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1 Combined and synergic effect of algerian natural fibres and biopolymers on 2 the reinforcement of extruded raw earth

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15

16 Abstract

17 This paper deals with the development of sustainable building earth-based materials. More
18 precisely, it addresses the study of the reinforcement of raw earth with natural fibres
19 originated from Algeria (diss and date palm tree fibres) and their stabilisation with xanthan
20 gum. The aim of this study is the design of extruded earth-based building blocks with
21 improved mechanical properties such as compressive strength and ductility. The effects of
22 separate and simultaneous addition of date palm trees or diss fibres (with length varying
23 between 5 and 15 mm at dosages of 1.5 and 3% in volume) and stabiliser (xanthan gum and
24 HMP at 1 and 2% of the dry earth mass) on the flexural and compressive strength of the
25 stabilised and unstabilised extruded materials are compared. Results show that adding only
26 fibers decreases the compressive strength of the earth in comparison with the unreinforced
27 sample. It is also shown that diss fibres provides better reinforcing efficiency than date palm
28 tree fibres and that a combined addition of xanthan gum and natural fibres create a synergic
29 effect that greatly improved the material mechanical behaviour: higher compressive and
30 tensile strengths and better ductile properties. These results are fully supported by
31 microscopic observations and pull-out tests carried out on single fibres.

32 **Keywords:** Biopolymer, natural fibre, raw earth, extrusion, pull-out tests.

33

34 **1. Introduction**

35 Climate change is the major challenge that currently faces humankind. Anthropogenic carbon
36 dioxide emissions weaken societies especially in less advanced and developing countries [1].
37 Building materials such as concrete are responsible of a significant part of this human carbon
38 footprint [2] and it is required to find efficient alternative to conventional building materials
39 in order to decrease drastically the building industry's environmental impact [3–5]. It is also
40 worth noting that world's population is still growing and that affordable and sustainable
41 housing solutions have to be found.

42
43 One promising solution lies on the valorisation of natural resources or inert by-products of the
44 construction industry such as extracted and raw earths [6–8]. For instance, according to
45 Hamard et al. [7], at the scale of the French Brittany region (27 200 km²), earthwork induced
46 0.7 Mt / year of non-valued excavated earth which can cover a large part of the material needs
47 for local housing. Since about twenty years, many works have been carried out to reinvent
48 vernacular construction techniques and makes it compatible with conventional construction
49 techniques in terms of productivity and cost. However, raw earth material is a variable
50 resource which is very sensitive to water and may present limited resistance to seismic
51 loading which prevents its use in compliance with structural design standards in many
52 countries [9,10].

53
54 It is therefore required to provide guaranteed mechanical properties and improve the
55 durability of earth material in order to make it compatible with modern building design and
56 standards requirements. One solution is the use of hydraulic binders that are known to
57 efficiently increase the water resistance of raw earth while increasing their compressive
58 strength. This solution has been used for different techniques such as compressed earth blocks
59 [11,12], rammed earth [13–15] or extruded blocks[16,17]. . But, even at a limited dosage,
60 cement addition can make earth materials having a higher carbon footprint than concrete
61 blocks [18]. Moreover, according to Van Damme and Houben [19], the ratio between carbon
62 dioxide emission and compressive strength (carbon intensity ratio) is higher for cement-
63 stabilised raw earth than for other construction materials such as concrete or unstabilised raw
64 earth. Another drawback of this stabilisation technique is that cement or lime stabilised
65 materials require to undergo a humid cure in order to allow for the binder hydration as shown
66 by [16].

67

68 Another promising method of earth stabilisation consists in the addition of biopolymers that
69 have been used for centuries worldwide in vernacular constructions methods [20]. Many
70 studies have dealt with the stabilising effects of biopolymers of earth-based materials since
71 the early 2010's. In 2012, Chang and Cho [21] first studied the effect of β 1,3/1,6 glucan
72 biopolymer on the compressive strength of residual Korean soil. They show that the addition
73 of a small amount (less than 5g/kg) of the studied biopolymer is able to triple the compressive
74 strength while the addition of 10% of cement only leads to double the mechanical strength.
75 The β 1,3/1,6 glucan biopolymer induces the formation of crosslinked hydrogen bonding with
76 the clay particles that allows for the soil strengthening. It is worth noting that, according to the
77 authors, this stabilisation solution is less expensive and has less environmental impact than
78 the cement stabilisation.

79

80 Since, different biopolymers have been tested including cow-dung [22], alginate salt [23–27],
81 natural gum such as guar [28] or xanthan [29,30], linseed oil [24], chitosan [31], ...

82 Each type of biopolymer allows for an improvement of the material compressive strength and
83 can present additional beneficial effects such as rapid strengthening (alginate soil) [26,27] and
84 water resistance. For instance, recent studies have shown that biopolymers such as xanthan
85 gum and linseed oil are efficient to increase both compressive strength and water resistance
86 even at low dosage [30,32]. For example, xanthan gum is able to form a gel that can be bond
87 with clay particles through hydrogen and ionic bonds [28,30,33,34] while keeping earth
88 recyclable [35].

89

90 Nevertheless, even with cement or biopolymers stabilisation, earth remains a fragile mineral
91 material that displays low tensile strength and can be subjected to shrinkage during drying and
92 to fractures occurrence. The addition of fibres is a solution to reduce these weaknesses.
93 Natural fibres such as hemp or flax fibres can be found in large amounts and are already
94 valorised in order to make high performance composites materials. In Algeria, large amounts
95 of fibres from diss and date palm tree remain unevaluated and can be used in order to
96 reinforce earth-based building materials. Moreover, it is interesting to note that the use of
97 extrusion process in order to make building blocks is able to enhance the reinforcement effect
98 of natural fibres (improved cracking resistance and tensile strength) by creating an extrusion
99 pressure-induced better interface as shown by recent studies carried out with flax fibres
100 [36,37]. Like other modern processes including self-compacting earth developed at ETH
101 Zurich [8,38–41], hypercompaction [42] or vibrocompaction [29], use of extrusion is also

102 very interesting in order to meet the lowest porosity and the highest mechanical strength
103 [36,43].

104 It is also important to note that the combined addition of natural fibres and xanthan gum is
105 efficient in order to reinforce sand for geotechnical applications [44] and can be a good way
106 for the mechanical improvement of earthen construction material.

107

108 This study deals with the stabilisation of extruded earth-based materials with xanthan gum
109 and their reinforcement with diss and date palm tree fibres from Algeria to provide tensile
110 strength and ductility. Compressive and flexural strength measurements are performed and
111 show the effect of biopolymer and natural fibres on the mechanical properties of the material
112 and results are supported by observations and pull-out tests. It is, to the authors knowledge,
113 the first measurements of pull-out strength of natural fibres in a biopolymer stabilised matrix.
114 It provides new insights on the bonding improvement between fibres and matrix, brought by
115 the biopolymer. It is finally shown that the combined addition of xanthan gum and natural
116 fibres (especially diss with its rough surface) is able to provide ductile properties with
117 significantly improved mechanical strength (from 3.3 MPa for the reference sample to 4.5
118 MPa for the compressive strength and from 3.6 MPa to 8.4 MPa for the tensile strength. The
119 maximum values are obtained with a Diss fibre volume content of 1.5% and a xanthan gum
120 dosage of 1% of the earth weight ratio). It is worth noting that this study is limited to two
121 types of natural fibres and on a specific earth. These results will need to be generalised to
122 other earth mineralogy and particles size distribution in further studies. Moreover, the
123 economic and environmental pertinence of the proposed solutions have to be discussed
124 considering the local resources and context.

125

126

127 **2. Methods and materials**

128 **2.1 Methods**

129

130 2.1.1 Mixing and samples fabrication

131

132 Samples are fabricated using extrusion. This fabrication method requires some rheological
133 requirements in terms of earth material consistency and stability [36,45]. A minimal shear
134 yield stress is required for the extrudates handling [46]. Toutou et al., for cement-based
135 materials, targets a shear yield stress of 20 kPa [46]. In order to check that the materials have

136 the required consistency, cone penetrometry has been performed using the fall cone
137 conventionally used for the determination of the consistency limits of the soil (tip angle 30°,
138 cone weight 80g). The ASTM standard D4318 is used for the test protocol [47]. Penetration
139 test is a fast and sufficiently accurate method that can be used for the consistency evaluation
140 and also for an estimation of the material's yield stress [48,49]. The penetration of the cone is
141 performed using a controlab cone penetration device. The cone tip is placed on the sample
142 surface (cylindrical cup, 50 mm high and 50 mm in diameter) and is then released for 5
143 seconds. The penetration depth is measured using a digital length measurement device which
144 has a 0.01 mm accuracy. Preliminary tests have shown that tested materials can be extruded
145 when the penetration depth ranges between 3 and 5 mm.

146

147 For each extrusion, a material's mass of 2.5 kg was prepared. Dry materials (dried earth,
148 fibres, additives) are first hand-mixed together during one minute. Then, water is added and
149 the samples is mixed using a Hobart mixer at low speed during one minute and at high speed
150 during 4 minutes. Then, the bowl is scrapped and the material is mixed during 2 minutes at
151 high speed.

152

153 Penetration test is then carried out and if the penetration depth ranges between 3 and 5 mm,
154 extrusion is performed. Otherwise, a water correction is performed (step by step addition of
155 20 g of water). The used extruder is a VARS 50A/2-type from ECT. Screw rotational speed
156 was 15 rpm. A vacuum system is fitted on the extruder in order to reduce porosity. The
157 mixed earth-based material is fed into the extruder chamber (50mm inner diameter barrel) of
158 the single screw extruder via the hopper. The cylindrical shaped extruder die extrudates with a
159 diameter of 35 mm. Note that for unreinforced earth, cylindrical samples of the same diameter
160 were cast in order to provide additional value of compressive strength of the samples at lower
161 densities (no vacuum system, lower processing energy).

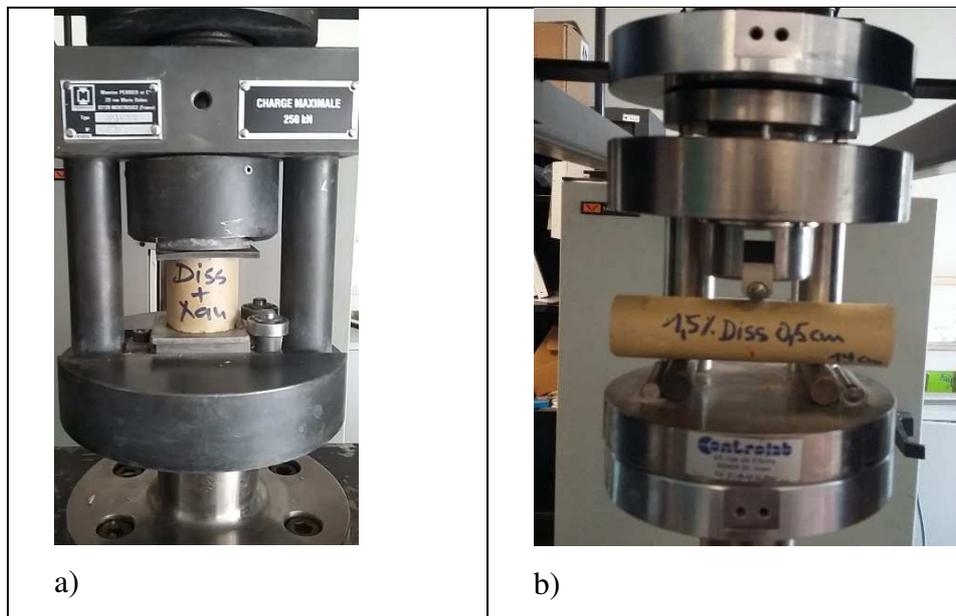
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163 2.1.2 Mechanical characterization

164

165 The mechanical characterizations were performed on an Instron 4505 load machine equipped
166 with a 100 kN load sensor (accuracy of 0.1 kN). Compressive and tensile (using 3-points
167 bending test) strengths are tested on 35 mm diameter cylindrical samples with lengths of 35
168 mm and 140 mm respectively, as shown in figure 1a and 1b. Samples are loaded using a
169 controlled displacement rate of 6 mm/min with an accuracy of 0.5%. It is an experimental test

170 protocol because there is no specific standard published with such geometry. For each tested
171 extrudates composition, five samples were tested in compression and in bending. Before
172 testing, samples are cut at the targeted length and are stored at controlled temperature of 40°C
173 with 50% of relative humidity until mass stabilisation, which occurs after approximatively
174 one week. Tests are carried out 14 days after the extrusion.
175



176
177 *Figure 1: Settings of strength measurement tests. a) compression configuration – b) 3-point*
178 *bending configuration*

179
180 2.1.3 Microstructural investigations

181
182 The transversal section of the fibres was measured using a CCD camera mounted on a LEICA
183 MZ16 trinocular magnifying glass. This device enabled to take pictures that were magnified
184 by 10 and allows for a length measurement with an accuracy of 1 μm .

185
186 Microscopic observations are carried out using a scanning electron microscope (SEM) to
187 characterise the morphology of Diss and Date Palm fibres. Fibres were cut transversely and
188 longitudinally, taking care not to alter their original state. Fibres and broken samples were
189 observed with a JEOL JSM-6460LV SEM at an acceleration voltage of 20 kV using
190 backscattered electron signals (BES).

191
192 2.1.4 Fibres tensile strength and Pull-out tests

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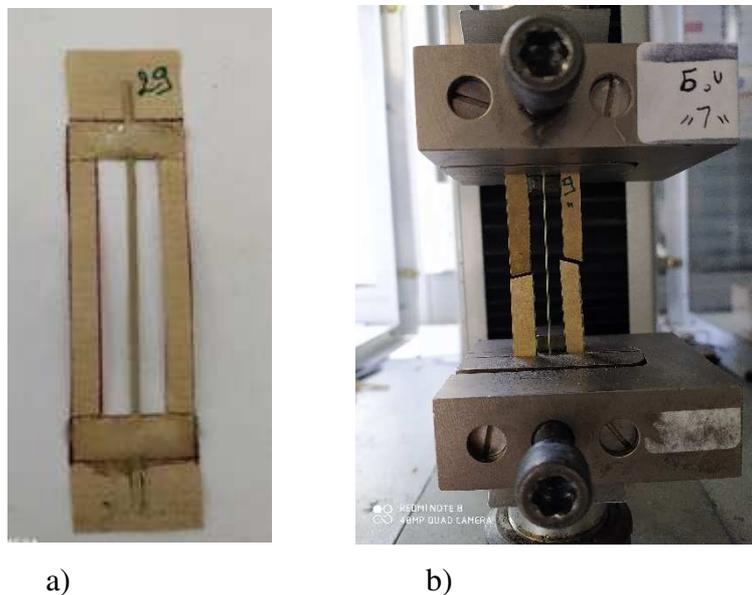
194 For the determination of the tensile strength of fibres, the used method is applicable for both
195 single ultimate fibre or bundles of fibres as in many works related to the topic [50–53].

196 Studied fibres have been attached to a hollow support made of paper as shown in figure 2a.
197 The hole has an opening of 60 mm which corresponds to the length submitted to tension. The
198 fibres are glued with araldite at their extremities in order to avoid any slippage at the device
199 fixation. Once prepared with their paper support, the fibres are attached on an MTS CMT4000
200 universal testing machine (figure 2b) used in a displacement-controlled mode at a constant
201 velocity of 0.1 mm/min with an accuracy of 0.1%. The load sensor has a capacity of 50 N
202 with a sensitivity of 1 N. It is an experimental test protocol because there is no specific
203 standard published.

204

205 In order to account for the natural variability of the fibres, tensile test measurements have
206 been carried out on 40 fibres which have been submitted to measurements of their transversal
207 section's dimensions. This allows for the computation of both, average tensile strength and
208 apparent Young modulus and the standard deviation of these results.

209



210

211

212

213 *Figure 2: Tensile strength measurements – a) Sample preparation with hollow support made*
214 *of paper and b) tensile loading machine.*

215

216 In order to investigate the quality of the bonds between stabilised earth and fibres, pull-out
217 tests are performed. The assessment of these interfacial properties is expected to help to

218 understand the reinforcement mechanisms and their potential efficiency for improving the
 219 tensile strength and the ductility of the extruded earth. The sample fabrication is based on the
 220 study of Lecompte et al. [37] who have developed a device that is intended to mimic the
 221 pressure effect induced by the extrusion process. As shown in figure 3a, the device consists of
 222 two drilled PVC plates, the lower plate is the bottom mould with a 1 mm diameter hole where
 223 the fibres can pass through. The top plate, with a 5 mm diameter hole, constitutes the cell
 224 mould into which the paste can be poured and pressed. An aluminium punch is used to apply
 225 a constant load on the poured earth. The pressure of 250 kPa is applied on the sample via the
 226 punch during 5 minutes. After the sample fabrication, it is removed from the plates 48 hours
 227 later. Then the samples are stored in a similar manner than the extruded samples until mass
 228 stabilisation before the mechanical characterisation.

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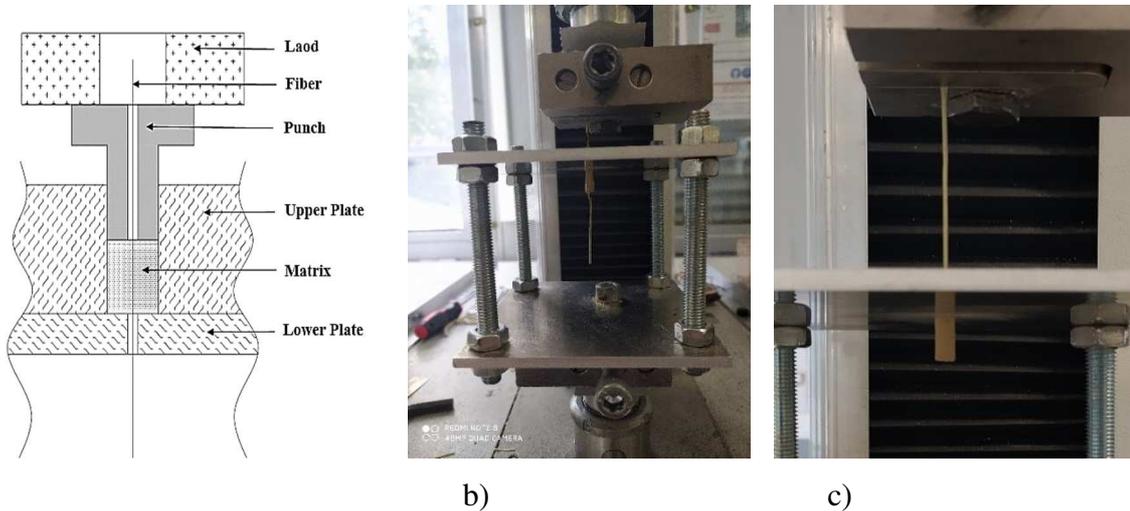


Figure 3: Pull out tests – a) sketch of the sample fabrication b) testing device c) sample mounted on the testing device.

236 Pull-out tests are performed using the same testing machine than the one used for the tensile
 237 strength of the fibres at a same constant controlled displacement velocity of 1 mm/s. A drilled
 238 dedicated plate is used to block the earth matrix while putting the fibre extension. It creates
 239 tension within the fibre and the shearing of the interface between the matrix and the fibre as
 240 shown in figures 3b and 3c. At least six samples were prepared for each type of fibres and
 241 matrix. During the test, the displacement and the tensile force are recorded. It is worth noting
 242 that no slippage occurred between the machine fixations and the fibre. The interfacial strength
 243 (pull-out strength) is considered to be the average interfacial shear stress which is computed

244 from the ratio of the maximum recorded force to the fibre section (measured using the
245 protocol provided in section 2.1.3).

246

247 **2.2 Materials**

248

249 2.2.1 Earth

250

251 The studied raw earth originates from the north of Rennes, France. It is a fine-grained clayey
252 soil, which displays a particle size distribution with 70% (in mass) of the particles having a
253 diameter under 20 μm (Figure 4). The particle size distribution is obtained through sieving
254 and laser diffraction technique for the particle having a diameter lower than 80 μm and the
255 average particle size is close to 10 μm . This earth has been used historically for cob
256 construction and the clayey part is composed of quartz, kaolinite, illite, chlorite and
257 vermiculite [25,32,54]. The earth plasticity index is 16.5 with a liquid limit of 46.2% and a
258 plastic limit of 29.7. The water content at the optimum proctor is 20.6% and the methylene
259 blue value of the soil is 1.03.

260

261 2.2.2 Natural fibres

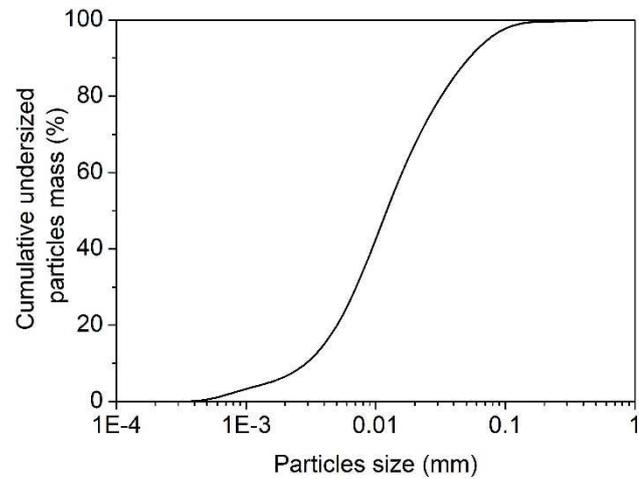
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263 In the frame of this study, natural fibres are used to reinforce earth-based materials by
264 providing them ductility and tensile strength. Diss and palm date tree fibres are tested in this
265 work.

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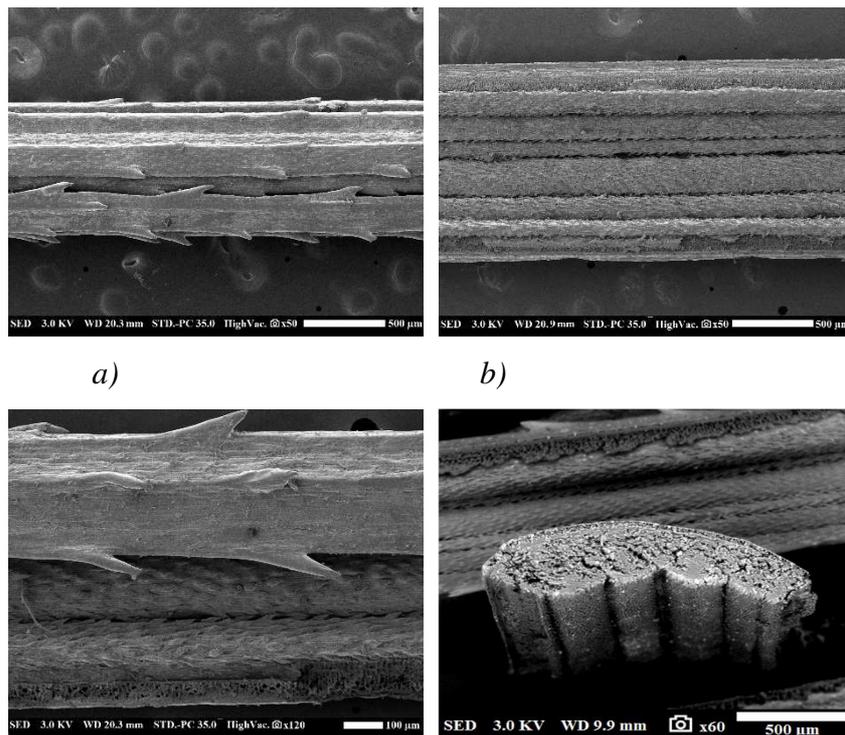
267 Diss (*Ampelodesmos mauritanicus*, Poaceae) is an herbaceous plant of the Gramineae family
268 with an average height of around one meter and containing extremely robust and rough fibres.
269 It is widespread over southern Africa, western Asia, south-western North America and
270 throughout the Mediterranean basin. Diss is abundantly available throughout the year
271 [55,56]. Diss fibres were historically vaporized as ropes, hats, bags and in construction of
272 diss fibres reinforced renders and hut roofs are reported taking advantages and the good
273 mechanical and thermal insulation properties. Recently, diss ability to reinforce matrix has
274 been assessed in order to develop cementitious or plastic composite materials [57–60]. The
275 specific mass of the diss is 1250 kg/m^3 . In this study, the used fibres were collected in the
276 region of Annaba (north-eastern Algeria). According to the study of Bourahli et al [61], diss

277 fibres contain about 44% of cellulose, 27% of hemi-cellulose, 17% of lignin, 9% of
278 extractives and 3% of ashes.



279
280 *Figure 4: Particle size distribution of the studied earth*

281
282 Fibres are cut in 5, 10 or 15 mm long pieces and present an average diameter of 0.94 mm
283 (measured using a trinocular magnifying glass). SEM observations of the Diss fibres (figure
284 5) show that outer surface of the fibres presents 100 μm long thorns, five times longer than
285 the inner ones (figure 5a to c). Thorns are distributed homogeneously all along the inner
286 surface. The fibres wall present a mixed tubular - cavernous structure with closed cavities
287 showing that they do not transport sap as shown by the cross-sectional view displayed in
288 figure 5d [59,62,63]. For the sake of simplicity, the fibres' sections are assumed cylindrical.



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c) d)

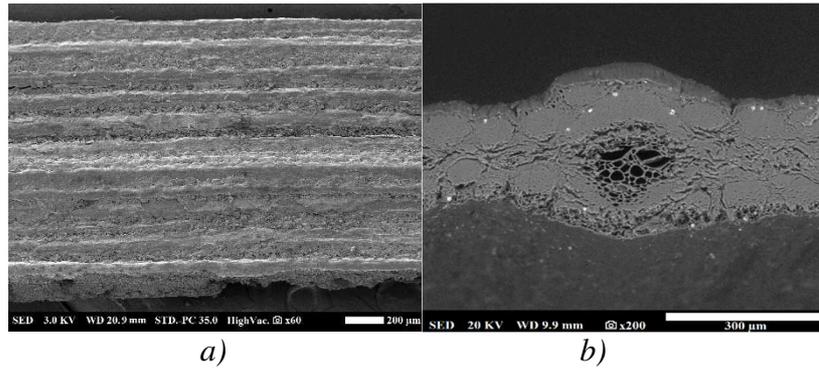
Figure 5: SEM observation of Diss fibres. a) outer surface, b) inner surface, c) mixed view of inner and outer surfaces, d) cross sectional view of diss fibres.

Tensile test measurements show that Diss fibres presents an average tensile strength of 82 MPa (standard deviation of 26 MPa) and a Young modulus of 5.8 GPa (standard deviation of 1.8 GPa).

The date palm (*Phoenix dactylifera*) is a hardy tree with a crown of leaves (the palms) and is well adapted to desert and arid regions around the world [64,65]. After date harvests, it is estimated that one and a half million tonnes per year (1.5 10⁶ t/year) of palms in the world remain unevaluated and become waste [51,66]. These residues are one of the renewable sources which can be recovered in the construction sector and even in the reinforcement of composite materials [64,67–71]. This study focuses only on fibres extracted from palm leaflets and produced using a Retsch-type grinder. Fibres are cut in 5, 10 and 15 mm long pieces and present a flat-shaped cross-sectional area with an average width of 1.41 mm and their specific mass is 1350 kg.m³. The tested date palm tree fibres originates from Biskra area (Algeria). According to the review of Jonoobi et al., the leaflets fibres contain between 4 and 8% of extractives, 40 and 54% of cellulose, 15 and 32% of lignin and 13 and 20% of hemi-cellulose [72].

The SEM morphological study shows that the date palm fibre has a heterogeneous structure and has a flat shape with rigid grooves [52,63,73]. The fibre structure is porous as shown in figure 6. The cross-section of a leaflet shows that it consists of bundles of ultimate fibres (fibril assembly) and grooves composed of conductive libero-linear vessels. The diameter of the ultimate fibres is of the order of 10 µm and the lumen has a diameter of 1 to 2 µm [63,74,75].

Tensile tests measurement shows that palm date tree fibres presents an average tensile strength of 164 MPa (standard deviation of 25 MPa) and a Young modulus of 8.7 GPa (standard deviation of 1.8 GPa).



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325

326 *Figure 6: SEM observation of palm date tree fibres. a) longitudinal view – b) cross-sectional*
327 *view.*

328

329 Water absorption of fibres was measured for diss and date palm tree fibres at 5 minutes and
330 24 h using the protocol described in Lecompte et al. [37]. At 5 minutes, the water absorption
331 coefficient is 70% for the diss while it is only 65% for the date palm tree fibres. At 24 hours,
332 these values increase at 140% for the diss and 130% for the date palm trees fibres.

333

334 2.2.3 Additives

335

336 In the frame of this study, xanthan gum has been used as an efficient earth-based materials
337 stabiliser [24,32]. Xanthan gum is a highly stable branched heteropolysaccharide produced by
338 fermentation of sugars by the “*Xanthomonas campestris*” bacterium. This type of gum is
339 mostly used as a consistency modifier in cosmetics or food industry (Additive E415). Recent
340 studies showed that xanthan gum (Xan) could also increase strongly the mechanical properties
341 of soils and earthen materials. These long macromolecules are likely to adsorb onto the
342 surface of clay particles. Xanthan gum increases the viscosity of the freshly mixed wet
343 material [34] and improves the water resistance of earth-based material because of the
344 formation of a gel within the clay particles porosity [76,77]. Two xanthan gum’s dosages
345 (provided by “wake-up-easy sportfood) have been tested: 0.5% and 1% of the mass of the dry
346 earth as proposed by Guihéneuf et al. [32].

347

348 In order to compensate for the thickening effect of the xanthan gum, sodium
349 hexametaphosphate was used as a fluidity agent in order to limit the initial water content of
350 the earth material. Hexametaphosphate (HMP) when added at a small concentration, can be an
351 efficient dispersant for clay particles [8,26,38,48]. The dosage chosen here is 0.3% in mass of
352 the dry earth material mass.

353

354 2.2.4 Mix design of materials

355

356 In order to meet the extrusion's consistency requirements for these earth-based materials, a
357 water content between 23 and 27% is needed for the earth without fibres and additives.
358 Additional mixes at close water contents 22 and 28% are cast in order to obtain additional
359 samples with lower densities. In the first part of the results section, the influence of additions
360 of natural fibres are tested on unstabilised earth. Two dosages of 1.5% and 3% volume
361 content are tested for 3 different fibre lengths of 5, 10 and 15 mm. This first study allows for
362 assessing the best dosage and length of fibres; i.e. fibres dosage and length that provide good
363 reinforcement with sufficient workability for the extrusion process.

364 The same materials were tested with additions of dosages of Xanthan gum of 0.5%; 1% and
365 2% and a dosage of HMP of 0.3%. A referencing system was chosen for the mix-design
366 denomination. A series of 5 letters, each followed by a number is used in order to identify the
367 samples mix-design. The first letter W indicates the water content (between 23 and 28), the
368 second and third letter L and C refers to the fibres length (in mm) and content (volume ratio)
369 and the fourth and fifth letters H and X refers to the stabilisation strategy. H is linked to the
370 HMP addition and can be followed by 0 (no HMP) and 1 (HMP added). X is the dosages of
371 xanthan gum and ranges between 0 and 2%. For example, the mix-design W25L10C3H1X1
372 has a water content of 25%, addition of 10 mm long fibres at a volume content of 3% and
373 contains 0.3% of HMP and 1% of xanthan gum (weight ratio). When natural fibres are added,
374 the name of the mix-design is followed by the fibre type (diss or date palm).

375 In the last part of the results section, combined additions of natural fibres and stabilising
376 additions are tested for the best fibre length and content. It allows studying the combined
377 effect of natural fibres and studied additives additions.

378 A summary of all tested mix-design is provided in table 1. A water content of 25% allows to
379 obtain required penetration depth for all tested fibres addition.

380

381 Table 1: Summary of tested mix design. The table provided the water content W in function
382 of the added fibres (length L and content C) and the stabilization strategy (addition of HMP H
383 and xanthan gum dosage X). H0X0 means that the mix doesn't contain stabiliser and L0C0
384 that the mix doesn't contain any fibre.

385

386

	H0X0	H1X0	H1X0.5	H1X1	H1X2
L0C0	W22 W23 W24 W25 W26 W27 W28	W22 W23 W24 W25 W26	W23 W24 W25 W26	W23 W24 W25	W22 W23 W24 W25 W26
L5C1.5	W25	-	-	-	-
L10C1.5	W25	W23	-	W23	-
L15C1.5	W25	-	-	-	-
L5C3	W25	-	-	-	-
L10C3	W25	-	-	-	-
L15C3	W25	-	-	-	-

387

388

389

390 **3. Results and discussions**

391 **3.1 Effects of fibres addition**

392

393 3.1.1 Compressive strength

394 The compressive strength of bricks made of earth-based material has to reach a minimal value
395 given by local standards. For instance, the French Standard XP P 13-901 [78] defines three
396 classes of bricks depending on their compressive strength at 2, 4 and 6 MPa. The German
397 standard also defines classes of bricks up to 6 MPa [79].

398 It has been shown that the compressive strength of a specific earth-based material is governed
399 by its density [25,29,32,39,42]. In this work, the obtained results confirm this statement: as
400 shown in figure 7, which displays the evolution of the compressive strength of the earth-based
401 samples in function of their densities, it can be seen that all results follow the same trend
402 whatever the type or dosage of fibres. For unreinforced sample (L0C0), the density variation
403 is linked to the initial water content of the earth.

404 It is also observed from figure 7 that the addition of fibres induces a decrease of the sample
405 dry density. Natural fibres are less dense than mineral materials and it is observed that the
406 sample density decreases with their fibres content.

407 Moreover, for a same dosage, the density decreases with the fibre length. A decrease of the
408 workability of cement-based materials was already reported in the literature with fibre

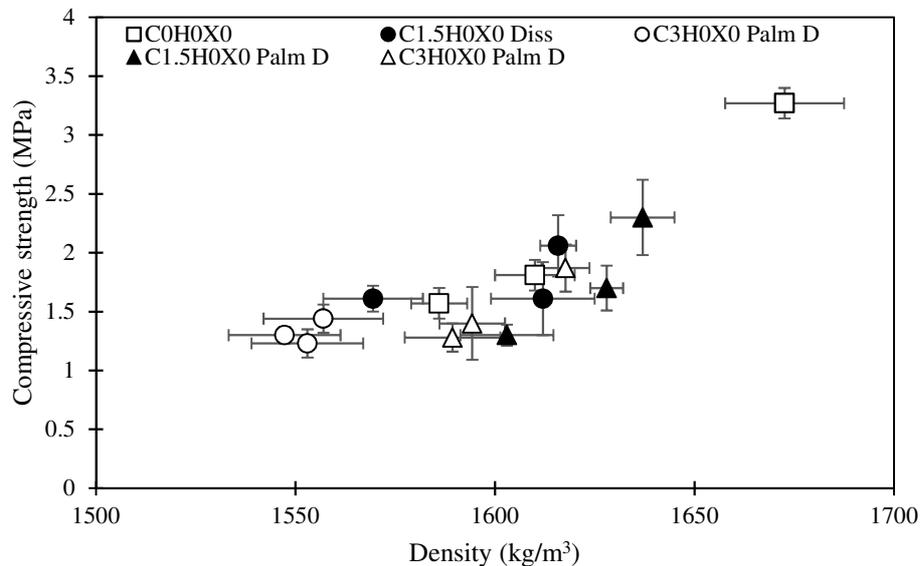
409 addition. Martinie et al. showed that this workability loss increases with the fibre aspect ratio
410 (with the fibre length at a constant fibre diameter [80–82]). The effect of fibre length observed
411 in this study is in line with the results of Martinie et al.

412 It is worth noting that for a same dosage and length, the reduction in dry density is higher for
413 the diss fibres than for the date palm fibres. This result can be explained by the fact that date
414 palm fibres exhibit less flexural rigidity than the diss fibres due to their flat shape. This lower
415 rigidity allows for higher fibre deformation that alters less the material rigidity [83].

416 It can be interesting to find solutions that allows reaching higher dry density for fibre
417 reinforced earth-based materials. The ability of xanthan gum and HMP to allow for a more
418 efficient densification of the earth-based matrix will be tested later in this work.

419

420



421

422 *Figure 7: Evolution of the compressive strength of fibre reinforced earth-based materials as a*
423 *function of sample dry density for different dosage of fibre type (Diss and Date palm), dosage*
424 *and length.*

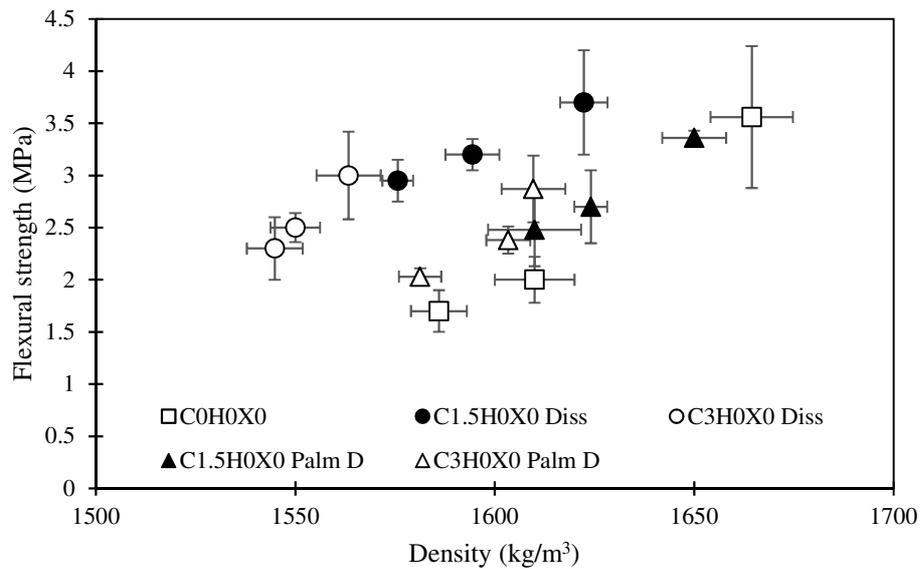
425

426 3.1.2 Tensile strength

427

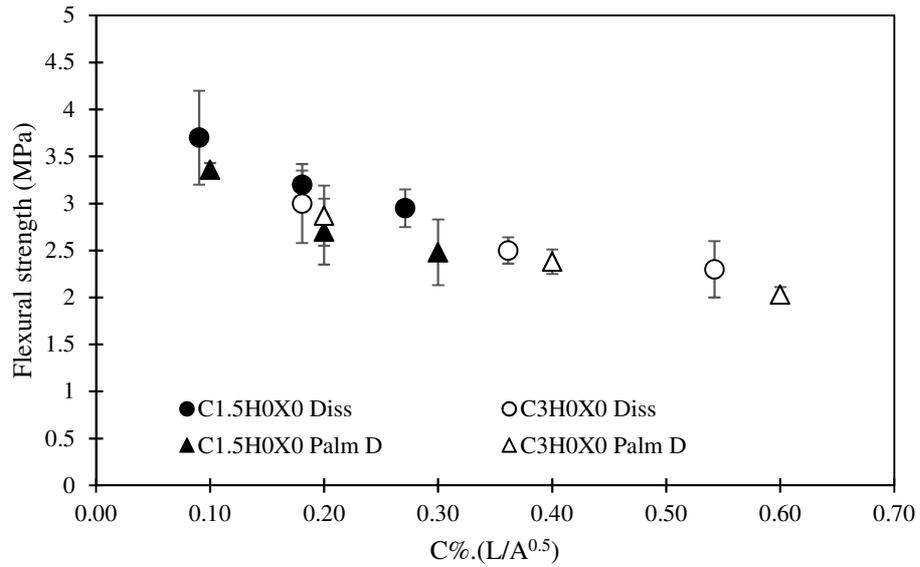
428 Figure 8 plots the evolution of flexural strength as a function of the dry density of the earth-
429 based samples for different types and dosages of fibres. As observed for the compressive
430 strength, the addition of fibres decreases the dry density of the samples. However, for a given
431 dry density of a sample, it is observed that material reinforced with diss fibre presents the
432 highest flexural strength, followed by the date palm fibre reinforced samples. Unreinforced

433 samples exhibit the lowest flexural strength. These observations confirm the reinforcing effect
 434 of natural fibres that increases earth-based material flexural strength [36]. It is interesting to
 435 note that diss fibres display a more efficient reinforcing effect than the date palm tree fibres.
 436 This enhanced effect is attributed to the diss fibre surface that presents thorns as shown in
 437 SEM observations displayed in figure 5 and is supported by the highest pull-out strength
 438 measured for diss fibres: the average interfacial shear strength measured for the diss is equal
 439 to 242 kPa while it is only of 150 kPa for date palm fibres.
 440



441
 442 *Figure 8: Evolution of the flexural strength of fibre reinforced earth-based materials as a*
 443 *function of sample dry density for different dosage of fibre type (Diss and Date palm), dosage*
 444 *and length.*

445
 446 The decrease of the dry density affects the mechanical strength and can be attributed to both
 447 low density of the fibres and workability loss. As shown in figure 9 and as predicted by recent
 448 literature of the rheology of fibre-reinforced suspensions, the effect of fibre addition can be
 449 described by a spatial congestion parameter, which is the product of the fibre dosage, by the
 450 fibre aspect ratio (fibre length L to square root of fibre cross-section $A^{0.5}$) and can be written
 451 $C/(L/A^{0.5})$ [80–83]. For a given type of fibres, flexural strength of the samples versus
 452 congestion parameter follows a same trend. It can also be seen that for a given value of spatial
 453 congestion parameter, the flexural strength is higher for diss fibre than for date palm tree
 454 fibre. This observation is in line with conclusions stated from figure 8.
 455



456

457 *Figure 9: Evolution of the flexural strength of fibre reinforced earth-based materials as a*
 458 *function of the spatial congestion parameter for different dosage of fibre type (Diss and Date*
 459 *palm), dosage and length.*

460

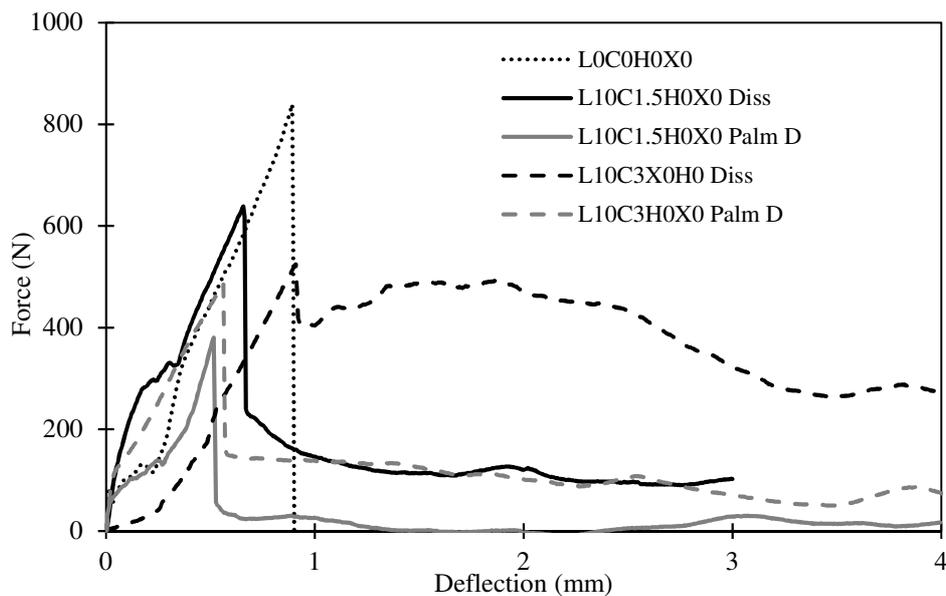
461 3.1.3 Ductility

462

463 Flexural test data shows that unreinforced earth samples display a fragile behaviour and after
 464 the force peak, the recorded force directly falls to 0, as shown in figure 10.

465

466



467

468 *Figure 10: Flexural strength measurements test for fibre-reinforced earth-based materials.*
469 *Force vs. deflection tests for different fibre dosage (1.5% and 3%) and fibre type (diss and*
470 *date palm tree).*

471

472 However, when fibres are added, a post-peak behaviour is observed with a residual force
473 value that increases with the fibre content. It is also worth mentioning that the residual force
474 is higher for the diss fibre-reinforced samples, probably due to the surface morphological
475 characteristics of these fibres. Such ductile behaviour properties can be very useful to prevent
476 dramatic collapse of structures made of earth.

477

478 **3.2 Effects of HMP and Xanthan gum**

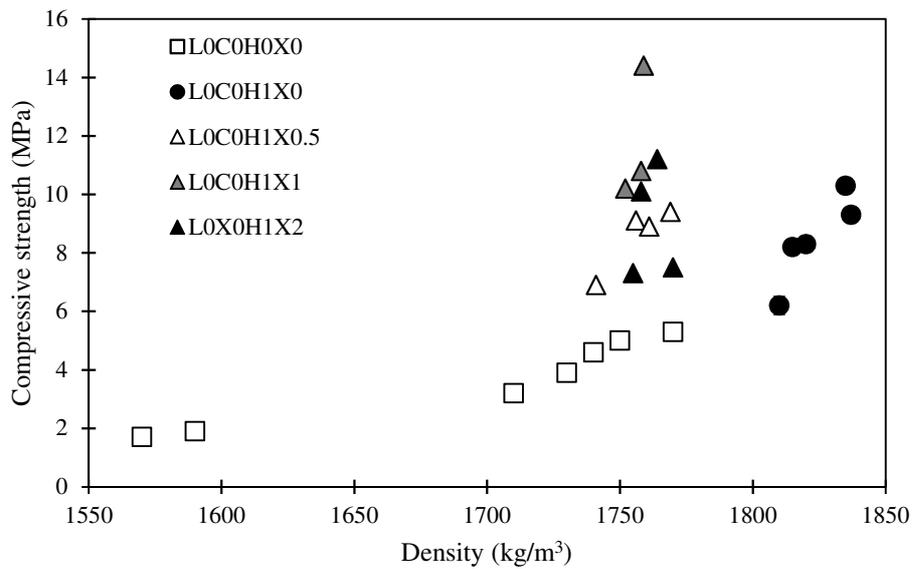
479

480 The figure 11 shows the effect of HMP and xanthan gum on the compressive strength of
481 unreinforced extruded earth-based samples. Many conclusions can be drawn from the
482 observation of this figure but we first have to take into consideration that it was not possible
483 to extrude earth sample with only xanthan gum and no HMP: the material appeared either too
484 viscous or too dry to be extruded at various water contents. Earth with only xanthan displays a
485 granular-like behaviour under a water content of 28%. Above this value of water content, the
486 material becomes pasty and shows a cone penetration between 3 and 5 mm but the material
487 viscosity is too high to allow for the material extrusion. It seems that the water demand of
488 xanthan gum is high and has to be compensate using a dispersing agent such as HMP.

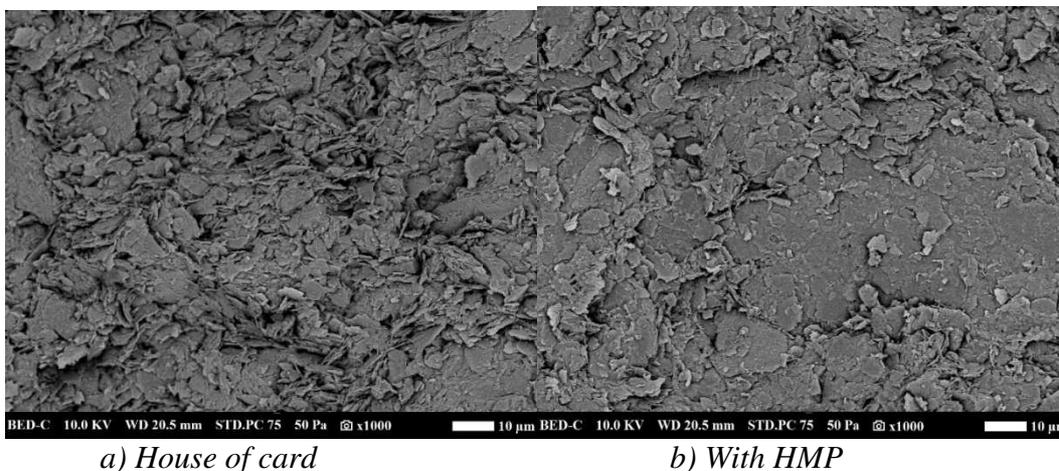
489 Addition of HMP allows increasing the earth sample dry density leading to higher
490 compressive strength. HMP changes the organization of the clay particles at the microscale
491 as demonstrated by the SEM observations displayed in figure 12. It can be seen that the
492 addition of HMP changes the particles network from a house-of-cards network to a more
493 dispersed network where all clay platelets particles are parallel and superimposed. This
494 observation is consistent with common results observed for kaolinite clay particles [48,84].
495 This change in particles' assembly leads to a decrease in the materials shear yield stress at the
496 fresh state [8,38,85] and an increase in the dry state compressive strength [25].

497 Xanthan gum is known as an efficient stabiliser for earth-based material in order to increase
498 both compressive strength and water resistance [32,86,87]. In this study, it can be seen that a
499 combined used of HMP and xanthan gum allows obtaining materials with increased
500 compressive strength and similar dry densities than for the unstabilised and reference earth
501 samples. Observation= of figure 11 seems to indicate that the optimal xanthan gum dosage is

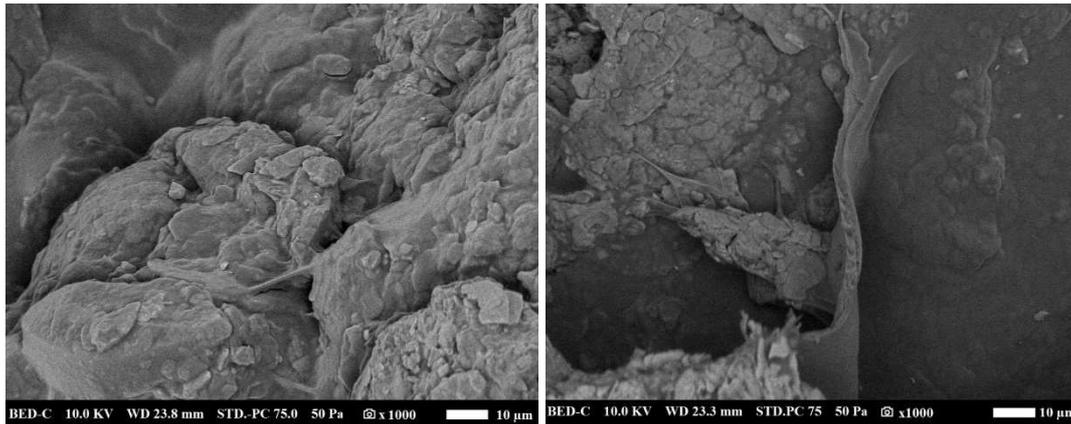
502 1% as this xanthan gum content provides the highest compressive strength. This result seems
 503 to be confirmed by the SEM observation of samples stabilised with 1% and 2% of xanthan
 504 gum along with HMP depicted in figure 13a and 13b respectively. It can be seen on these
 505 observations that a 1% dosage provides a homogeneous mix of clay particles covered and
 506 bonded by xanthan gum gel but that with a 2% dosage, a heterogeneous mix of uncovered
 507 clay particles and localized xanthan gum gel is encountered.
 508
 509



510
 511 *Figure 11: Compressive strength versus dry density for stabilised unreinforced earth-based*
 512 *materials containing HMP and HMP + varying dosage of xanthan gum.*
 513
 514



515
 516 *a) House of card* *b) With HMP*
 517 *Figure 12: SEM observation of the microstructural organisation of clay particles without and*
 518 *with HMP.*



519

520

a) Xan 1%

b) Xan 2%

521 *Figure 13: SEM observation of the microstructural organisation of clay particles with HMP*
 522 *and 1% and 2% xanthan gum.*

523

524 **3.3 Combined effects of stabilisers and fibres**

525

526 3.3.1 Compressive strength

527

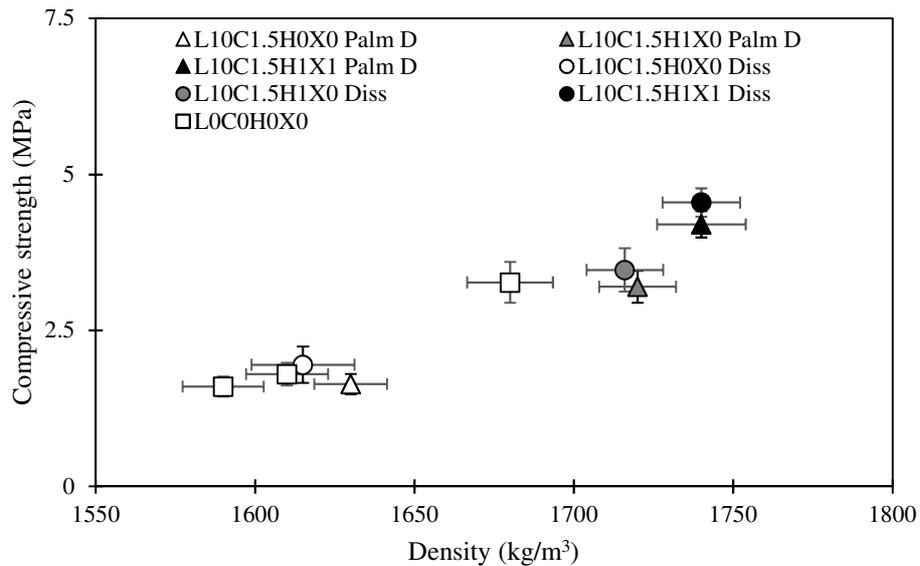
528 In this section, the effect of a combined addition of fibres (10 mm long at 1.5% dosage) and
 529 stabiliser (HMP and xanthan gum) on the material's mechanical properties is investigated.
 530 Materials are compared to reference materials without any fibres and stabilisers and with
 531 materials with fibres but without stabiliser. This choice of length and dosage is justified
 532 because these parameters allow for the best compromise between reinforcing ability and
 533 extrudability (limited workability loss).

534 In figure 14, the compressive strength of the samples is plotted as a function of the dry density
 535 of the samples. It is worth noting that addition of stabiliser allows increasing both
 536 compressive strength and dry density of the earthen materials. This effect is even more
 537 pronounced when xanthan gum is added along with HMP.

538 It is worth noting that for a given stabilisation strategy, diss fibres reinforced samples provide
 539 slightly higher compressive strength than samples reinforced with date palm tree fibres. This
 540 can also be attributed to the morphology of the surface of the fibres that exhibits thorns.

541 The simultaneous addition of stabiliser along with natural fibres seems to compensate for the
 542 workability loss induced by the natural fibres' presence. It allows reaching relatively high
 543 density (higher than the reference mixes, unreinforced and unstabilised) with materials having
 544 high compressive strength.

545



547
 548 *Figure 14: Compressive strength of earth-based materials as a function of sample's dry*
 549 *density for earth-based materials reinforced with natural fibres (10 mm long at 1.5%) and*
 550 *stabilised with HMP and HMP+Xanthan gum. For the sake of comparison, data obtained*
 551 *from reference and unstabilised samples are plotted.*

552

553 3.3.2 Tensile strength

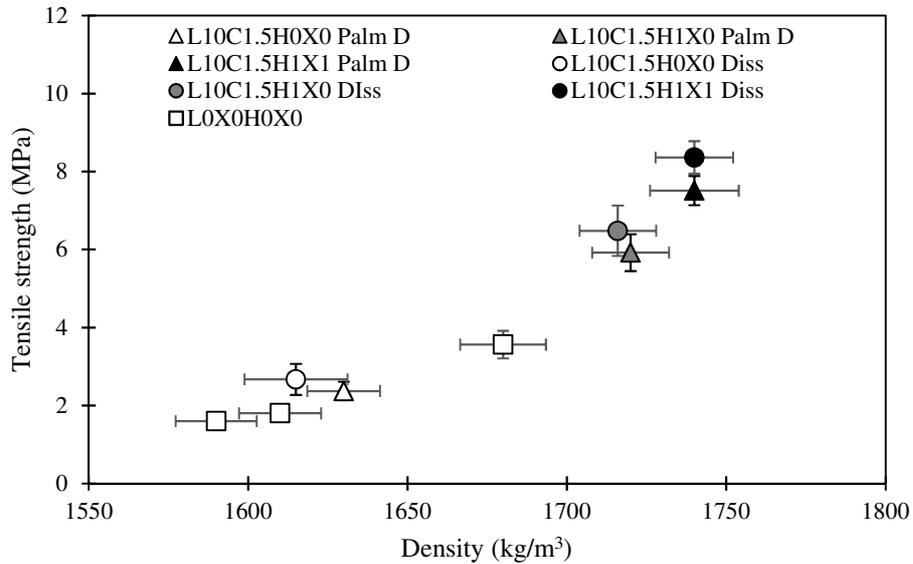
554

555 Combined additions of natural fibres and stabilisers induce an increase in both tensile strength
 556 (measured under bending) and dry density. As shown in figure 15, contrarily to unstabilised
 557 materials, the fibres addition does not seem to weaken the earth-based materials. The
 558 simultaneous addition of stabiliser with natural fibres seems to compensate for the workability
 559 loss induced by the natural fibres' presence. It allows reaching relatively high density (higher
 560 than the reference mixes, unreinforced and unstabilised) with materials having high tensile
 561 strength.

562 It is worth noticing that for a given stabilisation strategy, diss fibres reinforced samples
 563 provide slightly higher tensile strengths than samples reinforced with date palm tree fibres.
 564 Also, all reinforced and stabilised samples show higher tensile performance than the reference
 565 mixes while it is not the case without stabiliser (figure 8).

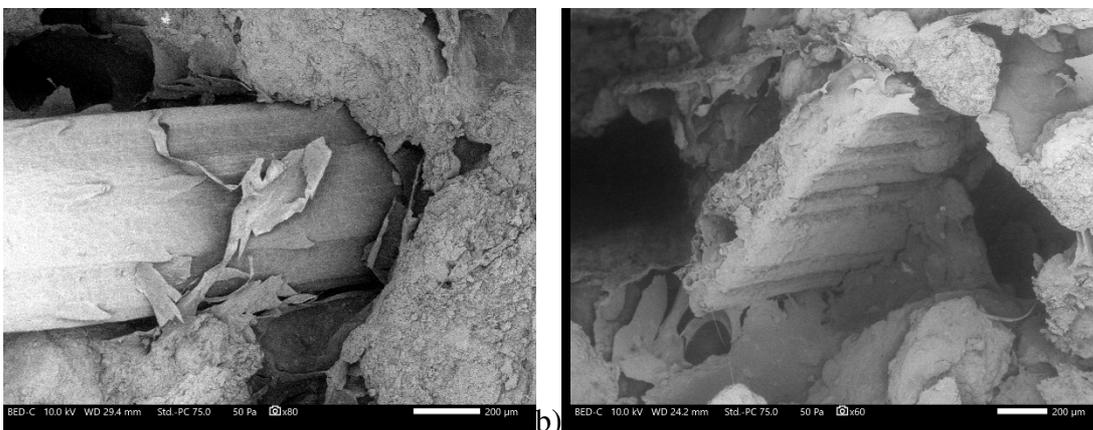
566 The only addition of HMP seems to be sufficient to improve the materials extrudability and
 567 allows for an efficient reinforcement of the earth-based material but the combination of HMP
 568 and xanthan gum as stabiliser provides the best results. SEM observation (figure 16) confirms
 569 the role of xanthan gum in the bonding between earth matrix and reinforcing fibres as a film

570 of xanthan gum can be observed on the surface of both diss and date palm tree fibres. This
 571 film is expected to enhance the interfacial strength between clay matrix and natural fibres.



572
 573 *Figure 15: Flexural strength of earth-based materials as a function of sample's dry density*
 574 *for earth based materials reinforced with natural fibres (10 mm long at 1.5%) and stabilised*
 575 *with HMP and HMP+Xanthan gum. For the sake of comparison, data obtained from*
 576 *reference and unstabilised samples are plotted.*

577
 578 Moreover, it is interesting to note that measured pull-out strengths provided in table 2 (called
 579 interfacial shear strength IFSS) are in line with improvement in tensile properties measured
 580 using 3-point bending tests. Highest IFSS values are obtained with HMP and xanthan gum
 581 stabilised mixes and then for HMP stabilised samples. For each type of stabilisation strategy,
 582 diss fibres shows the most resistant interface because of its irregular surface with thorns.



583 a)
 584 *Figure 16: SEM observation of fractures samples of earth-based materials reinforced with*
 585 *natural fibres (10 mm long at 1.5%) and stabilised with HMP+Xanthan gum. a) diss*
 586 *reinforced sample – b) date palm tree reinforced sample.*

587 *Table 2: Pull-out test results – average interfacial shear stress and standard deviation.*

	Diss			Date palm		
	H0X0	H1X0	H1X1	H0X0	H1X0	H1X1
IFSS (kPa)	242	269	368	150	237	340
Standard deviation (kPa)	42	48	45	16	22	34

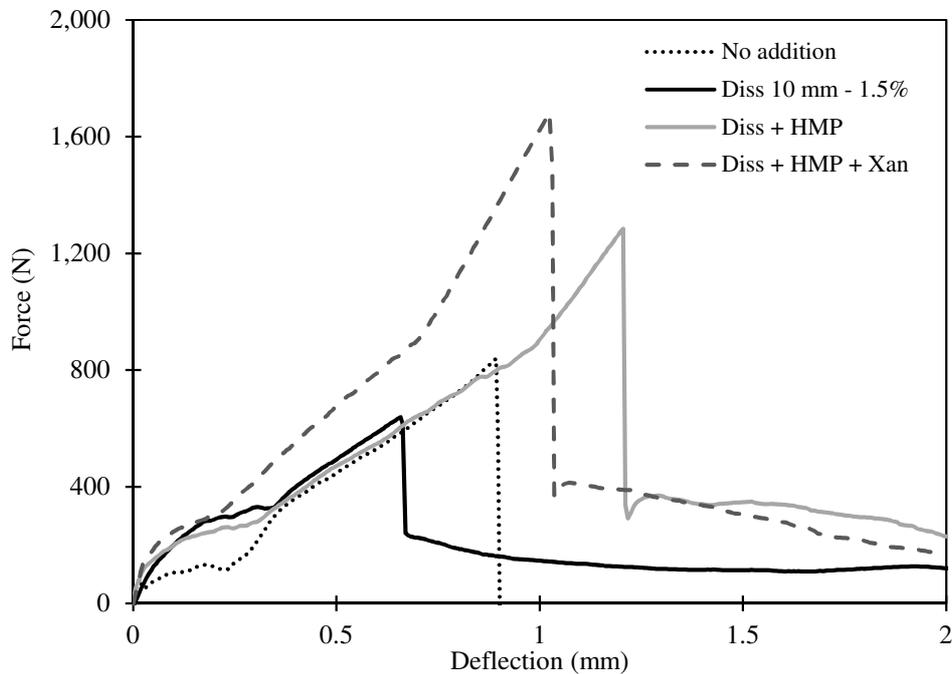
588

589

590 3.3.3 Ductility

591

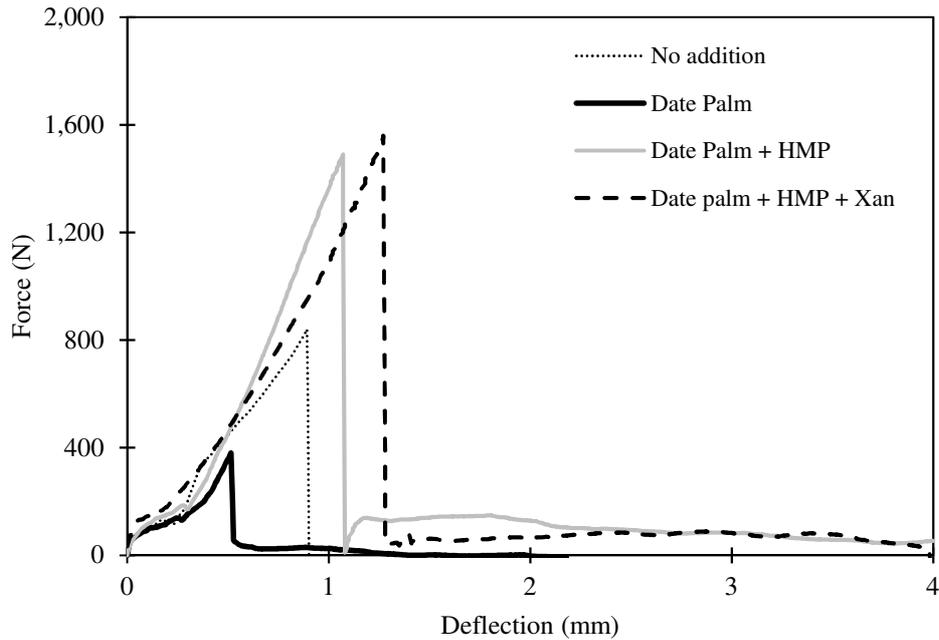
592 Figure 17 shows that during bending, diss fibre reinforced behaviour exhibit a post peak
 593 behaviour with a residual force value that increases when HMP or HMP and xanthan gum is
 594 added. On the contrary, figure 18 shows that even with the addition of HMP or xanthan gum,
 595 the residual force after the peak remains low for date palm tree fibre reinforced samples. This
 596 results clearly show the role of the fibre morphology on the stress transfer and the overall
 597 ductile behaviour of the earth composites. Diss fibres present surface roughness that allows to
 598 obtain a residual stress after the peak.



599

600 *Figure 17: Bending force as a function of sample's deflection for earth-based materials*
 601 *reference sample, reinforced with diss fibres (1.5%, 10 mm long), reinforced with diss fibres*
 602 *and stabilised with HMP and reinforced with diss fibres and stabilised with HMP+xanthan*
 603 *gum.*

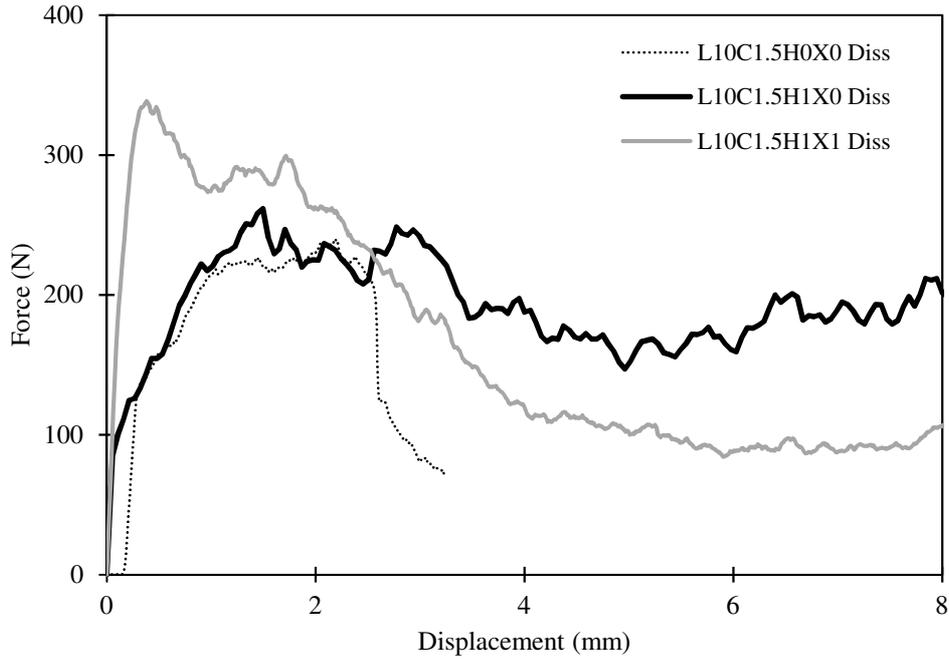
604



605
 606 *Figure 18: Bending force as function of sample's deflection for earth-based materials*
 607 *reference sample, reinforced with date palm tree fibres (1.5%, 10 mm long), reinforced with*
 608 *date palm tree fibres and stabilised with HMP and reinforced with date palm tree fibres and*
 609 *stabilised with HMP+xanthan gum.*

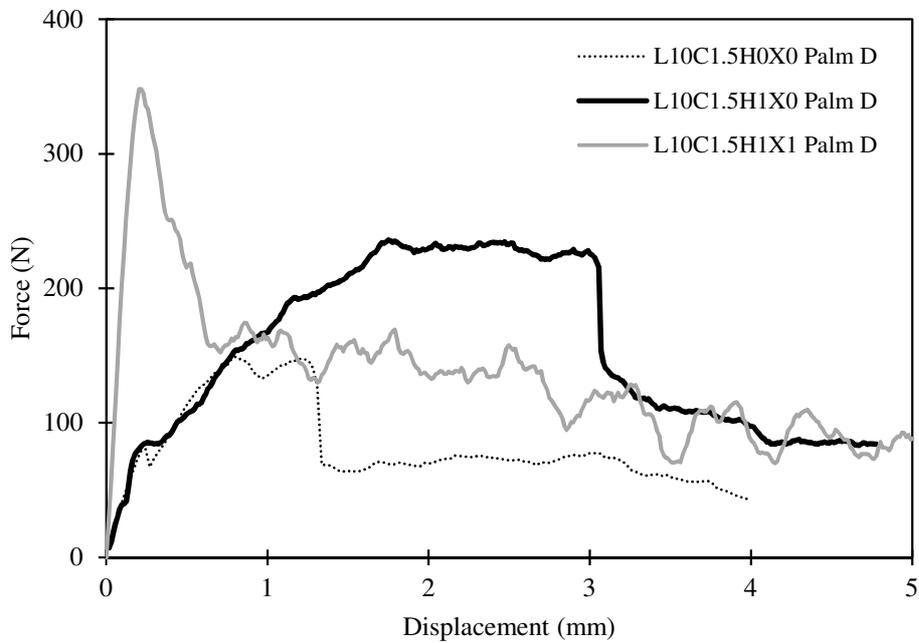
610
 611 This result is confirmed by the pull-out test data. Pull-out of diss fibres provides higher
 612 residual stress after the debonding peak in comparison with pull-out of data palm tree fibres
 613 whatever the stabilisation strategy as shown by figures 19 and 20. It is also worth mentioning,
 614 as shown in table 1, that the maximum pull-out force is higher for diss than for date palm tree
 615 whatever if the samples is stabilised or not. Moreover, the residual force is kept for longer
 616 pull-out displacement showing the prominent role of the diss fibre morphology on the stress
 617 transfer between natural fibre and matrix.

618
 619



620
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 622
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 625

Figure 19: Pull-out force for diss fibres in unstabilised matrix, matrix stabilised with HMP and matrix stabilised with HMP+xanthan gum.



626
 627
 628
 629
 630

Figure 20: Pull-out force for date palm tree fibres in unstabilised matrix, matrix stabilised with HMP and matrix stabilised with HMP+xanthan gum.

631 **4. Conclusions**

632 This paper highlights the beneficial effect of simultaneous natural fibres additions and earth
633 stabilisation by biopolymer (by adding HMP and xanthan gum) in order to obtain a structural
634 material displaying better compressive strength, good tensile strength and a ductile behaviour.
635 It is first shown that the addition of natural fibres alone is detrimental for the extrusion and
636 leads to less dense material with lower compressive strength ranging from 1.2 to 2.3 MPa
637 (instead of 3.3 MPa for the unreinforced sample) and similar tensile strength (around 3 MPa),
638 even if reinforced materials have ductile properties. This is attributed to a problem of
639 workability loss induced by the fibres. It is shown that the workability loss is induced by the
640 spatial congestion of the fibres network.

641 Then, in agreement with already-known results, it is shown that the stabilisation of the studied
642 earth with Na-HMP (0.25% of the earth weight) and xanthan gum leads to improve both
643 density and mechanical strength (up to 14 MPa at a dry density of 1759 kg/m³, xanthan gum
644 dosage of 1% of the dry earth weight). It is concluded that xanthan gum and HMP allow
645 compensating for the workability issue and thus allowing for higher compressive strength at a
646 given dry density.

647 Therefore, simultaneous addition of both natural fibre and stabilisation permits to obtain
648 earth-based materials with enhanced mechanical properties (in compression with a maximal
649 compressive strength of 4.5 MPa and in tension with a maximal tensile strength of 8 MPa for
650 10 mm long diss fibres at 1.5 %volume and xanthan gum at 1%weight) combined with
651 improved ductile properties. This synergic effect is even more obvious for diss fibres due to
652 the presence of a rough surface displaying thorns that allows for an efficient stress transfer
653 between the fibres and the matrix (as shown by pull-out tests).

654

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656 validation, M. B ., A. P.; formal analysis, S. G., A.P., M. B. ; investigation, M. B.; resources,
657 A. Pe.; writing—original draft preparation, A. P., M. B. ; writing—review and editing, S.G.,
658 R. B. supervision, R. B., A. P; project administration, A.P., R. B.. All authors have read and
659 agreed to the published version of the manuscript.

660

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