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1 **Effect of plant aggregates on mechanical properties of earth bricks**

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25 **Effect of plant aggregates on the mechanical properties of earth bricks**

26

27 ABSTRACT

28 A building material is mainly characterized by its mechanical performance, which
29 provides proof of its quality. However, the measurement of the compressive or
30 flexural strength of an earth-based material with plant aggregates, which is very
31 ductile, is not fully standardised. The objective of this study is to determine the
32 compressive and flexural strengths of a composite made of earth and 0%, 3% or
33 6% of barley straw, hemp shiv or corn cob. Given the manufacturing processes
34 available, cylindrical compressed specimens were studied in compression
35 whereas extruded specimens were studied in flexion. Two protocols were tested
36 for compressive strength measurements: one with direct contact between the
37 specimen and the press, and the other with reduced friction. The test with
38 reduced friction engendered a huge decrease of the stress and a slight decrease
39 of the strain. For both compressive and flexural strengths, the specimens made
40 of earth alone were the most resistant, followed by composites containing straw.
41 The influence of two different treatments applied to the straw is also discussed.

42

43 Keywords: mechanical properties, earth blocks, straw, hemp shiv, corn cob,
44 extrusion

45

46 INTRODUCTION

47 The building sector is currently innovating in order to use more environmentally
48 friendly materials and to ensure the comfort of users. To this end, it is developing
49 new ecological materials (such as lightweight concrete (Chabannes et al., 2014;
50 Magniont, 2010), or concrete using wastes (Palankar et al., 2015)) but it is also

51 looking into older, traditional ways, focusing on materials such as earth, stone or
52 wood.

53 Nowadays, around 30% of the world's population still lives in earth shelters,
54 especially in developing countries (Minke, 2006). Earth is a local resource that is
55 available in abundance and presents many other advantages. This material has
56 low environmental impact because of its recyclability, the little energy needed for
57 the transformation process, the minimal transport required and its energy
58 efficiency. Moreover, it is able to regulate indoor moisture and to improve the
59 comfort of the building's users (Islam and Iwashita, 2006; Minke, 2006).

60 However, earth material presents some weaknesses, such as low mechanical
61 strength, brittleness, hygroscopic shrinkage and limited durability with respect to
62 water (Aymerich et al., 2012; Islam and Iwashita, 2006). In order to reduce these
63 drawbacks, some authors have studied the effect of adding stabilizers such as
64 hydraulic binders and artificial or natural fibres or aggregates (Danso et al.,
65 2015a; Laborel-Préneron et al., 2016). The enhancement of soil blocks by
66 stabilizers was reviewed by Danso et al. (Danso et al., 2015a), especially
67 concerning mechanical and water absorption properties. The interest of adding
68 plant aggregates was also highlighted by Laborel-Préneron et al. (Laborel-
69 Préneron et al., 2016). Based on empirical knowledge, the use of natural fibres
70 and excrement has always helped to improve the properties of earth for building
71 (Chazelles et al., 2011; Millogo et al., 2016). Such additions are now being
72 increasingly studied within an earth matrix because of their apparently huge
73 potential to improve thermal insulation (Bal et al., 2013) and ductility (Mostafa
74 and Uddin, 2015) among other properties.

75 The present paper deals only with the mechanical properties of earth blocks
76 containing plant aggregates. These properties are indeed essential if the material
77 under study is to be used for construction purposes. They will determine whether

78 it can be used in a load bearing structure or not. However, the mechanical
79 requirements vary from one standard to another, as do the testing procedures,
80 which makes the characterization of this kind of material difficult. In the literature,
81 many studies focus on the influence of plant fibres or aggregates on compressive
82 strength. Twenty-three references investigating compressive strength on this kind
83 of materials are cited in (Laborel-Préneron et al., 2016). Several studies have
84 observed an increase of compressive strength with increasing proportions of
85 plant aggregates such as tea residue (Demir, 2006), sawdust, tobacco residue or
86 grass (Demir, 2008) or cassava peel (Villamizar et al., 2012). However, others
87 have found a decrease in strength: Algin et al. showed a 71% compressive
88 strength decrease with the addition of 7% of cotton waste (Algin and Turgut,
89 2008), and a decrease was also observed with straw (Mohamed, 2013) or
90 coconut fibres (Khedari et al., 2005). In some cases, the effect of fibre length was
91 studied. According to Millogo et al. (Millogo et al., 2014, 2015), the compressive
92 strength of the earth composite increased by as much as 16% with the addition of
93 short Hibiscus Cannabinus fibres (3 cm) but decreased with long ones (6 cm),
94 except for a content of 0.4%. An influence of the aspect ratio was also observed
95 by Danso et al. (Danso et al., 2015b) for coconut, bagasse and oil palm fibre, but
96 with an increase of compressive strength as the length of the added fibres
97 increased. None of these studies on earth material with plant aggregates deal
98 with the influence of the testing protocol. However, Morel et al. (Morel et al.,
99 2007) reviewed the various existing protocols for compressive strength testing of
100 blocks of earth alone. Aubert et al. (Aubert et al., 2013, 2015) have discussed the
101 testing of extruded earth blocks, considering the influence of: aspect ratio,
102 confinement (capping with Teflon or not), anisotropy and the mortar joint between
103 two half blocks, on the compressive strength measurement.

104 Several references focus on the flexural strength of these materials. An increase
105 in flexural strength is observed in most of the studies with an addition of plant
106 aggregates, e.g. Bouhicha et al. (Bouhicha et al., 2005) with barley straw or
107 Aymerich et al. (Aymerich et al., 2012) with wool fibres, but others have observed
108 a decrease, e.g. Villamizar et al. with cassava peels (Villamizar et al., 2012). In all
109 cases, ductility is greatly improved, as the fibre bridging of microcracks prevents
110 them from expanding (Galán-Marín et al., 2010; Mattone, 2005; Mostafa and
111 Uddin, 2015; Segetin et al., 2007).

112 A few, relatively recent, works have investigated the energy absorbed and the
113 mode of failure (Aymerich et al., 2016; Islam and Iwashita, 2006; Lenci et al.,
114 2012; Martins et al., 2014). In flexion, failure usually occurs by fibre gradually
115 slipping from the matrix, leading to both pull out and breaking of the fibres
116 (Mostafa and Uddin, 2015). Some authors have treated the fibres in an attempt to
117 improve the adhesion between the fibre and the matrix and thus enhance the
118 flexural or tensile strength. Some encouraging results have been obtained,
119 notably with acetylation, depending on the temperature of the chemical reaction
120 (Hill et al., 1998), or alkaline treatments on sisal fibres (Alvarez and Vázquez,
121 2006) or banana fibres (Mostafa and Uddin, 2015). However, a linseed oil
122 treatment used by Ledhem et al. on wood shavings gave less promising results,
123 with a decrease in strength, especially in traction.

124 The material studied in this paper is a bio-composite composed of earth and
125 three different plant aggregates: barley straw, hemp shiv and corn cob.
126 Composite specimens were manufactured according two processes:
127 compression or extrusion. After characterization of the earth used, the influence
128 of plant aggregate content on compressive strength and flexural strength was
129 analysed. Compressed specimens were tested in compression following two
130 protocols, one with friction and the other using a system to reduce friction. The

131 extruded specimens were tested in flexion. The effects of various treatments on
132 barley straw and the effect of its aspect ratio were investigated with this test. The
133 fracture energy developed during the test was also calculated.

134

135 MATERIALS AND METHODS

136 **Raw materials**

137 *Earth*

138 Earth used in this study was composed of quarry fines from aggregate washing
139 processes (FWAS). These fines, smaller than 0.1 mm, were generated by the
140 washing of limestone aggregates produced for the chemical or concrete industry.
141 The sludge created was left to dry in sedimentation basins and was then reduced
142 to powder to be used in different applications.

143

144 *Plant aggregates*

145 Three types of plant aggregates were used in this study: barley straw (two
146 different lengths), hemp shiv and corn cob. Barley Straw (S) is the part of cereal's
147 stem rejected during the harvest. Hemp shiv (H) is the by-product of the hemp
148 defibration process and corresponds to the lignin-rich part of the stem. Corn Cob
149 (CC) is the central part of the ear of corn cleared of grain and crushed. The
150 hardest part was studied here. The physical and chemical characteristics of these
151 plant aggregates were determined in (Laborel-Préneron et al., 2017) and are
152 recapitulated in Table 1. However, the previous characterization was done only
153 for the shortest straw (S_{short}), of average length 8 mm. In the present study, the
154 longest straw (S_{long}), of average length 15 mm, was used only for the flexural
155 strength test.

156 ***Insert Table 1 here***

157 *Surfactant additives*

158 In agriculture, the efficiency of crop protection products can be improved by the
159 addition of surfactants that increase the absorption of the product on the plants.
160 These additives can optimize spreading and reduce negative effects such as drift
161 and run off. In this study, the objective of using these surfactants was to increase
162 the adhesion between the plant aggregates and the earth matrix by reducing the
163 surface tension of the mixing water. Two types of surfactant additives were
164 tested: A1, which was soya lecithin based, and A2, which was latex based. They
165 were both applied to the long straw only.

166 To apply the surfactants to the straw, the particles were immersed for 1 hour in
167 the additive, diluted at the rate recommended by the supplier: 0.5% of the water
168 volume for A1 and 0.1% for A2. The straw was then sieved to remove extra water
169 before being dried at 30°C in an oven.

170

171 **Physical, chemical and mineralogical characterization of FWAS**

172 *Particle size distribution and Atterberg limits*

173 The size distribution was determined by sedimentation after wet sieving at 80 µm,
174 according to standard NF P94-057 (AFNOR, 1992). The geotechnical
175 characteristics were evaluated using the Atterberg limits, according to standard
176 NF P 94-051 (AFNOR, 1993).

177

178 *Chemical and mineralogical composition*

179 X-ray diffraction on a sample crushed to a size of less than 80 µm was carried
180 out with a Siemens D5000 powder X-ray diffractometer equipped with a
181 monochromator having a $K\alpha$ ($\lambda=1.789\text{\AA}$) cobalt anticathode. Thermal
182 mineralogical characterization was also performed by thermal gravimetric
183 analysis (TGA) of a crushed sample (< 80 µm) heated to 1050°C at a constant
184 rate of 10°C.min⁻¹. Major oxide composition was evaluated on the basis of

185 macroelemental analysis performed by Inductively Coupled Plasma-Atomic
186 Emission Spectrometry (ICP-AES) on crushed samples smaller than 80 μm . The
187 mineral composition was determined from X-ray diffraction results and the
188 chemical composition.

189

190 **Manufacturing process**

191 Specimens for the different tests were prepared by two manufacturing processes:
192 one using static compression and the other using extrusion. The proportion of
193 plant aggregates was expressed by dry weight content, according to formula (1):

$$Ag. \text{ content} = \frac{m_{Ag}}{m_{Ag} + m_{FWAS}} \times 100 \quad (1)$$

194 where Ag. content is the plant aggregate content in %, m_{Ag} is the dry mass of
195 plant aggregates and m_{FWAS} is the dry mass of earth.

196

197 *Compressed specimens*

198 Various mixtures were prepared to make the specimens: FWAS only and
199 mixtures containing one of the plant aggregates in a proportion of 3% or 6%. The
200 water contents of the mixtures were determined by the Proctor test, and then
201 rounded up because, according to Minke (Minke, 2006), this is a minimum value
202 for manufacturing compressed earth bricks.

203 Table 2 recapitulates the different mixture proportions and the dry densities of the
204 specimens obtained (average of six specimens). As expected, the water content
205 of the dry mass needed to make the mixtures increased when the plant
206 aggregate content increased. It was higher for straw than for hemp and corn cob
207 because straw particles have a higher water absorption coefficient than the other
208 two aggregates (414% vs. 380% for hemp and 123% for corn cob) (Laborel-
209 Préneron et al., 2017).

210 ***Insert table 2 here***

211

212 To manufacture the specimens, the earth and plant aggregate fractions were
213 poured into a blender and mixed by hand. Then, water was added and the
214 materials were mixed mechanically until a homogeneous mix was obtained. The
215 raw materials were mixed the day before moulding.

216 Cylindrical specimens 5 cm in diameter and 5 cm high ($\Phi 5H5$), intended for
217 compressive strength tests, were manufactured by double static compression at
218 the Proctor density. After demoulding, the height of the specimens containing
219 barley straw and hemp shiv increased significantly due to the high compressibility
220 of the plant aggregates. This increase reached 10% of the height for an addition
221 of 6% of hemp shiv, for example. This expansion led to the formation of
222 distributed cracks, specifically in the case of an addition of 6% of straw (Figure 1).

223 The specimens were first dried at 40°C for 24 hours, then the temperature was
224 increased by 0.1°C/min to 100°C and kept at 100°C until the weight became
225 constant (weight variation less than 0.1% between two weighings 24 hours
226 apart). This rise in temperature was carried out slowly to keep shrinking
227 homogeneous and to avoid mechanical stresses. The specimens were then
228 stored in a room regulated at 20°C and 50% relative humidity (RH) and were

229 tested when they were in equilibrium with the environment (about one week
230 later).

231 **Figure 1. Compressed specimens of FWAS (a) and S6 (b)**

232 *Extruded specimens*

233 Six types of specimens were prepared: specimens made with FWAS only (i), and
234 specimens made with 3% of short straw (ii), long straw (iii), hemp shiv (iv), long
235 straw treated with the A1 surfactant (v), or long straw treated with the A2
236 surfactant (vi). Corn cob was not tested in extrusion because of the poor
237 distribution of the particles observed in a preliminary trial and its low strength in
238 compression. To manufacture these specimens, earth and plant aggregate
239 fractions were poured into a blender and were mixed by hand. Then, the
240 materials were mixed mechanically in the blender and water was added
241 progressively until the consistency of the mixture was sufficiently homogeneous
242 and plastic to be extruded. The details of the mixes are recapitulated in

243

244 **Table 3.**

245 ***Insert table 3 here***

246

247 The specimens were manufactured with a medium sized laboratory extruder. The
248 mixture was extruded under vacuum through a 7 cm x 3.5 cm die (Figure 2). The
249 specimens were difficult to cut in the fresh state because of the presence of plant
250 particles. They were therefore air-dried until the weight become constant (weight
251 variation of less than 0.1% between two weighings 24 hours apart) and then cut
252 to a length of 18 cm with a circular saw. Treatment of the straw did not modify the
253 dry density of the composites. However, when the two manufacturing processes
254 were compared (

255 Table 2 and

256

257 Table 3), an increase of density was observed for the extruded specimens
258 containing plant aggregates. It was due to the extrusion of the material under
259 vacuum, which reduced porosity, and to the extrusion pressure due to the worm
260 screw.

261 **Figure 2. Vacuum extruder**

262 **Compressive strength test**

263 The compressive strength tests on the $\Phi 5H5$ specimens were performed using a
264 100 kN capacity hydraulic press. The load was applied at a constant deflection
265 rate of $3 \text{ mm}\cdot\text{min}^{-1}$. This speed was chosen as an intermediate value between the
266 $1.2 \text{ mm}\cdot\text{min}^{-1}$ specified in the French standard XP P 13-901 (AFNOR, 2001)
267 (intended for compressed earth blocks) and the $5 \text{ mm}\cdot\text{min}^{-1}$ used by Cerezo
268 (Cerezo, 2005) (intended for hemp concrete). Three specimens of each mixture
269 were tested in two different tests: one test with the specimen in direct contact with
270 the steel plates (generating friction) and the other including a system avoiding
271 friction (Figure 3) as described by Olivier et al. (Olivier et al., 1997). In the latter
272 case, a 2-mm-thick piece of Teflon and a thin neoprene sheet - with a drop of oil
273 between the layers - were placed between the earth specimen and the steel
274 (neoprene in contact with the specimen, and Teflon in contact with the steel).
275 Teflon was used because of its low friction coefficient and neoprene because of
276 its high mechanical resistance. Displacements and loads were measured in each
277 case. The Young's modulus of each specimen was then calculated from the
278 linear part of the stress-strain curve.

279 **Figure 3. Compressive test method: (a) with friction and (b) with reduced** 280 **friction**

281 **Flexural strength test**

282 The flexural strength tests on the extruded specimens were performed using a
283 100 kN capacity hydraulic press with a 10 kN sensor. The load was applied at a

284 constant deflection rate of 1 mm.min⁻¹ as was done by Aymerich et al. (Aymerich
285 et al., 2012). The samples were loaded under three point loading conditions with
286 the lower supports placed 10 cm apart, corresponding to the value given in the
287 French standard NF EN 196-1 intended for cements (AFNOR, 2006).
288 Measurements were made in triplicate.

289 This test was carried out in order to study the effect of the plant aggregate
290 addition on ductility. According to the literature, this kind of addition has a marked
291 effect on ductility (Aymerich et al., 2012; Bouhicha et al., 2005; Galán-Marín et
292 al., 2010; Ghavami et al., 1999). Deflection was measured from bottom to top on
293 an aluminium platelet glued in the middle of the sample, as can be seen on
294 Figure 4. The test was stopped for a deflection close to 3 mm, the limit of the
295 sensor stroke.

296 ***Figure 4. Flexural test set up***

297

298 In order to compare the flexural strength with values reported in the literature or
299 values from standards, the bending stress was calculated only at failure with the
300 beam theory. Considering that classical hypotheses of solid mechanics applied
301 and that the section was not cracked until peak load (elastic part of the curve)
302 (Lenci et al., 2012; Mostafa and Uddin, 2015), the stress σ (MPa) was calculated
303 from the following expression (2):

$$\sigma = \frac{3FL}{2bh^2} \quad (2)$$

304 with F the maximum load at failure (N), L the distance between the supports
305 (mm), b the width (mm) and h the height (mm) of the sample.

306

307 To determine the effect of the plant aggregate on the behaviour at failure and
308 post-peak, the fracture energy (G_f) was calculated. It provided information about

309 the amount of energy absorbed when the specimen was broken into two parts. It
310 was represented by the area under the load-displacement curve divided by the
311 projected fracture area (Guinea et al., 1992). Usually, it is measured on notched
312 samples (Aymerich et al., 2012, 2016; Guinea et al., 1992), so the whole load-
313 displacement curve is considered. However, as the samples did not have a
314 notch, the area was taken into account from the failure point and to a deflection
315 of 3 mm. The fracture energy was calculated from the expression (3):

$$G_f = \frac{\int_{\delta_f}^{\delta_{3mm}} F(\delta) d\delta}{S} \quad (3)$$

316 where δ_f is the deflection at failure (m), F is the load (N) and S is the initial
317 section (m²).

318 The Young's modulus of each specimen was then calculated from the linear part
319 of the stress-strain curve.

320

321 RESULTS AND DISCUSSION

322 **Characterization of earth**

323 *Particle size distribution and Atterberg limits*

324 The particle size distribution is presented in Figure 5 and compared with the size
325 distribution recommended for compressed earth blocks (CEB) in the XP 13-901
326 standard (AFNOR, 2001).

327 ***Figure 5. Comparative grain size distribution curve for earth: FWAS and*** 328 ***standard***

329 The earth was extremely fine: 99% of the particles were smaller than 80 μm and
330 the average particle size (D50) determined using the pipette analysis was 6.5
331 μm . The curve did not fit the limits recommended by the standard, the passing
332 mass being higher for each grain size. Atterberg limits were equal to 30% for the
333 liquid limit, 21% for the plastic limit and 9% for the plasticity index. The plasticity

334 of this material was not located in the spindle of the diagram recommended by
335 the XP 13-901 standard (AFNOR, 2001). However, even though the size
336 distribution and Atterberg limits did not meet the recommended criteria, it was
337 already shown that it was possible to manufacture CEBs with a huge variety of
338 earths (Aubert et al., 2014; Laborel-Préneron et al., 2016).

339

340 *Chemical and mineralogical composition*

341 The X-ray diffractogram is presented on Figure 6. This diagram reveals the large
342 presence of calcite (CaCO_3) and shows the presence of other minerals in smaller
343 quantities: kaolinite ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$), quartz (SiO_2), illite ($\text{KAl}_2(\text{AlSi}_3)\text{O}_{10}(\text{OH})_2$),
344 goethite ($\text{FeO}(\text{OH})$) and dolomite ($\text{CaMg}(\text{CO}_3)_2$).

345 ***Figure 6. X-ray diffraction pattern of the earth. (c) calcite, (d) dolomite, (g)***
346 ***goethite, (i) illite, (k) kaolinite, (q) quartz***

347 To complete its mineralogical characterization, the earth was subjected to
348 thermal gravimetric analysis, the results of which are presented in Figure 7. The
349 loss of mass around 105°C was due to the evaporation of water and that around
350 540°C indicated the removal of the constituting water, which led to the
351 transformation of kaolinite into metakaolinite (Kornmann and Lafaurie, 2005). The
352 greatest loss of weight, of about 25%, occurred around 910°C and was due to the
353 decarbonation of calcite and dolomite.

354 ***Figure 7. TG and DTG (Derivative Thermo-Gravimetric) curves of the earth***

355 The chemical composition of the earth is given in

356 Table 4, where a large amount of calcium is noticeable. Using the chemical
357 composition and the mineral characterization, it is possible to estimate the
358 proportion of each mineral. The fines used were thus composed for 60% of
359 calcite, 11% of kaolinite, 11% of illite, 10% of quartz, 6% of dolomite and 3% of
360 goethite.

361 ***Insert table 4 here***

362

363 **Compressive strength measured on compressed specimens**

364 The average over three specimens of dry density, maximum compressive
365 strength and other mechanical properties of each mixture and for each testing
366 protocol are reported in

367 Table 5. The compressive strength value required by the New-Zealand Earth
368 Building standard NZS 4298 (NZS 4298) is 1.3 MPa. This value was reached for
369 all the mixtures of this study, for both protocols, except for CC6 tested with
370 reduced friction (0.9 MPa).

371 ***Insert table 5 here***

372 *Influence of plant aggregate type and content on the bulk density*

373 A number of authors have shown that bulk density is influenced by the addition of
374 plant aggregates (Algin and Turgut, 2008; Demir, 2008; Khedari et al., 2005). The
375 bulk density of each mixture used here is plotted on Figure 8. As expected, bulk
376 density decreased as the aggregate content increased for the three kinds of plant
377 aggregates. However, some differences between the mixtures with straw or
378 hemp and the mixture with corn cob can be noted. Bulk density was higher for the
379 mixtures with corn cob than for those with straw or hemp. This difference may
380 have been due to the huge variability of the particle bulk densities: 497 kg.m^{-3} for
381 corn cob against 57 kg.m^{-3} and 153 kg.m^{-3} for straw and hemp shiv, respectively
382 (Laborel-Préneron et al., 2017).

383 ***Figure 8. Bulk density as a function of the plant aggregate content***

384 *Influence of the testing protocol on compressive strength*

385 Usually, only the compressive test with friction is performed ((Galán-Marín et al.,
386 2010; Mohamed, 2013; Villamizar et al., 2012)) and follows standards ASTM
387 D2166 (ASTM D 2166, 2004), XP P 13-901 (AFNOR, 2001) or TS EN 772-1 (TS
388 EN 772-1, 2002). However some authors have also measured the strength with
389 lower friction (using a layer of sand and a transparent film on either side of the
390 sample (Piattoni et al., 2011; Quagliarini and Lenci, 2010) or with Teflon (Aubert
391 et al., 2015)) to obtain the "real" compressive strength. Both methods, with
392 friction and with Teflon reducing friction, were carried out to see what difference
393 was actually observed. The results are shown in Figure 9.

394 ***Figure 9. Compressive strength of the mixtures according to the testing***
395 ***protocol***

396 For each composition, the compressive strength measured in the tests with
397 friction was greater than that found in tests with reduced friction because of the
398 confinement (transverse displacements not allowed at the ends of the
399 specimens). In the case of earth alone (FWAS) and S6 specimens, the decrease
400 in strength between the protocols was only about 3 to 5%, whereas it reached
401 between 28% (C6) and 59% (CC3) for the other mixtures. In some cases (FWAS
402 or CC6), standard deviation was quite high. In the case of CC6, for example, this
403 large variability of the results was due to one specimen having significantly higher
404 strength than the other two - probably because of the heterogeneity of the
405 material (Aubert et al., 2015), with a poor distribution of the corn cob granules.
406 The results of H3, H6, CC3 and CC6 measured with reduced friction are very
407 close; it is thus difficult to establish the highest strength with this protocol.

408 Unlike Aubert et al.'s finding (Aubert et al., 2015) that the strength decreased by
409 only 10% with the use of Teflon capping, the choice of the method was observed
410 to significantly affect the strength value measured here. It is thus important to
411 choose the most adequate method. In order to allow comparisons among
412 samples, and with the literature, only the values obtained with friction were kept
413 here. This protocol was also easier to set up and more similar to the behaviour of
414 a brick within a wall, with friction between the bricks.

415

416 ***Effect of the plant aggregates on compressive strength***

417 The compressive strengths of the specimens are summarized in Figure 10 for the
418 different plant aggregate types and contents when the protocol with friction at the
419 interface between the specimen and the press was employed.

420 The compressive strength of the specimen composed of earth alone is higher
421 than that of all the others, which is in accordance with the density values of the
422 various specimens. Its average strength of 4.0 MPa is higher than the typical
423 value for CEBs which is, according to Morel et al. (Morel et al., 2007), between 2
424 and 3 MPa. Furthermore, a decrease in compressive strength is noticeable when
425 hemp shiv and corn cob contents increase. The values are 2.4 and 1.8 MPa for
426 H3 and H6, and 3.2 and 1.8 MPa for CC3 and CC6 specimens. This reduction,
427 linked to the incorporation of particles with low compressive strength and
428 stiffness, can be correlated to the decrease in bulk density observed with the
429 addition of plant aggregate (Al Rim et al., 1999; Ghavami et al., 1999). In the
430 case of barley straw, the average strengths are 3.3 MPa and 3.8 MPa for S3 and
431 S6 respectively. The ultimate compressive strength of S6 specimens is thus
432 higher than that of S3 specimens. This can be explained by a consolidation
433 phenomenon due to the high compressibility of the straw that allows its porosity
434 to decrease as strain increases. This phenomenon is not observed for H6 or CC6
435 specimens because of the lower ductility of hemp and corn aggregates. This
436 difference could also be due to the different shapes of the particles, straw being
437 more elongated than hemp shiv (Laborel-Préneron et al., 2017). This kind of
438 result was also observed by Millogo et al. (Millogo et al., 2014) for the longest
439 fibres but for smaller quantities (less than 1%). This observation was explained
440 by the limitation of crack opening by the fibres.

441 ***Figure 10. Results for compressive strength test with friction***

442 *Effect of the plant aggregates on ductility*

443 Figure 11 shows the stress-strain curves of all the specimens. It can be noted
444 that FWAS specimens show brittle failure whereas the ultimate strain is high for
445 the specimens containing plant aggregates, especially those with 6%. Their peak
446 strain is, on average, 19.9, 10.7 and 2.5% for S6, H6 and CC6, respectively,

447 whereas it is only 1.3% for FWAS. Although these specimens are weaker than
448 FWAS specimens, they are also more ductile, with a larger zone of plasticity.
449 Ductility of the composite is thus increased by the addition of plant aggregates.
450 However, in calculating building structures, such deformations of the material
451 cannot be tolerated.

452 In order to make comparisons among the materials and to maintain a strain level
453 compatible with the intended use, we chose to limit the strain to 1.5% and to keep
454 the corresponding compressive strength value, as described by Cerezo (Cerezo,
455 2005) for hemp concrete. The maximum compressive strength was kept in cases
456 when the failure occurred before 1.5% strain (which only concerned FWAS
457 specimens).

458 These values are compared with the values at failure in Figure 12. For a given
459 deformation, compressive strength is higher for FWAS specimens. The values
460 are far below the maximum compressive strength and do not reach 1 MPa for the
461 specimens with straw or hemp shiv whereas the compressive strength is above
462 the limit of 1.3 MPa in the case of corn cob. In the cases where the materials do
463 not have the strength required to be used as bearing structures, they can be
464 used as infill material in a wood structure or as a partition wall, for instance.

465 ***Figure 11. Strain-stress diagram for all the specimens***

466 ***Figure 12. Maximum compressive strength (σ_c) and compressive strength***
467 ***at 1.5% strain ($\sigma_{c,1.5\%}$)***

468 *Influence of the testing protocol on Young's modulus*

469 Young's moduli were obtained from compressive strength tests and are
470 recapitulated in Figure 13, according to the testing protocol. Friction does not
471 seem to have any great influence on the modulus, which is of the same order of
472 magnitude for both situations (with quite large standard deviations). The most

473 striking result visible in the figure is that the Young's modulus of FWAS
474 specimens is the highest (around 500 MPa).

475 **Figure 13. Young's moduli of the materials for both protocols**

476 *Effect of the plant aggregates on Young's modulus*

477 The Young's modulus obtained from the tests with friction is represented
478 according to the plant aggregate content in Figure 14. The Young's moduli of the
479 specimens containing 3% of barley straw, hemp shiv and corn cob are
480 respectively 62, 75 and 217 MPa. For an addition of 6%, the moduli are 31, 26
481 and 102 MPa respectively for barley straw, hemp shiv and corn cob. Specimens
482 made with straw and with hemp shiv showed very similar stiffness for a given
483 content. With a modulus of 439 MPa, FWAS specimens had the highest stiffness.
484 For an increase of each plant aggregate content, there was a decrease in the
485 Young's modulus. This result can be explained by the high compressibility of the
486 plant particles (Cerezo, 2005) and is in agreement with various references (Al
487 Rim et al., 1999; Chee-Ming, 2011; Piattoni et al., 2011; Quagliarini and Lenci,
488 2010) stating that the straw addition controls the plastic behaviour of the
489 specimen through a lower homogeneity of the mixture. This decrease of Young's
490 modulus could be linked with the density of the specimens as shown in Figure 15.
491 An empiric exponential correlation between Young's modulus and dry density is
492 found: $E = 0.3184 \exp(0.0035\rho_{dry})$ with ρ_{dry} in kg.m^{-3} . Such a relation has
493 already been proposed by Al Rim et al. for earth specimens with wood
494 aggregates (Al Rim et al., 1999), but it was $E = 1127d^{3.142}$ with d the density of
495 the dry material relative to the density of water.

496 **Figure 14. Young's modulus from compressive test as a function of the**
497 **plant aggregate content**

498 **Figure 15. Young's modulus as a function of the density**

499 **Flexural strength measured on extruded specimens**

500 The average of dry density, the maximum flexural strength and other mechanical
501 parameters are reported in

502

503 Table 6. The minimum flexural tensile stress required by the Masonry Standards
504 Joint Committee (MSJC) (Masonry Standards Joint Committee (MSJC), 2008)
505 (quoted in (Villamizar et al., 2012)) for clay and concrete blocks is 0.21 MPa.
506 Another value, of 0.65 MPa, is required by the British Standard BS 6073 (BS
507 6073, 1981) (quoted in (Algin and Turgut, 2008)) for building materials to be used
508 in structural applications. All the flexural strengths of the specimens tested in this
509 study are above these two minimum requirements, the lowest strength being 1.34
510 MPa, found for H3 specimens.

511 ***Insert table 6 here***

512 *Effect of the plant aggregate type on the flexural strength*

513 The maximum flexural strengths of the different mixtures are represented in
514 Figure 16 (a). FWAS has the highest flexural strength, followed by S3_{short}, S3_{long}
515 and H3, with values of 2053, 1900, 1776 and 1453 N respectively. This result
516 could be correlated with the respective densities: the lower the density, the lower
517 the flexural strength.

518 It can be seen that the flexural strength is higher for the specimens with short
519 straw than for those with long straw. This result is contrary to the findings of some
520 other authors (Danso et al., 2015b; Mostafa and Uddin, 2015), who stated that an
521 increase of the fibre length increased the embedded length and thus the
522 adhesion area, leading to an improvement in flexural strength. This result could
523 be explained by the fact that, for the same straw content, there are more particles
524 in a mix with short straw than with long straw, engendering a better distribution of
525 the particles in the matrix. Another explanation could be the existence of a length
526 limit, depending on the specimen size, above which the difficulty of dispersion
527 offsets the positive effect of the reinforcement. Moreover, after being extruded
528 under vacuum, the specimens with short straw presented a better visual surface

529 quality than the specimens with long straw. This could lead to a better adhesion
530 between the earth and the straw, explaining the higher resistance.

531 Although most cases in the literature show an increase in flexural strength with
532 an addition of plant aggregate ((Al Rim et al., 1999; Aymerich et al., 2012;
533 Bouhicha et al., 2005; Galán-Marín et al., 2010)), an adverse effect (decrease of
534 flexural strength) was found by Villamizar et al. (Villamizar et al., 2012) with an
535 addition of cassava peels and by Algin and Turgut (Algin and Turgut, 2008) with
536 an addition of cotton wastes. This could be due to the heterogeneity of the
537 material or the weakness of the adhesion between the particles and the matrix
538 (Yetgin et al., 2008).

539 **Figure 16. Influence of the plant aggregate on flexural behaviour: (a)**
540 **Flexural load-carrying capacity, (b) Peak strain (ϵ_f), (c) Average fracture**
541 **energy (G_f) and (d) Young's modulus**

542 *Effect of the plant aggregate type on ductility and Young's modulus*

543 At the end of the tests, reinforced specimens were not totally split into two parts
544 (Figure 4) and extra manual force was necessary to separate them, whereas
545 FWAS specimens were divided into two parts. Figure 17 presents typical load-
546 deflection curves obtained during the bending test for the different samples.
547 These curves clearly show that the addition of plant aggregates increases the
548 ductility, increasing the deflection at failure and giving some residual strength.

549 Peak strain is represented in Figure 16 (b). As mentioned above, the strain is
550 increased with the addition of plant aggregates, especially for long particles. The
551 strain was 0.44 and 0.55% respectively for short and long straw. The lower value
552 in the case of hemp shiv (0.31%) could be attributed to a morphological effect:
553 the particle is indeed less elongated and so does not have as much surface area
554 in contact with the earth matrix as the straw particle.

555 Figure 16 (c) represents the average fracture energy for each composition. The
556 value is close to 0 J.m² for the FWAS specimens whereas the fracture energy of
557 the other specimens is higher: 296, 484 and 157 J.m⁻² respectively for S3_{short},
558 S3_{long} and H3. The addition of plant aggregates allows a huge increase in fracture
559 energy. The energy absorbed increases when the length of the fibre increases; it
560 is 39% higher with long than short straw, meaning that its residual strength is
561 greater. This result shows that the fracture response of materials reinforced with
562 plant aggregates or fibres is governed by mechanisms of toughening such as
563 fibre bridging and fibre pull-out (Aymerich et al., 2016). These effects occur only
564 for sufficient crack opening.

565 **Figure 17. Typical load-deflection curves**

566 The experimental values of Young's moduli are presented in Figure 16 (d). As for
567 the elastic moduli from the compressive test, they seem to decrease with the
568 addition of plant aggregates.

569 This result is partially correlated with the literature. Although the flexural Young's
570 modulus of an earth material with wood aggregates increased with between 10
571 and 20% of addition, it decreased above 20% (Al Rim et al., 1999).

572 *Effect of the surfactant on the flexural strength, post-peak behaviour and Young's*
573 *modulus*

574 The behaviour under flexion of the mixtures with untreated and treated long straw
575 is represented on Figure 18. The increase in flexural load capacity between S_{A2}
576 and S3_{long} is only about 3% and the standard deviations are high. The surfactant
577 has no effect on the flexural strength.

578 Peak strain is represented in Figure 18 (b). The strain decreases with the addition
579 of a surfactant, especially the A2 additive. Strain is 0.55, 0.49 and 0.36% for
580 S3_{long}, S_{A1} and S_{A2} respectively.

581 Figure 18 (c) represents also the average fracture energy for the untreated and
582 treated compositions. $S_{3_{long}}$ and S_{A1} present similar values, of 482 and 462 $J.m^{-2}$,
583 respectively but a small increase of 10% can be noticed for S_{A2} , with a fracture
584 energy of 538 $J.m^{-2}$.

585 Experimental values of Young's moduli are presented in the Figure 18 (d). The
586 elastic modulus is higher for the treated specimens, with values of 442 and 508
587 MPa for S_{A1} and S_{A2} , respectively, whereas it is only 385 MPa for $S_{3_{long}}$. The A2
588 additive again seems to be the more efficient of the two surfactants tested here,
589 giving an increase in stiffness of about 24%.

590 Even though the flexural strength is not increased by the straw treatment, the
591 stiffness of the material seems to be increased and the adhesion between the
592 straw and the matrix should also be improved. Surfactant A2 seems to have a
593 greater effect than A1. However, this is a preliminary study, which needs to be
594 pursued further, in particular to optimize various parameters such as the dilution
595 ratio, application method and drying temperature.

596 ***Figure 18. Influence of the surfactants on flexural behaviour: (a) Flexural***
597 ***load-carrying capacity, (b) Peak strain (ϵ_f), (c) Average fracture energy (G_f)***
598 ***and (d) Young's modulus***

599

600 CONCLUSION

601 The mechanical properties of compressed and extruded earth-based specimens
602 were tested. These two ways of manufacturing led to different densities for the
603 same formulation. However, compressive and flexural measurements were
604 independent. Several main conclusions can be drawn concerning the influence of
605 the various parameters such as the plant aggregate type, the protocol of the test
606 or possible treatment. Concerning the compressive tests, the measurement with
607 reduced friction gave a lower compressive strength and peak strain. This method

608 gives a more "realistic" resistance, but is still little used in the literature. At
609 rupture, strength was higher in the case of straw addition, followed by hemp shiv
610 and corn cob additions. For both compressive and flexural tests, the addition of
611 plant aggregates decreased the strength but improved the ductility of the
612 material, decreasing the Young's modulus. Concerning flexural strength, a better
613 resistance was observed for short than for long straw, but a higher strain was
614 noted for the longest straw. Strain at peak was lower when the straw was treated
615 with the A2 additive, but with the flexural strength was the same.

616 Various works have shown the diversity of mechanical tests existing for earth
617 bricks and these should be harmonized by means of more investigation and
618 standardization. However, the testing of bio-based earth materials should not be
619 forgotten as their behaviour is much more ductile and cannot be tested in the
620 same way. Although the treatment with surfactants did not improve the
621 mechanical strength of the composites, it did cause a slight decrease in the strain
622 at rupture. More investigation is thus required to optimize its effect on strength, in
623 particular concerning the treatment process (the dilution rate and details of the
624 straw treatment method). In this work, compressed specimens were used to
625 study the influence of plant aggregates and surfactant additives during
626 compression tests whereas extruded specimens were tested in flexion. However,
627 in further work it would be interesting to determine whether or not the adhesion
628 between earth and fibre differs according to the process used: compression or
629 extrusion.

630

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635

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771 **Table 1.** Physicochemical properties of the plant aggregates

Material	Barley straw	Hemp shiv	Corn cob
Designation	S _{short}	H	CC
Bulk density (kg.m ⁻³)	57.4 ± 1.2	153.0 ± 2.4	496.8 ± 14.0
Water absorption (%)	414 ± 4	380 ± 11	123 ± 2
Diameter* (mm)	2.33 ± 1.52	2.02 ± 1.23	2.63 ± 0.43
Thermal conductivity (W.m ⁻¹ .K ⁻¹)	0.046 ± 0.001	0.053 ± 0.002	0.097 ± 0.001
Chemical composition			
Lignin (%)	5.5	17.2	6.6
Cellulose (%)	37.7	50.3	41.4
Hemicellulose (%)	26.7	17.9	40.7

772 * Corresponding to average minor axis by image analysis

773 **Table 2.** Mixture proportions and Proctor density of compressed specimens

Reference	FWAS	S3	S6	H3	H6	CC3	CC6
Plant aggregate	-	Short straw	Short straw	Hemp	Hem p	Corn cob	Corn cob
Plant aggregate content (%)	0	3	6	3	6	3	6
Water content (%)	14	19	21	17	20	16	16
Dry density (kg.m ⁻³)	1988± 9	1520±1	1195±169	1553± 69	1190 ±44	1877±2	1704±71

774

775

776 **Table 3.** Mixture proportions of extruded specimens

Reference	FWAS	S3 _{short}	S3 _{long}	H3	S _{A1}	S _{A2}
Plant aggregate	-	Short straw	Long straw	Hemp	Long straw	Long straw
Plant aggregate content (%)	0	3	3	3	3	3
Water content (%)	20	24	26	25	24	25
Surfactant	-	-	-	-	A1	A2
Dry density (kg.m ⁻³)	1982±8	1781±10	1734±20	1712±11	1784±10	1782±12

777

778 **Table 4.** Chemical composition of the earth (LOI: Loss on Ignition)

Oxides	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	LOI
%	18.73	7.47	2.39	0.03	1.27	35.27	0.09	0.90	0.39	0.09	31.92

779

780 **Table 5.** Measured mechanical properties of the materials: dry density (ρ_{dry}) average compressive
781 strength (σ_c), average ultimate strain (ϵ_c), average compressive strength at 1.5% strain ($\sigma_{c,1.5\%}$) and
782 average experimental Young's modulus (E_c)

Testing protocol	Reference	ρ_{dry} (kg/m ³)	σ_c (MPa)	ϵ_c (%)	$\sigma_{c,1.5\%}$ (MPa)	E_c (MPa)
With friction	FWAS	1995 ± 0	4.0 ± 0.4	1.3 ± 0.1	4.0 ± 0.4	439 ± 54
	S3	1519 ± 1	3.3 ± 0.2	7.8 ± 0.6	0.7 ± 0.1	62 ± 3
	S6	1315 ± 27	3.8 ± 0.3	19.9 ± 1.1	0.4 ± 0.0	31 ± 1
	H3	1603 ± 57	2.4 ± 0.2	4.8 ± 0.3	0.7 ± 0.1	75 ± 8
	H6	1221 ± 70	1.8 ± 0.2	10.7 ± 3.1	0.4 ± 0.1	26 ± 3
	CC3	1878 ± 1	3.2 ± 0.2	2.4 ± 0.2	2.1 ± 0.3	217 ± 45
	CC6	1754 ± 13	1.8 ± 0.6	2.5 ± 0.5	1.3 ± 0.6	102 ± 69
Reduced friction (RF)	FWAS	1982 ± 10	3.9 ± 0.9	1.0 ± 0.1	3.9 ± 0.9	564 ± 161
	S3	1520 ± 1	2.1 ± 0.2	5.6 ± 0.5	0.6 ± 0.0	43 ± 5
	S6	1075 ± 30	3.6 ± 0.2	17.2 ± 1.5	0.3 ± 0.0	25 ± 0
	H3	1504 ± 54	1.6 ± 0.1	3.6 ± 0.3	0.7 ± 0.1	51 ± 5
	H6	1159 ± 41	1.5 ± 0.1	7.5 ± 1.1	0.4 ± 0.0	22 ± 1
	CC3	1876 ± 1	1.3 ± 0.1	1.2 ± 0.1	1.3 ± 0.1	136 ± 40
	CC6	1654 ± 53	1.0 ± 0.1	1.8 ± 0.2	0.9 ± 0.0	69 ± 9

783

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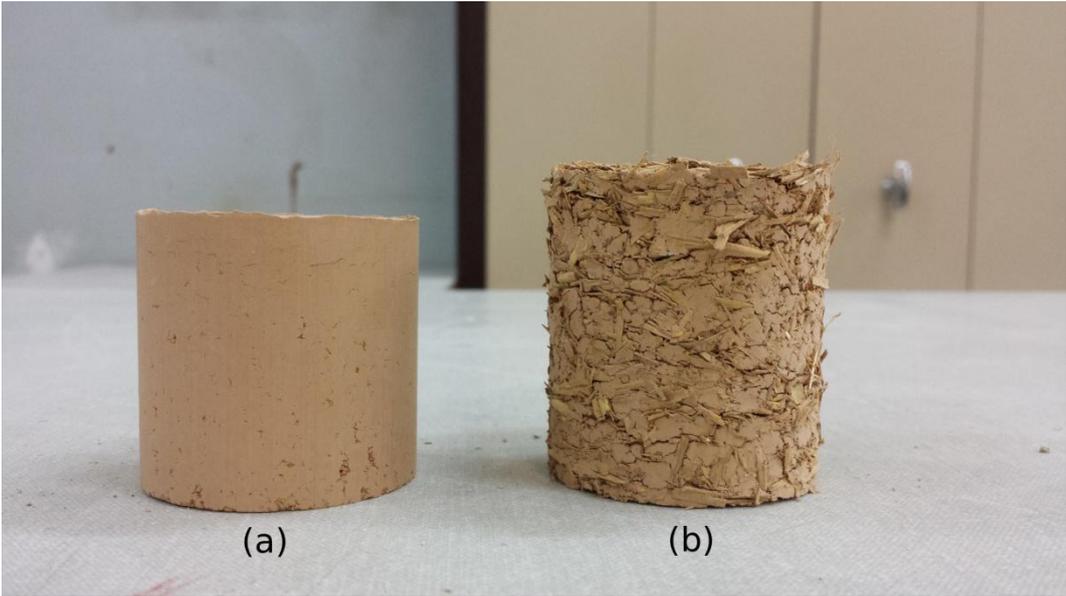
785 **Table 6.** Average experimental mechanical properties: dry density (ρ_{dry}), flexural strength (σ_f),
 786 ultimate strain (ϵ_f), experimental Young's modulus (E_f) and fracture energy (G_f)

Type	ρ_{dry} (kg.m ⁻³)	F (N)	σ_f (MPa)	ϵ_f (%)	E_f (MPa)	G_f (J.m ⁻²)
FWAS	1982 ± 8	2053 ± 120	1.88 ± 0.10	0.22 ± 0.02	856 ± 57	7 ± 0
S3 _{short}	1781 ± 10	1900 ± 123	1.80 ± 0.13	0.44 ± 0.11	475 ± 49	296 ± 50
S3 _{long}	1734 ± 20	1776 ± 135	1.69 ± 0.14	0.55 ± 0.14	385 ± 29	484 ± 41
H3	1712 ± 11	1453 ± 86	1.34 ± 0.08	0.31 ± 0.04	577 ± 72	157 ± 9
S _{A1}	1784 ± 10	1798 ± 163	1.69 ± 0.16	0.49 ± 0.03	442 ± 72	462 ± 11
S _{A2}	1782 ± 12	1824 ± 183	1.73 ± 0.10	0.36 ± 0.08	508 ± 67	538 ± 81

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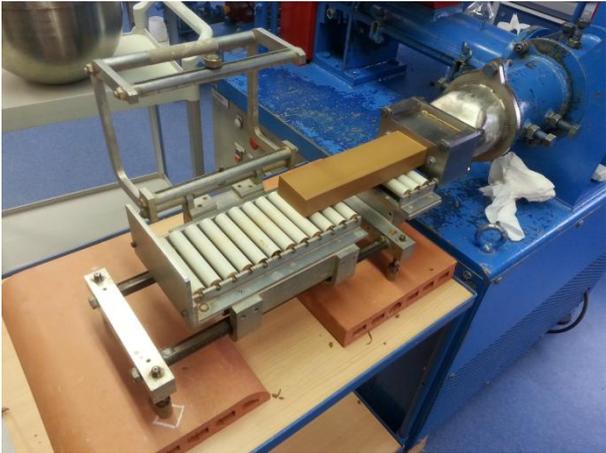
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789 Figure 1. Compressed specimens of FWAS (a) and S6 (b)



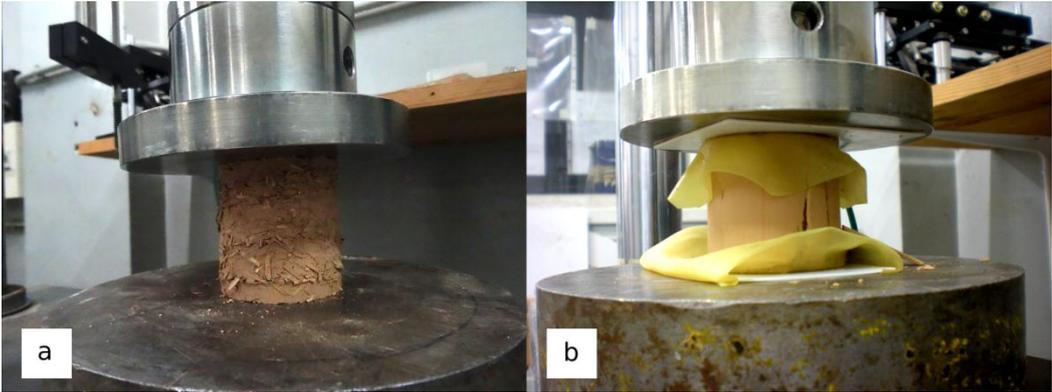
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792 Figure 2. Vacuum extruder



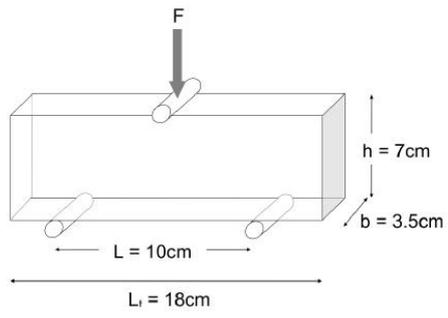
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794 Figure 3. Compressive test method: (a) with friction and (b) with reduced friction



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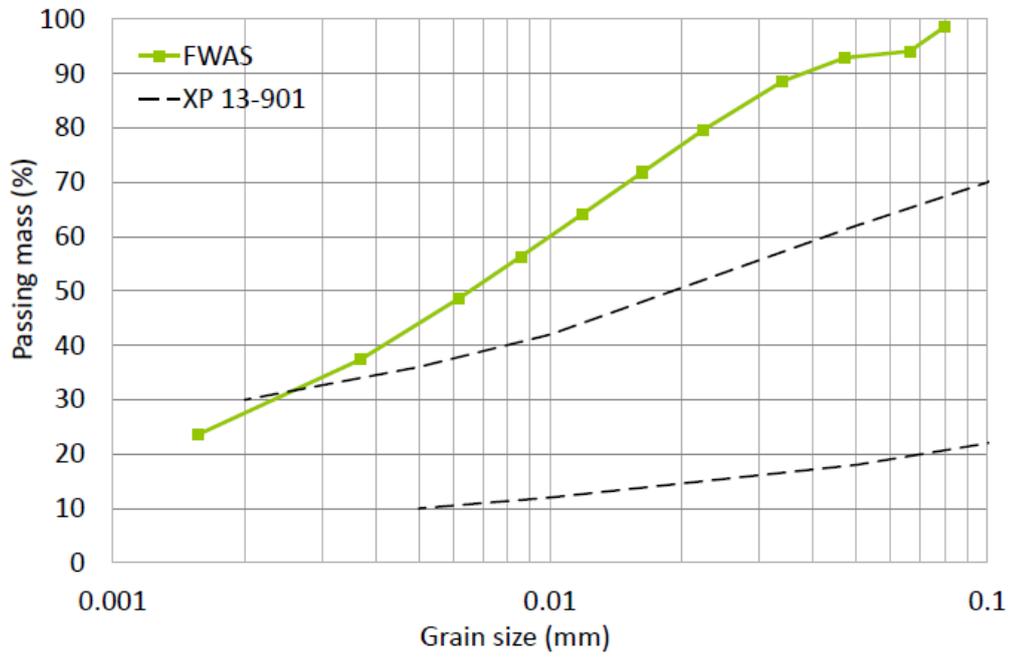
796 Figure 4. Flexural test set up



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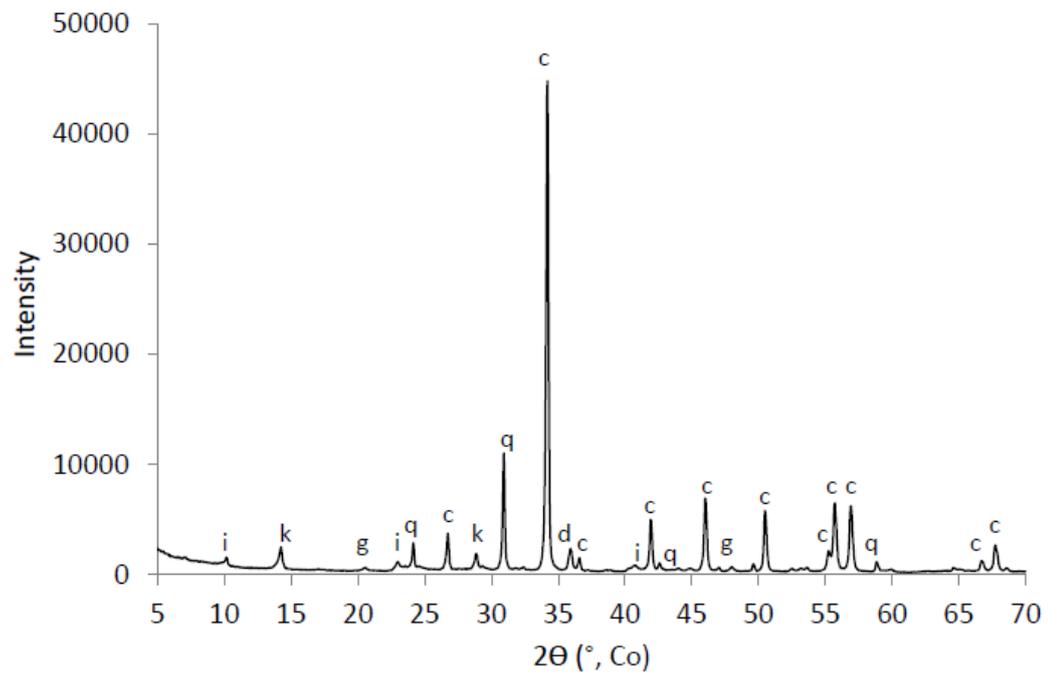


799 Figure 5. Comparative grain size distribution curve for earth: FWAS and standard



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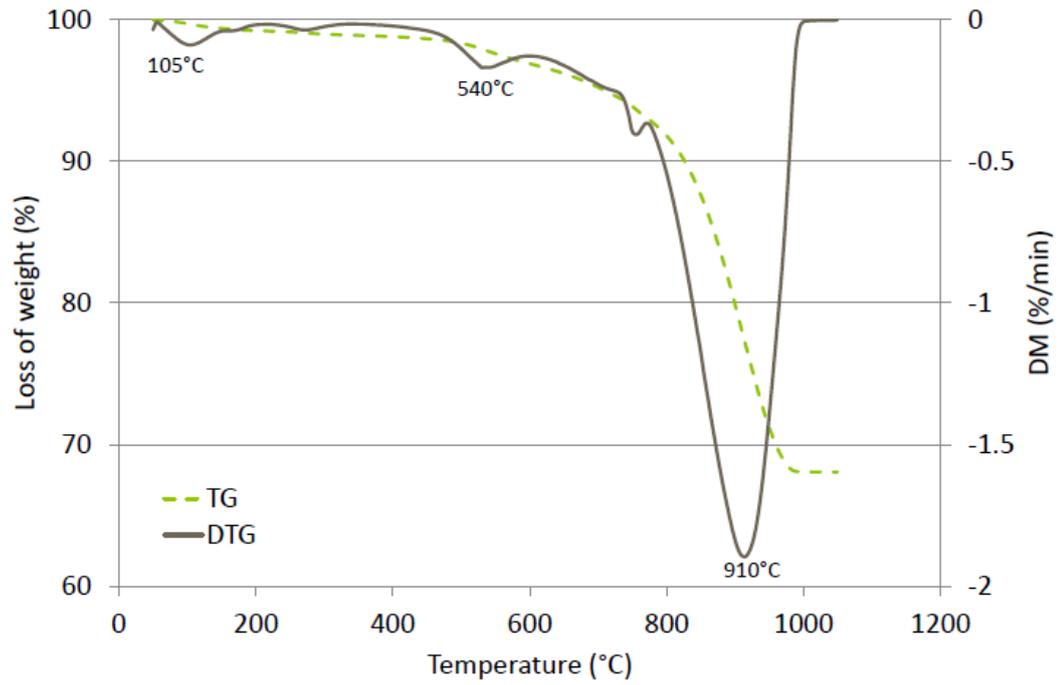
802 Figure 6. X-ray diffraction pattern of the earth.



(c) calcite, (d) dolomite, (g) goethite, (i) illite, (k) kaolinite, (q) quartz

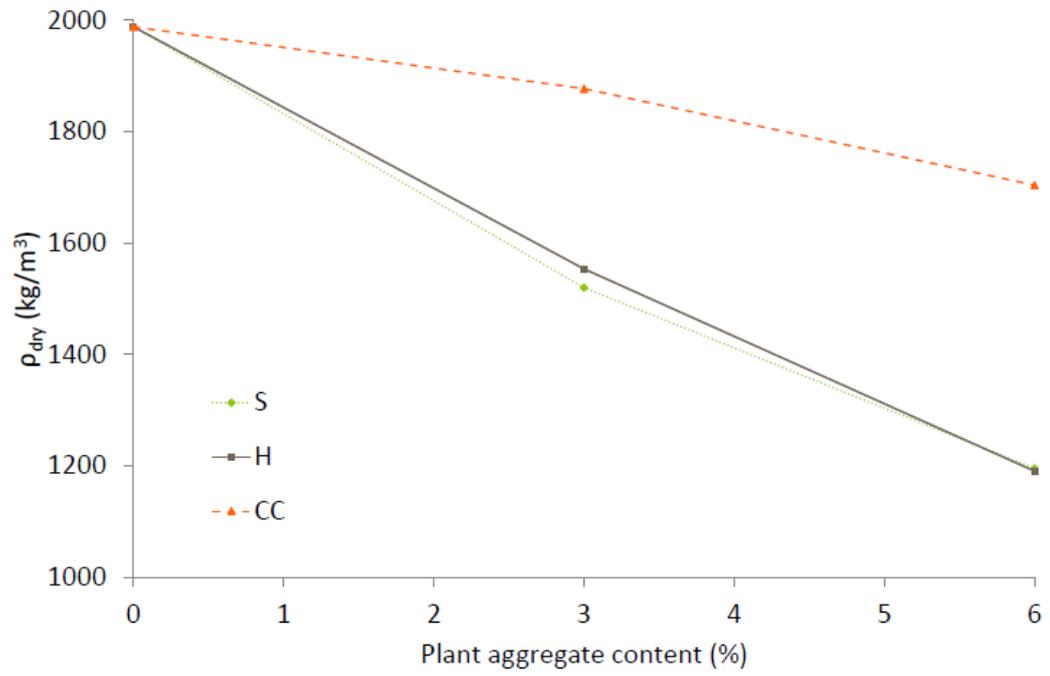
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805 Figure 7. TG and DTG (Derivative Thermo-Gravimetric) curves of the earth



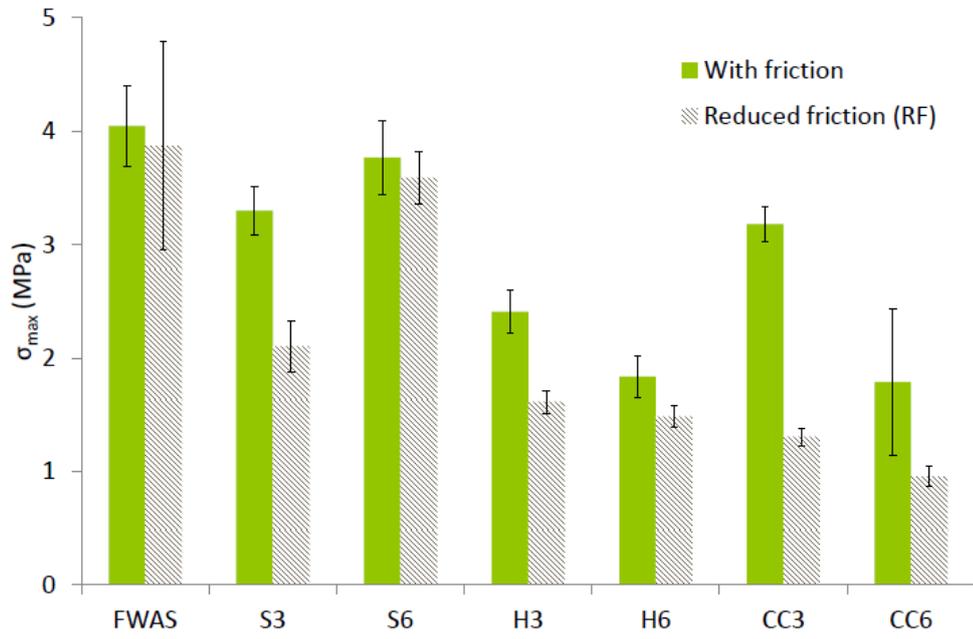
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808 Figure 8. Bulk density as a function of the plant aggregate content



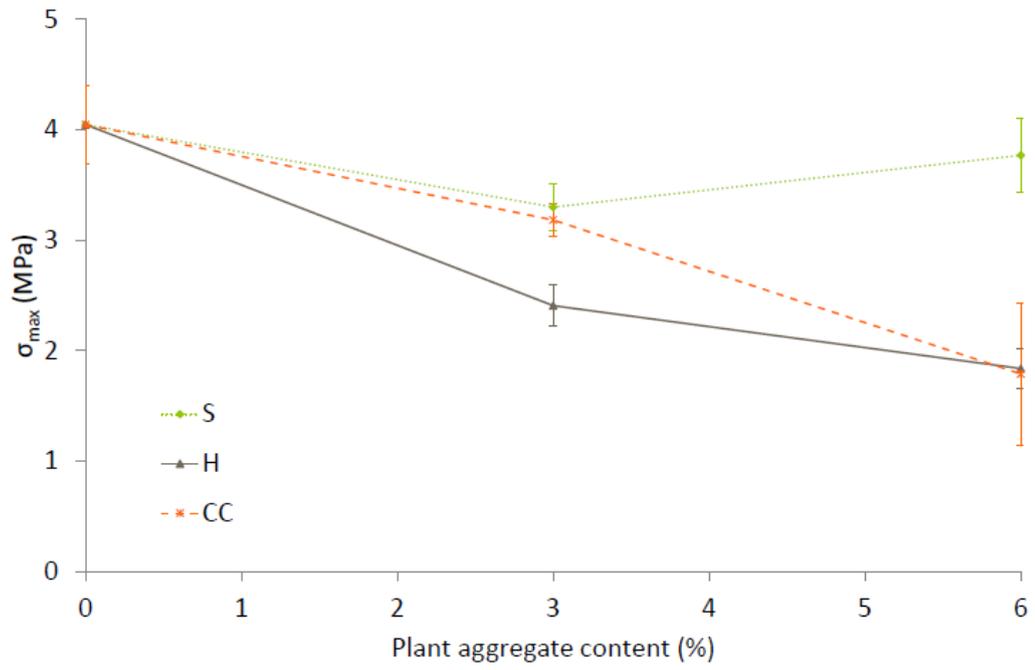
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811 Figure 9. Compressive strength of the mixtures according to the testing protocol



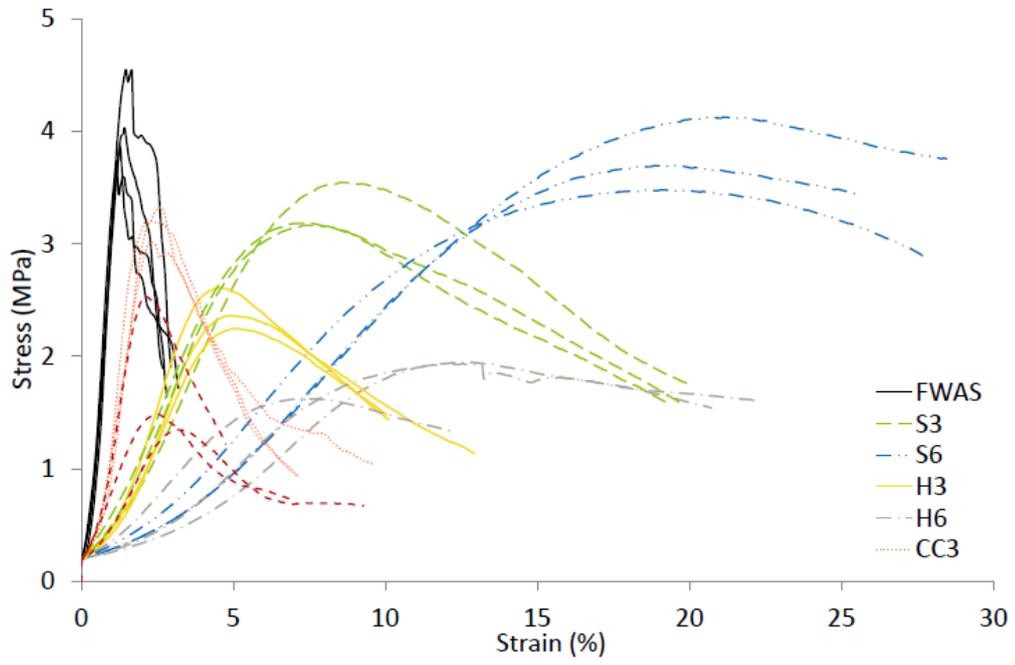
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814 Figure 10. Results for compressive strength test with friction



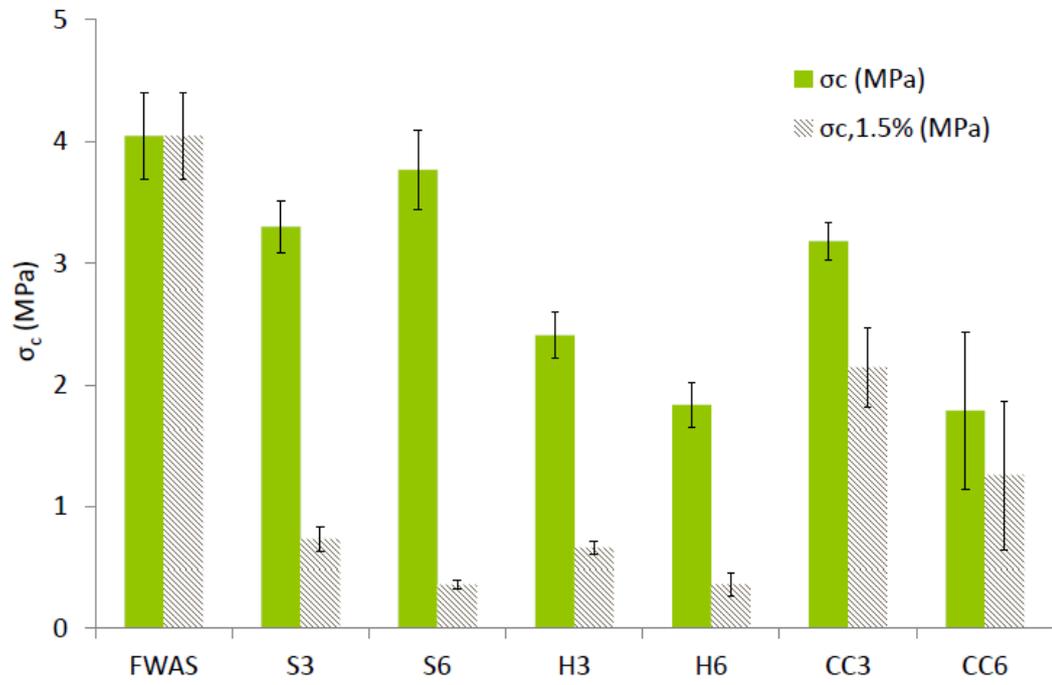
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817 Figure 11. Strain-stress diagram for all the specimens



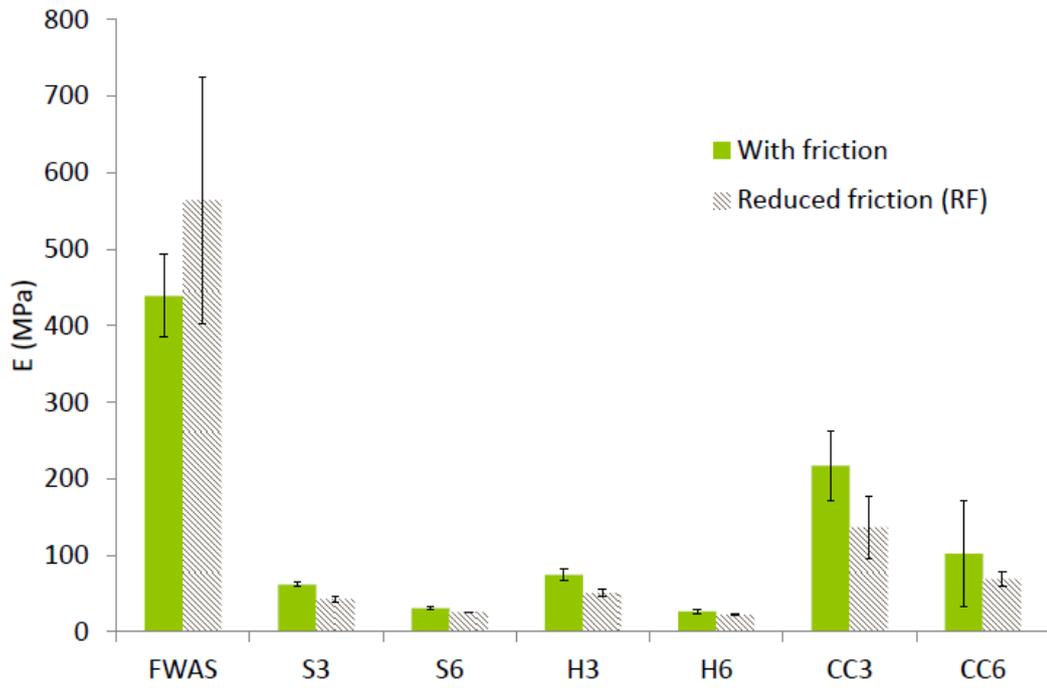
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820 Figure 12. Maximum compressive strength (σ_c) and compressive strength at
821 1.5% strain ($\sigma_{c,1.5\%}$)



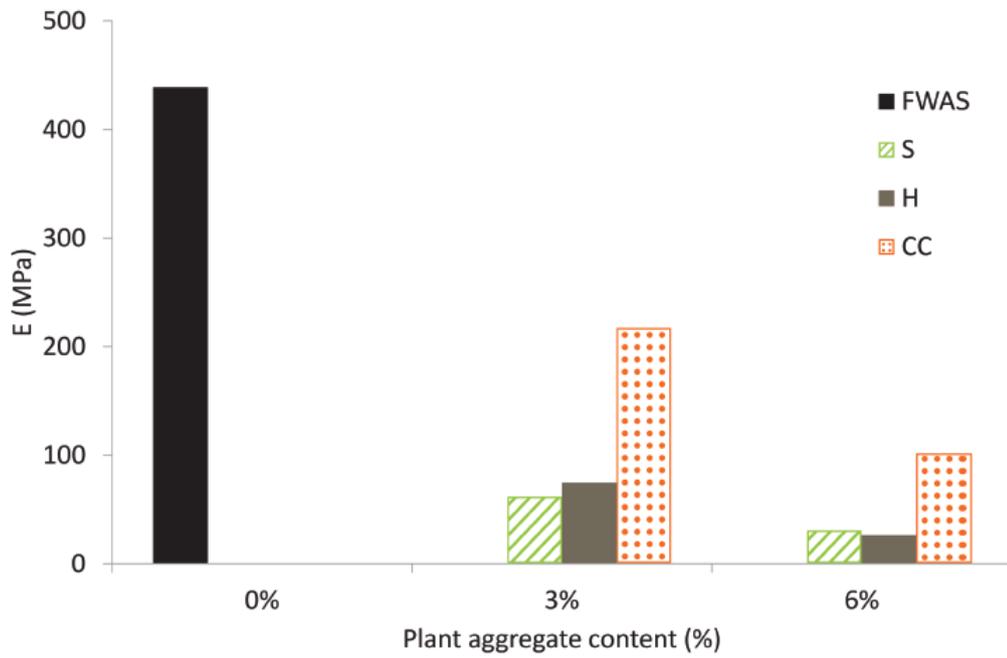
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824 Figure 13. Young's moduli of the materials for both protocols



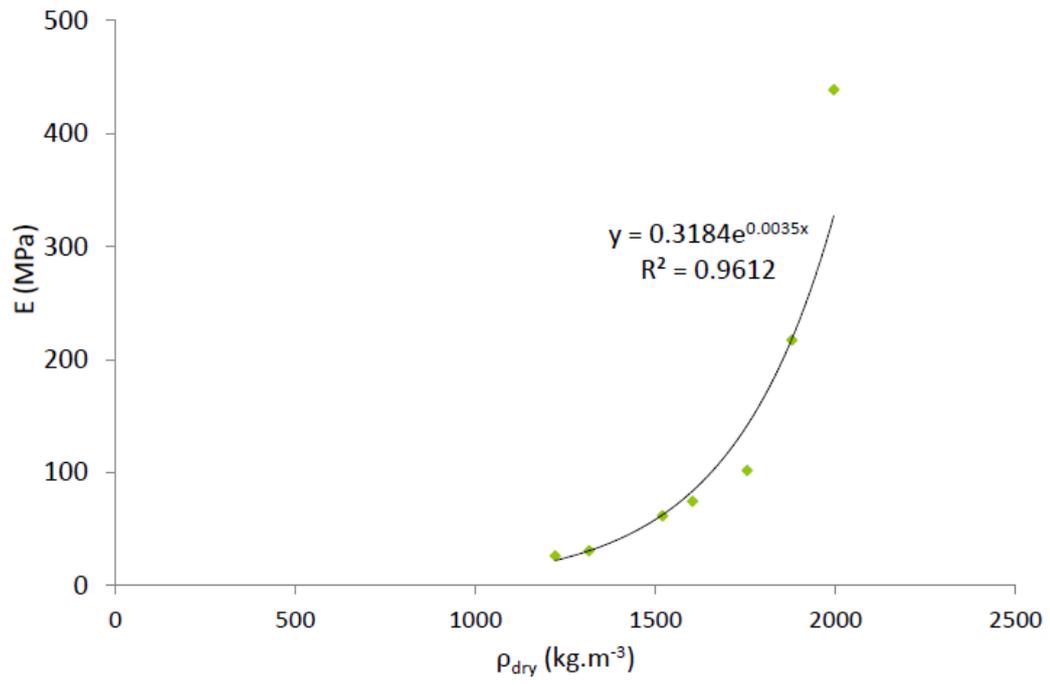
825
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827 Figure 14. Young's modulus from compressive test as a function of the plant
828 aggregate content



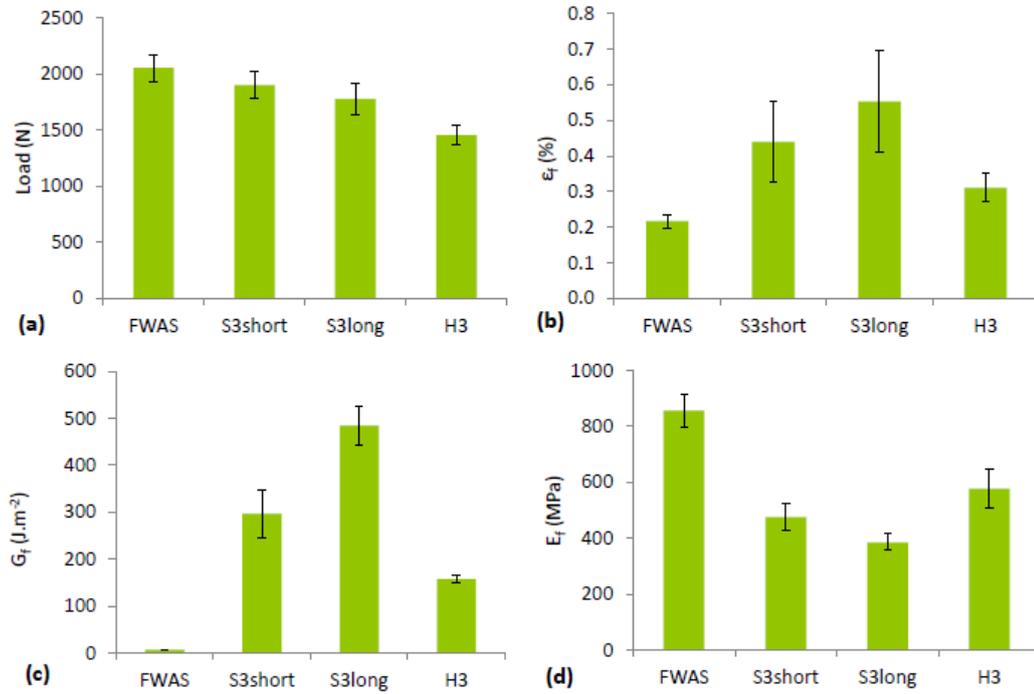
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831 Figure 15. Young's modulus as a function of the density



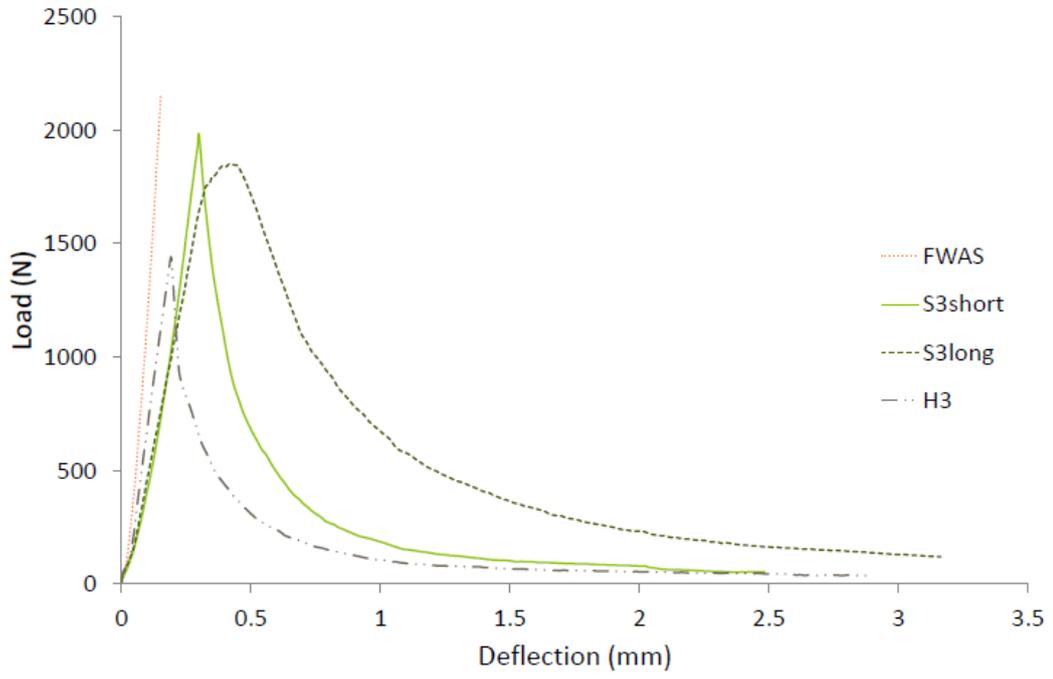
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834 Figure 16. Influence of the plant aggregate on flexural behavior: (a) Flexural load-
835 carrying capacity, (b) Peak strain (ϵ_f), (c) Average fracture energy (G_f) and (d)
836 Young's modulus



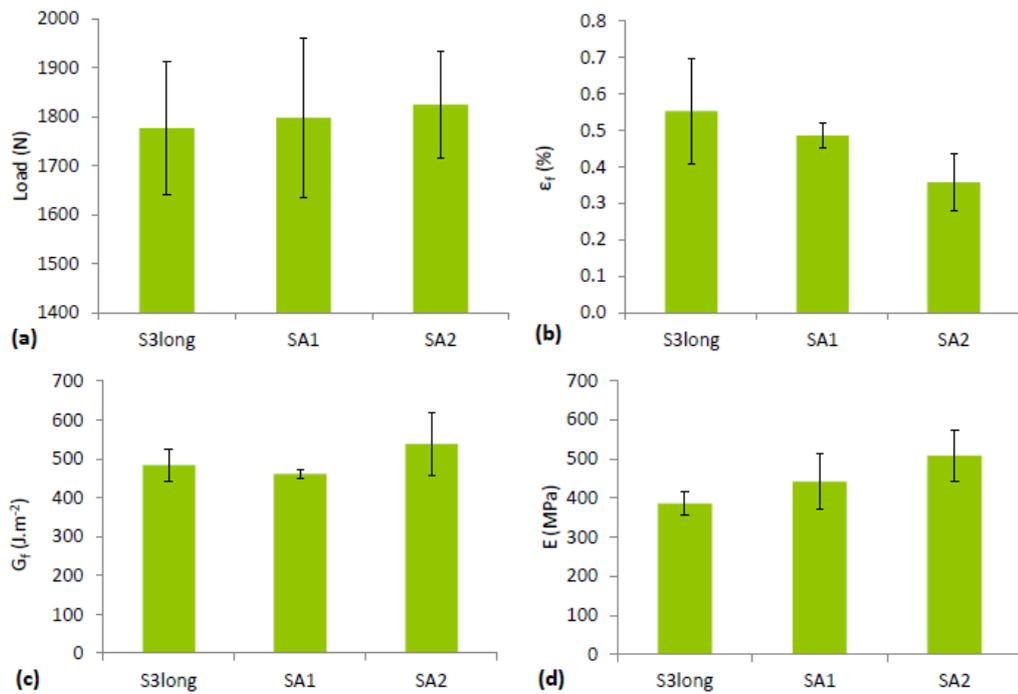
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839 Figure 17. Typical load-deflection curves



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842 Figure 18. Influence of the surfactants on flexural behavior: (a) Flexural load-
843 carrying capacity, (b) Peak strain (ϵ_f), (c) Average fracture energy (G_f) and (d)
844 Young's modulus



845