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1 DESIGN OF A SOIL CONCRETE AS A NEW BUILDING MATERIAL –
2 EFFECT OF CLAY AND HEMP PROPORTIONS

3
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10
11 **Abstract**

12 This study aims to optimize the composition of new ecological concrete constituted of upgraded
13 excavated soil. The novelty of this study is the fact that earth concrete is poured with classical
14 vibration as ordinary concrete. Several soil concrete mixtures, composed of different proportions of
15 clayey soil, sandy soil and small amounts of cement, lime and hemp fibers have been tested. The
16 mineralogical composition of clayey soil was studied by X-ray diffraction (XRD) analysis The
17 chemical composition was established by Environmental Scanning Electron Microscopy (ESEM)
18 coupled with the X-Ray Energy Dispersive Spectrometry (EDS). Casting of concrete mixtures has
19 been realized by vibration, as ordinary concrete, to obtain the required workability on construction
20 sites. Compressive tests have been carried out on samples at different curing times. Ultrasonic non-
21 destructive technique has been used to monitor the hardening of soil concrete. As this concrete
22 presents important volumetric changes that can cause the infiltration of water and impact their
23 durability, an experimental investigation on autogenous and drying shrinkage is reported. Water
24 porosity and water absorption tests have been also carried out to evaluate the transfer property of this
25 porous material. The results show that the compressive strength of soil concrete is greater than 1
26 MPa, which is sufficient for filling application (wall of a frame building) and increases to 5 MPa after
27 6 months. Compressive strength, density, and workability of the tested concrete mixtures decrease
28 with increasing clayey soil and hemp fibers. Desiccation shrinkage increases with the volume fraction
29 of clayey soil and hemp fibers.

31 **Keywords:** Earth concrete, hemp fibers, mechanical and physical properties, ultrasonic monitoring,
32 shrinkage.

33

34 **1 Introduction**

35 The ecological design of structures and sustainable development is nowadays of high importance in
36 the construction industry. Thus, alternative building materials such as soil concrete containing a
37 proportion of various ecological components are expected to be increasingly developed. The aim of
38 producing ecological concrete is to reduce the consumption of cement and thus the CO₂ production,
39 to provide an alternative to the scarcity of raw materials and to reduce the energy consumption in the
40 production process. Recently, many changes have been observed in the construction methods with
41 the aim to replace traditional concrete by alternative construction materials such as concrete
42 containing a high proportion of various ecological components called "green" while maintaining
43 acceptable properties for the desired application. The use of local materials is then strongly
44 encouraged to minimize energy consumption [Kenai & al., 2014; Gonçalves & Martins., 2012]. For
45 instance, constructions made of cost-effective raw soils are of real interest since their hydrothermal
46 performance and acoustic properties are more important than that of ordinary concrete [Henri &
47 Hugo, 2017, Palumbo & al., 2018]. However, more research is needed in order to have a better
48 understanding of the mechanical properties and the durability of soil concrete.

49 Regarding the use of subgrade soil in concrete, it can be stabilized by using different kind of binders
50 as lime and cement [Laborel-Préneron & al., 2016; Nalbantoglu & Tuncer, 2001; Rao & Shivananda,
51 2004; Tallah & al., 2016; Sariosseiri & Muhunthan, 2009; Makki-Szymkiewicz & al, 2015]. Soil-
52 lime stabilization is due to the pozzolanic reaction where aluminous and siliceous minerals in clay
53 react with lime to produce calcium silicates and aluminates that bond the particles together [Kumar &
54 Gupta, 2016; Maubec & al., 2017]. The addition of cement increases the mechanical properties faster
55 but can induce shrinkage and cracking [Kumar & Gupta, 2016; Costas, 2015]. Pozzolanic reactions
56 are time and temperature dependent requiring longer hydration time with lime than cement [Eades &
57 Grim, 1960]. Many studies showed that from 2% to 4% of lime, the Atterberg limits increase slightly,
58 then stabilize and decrease when the amount of lime reaches 8% [Bell, 1996; Khattab & al, 2007; Al-

59 Mukhtar & al, 2014]. The increase of the rate of lime and cement increases the compressive strength
60 [Bell, 1996; Costa, 2015]. The studies on lime modified soils showed that the optimal proportion of
61 lime is about 3-6% in order to considerably modify the mechanical and the physical properties of the
62 soil [Bell, 1996; Khattab & al., 2007; Al-Mukhtar & al, 2010]. Osinubi [Osinubi, 1998] and
63 Nalbantoglu [Nalbantoglu & Tuncer, 2001] showed that the compressive strength and the
64 permeability of soil strongly increase when the lime proportion is about 1-4%, while only a slight
65 increase has been observed when the lime is between 3% and 7% of the total mass. Recently a hyper-
66 compacted earth concrete was developed and showed interesting mechanical properties with
67 compressive strength up to 30 MPa [Bruno et al, 2017].

68 In most of these studies, the modified soil is set up by compaction to produce a construction material.
69 There is then a lack of knowledge regarding the use of soil in concrete having a minimum of
70 workability to be casted with traditional vibration procedure. The originality of the proposed research
71 study is that the formulated concrete has a good workability in order to be poured easily in
72 formworks. The research of Hibouche [Hibouche, 2013] showed that, the treatment of soil with 8%
73 of cement, 3% of lime and 0.4% of linen fibers allows the casting of a new soil concrete with
74 interesting performances ($f_c \geq 0.5$ MPa) for filing application in building. Recently, [Ouellet-
75 Plamondon & Habert, 2016] studied the rheological properties of self-compacted clay-based concrete
76 and showed the potential of this material for the construction industry.

77 The addition of natural fibers as hemp fibers is particularly interesting as it minimizes the volume of
78 waste in landfill. It is renewable and environmentally friendly [Zak & al., 2016; Khosrow & al.,
79 1999]. Moreover, hemp fibers are naturally produced, and require almost no energy for their
80 production and treatment. This makes hemp fibers concrete a carbon-negative construction material
81 [Boutin & al., 2005; Saez-Perez & al., 2020]. Different binders can be used in hemp concrete [Sinka
82 & al., 2018; Haik & al., 2020]. The addition of fibers can reduce the density, the shrinkage and
83 cracking of concrete and improve the hygrothermal and acoustic properties in addition to its fire
84 resistance [Makki-Szymkiewicz & al, 2015; Mostefai, 2015; Antonyova & al., 2017; Grubesa & al.,
85 2018; Del Mastro & al., 2019]. Kumar and Festugato [Kumar & Gupta, 2016; Festugato & al., 2017]
86 showed that the addition of fibers reduces efficiently the development of tensile, shear cracks and soil

87 deformation. This is due to the bridge effect of fibers and load redistribution related to the increase of
88 the total contact area between fibers and soil particles and consequently the friction between them
89 [Taallah & Guettala, 2016]. A review of the properties and the different factors that affect the
90 properties and the performance of hemp concrete can be found in [Jami & al., 2019; Saez-Perez &
91 al., 2020]

92 Concrete volume change is an unavoidable phenomenon, from very early age to long-term behavior
93 [Barcelo & al., 2001] and more particularly with soil concrete containing a high proportion of fines
94 [Kanema & al., 2016; Omid & al., 1996 a, b]. At early age, cementitious materials go through
95 negative volumetric variations, due to chemical origins and thermal shrinkage linked to the hydration
96 of the cement [Radocea, 1994]. The evaporation of water (drying shrinkage) and internal reactions
97 (autogenous shrinkage) will result in the development of stresses within the liquid phase that leads to
98 a volume reduction [Wang & al., 2001; Dias, 2003; Hover, 2006]. Autogenous shrinkage depends
99 mainly on the composition of concrete and develops more rapidly with time than drying shrinkage
100 [Audenaert & al., 2002; El-Dieb, 2007]. Drying shrinkage depends on the age of the beginning of
101 drying and external parameters such as relative humidity and specimen size. If the tensile strength of
102 concrete is lower than the stress level caused by movement restraint, cracking occurs [Hannant & al.,
103 1999]. This cracking during shrinkage depends on the type of restraint, caused by the structure
104 (externally applied restraint) and the material (internal restraint). Therefore, soil concrete structures
105 are vulnerable to self-stresses or shrinkage cracking which may reduce their serviceability and
106 durability. Thus, the understanding of shrinkage process and more particularly drying shrinkage,
107 known as the main cause of micro and macro cracking, is essential.

108 In this study, soil concrete, which can be set up by vibration as traditional concrete, has been
109 developed by incorporating optimal proportions of cement, lime and hemp fibers. Due to the
110 variability of the available soils, an experimental investigation is proposed to study the effect of the
111 proportion of clayey soil and hemp fibers on the mechanical and physical characteristics of the
112 designed concrete.

113 **2 Experimental program**

114 **2.1 *Materials and test methods***

115 Five different materials were used i.e. clayey soil, sandy soil, cement, lime, and hemp fibers. Cement
116 and lime were added to stabilize the soil and to increase the compressive strength. The soils used in
117 this study were obtained from two local construction sites and are classified according to the Unified
118 Soil Classification System (USCS). The distribution of coarse particles was determined by sieve
119 analysis while the distribution of fine particles was analyzed with the sedimentation method.

120 **2.1.1. *Clayey soil***

121 Clayey soil is characterized in laboratory. Table 1 presents the results obtained by granulometric and
122 sedimentation methods, Atterberg limits and methylene blue tests. They clearly indicate that the soil
123 is "clayey with low plasticity" ($I_p = 21.66$ and $W_l = 51.74\%$).

124 The clayey soil mineralogy was also studied by X-ray diffraction (XRD) analysis [Smith & al.,
125 2001]. XRD patterns were obtained using a PANalytical PW3020 Bragg-Brentano θ - 2θ geometry
126 diffractometer equipped with a secondary monochromator over an angular range $2\theta=3^\circ$ - 80° .

127 Figure 1 shows the XRD patterns. The obtained peaks were identified using embedded database
128 under EVA processing software. The diffractogram illustrates that the main minerals are:
129 palygorskite, calcite, muscovite, goethite and dominated mainly by quartz.

130 The Environmental Scanning Electron Microscopy (ESEM) coupled with the X-Ray Energy
131 Dispersive Spectrometry (EDS) was also used to observe the microstructure and complete the
132 chemical composition of clayey soil. Figure 2 shows the ESEM images and the corresponding X-Ray
133 EDS chemical maps. Figure 2a and 2b show a high magnification image of clayey soil while Figure
134 2c shows low magnification BSE image indicating a granular arrangement. The phase spectrum of
135 the sample is presented in Figure 2d. The mineralogical interpretation of the phase spectrum reveals
136 that it is dominated by quartz, muscovite and goethite.

137 *2.1.2. Sandy soil*

138 The main characteristics of the studied sandy soil are presented in Table 2. It is characterized by
139 medium fineness of 2.33 and about 72% of sand. The grain size distribution of clayey and sandy soils
140 is shown in Figure 3.

141 *2.1.3. Hemp fibers*

142 In this study, hemp fibers are used as a reinforcement material. Those fibers are one of the most
143 natural common fibers and low-cost in France. Hemp fibers stem is constituted of a woody core with
144 a hollow open sponge structure surrounded by bast fibers and are categorized as vegetal granulates.
145 Their lengths vary between 5 and 25 mm with diameters less than 2 mm. Hemp fibers density is
146 about 100 kg/m³ in ambient condition [Del Mastro & al. 2019]. The thermal conductivity is equal to λ
147 = 0.05 W/m.K. Hemp fibers are highly hydrophilic and can absorb water up to 2.5 times of their
148 weight.

149 *2.1.4. Lime*

150 The non-hydraulic lime (100 NHL5) from Saint Astier product (France), chosen in accordance with
151 the European standard EN 459-1, is added to the tested concrete mixtures.

152 *2.1.5. Cement*

153 The cement CEM V (SV) 42.5 N is chosen based on two different principal criteria (clinker ratio and
154 CO₂ impact). The main components and the mechanical properties of the cement are presented in
155 Tables 3 and 4.

156

157 **2.2 Composition of the tested concrete**

158 A series of laboratory tests have been conducted on different soil concrete mixtures in order to study
159 the possibility of increasing the clay proportion considering a mix design. Percentage of clayey soil
160 was varied between 0% and 40% (0A, 20A, 30A, 40A) while the volume fraction of hemp fibers was
161 modified from 0% to 1.2% (0F, 0.6F, 1.2F) for the 12 studied mixtures presented in Table 5.

162 The slump of these mixtures varies between 6.5 cm and 16.5 cm according to the percentage of
163 clayey soil and hemp fibers. As the percentage of water is kept constant, soil concrete molding was
164 more difficult with increasing the percentage of clayey soil and hemp fibers. For this reason, water
165 content was increased to keep acceptable workability for construction industry (slumps > 6 cm).

166

167 **2.3 Specimens dimensions and preparation**

168 Dry components, as shown in Figure 4a, were first introduced in a blender (cement, lime, soil, and
169 hemp fibers) and mixed for 5 minutes in order to obtain a homogeneous mixture. Water was then
170 progressively added to ensure the mixing homogenization (Figure 4b). Slump test was conducted just
171 after mixing to ensure a good workability with at least a slump of 7 cm.

172 Concrete was then poured in cubic molds with dimensions of $10 \times 10 \times 10 \text{ cm}^3$ (Figure 4c) in two
173 layers. Each layer was compacted with a vibrating needle as an ordinary concrete. At least three
174 samples were casted as replicates for each mix. Note here that the oversized gravels (higher than 10
175 mm) have been removed from the used soil to ensure a good workability. Specimens are conserved
176 under sealed conditions by covering them with a plastic sheet to prevent the drying of earth concrete.
177 After 24h, specimens were removed from the molds and conserved in a plastic box under a
178 temperature of 20°C and a relative humidity between 90% and 100%, without direct contact between
179 water and specimens.

180

181 **2.4 Compressive tests**

182 The unconfined compressive tests have been carried out by using an electromechanical machine
183 having a capacity of 50 kN. The loading of concrete has been applied with a steel plate at a constant
184 rate of 0.5 mm/min by means of jack displacement. Specimens have been equipped with two sensors
185 to measure the vertical displacement and two sensors for horizontal displacements (Figure 4d).

186

187 **2.5 Three-point bending test**

188 Three-point bending fracture tests were also achieved on soil concrete beams with the dimensions of
189 $100 \times 150 \times 600 \text{ mm}^3$ ($L \times h \times b$) and an effective span (S) equal to 500 mm. The fracture test uses a load-

190 controlled universal testing machine as per RILEM-TMC 50 recommendations [RILEM, 1985]. Tests
191 were conducted using an electromechanical machine with a capacity of 100 kN under closed-loop
192 crack opening displacement (CMOD) control with two LVDT sensors placed at the bottom of the
193 beam (Figure 5). The load was applied with a crack opening displacement rate of 0.2 mm/min.

194

195 **2.6 Measurement of the ultrasonic pulse velocity**

196 A movable system composed of a pulse generator PUNDIT (Portable Ultrasonic Nondestructive
197 Digital Indicating Tester) with a direct transmission mode was used (Figure 6). A pulse of ultrasonic
198 longitudinal stress waves with a frequency of 200 kHz is introduced into one surface of the concrete
199 by a transducer coupled to the surface with a coupling gel. The pulse travels through the concrete and
200 is received by a similar transducer coupled on the opposite surface. The propagation velocity is
201 calculated using the relation in equation 1. Before each measurement, the device was calibrated
202 according to the test procedure presented in figure 6.

$$203 \quad V = \frac{L}{t} \text{ (m/s)} \quad \text{Eq.1}$$

204

205 Where t is the propagation time and L the propagation distance.

206

207

208 **2.7 Durability tests**

209 The durability of earth concrete is closely related to the porosity and more particularly to the fluid
210 penetration and moving through the material. Thus, controlling the processes of drying and wetting
211 of concrete is of main importance in order to understand degradations, which can occur with time.

212 **2.7.1 Water porosity measurement**

213 The porosity can be used as an indicator of the durability of concrete. Thus, water porosity
214 measurements have been carried out and correlated with concrete properties as the compressive
215 strength and the corresponding effect of clayey soil and fibers. Two specimens with dimensions of
216 5×5×5 cm³ were used for each mix at 28 days. Specimens were first dried to constant weight in
217 ventilated oven at 60°C. Specimens were then placed in a hermetic glass bell under a low pressure of
218 one bar of vacuum during 24 h. Then, the bell was filled with water and the specimens kept under

219 vacuum with low pressure for 24 hours to equilibrate and ensure full saturation of specimens. The
220 weights of specimens were then measured in air and water. Porosity P (%) was calculated as follows:

$$221 \quad P = \frac{m_{sat} - m_{dry}}{m_{sat} - m_{sat}^{sub}} \times 100 (\%) \quad Eq.2$$

222 where:

223 m_{dry} : oven-dry weight of specimen.

224 m_{sat} : saturated weight of specimen (weighed in air)

225 m_{sat}^{sub} : saturated submerged weight of specimen (weighed in water)

226 The bulk density ρ_{app} (kg/m³) is also calculated as :

$$227 \quad \rho_{app} = \frac{m_{dry} * \rho_{wat}}{m_{sat} - m_{sat}^{sub}} (\text{kg} \cdot \text{m}^{-3}) \quad Eq.3$$

228 Where ρ_{wat} is the water density (1000 kg/m³).

229

230 2.7.2 Capillarity absorption measurement

231 The capillary water absorption was measured according to the AFNOR standard XP P 13-901
232 (AFNOR-XP P13-901). Specimens with dimensions of 10×10×10 cm³ have been used for each mix at
233 28 days. Specimens were first dried to constant weight in oven at 60°C. Then, the specimens were
234 immersed in a thin layer of water (10 mm) and the mass of specimens was continuously measured
235 (Figure 7).

236 The water absorption coefficient is calculated according to the following formula:

237

$$238 \quad C_b = \frac{100 * (P_1 - P_0)}{S \sqrt{t}} (\text{g/cm}^2 \text{min}^{1/2}) \quad Eq.4$$

239

240 Where:

241 C_b : capillary coefficient

242 P_1 : Weight of the specimen after immersion in water (g)

243 P_0 : Weight of the specimen before immersion in water (g)

244 S : Submerged surface of the specimen (cm²)

245 t : Water immersion time of the specimen (min)

246

247 **2.8** *Shrinkage and water loss measurement tests*

248 Soil concrete specimens were prepared with prismatic molds of 4x4x16 cm³. Specimens were
249 covered with a thin sheet of plastic to prevent water loss and maintained at 20°C during 24 h. Then,
250 specimens were unmolded and shrinkage measurements were performed on drying and sealed
251 specimens (Figure 8a). For this latter, the exchange of moisture was prevented by covering specimens
252 with a double layer of self-adhesive aluminum paper. Shrinkage tests were performed in a controlled
253 climate chamber at 60% of RH and a temperature of 20°C.

254 For drying shrinkage, specimens were not covered on lateral sides, except for the top surfaces, in
255 order to create a one-dimensional drying. Shrinkage of hardened soil concrete was measured with a
256 device equipped with an LVDT sensor (Figure 8b), which allows following the length of the
257 specimen. Weight loss was simultaneously measured in parallel for a better comprehension of
258 shrinkage phenomenon.

259 **3 Results and discussions**

260 **3.1** *Compressive test results*

261 Three specimens have been tested for each mixture and the mean value and the standard deviation
262 have been calculated. The uniaxial compressive strength of the tested specimens, with free lateral
263 expansion, is defined as the ratio of the axial ultimate force to the cross-section. Figure 9 shows
264 typical curves of the compressive strength versus the vertical and horizontal strain at 7 days, 28 days,
265 and 180 days for the mixture N°12 (40% of clayey soil and 1.2% of hemp fibers). The results show
266 that the mechanical properties (compressive strength and Young modulus) increase significantly
267 even after 28 days, on the contrary to ordinary concrete. After 180 days, compressive strength
268 reaches values more than twice that measured at 28 days. The elastic modulus increases from 2 GPa
269 at 7 days to 8 GPa at 180 days. After the maximum loading, mechanical behavior of the material is
270 less ductile with respect to curing time. This strength increase, after a long curing, is related to the
271 formation of hydration products as the CSH and ettringite due to the presence of cement and lime in
272 addition to the carbonation that may be responsible of a denser structure [Balciunas & al., 2018].

273 Figures 10 to 12 show the effect of clayey soil and hemp fibers on the compressive strength at 7, 28,
274 and 180 days respectively when specimens were cured under controlled relative humidity (20°C and
275 90-100% RH). The standard deviation of the results is less than 0.025 MPa, which is of about 4% at 7
276 days. This variability is due to the heterogeneity of sandy and clayey soil and to the multi-scale
277 porous structure [Collet & al. 2008].

278 The results show that the compressive strength decreases slightly with the addition of clayey soil at 7
279 days and varies between 0.6 and 1.2 MPa (Figure 11). The compressive strength varies between 1
280 and 2.4 MPa at 28 days and between 2.5 and 5 MPa at 180 days (Figure 11, and 12). However, the
281 effect of clay proportion on compressive strength is small (less than 0.3 MPa) when clayey soil
282 volume fraction varies from 20 to 40%. This effect is not significant when the compressive strength
283 is stabilized at 180 days.

284 The addition of fibers in soil concrete with 0% of clayey soil decreases the compressive strength at 7,
285 28 and 180 days. This effect is more significant at 28 and 180 days (about 0.8 MPa of variation).
286 However, with the addition of clayey soil, the effect of fibers shows low variations. A significant
287 effect can be only observed for 1.2% of fiber at 28 and 180 days in which the compressive strength
288 decreases of about 0.5 MPa. This negative effect of fibers on the compressive strength may be due to
289 the lower density, the change of the soil concrete structure, the intergranular void and pore
290 distribution by introducing voids and discontinuity [Awwad & al., 2012]. The addition of fibers as
291 reinforcement in soil concrete specimens can hinder the lateral strain during compressive loading
292 [Hannawi & al., 2016], which can explain the observed ductility on the stress-strain curves of soil
293 concrete with fibers. In addition, fibers can be responsible of the increase of the friction angle at the
294 shear cracking surface [Chabannes & al., 2017].

295 The effect of the curing time of soil concrete on the compressive strength has also been studied.
296 Figure 13 shows the evolution of the compressive strength for the different mixtures at 7, 28, and 180
297 days. The results show that the compressive strength increases even after one month. This is an
298 important property of this concrete compared to traditional concrete. The short-term compressive
299 strength is mainly associated to cement hydration, while the long-term compressive strength may be
300 provided by the hydration reaction, the pozzolanic reactions between clay minerals and calcium

301 hydroxide formed by cement hydration [Si Ho & al., 2017]. In addition, a part of water is stored in
302 claim which leads to the hydration of cement even after 28 days as long as water is available.

303 The measured compressive strength of soil concrete is low (from 1 to 2.4 MPa at 28 days) compared
304 to ordinary concrete. However, these strengths are acceptable regarding the application of this kind of
305 concrete which is used as a filling concrete and not for assuring high load capacity (e.g. walls,
306 Blocks, etc.) [Mazhoud & al., 2017]. This is due to the very low percentage of cement the higher
307 porosity of soil concrete constituted of fine-grained mixtures and the higher water content required to
308 achieve an acceptable workability. However, the acoustic and thermal properties could be better than
309 traditional concrete due to the use of clayey soil and hemp fibers.

310

311 ***3.2 Bending test***

312 The knowledge of tensile strength is important as tensile stresses can be generated by shrinkage, by
313 seasonal variations in temperature, by alternate wetting and drying and by loading that can generate
314 tensile and shear stress [Ozkul & Baykal, 2007]. Figure 14 shows the average load CMOD curves for
315 soil concrete with respect to clayey soil proportion variation from 0 to 40 % and the percentage of
316 fibers from 0 to 1.2%. The load-CMOD variations are linear up to about 80% of the ultimate load
317 followed by a nonlinear variation up to the peak load. A stable failure was then observed in the post-
318 peak region. The results show that the bending strength decreases largely with the addition of clayey
319 soil. However, the addition of hemp fibers improves the fracture properties as the bending strength,
320 the fracture energy and the ductility of soil concrete. This may be attributed to the good interfacial
321 adhesion existing between the fibers and the matrix leading, at some load level, fibers bridging the
322 crack to be activated in carrying tensile stresses and thus decreasing the crack propagation kinetic
323 [Donkor & Obonyo, 2015; Iucolano & al., 2019].

324

325 ***3.3 Monitoring of soil concrete by using the Ultrasonic method***

326 The Ultrasonic Pulse Velocity (UPV) of the mechanical P waves depends on the same parameters
327 that influence the mechanical properties such as density, porosity, and elasticity of the material
328 [Bungey & al., 2006; B.S., 1986]. Thus, the elasticity modulus and the compressive strength can be

329 determined based on the UPV values. The UPV is a non-destructive test that allows the monitoring of
330 concrete hardening and can be used to estimate the time of removing formworks, which can optimize
331 construction cost.

332 In this study, the UPV has been measured in order to study the effect of fibers and clayey soil on the
333 strengthening of the designed concrete mixtures with age. Cubic specimens with dimensions of
334 $10 \times 10 \times 10 \text{ cm}^3$ have been tested during four months of curing (from 5 days until stabilization).

335 The UPV of specimens of all mixes increases during the curing period with an important rate during
336 the first days indicating that soil concrete develops mechanical strength at early age (Figure 15).
337 After one month, UPV continues to increase slightly.

338 The effect of the variation of the volume ratio of fibers on the UPV is illustrated in Figure 15 a, b, c
339 and d for 0%, 20%, 30%, and 40% of clayey soil, respectively. The addition of hemp fibers decreases
340 slightly the UPV due to the decrease of the density. This slight effect is also observed for
341 compressive strength, which confirms the UPV results. It can be also noted that the UPV decreases
342 with the increase of clayey soil ratio, which could be related to the increase of concrete porosity
343 [Mandal & al. 2016]. In addition, UPV increases with a more important rate and amplitude for soil
344 concrete with 0% of clayey soil in comparison with mixtures with 20%, 30%, and 40% where a slight
345 difference has been observed for compressive tests.

346 Figure 16 presents the correlation between the compressive strength and the corresponding UPV
347 values at 7, 28, and 180 days. An exponential function can be considered by a regression analysis.
348 This statistical regression analysis consisted in calculating the exponential function parameters by
349 using least mean squares method that minimizes the error between the proposed function
350 (exponential in this case) and the experimental measurements. The results are presented in Figure 16
351 with a coefficient of determination of about $R^2 = 0.75$ that indicates a good correlation. Then, the
352 UPV measurements can provide effective means to determine the mechanical properties of soil
353 concrete [Mandal & al., 2016]. The UPV can be then used for on-site monitoring of soil concrete in
354 order to control the compressive strength variations during construction.

355

356 **3.4 *Shrinkage tests***

357 Figure 17 presents the evolution of autogenous and drying shrinkage versus time of soil concrete with
358 0%, 20%, 40% of clayey soil, and 0%, 1.2% of hemp fibers. The rate of autogenous shrinkage is
359 important during the first three days and decreases gradually with time (Figure 17a). Autogenous
360 shrinkage occurs independently of external water loss. It is a result of chemical shrinkage and self-
361 drying shrinkage. The reduction in the relative humidity in the pore system causes water–air
362 meniscus that subjects the pore walls to considerable stress and leads to substantial self-drying
363 shrinkage. The results show that autogenous shrinkage of soil concrete without fibers increases with
364 the proportion of clayey soil with values four times more important for the mixes with 40% of clayey
365 soils. The addition of 1.2% of fibers shows a slight increase of autogenous shrinkage for the mixes
366 with 0% and 20% of clayey soil. However, the addition of fibers decreases significantly the
367 autogenous shrinkage of soil concrete with 40% of clayey soil. These differences are related to the
368 variation of the global porosity between soil concrete mixes and the high water absorption of fibers
369 [Fourmentin & al., 2016; Stevulova & al., 2015].

370 Figure 17b represents the drying shrinkage calculated as the subtraction of the autogenous shrinkage
371 from the overall shrinkage. The rate of drying shrinkage increases quickly at the beginning to
372 stabilize between 10 and 15 days.

373 Drying shrinkage deformation increases with the rate of clayey soil and reaches important values for
374 soil concrete with 40% of clayey soil (6 times higher than that with 0% of clayey soil). The addition
375 of 1.2% of fibers influences slightly the amplitude of the shrinkage with 0% and 20% of clayey soil,
376 however it decreases the amplitude of drying shrinkage for the mix having 40% of clayey soil with an
377 important rate.

378 Water weight loss is also measured during drying shrinkage and presented in Figure 18a. The
379 variation of water weight loss transcribes the diffusion capacity of the material. The weight loss is
380 important during the first 15 days. The water weight loss shows the same tendency as drying
381 shrinkage. The water weight loss increases with the proportion of clayey soil, which could explain
382 the increase of drying shrinkage. The addition of fibers increases the water weight loss for soil
383 concrete with 0% and 20% of clayey soil while it decreases the water weight loss for soil concrete

384 with 40% of clayey soil. The water weight loss shows a good correlation with the amplitude of
385 shrinkage. Thus, the evolution of the drying shrinkage is also plotted as a function of the weight loss
386 (Figure 18b). Two phases can be distinguished, during the first phase called sleeping zone, the
387 gradient of water content due to drying generates a stress gradient and thus a high tension in the skin
388 layer and cracking. The surface area to volume ratio is an important factor in this phase. During the
389 second phase, gradients become more pronounced and the cracking in the skin remains unchanged
390 and shrinkage is proportional to drying (linear zone). Soil concrete shrinkage is very high in
391 comparison with ordinary concrete due to the absence of large aggregate that restrain the overall
392 shrinkage and to the higher porosity related to the incorporation of clayey soil and the high water
393 content.

394

395 ***3.5 Durability tests: water porosity and water absorption***

396 Figure 19a presents the evolution of the bulk density versus the clayey soil proportion and hemp
397 fibers at 7 and 28 days. The results show that the increase of the percentage of clayey soil and fibers
398 decreases the bulk density. The bulk density is about 1763 kg/m^3 for soil concrete with 0% of clayey
399 soil and decreases to 1534 kg/ m^3 with the addition of 1.2% of hemp fibers at 28 days. In addition,
400 the bulk density increases with age due to different hardening mechanisms as cement hydration.
401 These values are in accordance with those obtained in the literature and indicate the potential of hemp
402 fibers and clayey soil to reduce the thermal conductivity of concrete [Taallah & Guettala. 2016].

403 Figure 19b describes the correlation between the compressive strength and porosity at 7 days and 28
404 days. An exponential regression equation is fitted to the data in accordance with the literature for
405 porous material [Lian & al., 2011]. As expected, the compressive strength decreases with mixtures of
406 higher porosity. In fact, as the density decreases, the number of contact points, responsible for
407 transmitting stress, decreases leading to the decrease of the compressive strength.

408 Capillarity absorption measurements were conducted in order to study the ability of the material to
409 absorb water. The capillary suction through the pores system can be then used as an indicator of the
410 open porosity. Figure 20a represents the water absorption coefficient for soil concrete with various
411 fibers and clayey soil content. The results show that the addition of clayey soil and hemp fibers

412 increases the capillary absorption. The kinetic of water absorption is related to the kinetic of filling
413 pores with water shown by a stabilization of weight specimens. This kinetic depends on complex
414 phenomenon related to the connectivity between the pores where water may be transferred through
415 the multiscale micro porosity in the matrix, at the interface between the matrix and the fibers or even
416 in the cell structure of hemp fibers [Colinart & al., 2020]. Figure 20b shows that the water absorption
417 coefficient (calculated at 6 hours) is between 8.2 and 14.3 for soil concrete without fibers, while the
418 water absorption coefficient for soil concrete with fibers varies from 11.4 to 15.2. This can be
419 explained by the increased voids created in the mixture due to the existence of fibers and clay and
420 their hydrophilous behavior [Khiari & al., 2010, Shafiei & al., 2010; Pejic & al., 2008]. Similar
421 values have been obtained by [Colinart & al., 2020].

422 **4 Conclusions**

423 The development of a new environmentally friendly construction material has been realized in this
424 study using local soil as a principal component. The effect of clayey soil and hemp fibers on the
425 mechanical properties of soil concrete have been studied. Twelve concrete mixtures with different
426 percentages of clayey soil and hemp fibers have been tested under controlled relative humidity.

427 The results show that the compressive strength of the tested concrete decreases with increasing the
428 proportion of hemp fibers and clayey soil which could be related to the increase of the porosity of soil
429 concrete. The slight negative effect of fibers on the compressive strength may be also due to the
430 lower density and the change of the soil concrete structure and pore distribution by introducing voids
431 and discontinuity. In addition, the compressive strength continues to increase even after one month
432 with values two times higher than that measured at 28 days. The measured compressive strength
433 varies from 1 MPa to 5 MPa with slump higher than 6.5 cm depending on the curing condition, the
434 clayey soil, and hemp fibers proportions. The UPV decreases with the addition of clayey soil and
435 hemp fibers showing a good correlation with the compressive strength.

436 Autogenous shrinkage increases with the increase of the proportion of clayey soil. Drying shrinkage
437 increases with the rate of clayey soil and reaches important values for soil concrete with 40% of
438 clayey soil (5 to 6 times higher than that with 0% of clayey soil). The addition of 1.2% of fibers

439 influences slightly the amplitude of shrinkage with 0% and 20% of clayey soil. However, it increases
440 the amplitude of drying shrinkage for the mix having 40% of clayey soil with an important rate due to
441 the change in the porosity that modifies the evaporation rate and consequently the rate of shrinkage.
442 Durability tests indicate that the porosity and water absorption increase with increasing soil
443 proportions. The incorporation of hemp fiber for density reduction and improving the thermal and
444 acoustic properties leads to an increase of the water absorption of about 9% for concrete with 20% of
445 clayey soil.

446 The generalization of this study may have a limitation since a specific clayey soil has been used
447 without the incorporation of additives. Additional studies should be done in order to evaluate the
448 effect of clay mineralogy and other additions, such as water reducer plasticizer, on the mechanical
449 and physical properties of earth concrete. Tests are currently investigated in order to study the
450 dimensional stability of soil concrete regarding shrinkage at early age, creep and
451 humidification/drying cycles.

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651 **TABLES**

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653 **Table 1: Characteristics of clayey soil**

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Test	Criterion	Value (%)	USCS
Atterberg limits	Liquid limit W_L	51.74	Clayey with low plasticity (CL)
	Plastic limit W_P	30.08	
	Plasticity index I_P	21.66	
Sedimentation and Granulometric tests	Clay (< 0,002 mm)	25.06	
	Silt (0,002 – 0,06 mm)	55.94	
	Sand (0,06 – 2 mm)	19	
	Gravel (>2 mm)	0	
Methylene Blue test	VBS	5.72	Clayey silty soil

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657 **Table 2: Characteristics of sandy soil**

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Test	Criterion	Value (%)	USCS
Granulometric	Silt (0,002 – 0,06 mm)	0.64	
	Sand (0,06 – 2 mm)	72.54	
	Gravel (> 2 mm)	26.82	
Blue methylene	VBS	0.67	Sandy soil
Specific density (kg/m ³)		2.33	
Fineness modulus		2.57	SP
C_U		4.38	Poorly graded sands, gravelly sands, low fines
C_C		2.28	
Sand equivalent			
Visual		78.44	
With the piston		76.32	

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661 **Table 3: Mineralogical composition of cement**

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Type of cement	Main components (% by weight)			Secondary component
	Clinker Portland	Blast furnace cinder	Fly ash	
CEM V/A (S-V)	40 - 64	18 – 30	18 - 30	0 - 5

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Table 4: Compressive strength of cement

Resistance class	Compressive strength (MPa)			Time of setting (min.)	
	Short-term strength		strength at 28 days		
	2 days	7 days			
42,5 N	≥ 10,0	-	≥ 42,5	≤ 62,5	≥ 60

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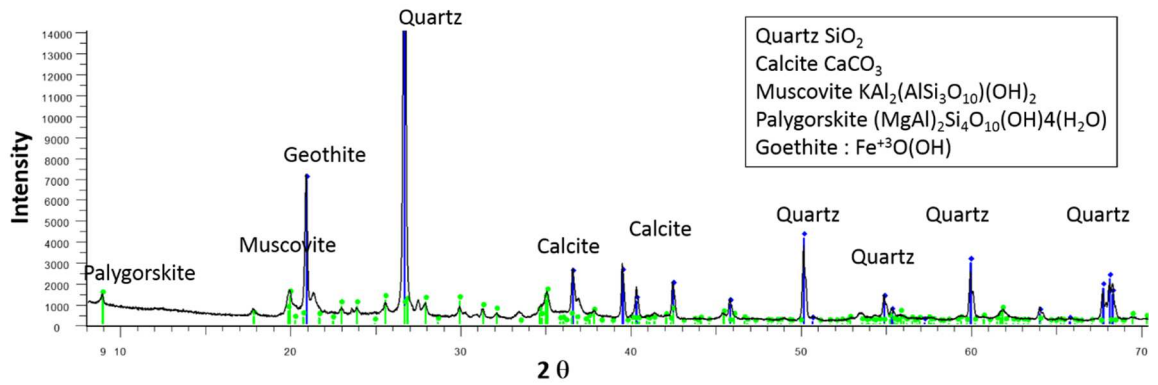
Table 5: Proportions of the different soil concrete mixtures

N°	Mixes	Clayey soil (kg/m ³)	Sandy soil (kg/m ³)	Cement (kg/m ³)	Lime (kg/m ³)	Fibers (kg/m ³)	Water (kg/m ³)	Slump (cm)
1	0A0F	0.00	1386.8	151.8	45.0	0.0	330.6	16.5
2	0A0.6F	0.00	1306.2	144.3	42.8	12.0	314.2	16.2
3	0A1.2F	0.00	1238.2	138.0	40.9	22.9	300.6	15.7
4	20A0F	247.8	991.4	135.6	40.2	0.0	398.9	10.5
5	20A0.6F	241.4	965.7	133.3	39.5	11.1	392.1	14.8
6	20A1.2F	236.6	946.7	131.9	39.1	21.9	388.0	9.5
7	30A0F	368.3	859.5	134.4	39.9	0.0	417.6	9.5
8	30A0.6F	356.3	831.5	131.2	38.9	10.9	407.7	6.5
9	30A1.2F	345.3	805.7	128.3	38.1	21.3	398.7	14.0
10	40A0F	501.1	751.7	137.1	40.7	0.0	466.1	12.5
11	40A0.6F	476.6	714.9	131.6	38.8	10.9	447.3	7.3
12	40A1.2F	454.4	681.6	126.6	37.6	21.0	430.5	10.5

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684 FIGURES

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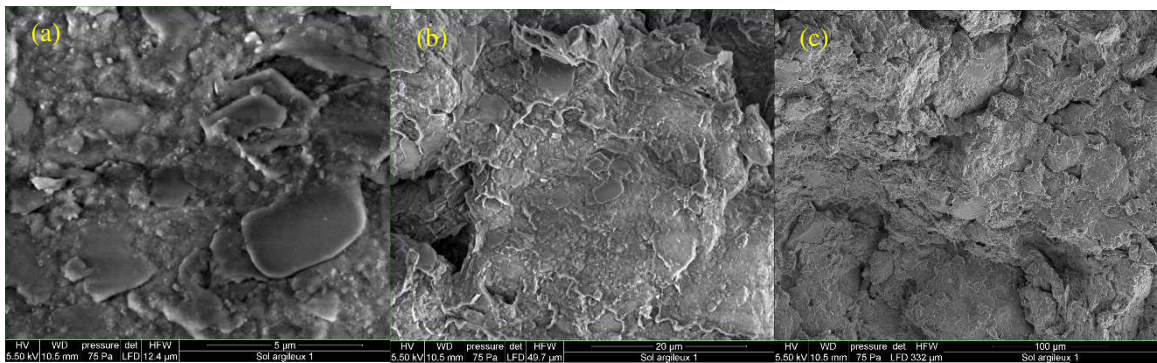
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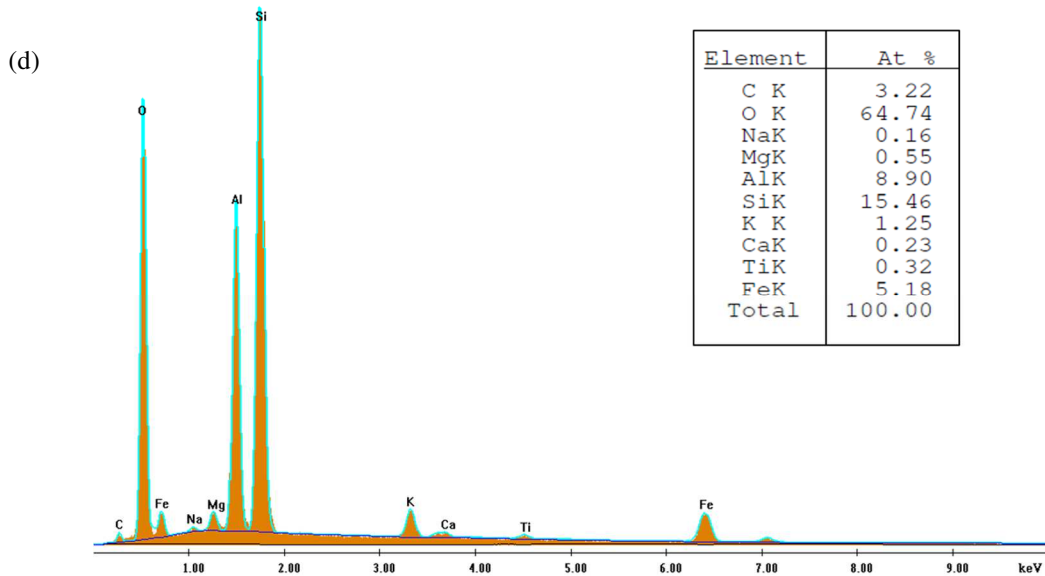
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Figure 1: X-Ray Diffraction patterns of clayey soil sample



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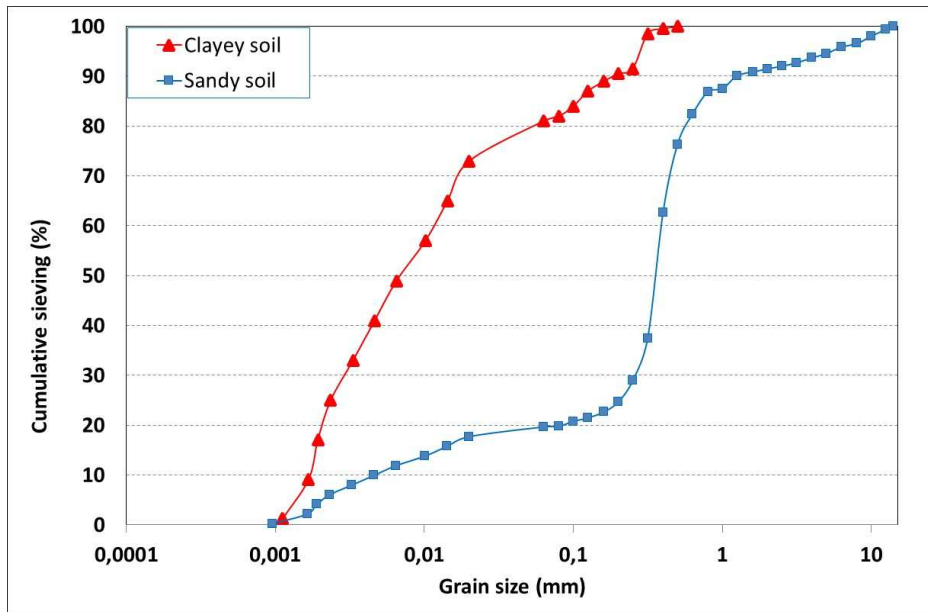
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Figure 2: Secondary Electron (SE) high magnification image (a,b), Back Scattered Electrons (BSE) low magnification image (c) Average phase spectrum



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Figure 3: Grain distribution of clayey and sandy soil.



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Figure 4: General view of the casted concrete, a) dry materials, b) fresh soil concrete, c) fresh concrete in cubic molds d) compressive test setup on cubic soil concrete (d)



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Figure 5: General view of the three-point bending test on soil concrete beams

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Figure 6: Measurement of the Ultrasonic Pulse Velocity

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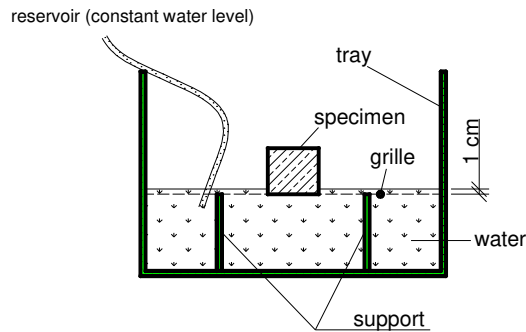


Figure 7. Schema of capillary absorption measurement

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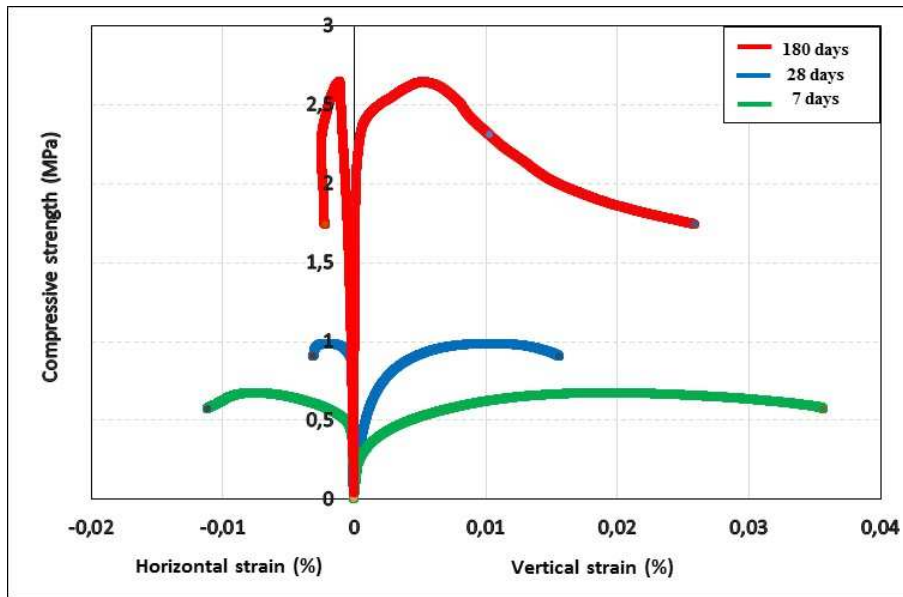
Figure 8a



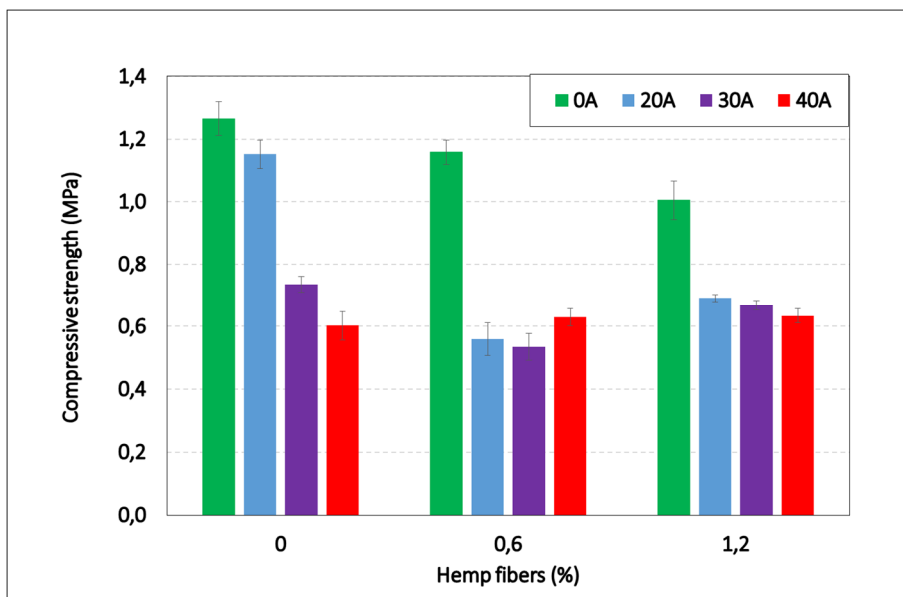
Figure 8b

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Figure 8 : Autogenous and drying conditions of specimens and device measurement



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Figure 9: Compressive strength versus vertical and horizontal strain curves at 7 days, 28 days and 180 days



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Figure 10: Effect of clayey soil and fibers on the compressive strength at 7 days.

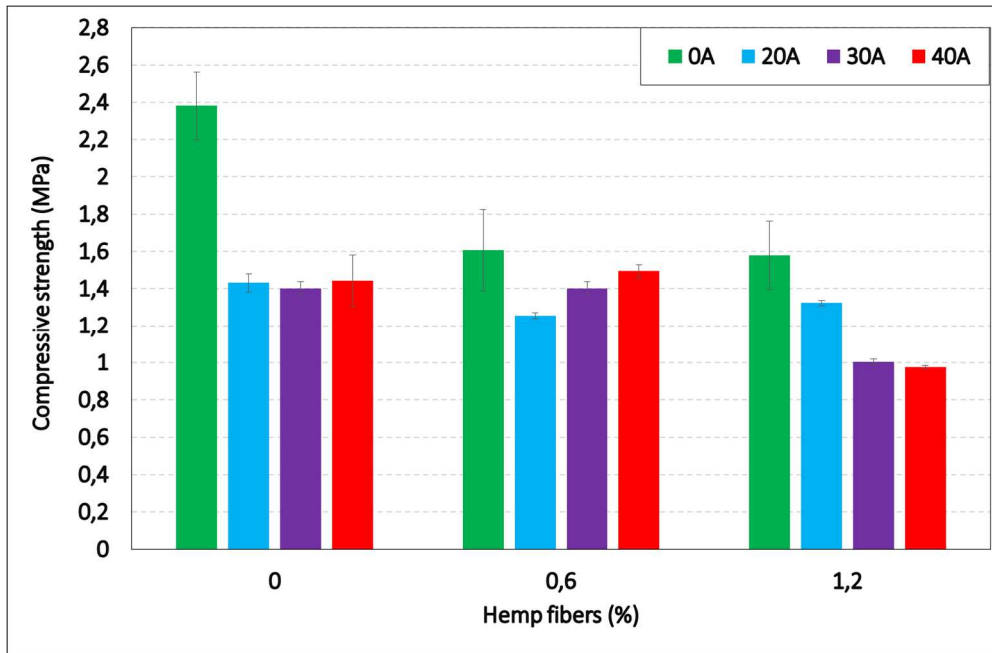


Figure 11: Effect of clayey soil and fibers on the compressive strength at 28 days.

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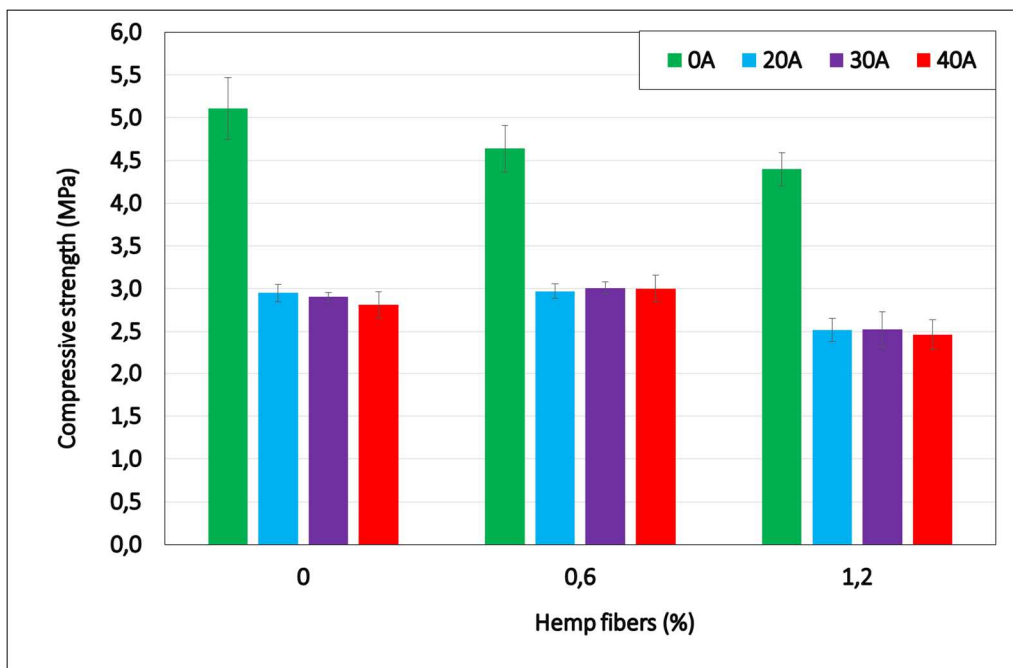


Figure 12: Effect of clayey soil and fibers on the compressive strength at 180 days.

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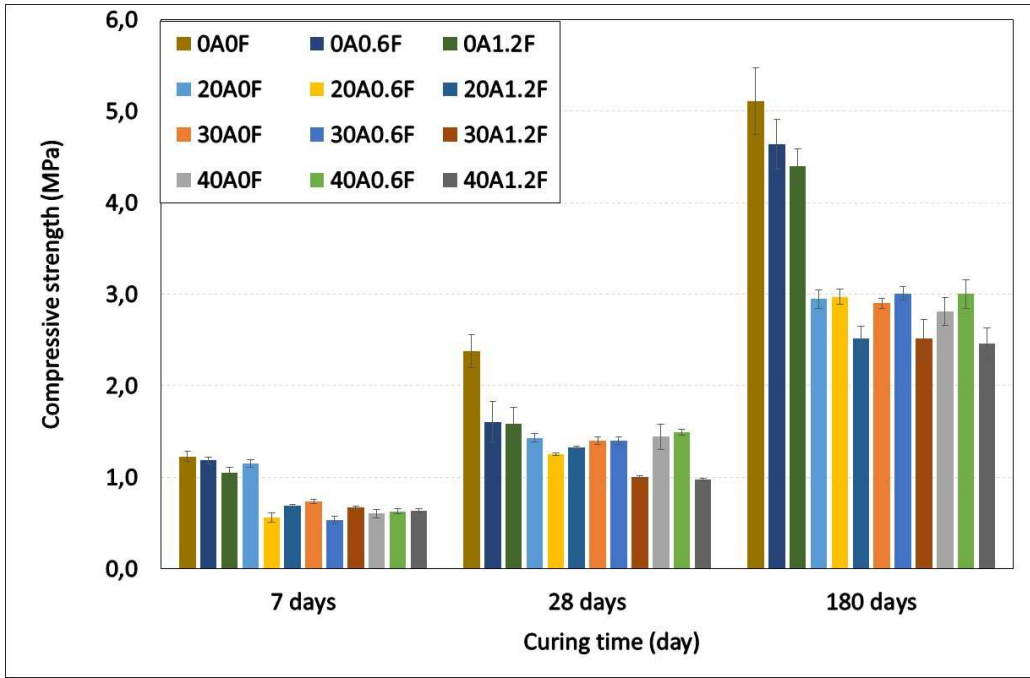


Figure 13. Compressive strength at 7, 28, and 180 days.

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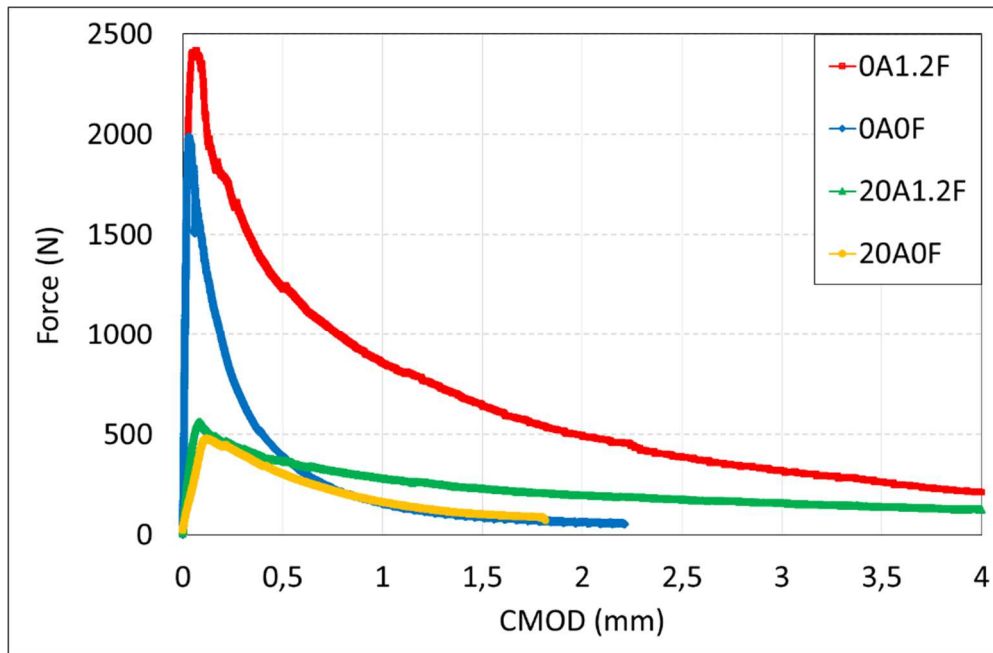
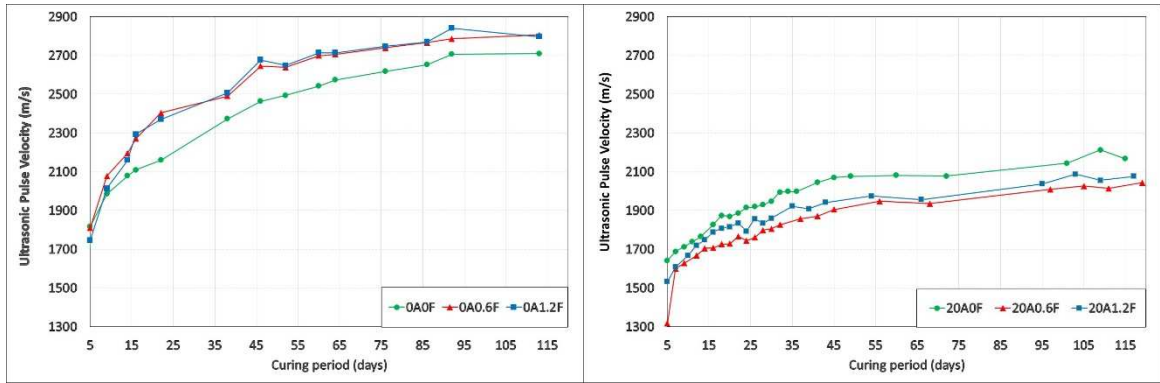


Figure 14: Influence of clayey soil and fibers on the flexural behavior

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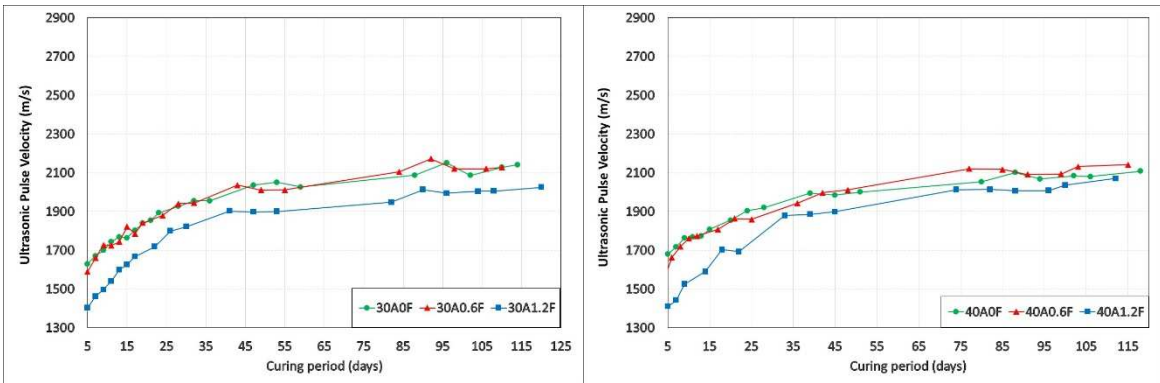
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(a)

(b)

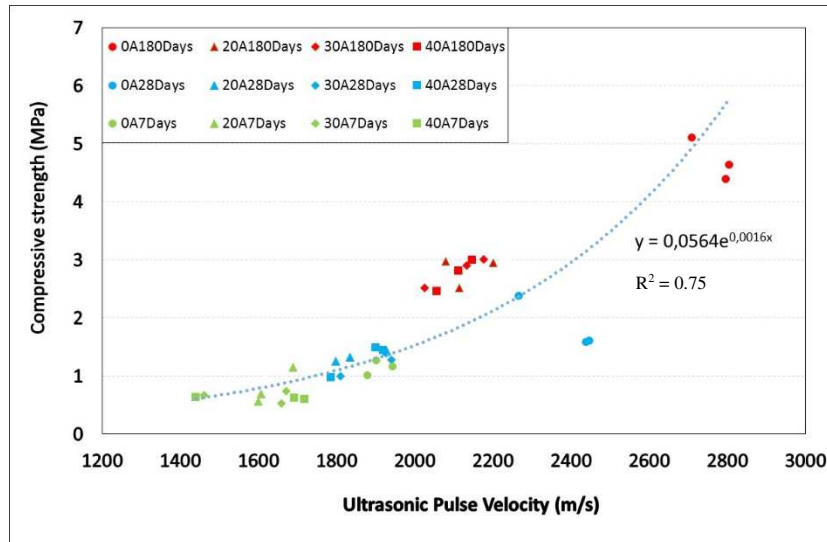


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(c)

(d)

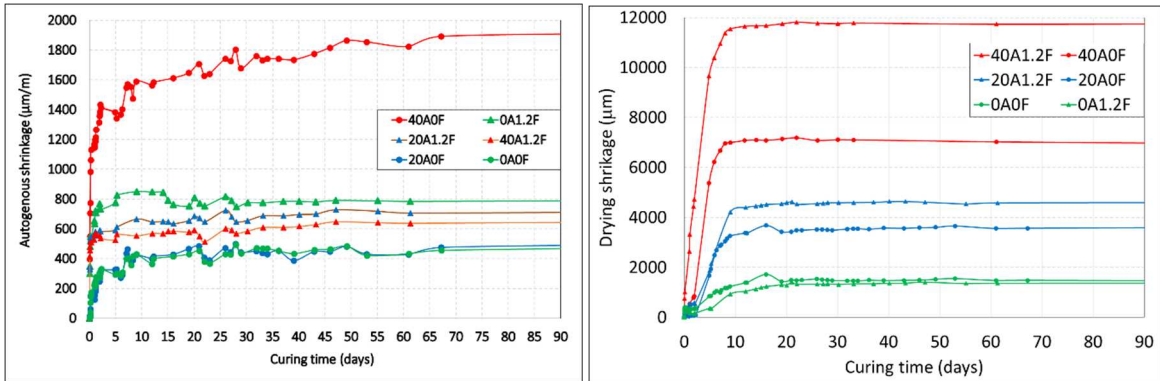
Figure 15: Influence of clayey soil and fibers on the Ultrasonic Pulse Velocity



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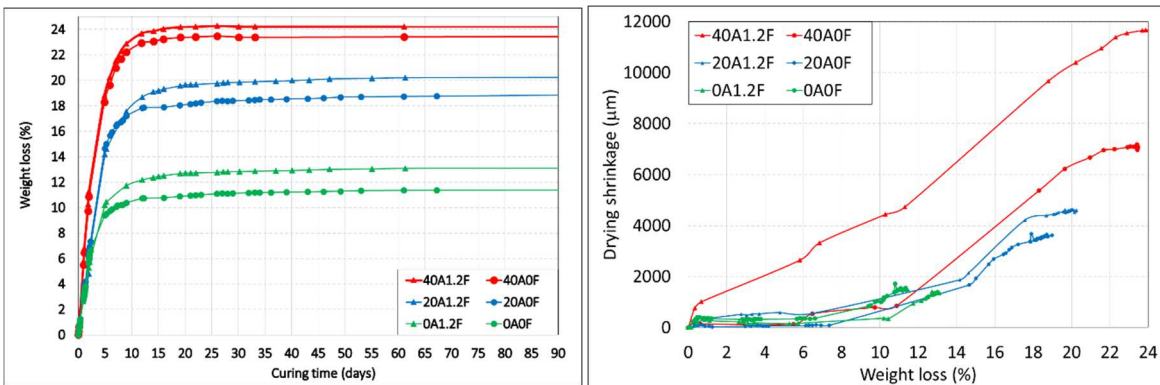
Figure 16: Correlation between Ultrasonic Pulse Velocity and compressive strength (at 7 days, 28 days and 180 days)

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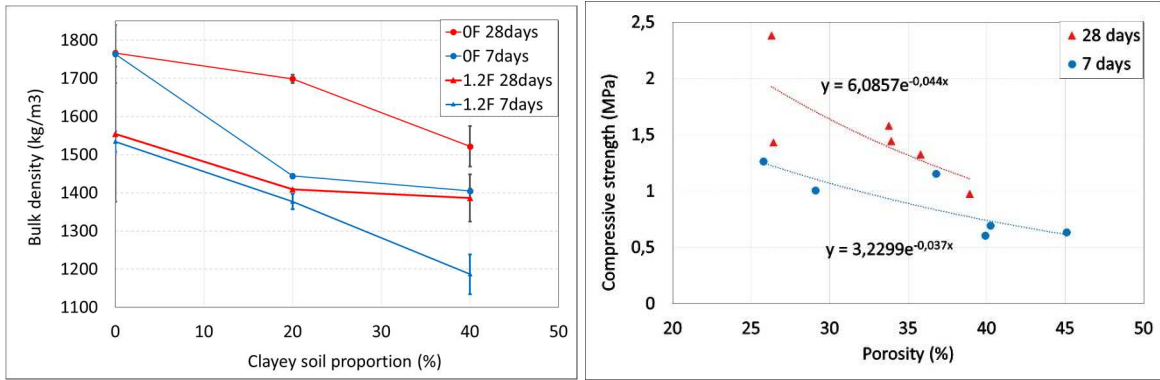
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Figure 17: Influence of fibers and clayey soil on the evolution of autogenous (a) and drying shrinkage (b)



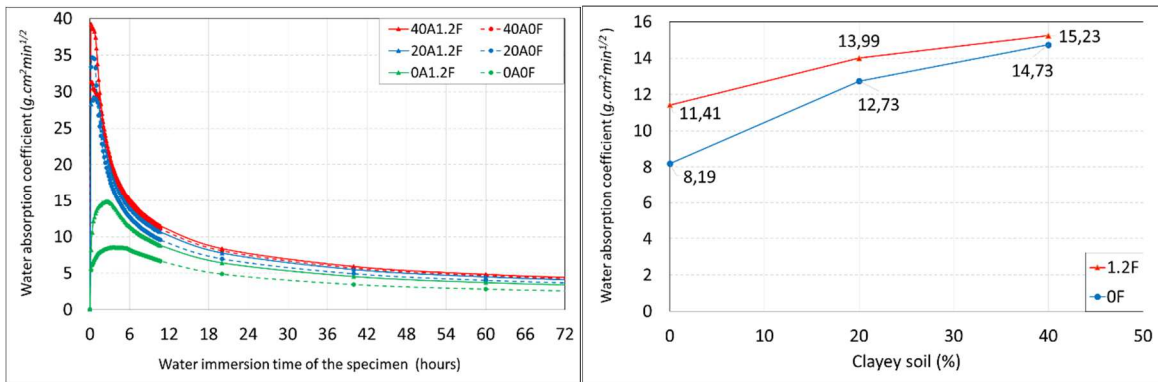
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Figure 18: Evolution of the relative weight loss during drying in function of time (a) and correlation with drying shrinkage (b)



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Figure 19: (a) Influence of fibers and clayey soil on the bulk density, (b) correlation between compressive strength and porosity



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Fig. 20a : The evolution of water absorption coefficient Fig. 20b : Water absorption coefficient at 6 hours

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Figure 20: Effect of fibers and clayey soil proportions on water absorption coefficient

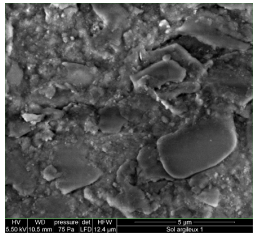
Design of ecological concrete with natural soil and hemp



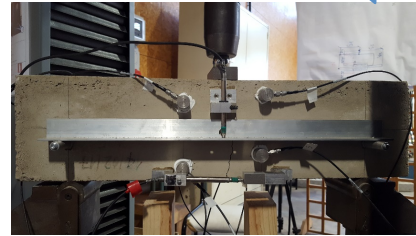
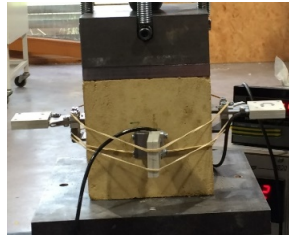
Local natural materials



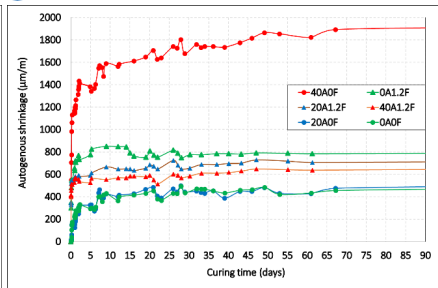
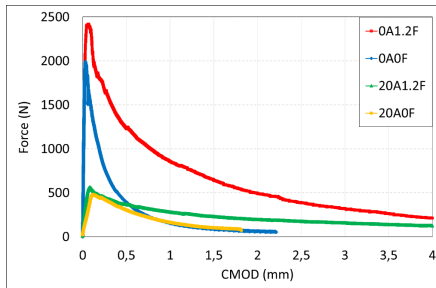
Plastic workability



X-ray



Mechanical properties and NDT testing



Filing concrete with interesting mechanical and physical properties with hemp incorporation