of the compaction technique a Proctor-type dynamic compaction was used to make 150 mm diameter and height samples. Samples were compacted in CBR mold, in five layers with 56 blows 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 an aspect ratio of one (sample height to diameter for cylindrical samples or sample side length for prismatic samples), it is considered that mechanical measurements can be compared even if their geometries are different. The comparison between results obtained with those different sizes and shapes of samples was acceptable as it has been shown that at a same aspect ratio, the strength variation due to shape variation is lower than 5% [28]].

Samples were then conserved in a 50°C temperature controlled store until weight stabilization. Such a temperature allows a relatively fast drying and ensures that only free water leaves the sample. After this curing step, once the sample weight was stabilized, it was considered that the samples were dry. The compressive strength of the sample was then measured using a 50 kN loading frame. The test was 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 (the test duration ranging between 2 and 15 minutes, maximum strain rate of 2% per minute).

III Effect of particle size distribution and processing

III.1 Effect of particle size distribution

The particle size distribution of the mortar was designed to obtain the highest density once placed. Concepts from concrete mix-design were 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 will ensure sufficient cohesion within the sample.

It is interesting to note that using the Dreux and Gorisse method, the amount of binder is equal to 17% of the total mass of powder. This value can be considered as lower bound when dealing with clay content commonly found in earth construction.

In order to emphasize that this step of PSD optimization is paramount, clay samples, of binary mixes (fine sand + kaolin) and of ternary mixes (coarse sand + fine sand + kaolin), were prepared with different water contents ranging from 5% to 10% , these were then compacted in a CBR mould in 5 layers using 56 blows per layer. The samples were weighted after drying and mechanically tested to measure their compressive strength.

Figure 4 shows the compressive strength as a function of the dry density of the samples. 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 [29, 30].

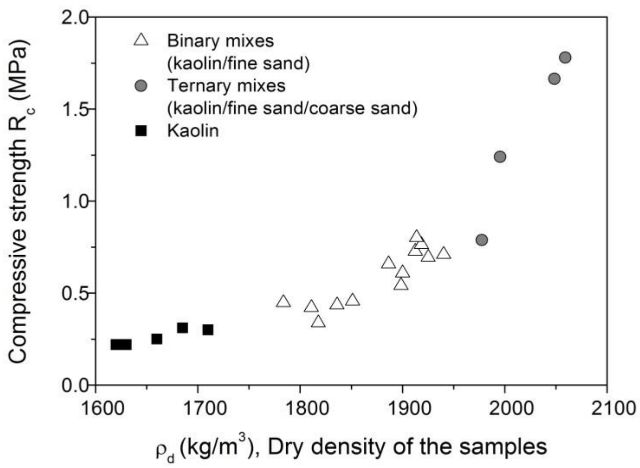

Fig. 4: Compressive strength as a function of dry density for kaolin, binary mix (fine sand+kaolin) and ternary mix (coarse sand+fine sand+kaolin)

In the following sections of this paper, only the ternary mix was used.

It is interesting to note that we 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 shown in figure 3). Using this fourth material, optimized PSD provides kaolin volume fraction of around 10% that was not sufficient to obtain a cohesive product after casting or compaction. This result is in agreement with that which can be found in the literature suggesting that a minimal content of clay is needed to make earth-based materials for construction [31–33].

Another crucial point is that for the cob earth the results were opposite: Using the same methodology, we obtained a mix of 40% cob earth, 29% fine sand and 31% coarse sand. Such mixes result in an increase in the dry density of the mixture, initial values ranging between 1780 and 1850 kg/m^3 which increased to values ranging from 1950 to 2050 kg/m^3. However, this densification of the dry matrix leads to a decrease of the compressive strength from above 8 MPa to values of the order of 2.5 MPa. Therefore, for the cob earth which contains clay that can induce relatively high compressive strength (8 MPa for an earth-based materials), the strength of the material appears to be directly linked to the clay content (Figure 5).

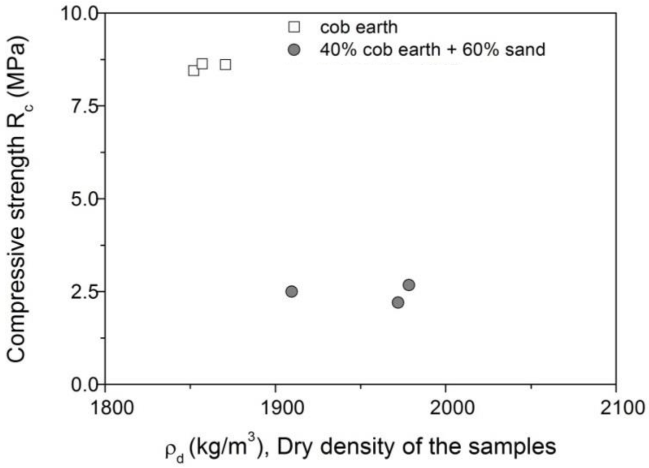

Fig. 5: Compressive strength as a function of dry density for cob earth with and without additional sand.

The effect of the densification of earth-based material strengthening directly depends on the type of clays contained in the earth. With pure kaolinite, which has a low compressive strength (around 500 kPa), a densification of the matrix with sand, leads to a significant increase in strength. As opposed to this, the high strength cob earth content directly governs the strength of the samples.

III.2 Effect of processing and dispersant

This part of the study is focused on the kaolin mortar and it is to be noted that the same kind of trend has been observed for the cob earth.

Figure 6 shows the evolution of the dry density of cast and compacted samples with respect to initial water content. The curves show that the optimal water content for obtaining the densest material depends on the forming process. Dynamic compaction required the smallest water content, in this case 5.5% of the dry particles mass, whereas casting required more water (14%) to obtain the densest material, and was therefore the material with the best mechanical properties. Between these two forming process, static compaction (maximum load of 25 MPa) showed a maximum dry density for an initial water content of 10%. These results indicate that the rheology (or the consistency) of the wet material must be optimized with regard to the forming process.

It is also interesting to note that the maximum density obtained for each type of tested forming process was in the same range (between 2050 and 2080 kg/m^3). Using higher energy of compaction would result in a higher density as proposed by [34].

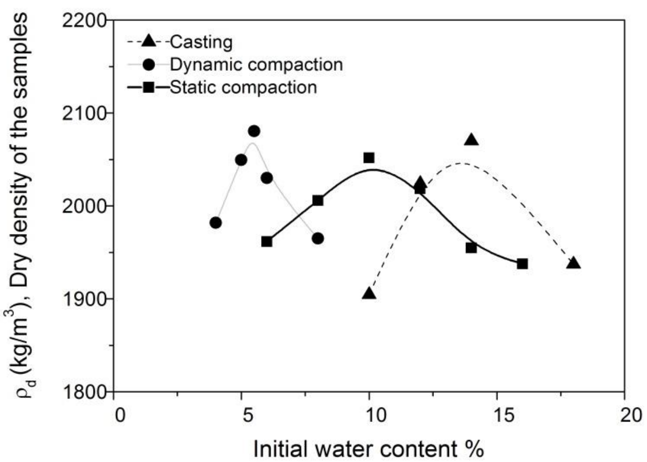

Fig. 6: Influence of the initial water content (water added during mixing) on the dry density of the samples for the three forming process. .

For the optimized water content for the static compaction at 25 MPa, it was observed that an increase of the vertical stress from 25 to 45 MPa led to an increase of the dry density from

2060 to 2100 kg/m3. Thus, for the static compaction process, the final dry density was also depended on the loading.

The curve of the compressive strength versus the dry density is shown in figure 7. All the results are grouped around two lines, the first relate to the mixes containing HMP and the second to the mixes without HMP. For a same density, mixes with HMP present a higher mechanical strength. This increase could be due to a better dispersion of the clay particles, as shown by [4, 6] , that would improve the mechanical properties of the dry materials.

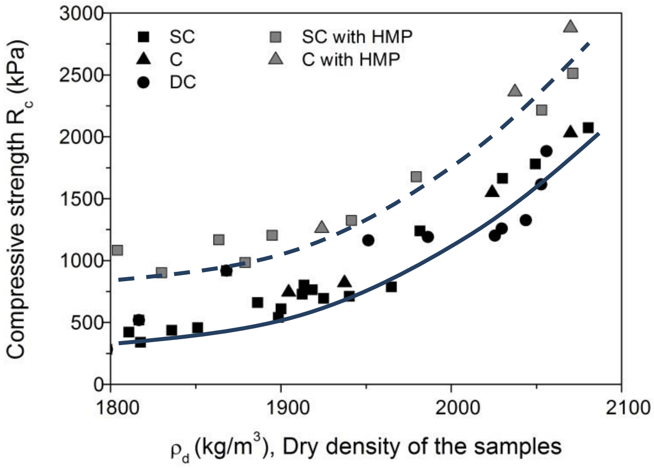

Fig. 7: Evolution of the compressive strength of the sample after drying versus the dry density for the different forming processes and with and without HMP addition.

It can be seen that the compressive strengths of the dry samples increases from 0.5 MPa to 2 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. This trend can be explained by a better distribution of the clay particles with HMP. HMP reduces interaction forces between clay particles in a fresh state and allows for an increase of the distance at the contact point between particles and a decrease of the average pore size [6]. In this case, the effect of HMP would be the same as the one of superplasticizer within cement paste [23].

It is also worth noting that the forming process does not influence the mechanical strength. Two samples made with different forming processes, both having the same dry density, will have the same compressive strength.

IV Fibers and fabrics reinforcement

IV.1 Woven fabric

The woven flax fabric was placed between layers of earth-based material, compacted or cast in the surface perpendicular to the direction of loading during compressive strength measurements. All test samples had an aspect ratio of 1. The number of woven fabric sheets in a sample, tested in this study, ranged from 1 to 4. The sample containing one woven fabric present two layers of material with a dimensionless height of 0.5 (ratio of the layer height to the total sample height). In a general form, the height of cast and compacted earth-based materials is equal to 1/(n+1) where n is the number of woven fabric sheets. It is to be noted that in order to obtain layers of equal height a target mass of earth-based material for a layer was computed assuming the density obtained with no woven fabric.

In Figure 8, the dimensionless compressive strengths of samples with woven fabrics (i.e. the ratio of the compressive strength to the compressive strength of the samples without fabric) are plotted versus the dimensionless height of earth-based material layer. It appears that the reinforcement effect of woven fabric did not depend on the forming process.

For the tested materials (kaolin mortar and cob earth), it appears that there is a relationship between the reinforcement effect of the woven fabric and the height of an elemental layer of earth-based material between woven fabric sheets. These results are in agreement with results previously obtained in the work of P'kla [35, 36] and more generally with works on the reinforcement of soils by geotextiles and geomembranes [37, 38].

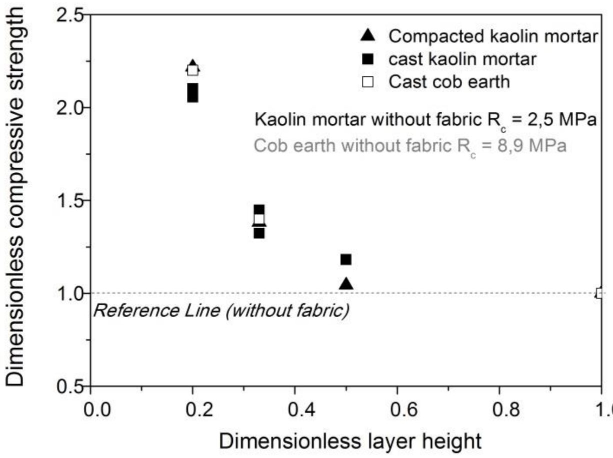

Fig. 8: Dimensionless compressive strength of fabric reinforced samples versus the dimensionless height of layers of earth-based materials.

Figure 9 shows a fabric reinforced sample before and after a compressive strength test. Fracture occurred at the fabric interface which indicates shear at this interface. Moreover, the vertical fractures do not always cross the fabric interface from one layer to another thus indicating that the sample behaves as a vertical assembly of partially independent layers of earth-based materials. As these elemental layers have a lower aspect ratio, the compressive strength of the sample increases as the height of the elemental layer decreases.

Fig. 9: Observation of the dynamically compacted samples with 4 woven fabric sheets before and after the compressive strength test.

To conclude, it is interesting to note that the maximum compressive strengths of the sample was obtained with 4 woven fabric sheets (the maximum number of fabric sheets tested); the compressive strength were 4.5 MPa for cast samples, 4.35 MPa for compacted samples for the kaolin mortar and 17.6 MPa for the cast cob earth. Another benefit of woven fabric is that the large increase in compressive strength is accompanied by a decrease in dry density of the sample; dry densities are reduced 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 cast samples).

4.2 Flax fibers

Flax fibers were mixed with the dry powder before the addition of water. Volume fractions of fiber ranging from 1 to 4% were tested in this study. Figure 10 shows the evolution of dimensionless compressive strength of the sample versus the fiber volume fraction added to the earth-based materials. It can be seen that in the case of kaolin mortar, the increase of the compressive strength does not depend on the forming process but is directly linked to the fiber content; the higher the fiber content, the higher the compressive strength. This observation is generally true for the tested materials provided that the fibers do not cause workability issues as is commonly observed in fiber-reinforced concrete rheology [39, 40].

For the statically compacted samples with 4% volume content of flax fiber, the compressive strength was 5.6 MPa, which is more than twice the compressive strength obtained without fibers. Moreover, it is important to note that the dry density of this sample decreased from 2070 to 1920 kg/m^3.

For kaolin mortar, the increase in compressive strength with fiber content is quite surprising because it is not observed with cement-stabilized clay or concrete [14]. However, in this case, the tested mineral matrix has a lower mechanical strength and the mechanical contribution resulting from the friction/shear at the fiber/matrix interface becomes a non-negligible factor in compressive strength.

This latter supposition is supported by the fact that in the case of cob earth, which has a higher compressive strength, the contribution of fibers to the compressive strength is less than that seen in the case of kaolin mortar, see Figure 10.

This observation indicates that the reinforcement contribution of fiber to the overall compressive strength depends on the relative strength of the fiber interface with respect to the strength of the matrix; that is to say the lower the matrix strength the higher the fiber reinforcement's contribution to strength.

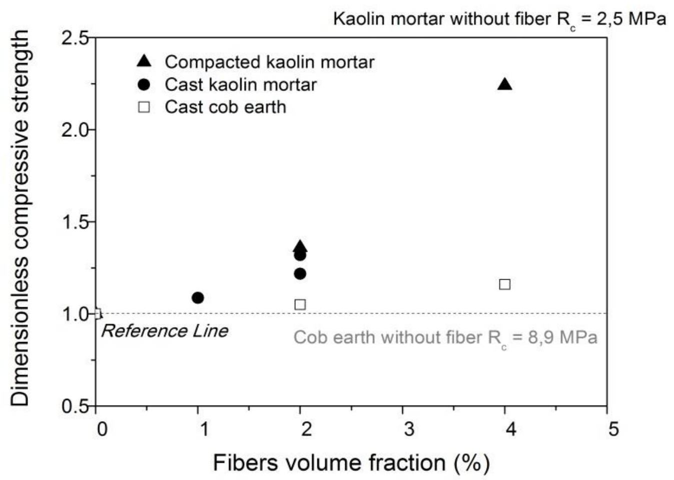

Fig. 10: Dimensionless compressive strength of fiber reinforced samples versus the volume fraction of fibers contained in earth-based materials.

V. Effect of alginate biopolymer

Once the samples were dry compressive strengths of the samples are measured once the samples were dry to provide a reference state for further testing. Figure 11 shows the evolution of the compressive strength with respect to sample dry density for kaolin mortar samples made with different amounts of alginate; Figure 12 shows a similar evolution for the cob earth from Saint-Sulpice-La-Forêt.

For kaolin mortar, the addition of alginate at a 1% dosage did not change the mechanical strength of the sample. In this case, the amount of alginate may not be sufficient to build a gel network able to reinforce the material. However, for higher dosage, the compressive strength of the sample increased with the alginate dosage. For a 3% dosage, and a dry density of 2050 kg/m^3, the addition of alginate more than doubled the compressive strength (from 2.25 MPa to 5.9 MPa). At a dosage of 5%, the compressive strength reached its maximum value of 7.1 MPa. It would be of interest to test higher dosages in further work to verify if increased dosage result in a higher compressive strength and what is the critical dosage for which the compressive strength reaches a plateau.

For the cob earth from Saint-Sulpice-La-Forêt, the addition of alginate did not change the compressive strength of the samples. Figure 12 shows that the evolution of sample compressive strength with respect to dry density was not influenced by the addition of alginate in the range of dosage tested (from 0 to 4%). It can be assumed that structure of the material without alginate is stronger (or at least of equal strength) than the alginate gel network. Therefore, it is noted that the addition of alginate did not modify the mechanical strength of the samples as it did not reinforce the soils particles network that has stronger interactions; this maybe due to the presence of swelling clays like smectite at a dry state (high suction effect).

By comparing the effect of alginate addition on the compressive strength of both materials, it can be concluded that the ability of alginate to strengthen an earth-based materials depends on its dosage and on the mineralogy of the clay particles in the soil. Figure 13 summarized the effect of alginate on both tested materials with respect to its dosage.

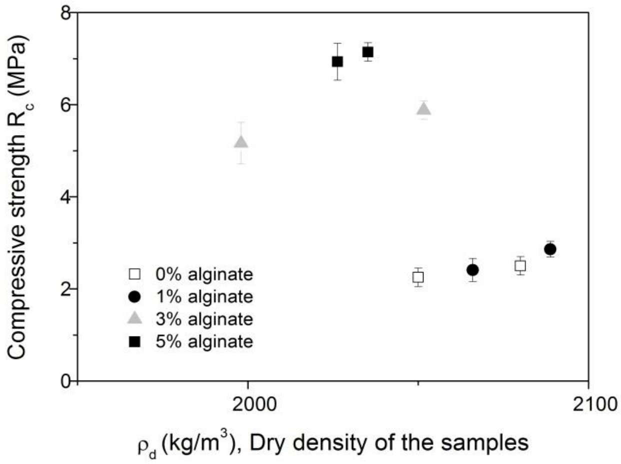

Fig. 11: Compressive strengths versus dry density curves of cast kaolin mortar samples with alginate content (mass fraction of the kaolin powder) ranging from 0 to 5%.

For kaolin earth-based material, the addition of a sufficient amount of alginate was able to strengthen the material (up to three times the compressive strength of the sample without any alginate).

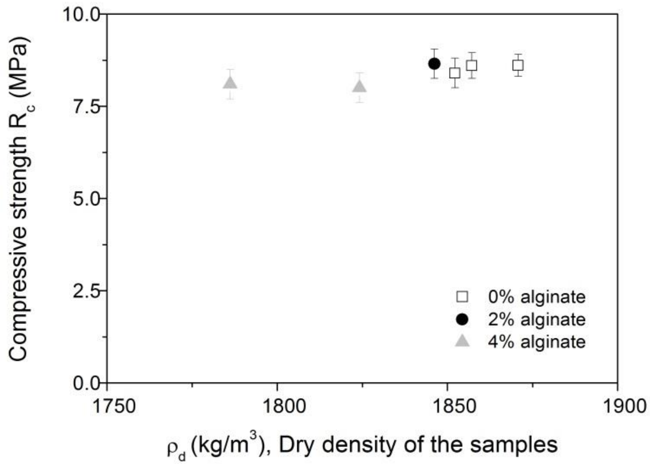

Fig. 12: Compressive strengths versus dry density curves of cast cob earth (Saint-Sulpice-La-Forêt) mortar samples with alginate content (mass fraction of the soil) ranging from 0 to 4%.

On the other hand, in the case of the soil from Saint-Sulpice-La-Forêt that contains swelling clay (smectite), alginate does not increase the compressive strength of the material, even at high dosage. The gel strength appears to be weaker than the interaction within clay particle network.

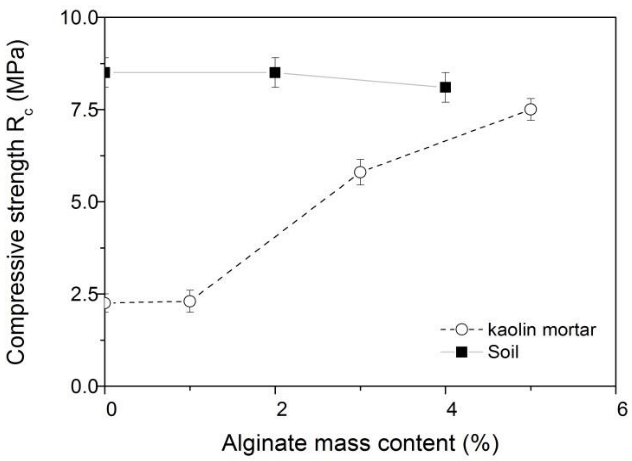

Fig. 13: Evolution of compressive strength of tested materials with alginate dosage at a fixed dry density (extrapolated value at 2050 kg/m^3 for the kaolin mortar and 1850 kg/m^3 for the cob earth from Saint-Sulpice-La-Forêt).

VI Coupled reinforcement effects

This section reports on a study made of the effect of coupled reinforcement strategies used to strengthen the material. This work focused on kaolin mortar because only the fabric sheets have been shown able to increase the compressive strength of cob earth whereas for the kaolin paste, all types of reinforcements have strengthened the material.

VI.1 Alginate and flax fibers

Figure 14 shows the evolution of the compressive strength of the kaolin mortar sample with respect to dry density. Firstly, it can be seen that the addition of flax fibers induces a decrease in the sample density. This decrease can be attributed to two phenomena: a workability decrease due to the fibers (leading to higher void content) and to the low density of the fibers.

Secondly, the mechanical strength of the samples only increases with the addition of fibers for an alginate dosage of 1%. It appears that for higher dosage, fibers do not increase the compressive strength of the samples because the cohesion of the material is higher than the interfacial strength between fiber and mineral matrix as shown in Menasria et al.[25]. For dosages of 3 and 5% of alginate, the addition of fibers appears to have no effect as the mechanical strengths of samples with and without fibers lie along the same strength density curve for each fiber dosage (Figure 14).

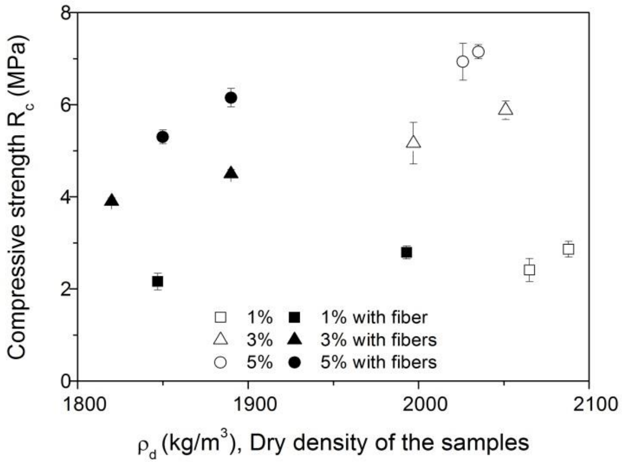

Fig. 14: Evolution of sample compressive strength of kaolin mortar with dry density for different dosages or alginate (1, 3 and 5%) with and without flax fibers. The compressive strength of the kaolin without fiber is 2 MPa for a dry density of 2080 kg/m^3

One beneficial aspect brought about by the fibers is the increased ductility of the material. Figure 15 shows force displacement curves obtained during the compressive strength measurements with and without fibers for alginate dosages of 3 and 5%. If the curves for samples with and without fibers are compared, it can be see that the elastic parts of the curve before the peak are close, thus indicating that fiber addition does not significantly influence the elastic modulus. The load peak is higher for samples without fibers, as confirmed by Figure 8, however, after the load peak; the load decrease is much slower for samples with fibers. Such type of behavior indicates an increase in the ductility of the sample; this is a very interesting material property for earth construction in a seismic area, for example.

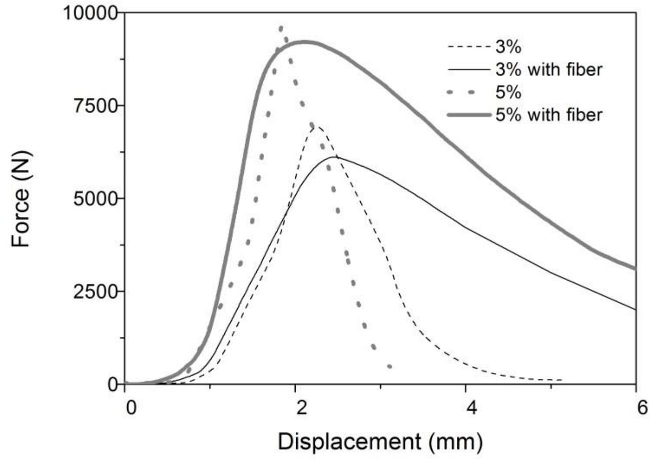

Fig. 15: Force versus displacement curves obtained during the compressive strength measurements on kaolin mortar with and without fiber for alginate dosages of 3 and 5%.

Figure 16 shows the evolution of flexural strength of the kaolin mortar samples with respect to dry density, for different dosages of alginate (1, 3 and 5%) with and without fibers. The results are close to those obtained for compressive strength. Once again, the beneficial effect of fibers on the strength is obtained only for the lowest alginate dosage for which the mineral matrix is the weakest. For higher dosages of alginate, the influence of fibers is not so obvious but the flexural strength remains constant even if the dry density decreases with the addition of fibers. This type of behavior can be attributed to the level of tensile strength of the flax fibers that can act in tension when embedded in a low-strength material.

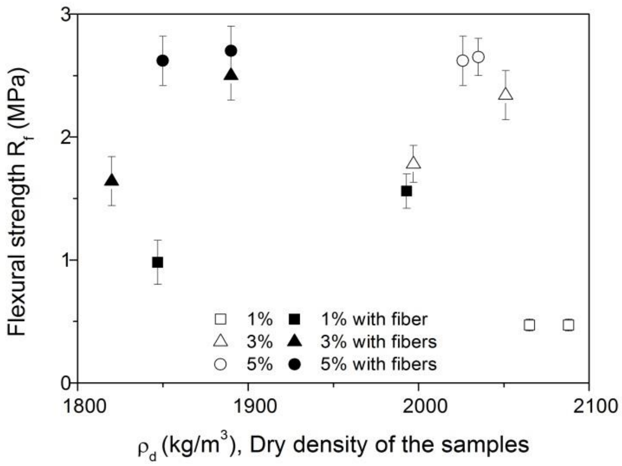

Fig. 16: Evolution of compressive strength of samples of kaolin mortar with dry density for different dosages or alginate (1, 3 and 5%) with and without flax fibers.

Figure 17 shows the force displacement curves measured during the flexural strength tests. We can see that samples without fiber exhibit a brittle behavior with a sudden failure obtained after the load peak whereas the samples with fibers shows a post-peak behavior with a smooth decrease of the load due to the continuous failure of the interfaces between fibers and matrix [14].

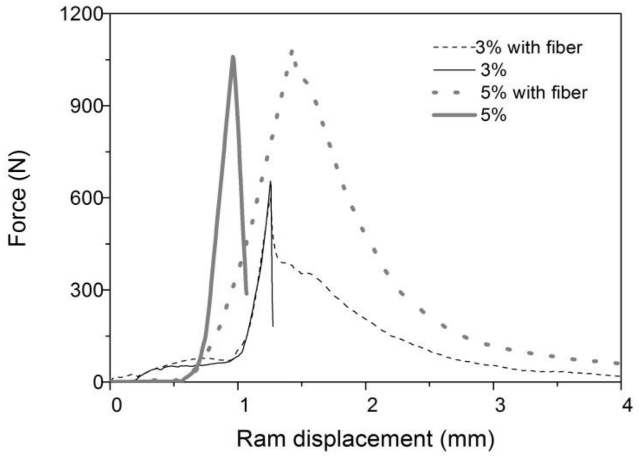

Fig. 17: Force versus displacement curved obtained during the flexural strength measurements on kaolin mortar with and without fiber for alginate dosages of 3 and 5%.

VI.1 Alginate, flax and fabric: Toward earth-based high performance composites.

In order to complete this study of reinforcement of earth-based materials, a study was carried out on the effect of combining alginate, fibers and woven fabrics on the compressive strength of the kaolin mortar. A kaolin mortar with a water content of 12% containing HMP and an alginate dosage of 3% and with a volume fraction of flax fiber of 4% was cast in 40x40x160 mm^3 mould in five layers separated by the tested woven fabric. After the drying stage, the sample was tested in compression. The compressive stress vs. the deformation curve (Figure 18) shows that the compressive strength of the material was quite high 17.5 MPa. However, the elastic modulus remained only at a value of 110 MPa, which is quite low in comparison with the elastic modulus of concrete at the same level of compressive strength.

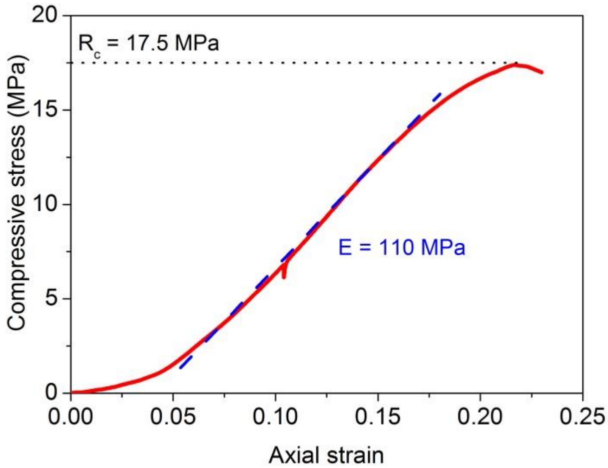

Fig. 18: Stress versus deformation curves obtained during the compressive strength measurements on 40x40x40 cubic samples of kaolin mortar with 4% fibers, 0.25% HMP, alginate dosage of 3% and 4 woven fabrics.

This shows that the reinforcement strategies and their combination help to delay the failure of the samples by giving some bridging between clay particles provided by alginate or fibers. However, it clearly appears that these reinforcements do not affect the elastic modulus, which is always of the order of kaolin without reinforcement (150 MPa for the same material without fibers and alginate).

VII Conclusions

In this article, several strategies for optimizing the mechanical resistance of the earth material were tested. It appears that the effect of the reinforcement depends on the nature of the soil tested and of the mineralogical nature of the clay.

Firstly, we have been able to assess the influence of dry density and dispersion of clay particles (by using HMP and granular optimization) for a cob earth and a kaolin mortar. In the case of kaolin mortar, which had the highest dry density, optimization of the compressive strength was possible whereas in the case of cob earth containing other types of clay (smectite), it was observed that the compressive strength is governed by the clay content and could not be optimized.

An interesting result shows that the compressive strengths of the dry samples do not depend on the forming process but only on the dry density of the material.

The benefit provided by alginate and textile reinforcements depended on the nature of the earth. While their actions are highly beneficial for kaolin-based soils, it is almost negligible for materials containing swelling clay that initially have a high initial resistance (>8 MPa) in the dry state.

Finally, by combining all types of reinforcement strategies, it was possible to make a material with high compressive strength (18 MPa) and high deformability.

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