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

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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.

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

26

27 **I Introduction**

28

29 Earthen construction has recently regained much attention in the building industry due to its
30 low environmental impact and recyclability [1–4]. The development of earthen construction is
31 still limited because of the time required for the material to harden and by the difficulty to
32 achieve a mix-design that allows for both fast casting and sufficient strength in the dry state.
33 In order to address both problems and to improve mix-design of earth-based mortars, a recent
34 trend has been to apply scientific knowledge and expertise, developed by the concrete
35 industry, to earthen construction[4–8].

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

47 In this study, the first option was used to obtain a material with a continuous particle size
48 distribution, leading to a dense matrix, by adding fine and coarse sand. Two materials were
49 used, a commercial kaolin powder mixed with sand and an earth-based material which is

50 known to be suitable for cob construction. The earth-based mortar can be either compacted or
51 cast by adding a dispersant hexametaphosphate (HMP) thus making the mortar flowable. In
52 this study, HMP was used as a dispersant because it has been shown to be more efficient than
53 cement superplasticizer for reducing the yield stress of kaolin mortar [6]. Finally, alginate was
54 also added in order to obtain a rapid strength gain of the earth. The effects of alginate and
55 dispersant on the compressive strength of the materials were also tested.

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

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

67

68 **II Materials and methods**

69

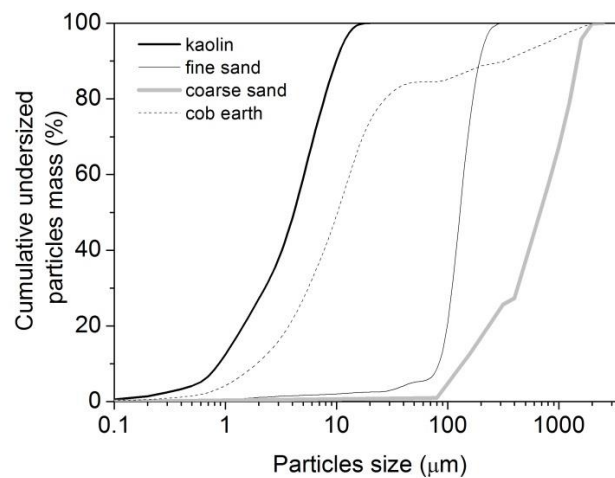
70 **II.1 Materials**

71 The kaolin clay used was provided by Imerys and came from the “Kaolins de Bretagne”
72 quarry at Ploemeur, France. The kaolin clay had a specific gravity of 2.65 and a specific
73 surface area of 10 m²/g (data provided by the supplier). The largest clay grain size was
74 approximately 10 μm and the mean kaolin grain size approximately 4 μm. The particle size

75 was measured using a laser particle size analyzer and is set out in figure 1. Before
76 measurement, the sample was dispersed in a suspension of distilled water with a deflocculant
77 agent (sodium hexametaphosphate Na-HMP) at 2,500 rpm stirrer speed. The suspension was
78 placed in the measurement cell, and an ultrasonic stimulation was carried out for 30 seconds
79 before measurement.

80

81 The mortar used in the tests consisted of a mixture of kaolin clay powder, sand and water. The
82 clay was mixed with two different sands: fine sand, with grain size ranging from 63 to
83 200 μm , and coarser sand with grain size ranging from 0 to 4 mm. The grain size distributions
84 of the sands are also plotted in figure 1. The fine sand particle size distribution was obtained
85 by laser diffraction and the coarse sand distribution was obtained by sieving.



86

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

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

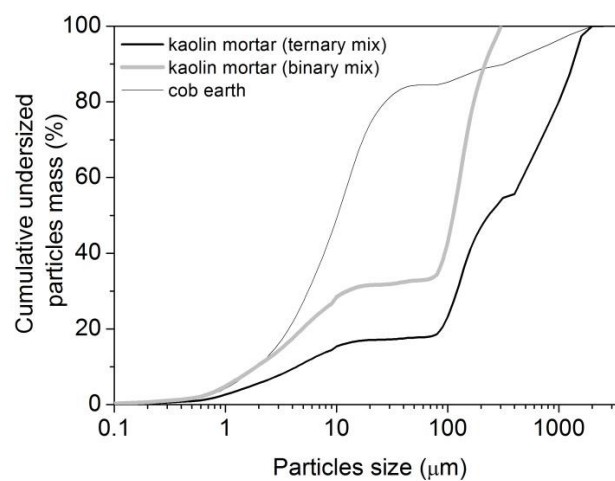
93 of the binary mix was then used together with the PSD of the coarse sand to find the
94 optimized PSD of the ternary mix of clay/fine sand/coarse sand.

95

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

102

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



109

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

112

113 The alginate used in the study was a white powder of alginic salt Cimalgin HS3® provided by
114 Cimaprem (Redon, France). It is designed to make high strength gel for arts and molding
115 applications. Dosage rates used ranged from 1% to 5% of particles smaller than 10 µm. The
116 HS3 product is mostly composed of alginate salt with an “on demand” calcium release agent
117 that allows the monitoring of the duration of the alginate gel network creation. Alginate can
118 form a cross-linked isotropic insoluble gel when a soluble form of alginate nucleates with
119 divalent metal cations, like Ca^{2+} , which can be found in earth-based materials. Chains of
120 alginate make junctions by intercalating divalent cations creating a sort of egg-box connection
121 [26]. In order to aid the dispersion of alginate within the earth material, the HS3 powder is
122 firstly mixed with an equal mass of water.

123 Hexametaphosphate (HMP) was used in this study as a dispersant to make a mortar flowable.
124 For the kaolin mortar, a dosage of 0.25 % of the kaolin clay content was tested, this being
125 based on previously obtained results on the effect of dispersant on the rheological behavior of
126 clay pastes [6]. For the cob earth from Saint-Sulpice-La-Forêt, the mass ratio of HMP was
127 0.3% of the dry material. The choice of this dosage was made using the same methodology as
128 that used for the kaolin mortar in [6].

129

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

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



137

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

139

140 II.2 Methods

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

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

151 Cylindrical samples of 50 mm diameter and height were compacted using static compression
152 with a 200 kN loading frame at a maximum vertical stress of 45 MPa. To compare the effect
153 of the compaction technique a Proctor-type dynamic compaction was used to make 150 mm
154 diameter and height samples. Samples were compacted in CBR mold, in five layers with 56
155 blows of CBR ram for each layer. For cast samples, cement mortar 40x40x160 mm³ moulds
156 were used.

157 Because all the compressive tests were carried out with samples of an aspect ratio of one
158 (sample height to diameter for cylindrical samples or sample side length for prismatic
159 samples), it is considered that mechanical measurements can be compared even if their

160 geometries are different. The comparison between results obtained with those different sizes
161 and shapes of samples was acceptable as it has been shown that at a same aspect ratio, the
162 strength variation due to shape variation is lower than 5% [28]].

163 Samples were then conserved in a 50°C temperature controlled store until weight
164 stabilization. Such a temperature allows a relatively fast drying and ensures that only free
165 water leaves the sample. After this curing step, once the sample weight was stabilized, it was
166 considered that the samples were dry. The compressive strength of the sample was then
167 measured using a 50 kN loading frame. The test was carried out at a constant velocity of
168 1 mm/min which is in agreement the French national standard recommendation for soils
169 testing XP CEN ISO TS 17892-7 (the test duration ranging between 2 and 15 minutes,
170 maximum strain rate of 2% per minute).

171

172 **III Effect of particle size distribution and processing**

173

174 **III.1 Effect of particle size distribution**

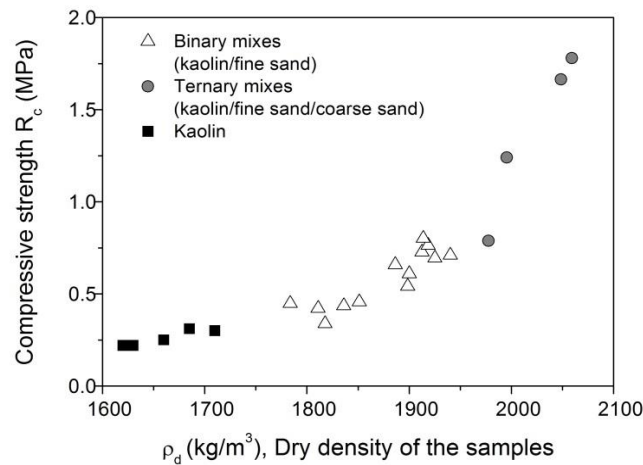
175 The particle size distribution of the mortar was designed to obtain the highest density once
176 placed. Concepts from concrete mix-design were used in order to obtain the densest packing.

177 It is also important to note that the binder content (here the kaolin clay) must be kept higher
178 than a critical value that will ensure sufficient cohesion within the sample.

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

182 In order to emphasize that this step of PSD optimization is paramount, clay samples, of binary
183 mixes (fine sand + kaolin) and of ternary mixes (coarse sand + fine sand + kaolin), were
184 prepared with different water contents ranging from 5% to 10% , these were then compacted

185 in a CBR mould in 5 layers using 56 blows per layer. The samples were weighted after
 186 drying and mechanically tested to measure their compressive strength.
 187 Figure 4 shows the compressive strength as a function of the dry density of the samples.
 188 Results show that the widening of a continuous particle size distribution increases dry density
 189 of the samples and therefore their compressive strength, as commonly observed [29, 30].



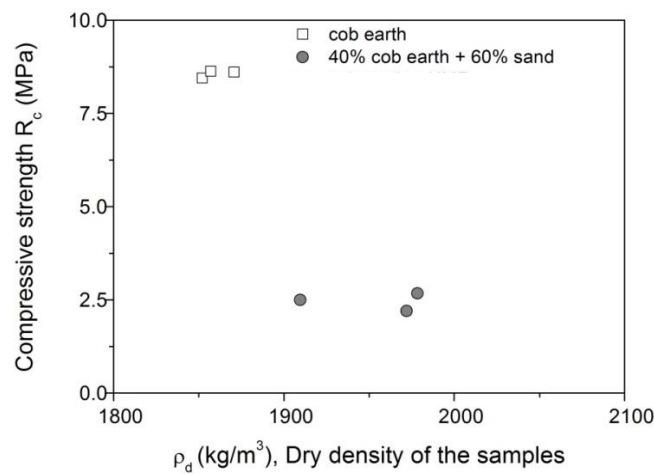
190
 191 *Fig. 4: Compressive strength as a function of dry density for kaolin, binary mix (fine*
 192 *sand+kaolin) and ternary mix (coarse sand+fine sand+kaolin)*

193
 194 In the following sections of this paper, only the ternary mix was used.

195 It is interesting to note that we attempted to add a limestone filler with a particle size
 196 distribution ranging from 10 to 63 μm (ie in the range of the size not present in the PSD
 197 shown in figure 3). Using this fourth material, optimized PSD provides kaolin volume fraction
 198 of around 10% that was not sufficient to obtain a cohesive product after casting or
 199 compaction. This result is in agreement with that which can be found in the literature
 200 suggesting that a minimal content of clay is needed to make earth-based materials for
 201 construction [31–33].

202 Another crucial point is that for the cob earth the results were opposite: Using the same
 203 methodology, we obtained a mix of 40% cob earth, 29% fine sand and 31% coarse sand. Such

204 mixes result in an increase in the dry density of the mixture, initial values ranging between
 205 1780 and 1850 kg/m³ which increased to values ranging from 1950 to 2050 kg/m³. However,
 206 this densification of the dry matrix leads to a decrease of the compressive strength from above
 207 8 MPa to values of the order of 2.5 MPa. Therefore, for the cob earth which contains clay that
 208 can induce relatively high compressive strength (8 MPa for an earth-based materials), the
 209 strength of the material appears to be directly linked to the clay content (Figure 5).



210
 211 *Fig. 5: Compressive strength as a function of dry density for cob earth with and without*
 212 *additional sand.*

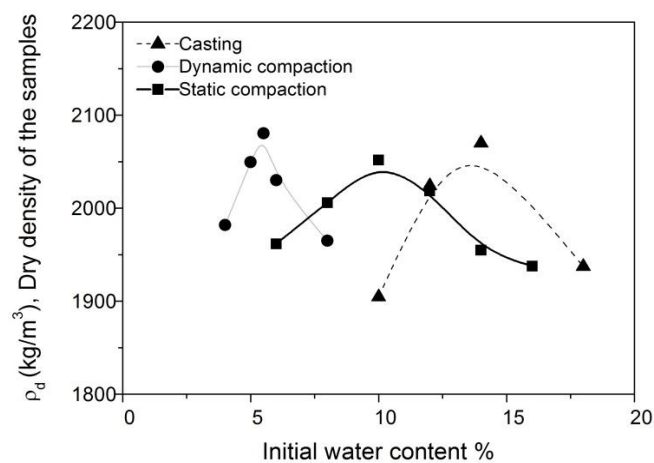
213
 214 The effect of the densification of earth-based material strengthening directly depends on the
 215 type of clays contained in the earth. With pure kaolinite, which has a low compressive
 216 strength (around 500 kPa), a densification of the matrix with sand, leads to a significant
 217 increase in strength. As opposed to this, the high strength cob earth content directly governs
 218 the strength of the samples.

219
 220 III.2 Effect of processing and dispersant

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

223 Figure 6 shows the evolution of the dry density of cast and compacted samples with respect to
224 initial water content. The curves show that the optimal water content for obtaining the densest
225 material depends on the forming process. Dynamic compaction required the smallest water
226 content, in this case 5.5% of the dry particles mass, whereas casting required more water
227 (14%) to obtain the densest material, and was therefore the material with the best mechanical
228 properties. Between these two forming process, static compaction (maximum load of 25 MPa)
229 showed a maximum dry density for an initial water content of 10%. These results indicate
230 that the rheology (or the consistency) of the wet material must be optimized with regard to the
231 forming process.

232 It is also interesting to note that the maximum density obtained for each type of tested
233 forming process was in the same range (between 2050 and 2080 kg/m³). Using higher energy
234 of compaction would result in a higher density as proposed by [34].

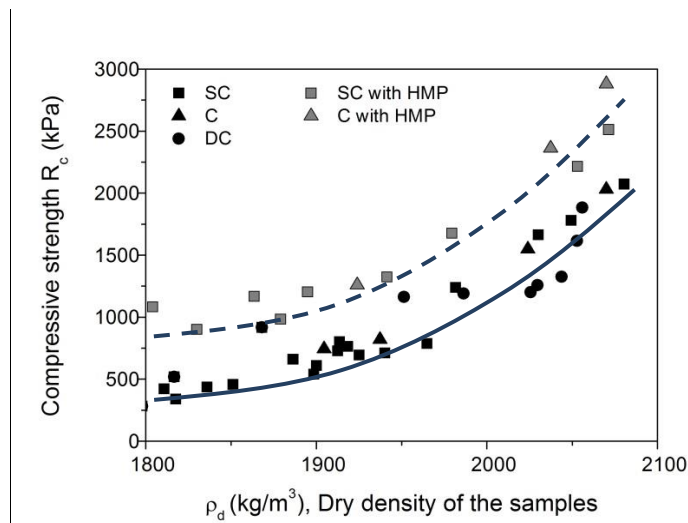


235
236 *Fig. 6: Influence of the initial water content (water added during mixing) on the dry density of*
237 *the samples for the three forming process. .*

238
239 For the optimized water content for the static compaction at 25 MPa, it was observed that an
240 increase of the vertical stress from 25 to 45 MPa led to an increase of the dry density from

241 2060 to 2100 kg/m³. Thus, for the static compaction process, the final dry density was also
242 depended on the loading.

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



248
249 *Fig. 7: Evolution of the compressive strength of the sample after drying versus the dry density*
250 *for the different forming processes and with and without HMP addition.*

251
252 It can be seen that the compressive strengths of the dry samples increases from 0.5 MPa to 2
253 MPa, for mixes without HMP, and from 0.8 MPa to 2.8 MPa, for mixes containing HMP,
254 when the dry density increases from 1800 to 2080 kg/m³. This trend can be explained by a
255 better distribution of the clay particles with HMP. HMP reduces interaction forces between
256 clay particles in a fresh state and allows for an increase of the distance at the contact point
257 between particles and a decrease of the average pore size [6]. In this case, the effect of HMP
258 would be the same as the one of superplasticizer within cement paste [23].

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

262

263 **IV Fibers and fabrics reinforcement**

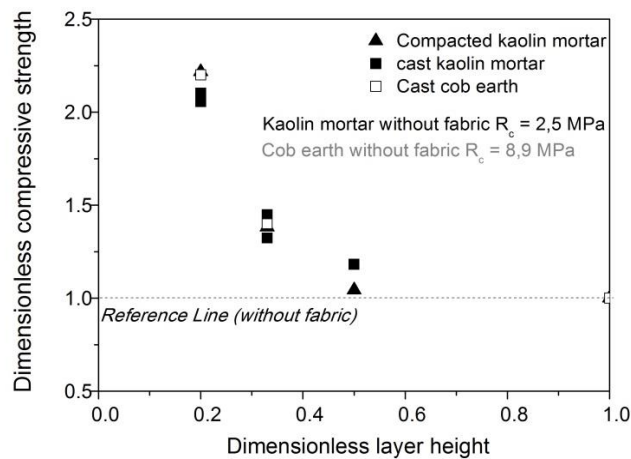
264

265 IV.1 Woven fabric

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

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

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



284

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

287

288 Figure 9 shows a fabric reinforced sample before and after a compressive strength test.

289 Fracture occurred at the fabric interface which indicates shear at this interface. Moreover, the

290 vertical fractures do not always cross the fabric interface from one layer to another thus

291 indicating that the sample behaves as a vertical assembly of partially independent layers of

292 earth-based materials. As these elemental layers have a lower aspect ratio, the compressive

293 strength of the sample increases as the height of the elemental layer decreases.



294

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

297

298 To conclude, it is interesting to note that the maximum compressive strengths of the sample
299 was obtained with 4 woven fabric sheets (the maximum number of fabric sheets tested); the
300 compressive strength were 4.5 MPa for cast samples, 4.35 MPa for compacted samples for the
301 kaolin mortar and 17.6 MPa for the cast cob earth. Another benefit of woven fabric is that the
302 large increase in compressive strength is accompanied by a decrease in dry density of the
303 sample; dry densities are reduced from 2080 to 2050 kg/m³ in the case of compacted samples
304 and from 2070 to 1930 kg/m³ in the case of cast samples).

305

306 4.2 Flax fibers

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

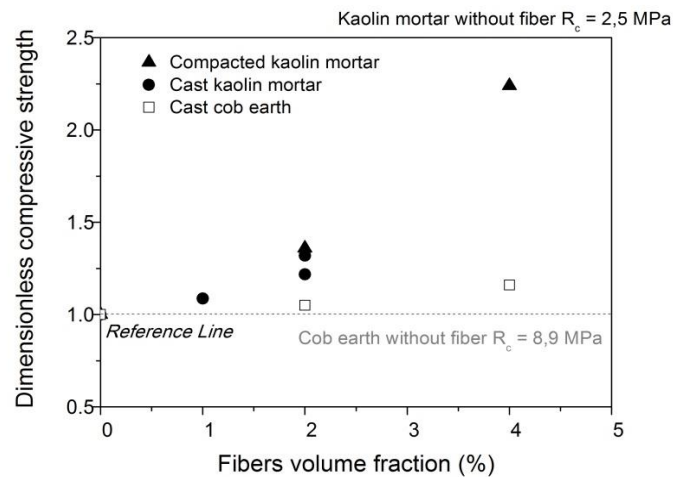
315 For the statically compacted samples with 4% volume content of flax fiber, the compressive
316 strength was 5.6 MPa, which is more than twice the compressive strength obtained without
317 fibers. Moreover, it is important to note that the dry density of this sample decreased from
318 2070 to 1920 kg/m³.

319 For kaolin mortar, the increase in compressive strength with fiber content is quite surprising
320 because it is not observed with cement-stabilized clay or concrete [14]. However, in this case,
321 the tested mineral matrix has a lower mechanical strength and the mechanical contribution

322 resulting from the friction/shear at the fiber/matrix interface becomes a non-negligible factor
323 in compressive strength.

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

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



331
332 *Fig. 10: Dimensionless compressive strength of fiber reinforced samples versus the volume*
333 *fraction of fibers contained in earth-based materials.*

334

335 **V. Effect of alginate biopolymer**

336

337 Once the samples were dry compressive strengths of the samples are measured once the
338 samples were dry to provide a reference state for further testing. Figure 11 shows the
339 evolution of the compressive strength with respect to sample dry density for kaolin mortar

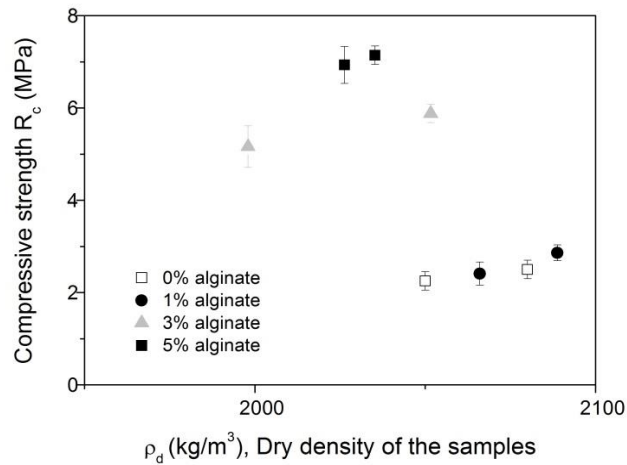
340 samples made with different amounts of alginate; Figure 12 shows a similar evolution for the
341 cob earth from Saint-Sulpice-La-Forêt.

342 For kaolin mortar, the addition of alginate at a 1% dosage did not change the mechanical
343 strength of the sample. In this case, the amount of alginate may not be sufficient to build a gel
344 network able to reinforce the material. However, for higher dosage, the compressive strength
345 of the sample increased with the alginate dosage. For a 3% dosage, and a dry density of 2050
346 kg/m^3 , the addition of alginate more than doubled the compressive strength (from 2.25 MPa to
347 5.9 MPa). At a dosage of 5%, the compressive strength reached its maximum value of 7.1
348 MPa. It would be of interest to test higher dosages in further work to verify if increased
349 dosage result in a higher compressive strength and what is the critical dosage for which the
350 compressive strength reaches a plateau.

351

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

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

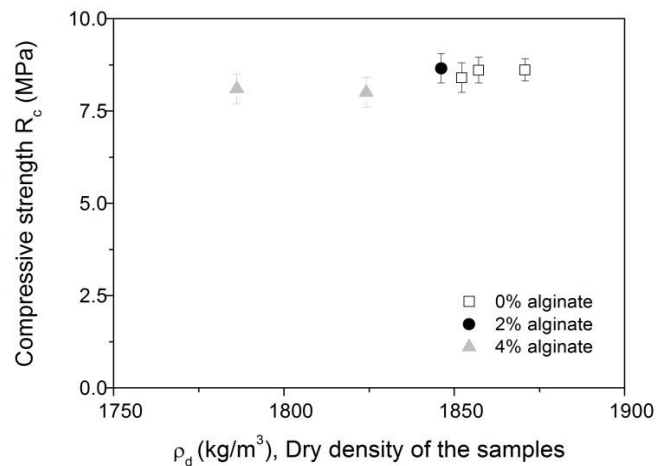


366

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

369

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



373

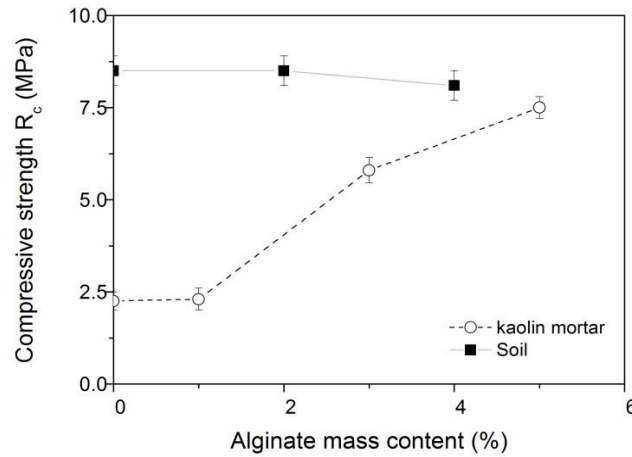
374 *Fig. 12: Compressive strengths versus dry density curves of cast cob earth (Saint-Sulpice-La-*
 375 *Forêt) mortar samples with alginate content (mass fraction of the soil) ranging from 0 to 4%.*

376

377 On the other hand, in the case of the soil from Saint-Sulpice-La-Forêt that contains swelling
 378 clay (smectite), alginate does not increase the compressive strength of the material, even at

379 high dosage. The gel strength appears to be weaker than the interaction within clay particle
380 network.

381



382

383 *Fig. 13: Evolution of compressive strength of tested materials with alginate dosage at a fixed*
384 *dry density (extrapolated value at 2050 kg/m³ for the kaolin mortar and 1850 kg/m³ for the*
385 *cob earth from Saint-Sulpice-La-Forêt).*

386

387 VI Coupled reinforcement effects

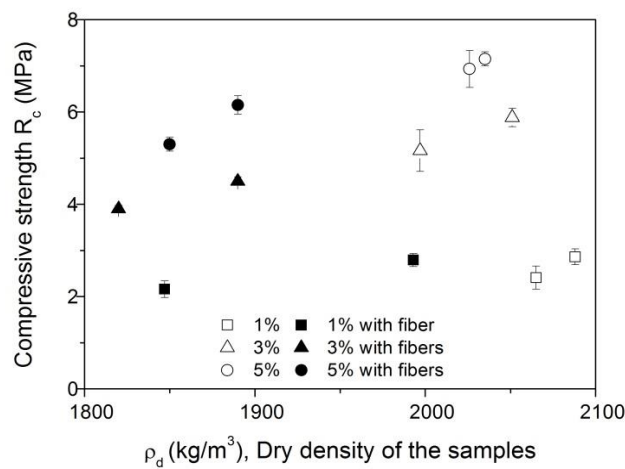
388 This section reports on a study made of the effect of coupled reinforcement strategies used to
389 strengthen the material. This work focused on kaolin mortar because only the fabric sheets
390 have been shown able to increase the compressive strength of cob earth whereas for the kaolin
391 paste,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

392

393 VI.1 Alginate and flax fibers

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

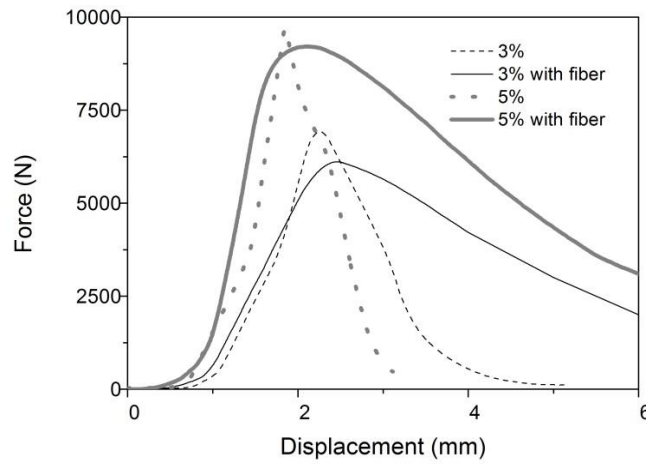
398 Secondly, the mechanical strength of the samples only increases with the addition of fibers for
 399 an alginate dosage of 1%. It appears that for higher dosage, fibers do not increase the
 400 compressive strength of the samples because the cohesion of the material is higher than the
 401 interfacial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



405
 406 *Fig. 14: Evolution of sample compressive strength of kaolin mortar with dry density for*
 407 *different dosages of alginate (1, 3 and 5%) with and without flax fibers. The compressive*
 408 *strength of the kaolin without fiber is 2 MPa for a dry density of 2080 kg/m³*

409
 410 One beneficial aspect brought about by the fibers is the increased ductility of the material.
 411 Figure 15 shows force displacement curves obtained during the compressive strength
 412 measurements with and without fibers for alginate dosages of 3 and 5%. If the curves for
 413 samples with and without fibers are compared, it can be see that the elastic parts of the curve
 414 before the peak are close, thus indicating that fiber addition does not significantly influence
 415 the elastic modulus. The load peak is higher for samples without fibers, as confirmed by
 416 Figure 8, however, after the load peak; the load decrease is much slower for samples with

417 fibers. Such type of behavior indicates an increase in the ductility of the sample; this is a very
418 interesting material property for earth construction in a seismic area, for example.

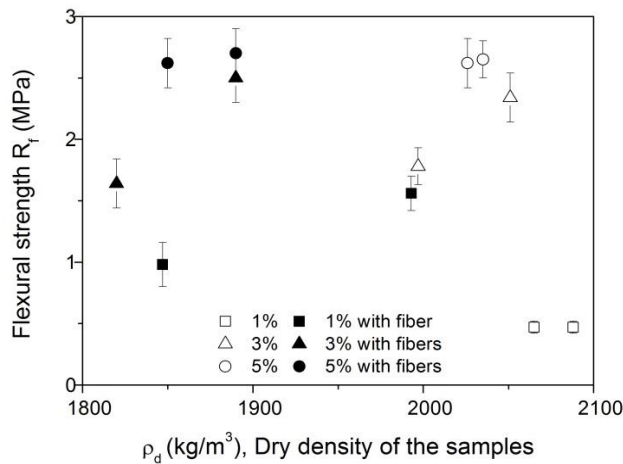


419

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

422

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



431

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

434

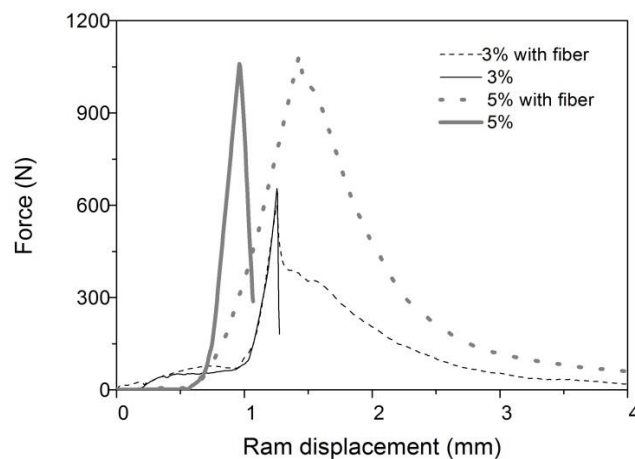
435 Figure 17 shows the force displacement curves measured during the flexural strength tests.

436 We can see that samples without fiber exhibit a brittle behavior with a sudden failure obtained

437 after the load peak whereas the samples with fibers shows a post-peak behavior with a smooth

438 decrease of the load due to the continuous failure of the interfaces between fibers and matrix

439 [14].



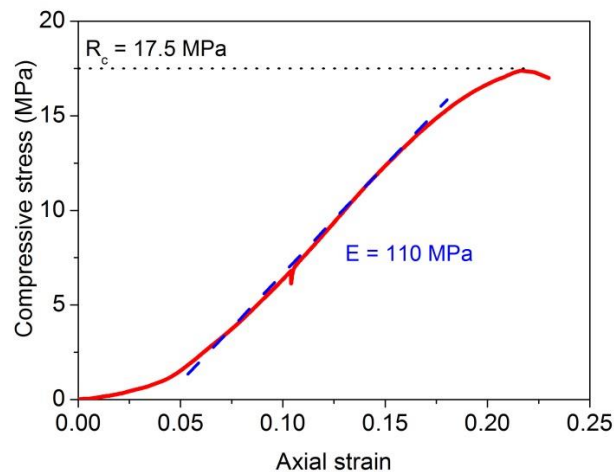
440

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

443

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

445 In order to complete this study of reinforcement of earth-based materials, a study was carried
446 out on the effect of combining alginate, fibers and woven fabrics on the compressive strength
447 of the kaolin mortar. A kaolin mortar with a water content of 12% containing HMP and an
448 alginate dosage of 3% and with a volume fraction of flax fiber of 4% was cast in
449 $40 \times 40 \times 160 \text{ mm}^3$ mould in five layers separated by the tested woven fabric. After the drying
450 stage, the sample was tested in compression. The compressive stress vs. the deformation
451 curve (Figure 18) shows that the compressive strength of the material was quite high 17.5
452 MPa. However, the elastic modulus remained only at a value of 110 MPa, which is quite low
453 in comparison with the elastic modulus of concrete at the same level of compressive strength.



454

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

458

459 This shows that the reinforcement strategies and their combination help to delay the failure of
460 the samples by giving some bridging between clay particles provided by alginate or fibers.
461 However, it clearly appears that these reinforcements do not affect the elastic modulus, which

462 is always of the order of kaolin without reinforcement (150 MPa for the same material
463 without fibers and alginate).

464

465 **VII Conclusions**

466

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

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

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

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

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

484

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488

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