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1 **Comparative study of effects of various**  
2 **seaweed parietal polysaccharides on**  
3 **rheological, mechanical and water-durability**  
4 **properties of earth-based materials**

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## 38 **Conflicts of interest**

39 The authors declare no conflict of interest.

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41 The data that support the findings of this study are available from the corresponding  
42 author, S. G., and the first author Y.A. upon reasonable request.

## 43 **Authors contributions**

44 Conceptualization, N.B., A.P.; S.G.; Validation, Y.A., N.B., S.G., A.P.;  
45 Investigation, Y.A., S.G., A.P.; Writing-original draft, Y.A.; Writing-review and  
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## 47 **Abstract**

48 In Brittany, invasive algae represent a real problem, unbalancing local ecosystems  
49 and threatening the economy and tourism, with massive strandings, especially in  
50 summer. The valorization of invasive algae in green processes and materials such  
51 as ecological building materials could represent a real opportunity to try to control  
52 the spread of these species. Raw earth is a locally sourced building material, non-  
53 toxic and sustainable. In this work, we propose then to compare the effect of four  
54 invasive Brittany seaweeds, exotic or indigenous, on the fresh state and hardened  
55 properties of raw earth material. In particular, we investigated the performance of  
56 *Polyopes lancifolius*, *Solieria chordalis*, *Ulva sp.* and *Sargassum muticum* on the  
57 compressive strength, water resistance and extrudability of the raw earth material.  
58 Several forms of seaweed extracts were tested, raw seaweeds dried and ground,  
59 freeze-dried hot water extracts and extracted polysaccharides. Our results showed  
60 that the incorporation of *S. chordalis* and *S. muticum*, in the freeze-dried form or

61 polysaccharides, allows a 3-fold increase in the compressive strength and a better  
62 resistance to water.

63 **Keywords:** *Invasive seaweeds, Polysaccharides, Raw earth construction,*  
64 *Compressive strength, Water durability, Extrusion*

## 65 **1. Introduction**

66 Global warming, environmental degradation and pollution are among the major  
67 concerns for the decades to come. The construction sector, with its extensive need  
68 of natural materials like sand or gravel for concrete production [1, 2], is responsible  
69 for resources overconsumption and generation of large quantities of greenhouse  
70 gases and wastes [3]. The production of cement-based materials, with high energy  
71 consumption and carbon footprint is one of the main causes of pollution [4]. The  
72 development of less polluting construction techniques and materials, using local  
73 and sustainable resources, is now required to meet the growing need for housing  
74 and equipment of our societies (United Nations, Department of Economic and  
75 Social Affairs, World population prospects Highlights, 2019). In this context,  
76 earthen construction could be one of the solutions. Earthen construction is a  
77 traditional technique that has been used for thousands of years across the world, but  
78 was within a certain limit neglected in the last century due to the industrial  
79 development of steel and concrete building that ensures better mechanical  
80 performance, production rate and reproducibility [5]. Yet this material presents  
81 some advantages: it has a low environmental impact, it is recyclable and available  
82 locally [6] and presents good hygrothermal [7] and sound insulation properties.  
83 However, its water sensitivity is often quoted as its main weakness related to  
84 durability because humidity can alter the material and strongly reduce its  
85 mechanical properties [8]. However, the ability of this material to adsorb and  
86 release moisture from the atmosphere of a building and regulate its indoor  
87 temperature and humidity is a strong asset. Nowadays, the development of earthen  
88 construction is still limited due to limited industrial implementation and drying

89 times and by the difficulty to achieve a mix-design that allows for both fast  
90 processing and sufficient strength at dry state [9].

91 An often-quoted method to improve the mechanical and water durability properties  
92 of raw earth is its stabilization with cement or lime [10, 11]. But these stabilisers  
93 are non-renewable, present large carbon footprint and require high energy  
94 consumption. New alternatives to these stabilisers inspired from vernacular earthen  
95 construction techniques must be developed, that offer more environmentally  
96 friendly solutions. Several organic additives have been used historically in the  
97 production of earthen buildings, depending on what was locally available, such as  
98 fibres, seaweed, barks, fruits, oil [12]. With the purpose to optimize mechanical  
99 properties, to reduce the water sensitivity and to improve existing or develop new  
100 and more efficient processing methods such as 3D printing, extrusion or poured  
101 earth, several bio-based additives such as xanthan gum, linseed oil, ovalbumin,  
102 casein, alginates or tannins have been already studied [9] [13].

103 Over the past few decades, various macroalgae have been introduced in Brittany.  
104 Among these species, *Polyopes lancifolius* and *Sargassum muticum*, both native  
105 from Asia, were probably introduced in Brittany via the imports of Pacific oysters  
106 (*Crassostrea gigas*). *P. lancifolius* red algae (*Halymeniales*) has been first observed  
107 in the gulf of Morbihan during the summer of 2008 [14] and *S. muticum* brown  
108 algae (*Fucales*) has been first observed in France in 1980 at Brest and Port Blanc  
109 [15]. *Ulva sp.* and *Solieria chordalis* native macroalgae have developed  
110 significantly in recent years as a result of global warming and eutrophication of the  
111 marine waters mainly due to land runoff, with significant strandings on Brittany  
112 beaches. *Ulva sp.* green seaweeds (*Ulvales*) mass blooms have been frequently  
113 reported during spring and summer in semi-enclosed lagoons since 1970 but also  
114 along beaches largely open to the sea and subject to a strong tidal movement [16].  
115 100 000 tons of green stranded seaweeds are collected each year in Brittany. *S.*  
116 *chordalis* red seaweed (*Gigartinales*) appears every year from June to November

117 in south Brittany, on the peninsula of Rhuys [17]. In Morbihan, up to 15 000 tons  
118 per year of red stranded seaweeds, essentially *S. chordalis* are collected.

119 Worldwide, seaweeds have been increasingly exploited for their ability to produce  
120 compounds of interest. The use of invasive species to obtain natural compounds  
121 presents therefore a two-folded opportunity: a high availability of the biological  
122 material and through specimen collection, mitigation of negative effects caused by  
123 invasive species, contributing for ecosystem integrity and sustainability. Among all  
124 these compounds of interest, cell wall polysaccharides are used in a wide range of  
125 applications, particularly in the food industry [18] and pharmaceutical fields [19,  
126 20], for their capacity to hold water, form gels and stabilize emulsions. They have  
127 a biological function similar to that of hemicellulose in terrestrial plants, but with  
128 higher flexibility that can withstand strong ocean waves and currents.  
129 Polysaccharides also prevent seaweed desiccation and allow ion-exchange function  
130 [21]. Above all, they are non-toxic and biodegradable. Cell wall polysaccharides  
131 have also been used in recent years for the production of eco-materials, such as  
132 bioplastics [22], aerogels for insulation boards [23] or bioasphalts [24].

133 Red algae cell walls are known to be composed of galactans generally built on  
134 repeated alternating 1,3 linked alpha-D-galactopyranose and 1,4 linked beta-D-  
135 galactopyranose units, and differ in their level and pattern of sulfation, in  
136 substitution by methoxyl and/or pyruvate groups and by other sugar residues  
137 (anhydrogalactose, glucose, xylose). There are also differences in 3,6-  
138 anhydrogalactose content and the configuration of 1,3-linked ol-galactopyranose  
139 residues (L for agars and D for carrageenans) [25]. The genus *Solieria* is  
140 acknowledged to contain mainly ι-carrageenan disaccharide repeating units (beta-  
141 D-galactose-4-sulfate linked to 3,6-anhydro-alpha-D-galactose-2-sulfate) [26] [17].  
142 *P. lancifolius* matricial cell wall contains mainly κ-carrageenan (beta-D-galactose-  
143 4-sulfate linked to 3,6-anhydro-alpha-D-galactose) with potential presence of agar  
144 [32]. Brown seaweed *S. muticum* is the main source of alginate linear co-polymer  
145 made of β-D-mannuronic acid (M) and α-l-guluronic acid (G) [28]. In the seaweed,  
146 alginate is present as a mixed sodium and/or potassium, calcium and magnesium  
147 salt. Ulvan is a cell wall polysaccharide of green seaweed and is mainly composed  
148 of sulfated rhamnose, uronic acids (glucuronic acid and iduronic acid) and xylose

149 [29]. All these polysaccharides have the capacity to hold water and form gel. This  
150 effect is reinforced by the presence of metal cations ( $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Mg}^{2+}$ ,  $\text{Ca}^{2+}$ ,  $\text{Fe}^{2+}$ ,  
151  $\text{Fe}^{3+}$ ,  $\text{Al}^{3+}$ ,  $\text{Cr}^{3+}$ ), thanks to the capacity of polysaccharides to form bonds with  
152 the cations [30, 31, 32]. But these cations can induce different gelling properties  
153 and mechanisms with the different chemical structures of all these polysaccharides  
154 and difference in sulfation degree.

155 In our study, the research is focused on the field of building materials, in particular  
156 the incorporation of polysaccharides in raw earth constructions. The objective is  
157 mainly to increase mechanical properties and water resistance of this natural but  
158 still sensitive material, with the ultimate goal to replace highly polluting cements  
159 and concretes. Several studies have demonstrated a stabilizing effect of alginates  
160 extracted from brown seaweeds on raw earth construction [33], attributed to the  
161 ionic bonding between the alginate polymer and the soil's divalent calcium cations  
162 [34], [32]. Even if previous studies have already shown the positive effects of  
163 carrageenan extracted from red seaweeds on water durability and mechanical  
164 strength of earth material [3], this type of mechanism is not precisely described for  
165 agar and ulvan extracted respectively from red and green seaweeds. This paper  
166 describes an experimental study aimed at investigating the potential of  
167 ingredients/products from invasive Brittany seaweeds to fine-tune its fresh-state  
168 properties and to increase mechanical properties of raw earth-based building  
169 materials. We propose to evaluate three ingredients/products: 1) at very low cost  
170 whole dried seaweed milled, 2) at low cost hot aqueous/water extract that has been  
171 lyophilized, 3) at a higher cost purified polysaccharide. Four different species of  
172 Brittany seaweeds are studied. The objective is twofold: on the one hand, the  
173 development of a low-polluting eco material for building construction, and on the

174 other hand, the valorisation of invasive algae, an available material with negative  
175 impacts today.

## 176 2. Materials and methods

### 177 2.1. Materials

#### 178 2.1.1. Seaweeds

179 *S. chordalis* were collected in Saint Gildas de Rhuy (latitude: 47°30'0''N,  
180 longitude: 2°49'60''O, France) and samples of *P. lancifolius* in Locmariaquer  
181 (latitude: 47°33'14''N, longitude: 2°56'23''O), France) in September 2020. *S.*  
182 *chordalis* and *P. lancifolius* are red seaweeds.

183 Samples of brown algae *S. muticum* were collected in January 2022 in Saint Gildas  
184 de Rhuy (latitude: 47°30'0''N, longitude: 2°49'60''O, France).

185 Samples of *Ulva* were collected in February 2019 in Sarzeau (latitude:  
186 47°31'39''N, longitude: 2°46'09''O, France).

187 The chemical compositions of the seaweeds, based on measurements carried out in  
188 the authors institute [27, 35, 36] are provided in Table 1.

(% dry algae)	Ash	Neutral sugars	Proteins	Lipids
<i>Ulva sp.</i>	15.9 ± 1.20*	23.2 ± 1.40*	24.4 ± 0.10*	0.6 ± 0.0*
<i>Sargassum muticum</i>	25.4 ± 1.00*	5.2 ± 1.10*	24.3 ± 4.30*	1.0 ± 0.10*
<i>Solieria chordalis</i>	39.5 ± 1.10*	30.2 ± 1.20*	16.2 ± 0.60*	0.9 ± 0.10*
<i>Polyopes lancifolium</i>	12.6% ± 0.03	25.1% ± 1.09	15.0% ± 1.03	0.3% ± 1.10

189 **Table 1:** Chemical composition of the seaweeds. Values are means ± SD (n =3). Values with \* are  
190 significantly different (p <0.05) [27, 36]

191

#### 192 2.1.2. Tested earthen materials

193 In order to improve the earth particle size distribution as done in the work of Perrot  
194 et al. [35], two reference soils were reformulated in laboratory, using a clayey  
195 material (0-80 µm), fine sand (63-200 µm) and normalised sand (0-4 mm). The



196 clayey material is a quarry waste (Clayey mud) originated from Brittany and  
197 displays the following properties: A plastic limit ( $W_P$ ) of 27.7%, a liquid limit ( $W_L$ )  
198 of 64.6%, a methylene blue value (MBV) of 2.1 and 67.8% of its particles finer than  
199 20  $\mu\text{m}$  (PSD laser diffraction analysis). Fine sand and normalised sand are supplied  
200 by Société Nouvelle du Littoral (Leucate, France).  
201 The two reformulated soils present the following compositions: Soil n°1 is  
202 composed of 20% clay, 30% fine sand and 50% normalised sand, Soil n°2 is finer  
203 and composed of 40% clay and 60% find sand.

### 204 *2.1.3. Other materials*

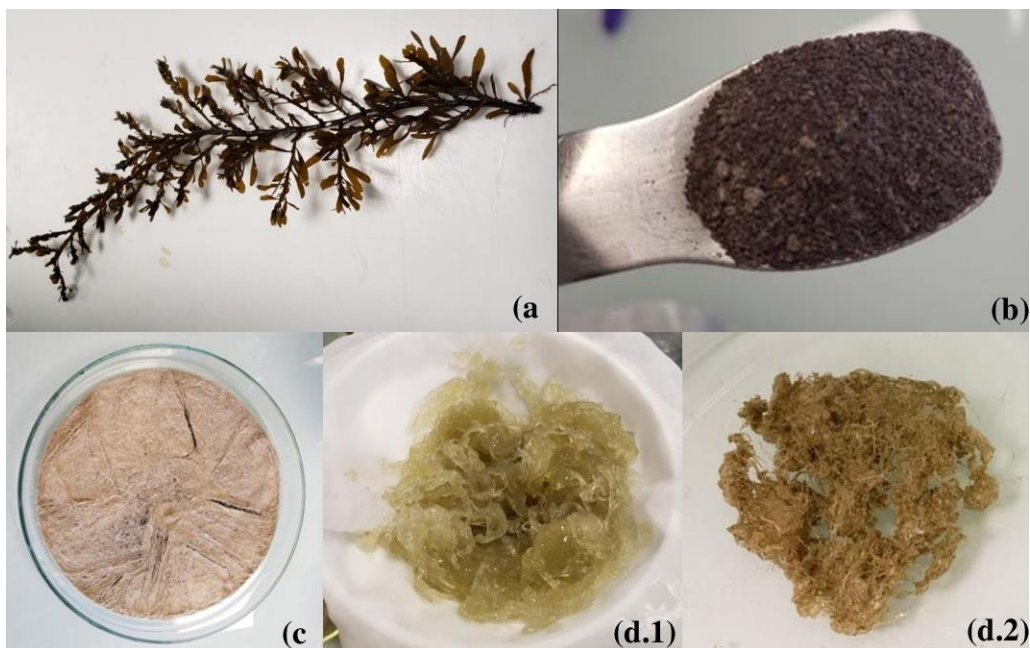
205 A commercial alginate was used in this study for build-up tests. It was a white  
206 powder alginic salt Cimalgin HS3® provided by Cimaprem (Redon) [33].  
207 Hexametaphosphate (HMP) was used as a dispersant for clay particles to make the  
208 mixtures more flowable and reduce water content. Minimizing the water ratio in the  
209 mixtures allows to increase material density and thus increase its mechanical  
210 properties and its resistance to water [9].

## 211 **2.2. Methods**

### 212 *2.2.1. Seaweed extracts preparation*

213 All seaweed samples were cleaned from their epiphytes and rinsed with tap water  
214 to remove salts and debris. Samples of *P. lancifolius*, *S. chordalis* and *S. muticum*  
215 were then dried in an oven at 40°C for 24h. After rinsing, samples of *Ulva sp.* were  
216 pre-mixed and freezed.

217 Three experiments have been conducted with different treatments realized on each  
218 type of seaweeds from raw material (RM), freeze-dried hot water extract (FDE) and  
219 purified polysaccharides (PP) (Fig. 1).



220

221 **Fig. 1:** (a) raw seaweed (*S. muticum*); (b) dried and ground seaweed (*S. chordalis*); (c) : freeze-  
 222 dried extract (*P. lancifolius*); (d.1) and (d.2) : wet and dry precipitated polysaccharides (*P.*  
 223 *lancifolius*)

224 **Raw material (RM)**

225 Raw material corresponds to the whole dried seaweed milled. For each species,  
 226 dried seaweeds were powdered in a mixer.

227 **Freeze-dried hot water extract (FDE)**

228 Freeze-dried hot water extract corresponds to an hot aqueous/water extract that has  
 229 been lyophilized. The method of preparation of the aqueous extract is specific to  
 230 each type of alga wall. Polysaccharides from dried seaweed powder (< 5 mm  
 231 particle size) were extracted in hot distilled water under agitation, with an initial dry  
 232 matter content of 5% for *S.chordalis*, *S. muticum* and *Ulva sp.* and 3.5% for *P.*  
 233 *lancifolius*. For *S. chordalis* the heating temperature was 85°C during 4h [26], for  
 234 *P. lancifolius* it was 80°C for 4h, for *Ulva sp.* It was 90°C for 2h [38] and for *S.*  
 235 *muticum* it was 80°C for 4h with the addition of a reagent (Na<sub>2</sub>CO<sub>3</sub> 3%) [39]. The  
 236 total hot water extract was then freeze-dried and the dry extract was crushed in a  
 237 mixer.

238 **Purified polysaccharide extracts (PP)**

239 Cell wall polysaccharide extract corresponds to purified polysaccharide extracted  
 240 from seaweed. Polysaccharides from air-dried seaweed powder (< 5 mm particle  
 241 size) were extracted in hot distilled water under agitation, with an initial dry matter  
 242 content of 5% for *S. chordalis*, *S. muticum* and *Ulva sp.* and 2% for *P. lancifolius*.

243 Process parameters and duration for each seaweed were similar to those applied for  
244 freeze-dried hot water extraction. The separation of the soluble extract from  
245 insoluble debris was done by centrifugation. The filtrate was poured into 2 volumes  
246 of absolute ethanol, with stirring. The precipitate was recovered, washed with  
247 acetone and dried under fume hood. Finally, the dry extract was crushed in a mixer.  
248 For each of these purified polysaccharide extracts, extraction yield (%) was  
249 calculated by equation 3 according to:

$$250 \text{ Polysaccharide yield} = \frac{\text{extracted polysaccharide weight (dry)}}{\text{initial seaweed weight (dry)}} \times 100 \quad (3)$$

251 The yields of extraction (in % of algal dry weight) of the different polysaccharides  
252 from seaweed dried powders with hot water are as follows:  $61.8 \pm 2.2$  (% w/w) for  
253 *P. lancifolius*,  $13.3 \pm 2.2$  (% w/w) for *S. chordalis*,  $29.6 \pm 3.7$  (% w/w) for *Ulva sp.*  
254 And  $29.3$  (% w/w) for *S. muticum*. The extraction yield for *S. chordalis* is consistent  
255 with the results obtained by Bondu et al. [26] who reported a yield of 14,6%. Kidgell  
256 et al. [29] have compiled on their side median extraction yields of 40% for *Ulva*  
257 *armoricana* and 16,6% for *Ulva lactuca*. Mohamed et al. [28] obtained a yield of  
258 20% for alginate extraction from *S. muticum* at 50°C. It must be noted that real  
259 extraction yields may be slightly lower than those found as final purification steps  
260 were not performed during the extraction procedure and some compounds like  
261 pigments, phenols and/or fucoidans must be still present. It was then estimated, for  
262 the specimens' preparation used in the different tests on earth, that the concentration  
263 of free polysaccharides in the freeze-dried extracts (FDE) and the concentration of  
264 polysaccharides present in the seaweed walls in raw seaweed extracts (RM) were  
265 identical to the extraction yields determined above. For instance, to aim for a 0.25%  
266 concentration of *P. lancifolius* polysaccharide using RM or FDE, we had to add  
267 0.38% of RM or FDE ( $\frac{\text{Aimed concentration (0.25\% or 0.5\%)}}{\text{polysaccharide extraction yield}}$ ).

### 268 2.2.2. Preparation of earth material specimens and testing procedure

#### 269 **Compressive strength and water durability tests**

270 For the preliminary study, the experimental methodology to prepare the samples is  
271 based on the preparation of different mixes of soil, water and specific seaweed  
272 extract (raw material, freeze-dried extract, polysaccharides). Mix proportions were  
273 adapted for each product to ensure that each batch contained approximately a  
274 polysaccharide equivalent of 0.25% or 0.5% of dry earthen material content (Table

275 2). The materials were then homogenized in a mortar mixer and hand compacted in  
 276 moulds (40 mm x 40 mm x 160 mm). Samples were conserved during one week at  
 277 ambient temperature then dried in an oven at 45°C until weight stabilization. Tests  
 278 performed on each sample were dry density measurement, compressive strength at  
 279 dry state and after a five-minutes immersion in water (water durability). Density  
 280 and compressive strength were determined on one half of each specimen, after  
 281 breaking them in a three-point bending device, whereas water durability was tested  
 282 on the second half of each specimen after immersing them in water during 5  
 283 minutes. Density of dry specimens was determined by using a hydrostatic balance  
 284 and compressive strength on dry and wet specimens was determined using a 50 kN  
 285 loading frame and controlled at a constant displacement rate of 1 mm/min. Tests  
 286 were also carried out on reference specimens made with soil and different amounts  
 287 of water. All of the compressive tests were carried out on samples with an aspect  
 288 ratio of 1 following an adopted procedure in agreement with different French  
 289 compressive test procedures (AFNOR [NF EN 196-1], AFNOR [XP P 13-901] and  
 290 AFNOR [NF EN ISO 17892-7]). For the second part of the study, four specimens  
 291 containing 0.5% of *S. chordalis* polysaccharides and four specimens with *S.*  
 292 *muticum* freeze-dried extract containing a polysaccharide equivalent of 0.5 % were  
 293 prepared using the same methodology as for the preliminary study. Four reference  
 294 soil specimens were also prepared with 18% of water. After a prior drying phase,  
 295 specimens were broken in a three-point bending tester. Two halves of specimen  
 296 were kept in the oven, one half was kept during 5 days at room temperature and  
 297 humidity in the laboratory, one half was kept during 7 days in a room at a  
 298 temperature of 22°C and a relative humidity of 80%. Finally, four halves were kept  
 299 in an atmosphere saturated in moisture. Compressive strength tests were performed  
 300 on each sample. For samples kept in saturated atmosphere, tests were performed  
 301 after 24h, 48h, 72h and 7 days as in a previous study [9] in order to see the impact  
 302 of the water uptake due to environmental ambiance on the material compressive  
 303 strength.

<b>Sample reference</b>	<b>Seaweed extract type</b>	<b>Soil n°1 (%)</b>	<b>Seaweed extract (%)</b>	<b>Water content (%)</b>
<b>T13</b>	-	100	-	13
<b>T15</b>	-	100	-	15
<b>T16,5</b>	-	100	-	16,5

<b>T18</b>	-	100	-	18
<b>T20</b>	-	100	-	20
<b>T22</b>	-	100	-	22
<b>T25</b>	-	100	-	25
<b>Pp0.25</b>	<i>P. lancifolius</i> PP	100	0.25	22.4
<b>Pp0.5</b>	<i>P. lancifolius</i> PP	100	0.5	26
<b>PI0.25</b>	<i>P. lancifolius</i> FDE	100	0.38	20.3
<b>PI0.5</b>	<i>P. lancifolius</i> FDE	100	0.77	22.6
<b>Pa0.25</b>	<i>P. lancifolius</i> RM	100	0.38	16.5
<b>Pa0.5</b>	<i>P. lancifolius</i> RM	100	0.77	18.3
<b>Sp0.25</b>	<i>S. chordalis</i> PP	100	0.25	16.5
<b>Sp0.5</b>	<i>S. chordalis</i> PP	100	0.5	16.5
<b>SI0.25</b>	<i>S. chordalis</i> FDE	100	1.25	21.9
<b>SI0.5</b>	<i>S. chordalis</i> FDE	100	2,5	25,3
<b>Sa0.25</b>	<i>S. chordalis</i> RM	100	1.25	18.1
<b>Sa0.5</b>	<i>S. chordalis</i> RM	100	2.5	22
<b>Up0.25</b>	<i>Ulva sp.</i> PP	100	0.25	20.8
<b>Up0.5</b>	<i>Ulva sp.</i> PP	100	0.5	22.1
<b>UI0.25</b>	<i>Ulva sp.</i> FDE	100	0.71	21.9
<b>UI0.5</b>	<i>Ulva sp.</i> FDE	100	1.43	23.5
<b>Ua0.25</b>	<i>Ulva sp.</i> RM	100	0.71	18.6
<b>Ua0.5</b>	<i>Ulva sp.</i> RM	100	1.43	20.6
<b>SAP0.25</b>	<i>S. muticum</i> PP	100	0.25	16.5
<b>SAP0.5</b>	<i>S. muticum</i> PP	100	0.5	18.6
<b>SAI0.25</b>	<i>S. muticum</i> FDE	100	0.71	16.5
<b>SAI0.5</b>	<i>S. muticum</i> FDE	100	1.43	19.2
<b>SAa0.25</b>	<i>S. muticum</i> RM	100	0.71	18
<b>SAa0.5</b>	<i>S. muticum</i> RM	100	1.43	19.7

304 **Table 2:** Samples composition for compressive strength tests (% / dry soil weight)

305 **Structural build-up test**

306 The evolution of the consistency of the earth-based materials with time is of  
307 importance when considering new processing routes such as poured earth and 3D  
308 printing [37] [40]. In order to follow the structural build-up of earth with time, a  
309 fall cone penetrometer, which enables to determine the yield stress, is used. The fall

310 cone penetrometer is usually used to determine the consistency limits of soil but  
311 can also be used to follow the shear yield strength of soil with time. The end of  
312 penetration is reached when the friction forces acting on the cone surface balance  
313 the weight of the penetration cone. When the material consistency is liquid or  
314 plastic, it is generally considered that the friction stress is equal to the shear yield  
315 stress of material [41]. The shear yield stress depends on both cone geometry and  
316 penetration depth according to the equation:

$$317 \quad \tau_0 = \frac{wg \sin \alpha/2}{\pi (h \tan \alpha/2)^2} \quad (1)$$

### 318 **Extrusion tests**

319 Extrusion is an efficient industrial process that is able to industrially shape building  
320 blocks as done for fired blocks [42, 43]. However, extrudability depends on earth  
321 materials fresh properties that could not suit the process requirements [44, 45].  
322 Therefore, it is interesting to study the improvement of extrudability of an earth-  
323 based material using algae extracts. Extrusion tests were conducted using a ram  
324 extruder and a 50 kN loading frame and carried out at a constant velocity of 5 mm/s.  
325 The extruder barrel is a vertical stainless-steel barrel with an inlet diameter of 50  
326 mm and a total length of 200 mm. Two die orifice diameters were tested (16 mm  
327 and 24 mm). The material is pushed inside the barrel with a Teflon ram. The total  
328 extrusion force (F) required to overcome the friction force on the extruder barrel  
329 and the shaping force at die outlet is measured. Curves representing the evolution  
330 of the total extrusion force (F) versus the remaining billet length (LB) are plotted.  
331 In their study, Perrot et al. [46] highlight an example of the curve obtained for a  
332 material with a good formulation to be extruded that remains homogeneous during  
333 the process. Three different parts are visible on the curve they obtained. The first  
334 part corresponds to the flow initiation. During this moment, when the ram begins  
335 to move, the material is compacted in the barrel. The extrusion total force increases  
336 very strongly and reaches a maximum which corresponds to the beginning of the  
337 extrusion process. In the second part of the curve, the extrusion force linearly  
338 decreases with the ram movement. As the billet length reduces, the surface of  
339 friction between the material and the extruder barrel wall linearly decreases. It is  
340 worth noting that if the earth does not show sufficient water retaining properties,  
341 the material inside the barrel will consolidate and the extrusion force increase. Such

342 behaviour is not suited for extrusion. The friction stress ( $K_w$ ) can then be deduced  
343 from the slope of the second part of the curve by the following equation:

$$344 \quad K_w = \frac{1}{\pi D} \frac{dF}{dL_B} \quad (2)$$

345 where F (N) is the total extrusion force,  $L_B$  (m) the remaining billet length and D  
346 is the extruder barrel inlet diameter (m). The third part of the curve corresponds to  
347 the end of the extrusion process, when the ram approaches the die orifice. The  
348 recorded force can be constant or increases [46]. The experimental methodology to  
349 prepare the samples is based on the preparation of different mixes of soil, water,  
350 and specific seaweed extracts (freeze-dried extract and polysaccharides). Mix  
351 proportions were adapted for each product to ensure that each batch contained  
352 approximatively a polysaccharide equivalent of 0.5% of dry material content and  
353 that its shear yield stress, which reflects the material consistency, was equal to 10  
354 kPa, 15 kPa or 20 kPa (controlled by a fall cone penetrometer before the beginning  
355 of the extrusion test). The materials were then homogenized in a mortar mixer and  
356 the extruder barrel was filled by hand. The material billet length was determined at  
357 the beginning of each test. Tests were performed twice on each mixture and for each  
358 die orifice diameter.

### 359 **3. Effect of seaweeds extracts on compressive** 360 **strength**

#### 361 **3.1. Preliminary study**

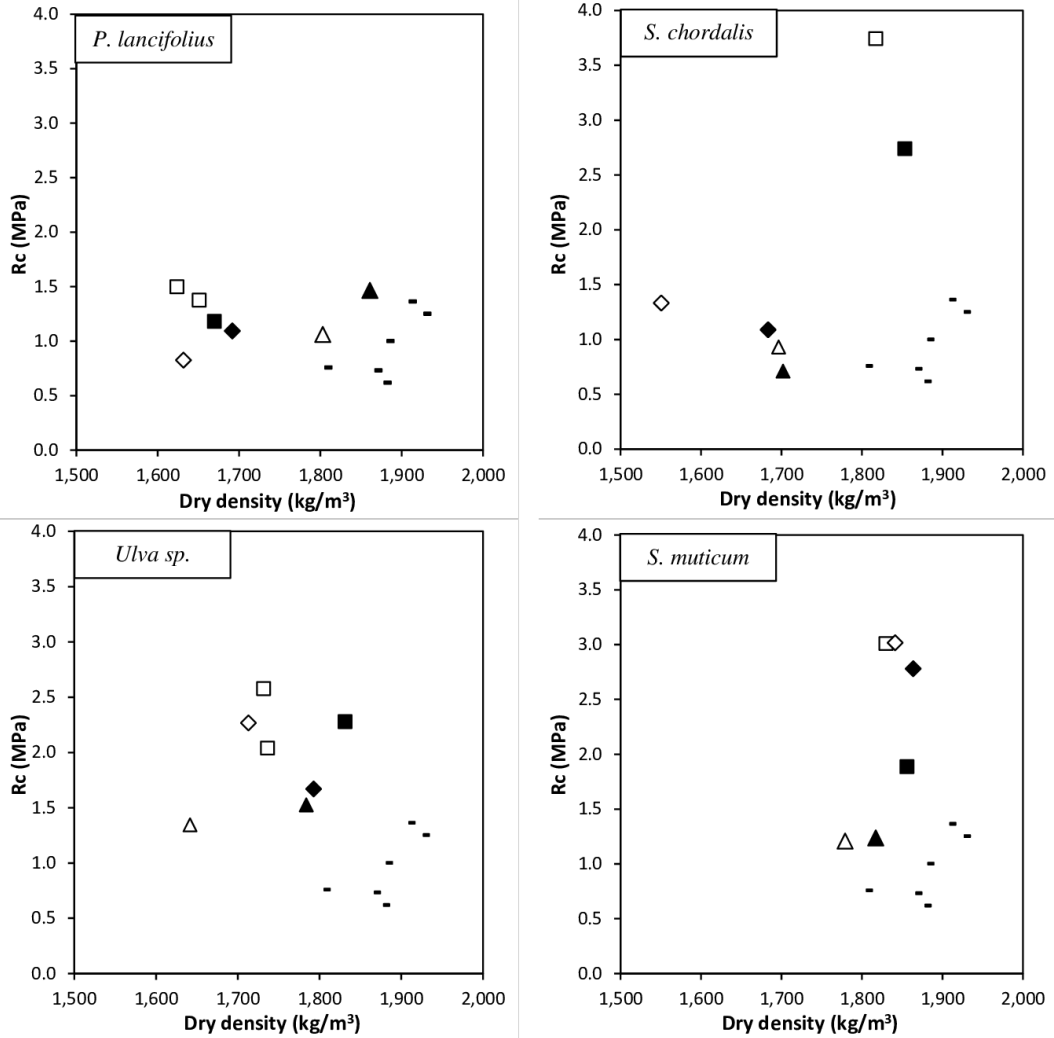
##### 362 *3.1.1. Tests on dry specimen*

363 The obtained results during for the compressive strength test in the preliminary  
364 study are shown in Fig. 2. Each value represents the strength measured on a single  
365 specimen. The dry density of the specimens ranges between 1500 and 2000 kg/m<sup>3</sup>,  
366 which corresponds to the expected range. Variations could be caused by variations  
367 in hand compaction during the specimens' production and by the amount of water  
368 required to obtain a workable mixture. Compressive strength results on dry  
369 specimens show that the addition of raw seaweed extracts does not increase the  
370 mechanical resistance for any species of seaweed, the compressive strength  
371 remaining between 0.5 MPa and 1.5 MPa, which is similar to soil reference

372 specimens, which display an average compressive strength around 1 MPa. For *P.*  
373 *lancifolius*, freeze-dried extract and polysaccharides ( $\kappa$ -carrageenan/agar) have no  
374 positive effect on mechanical resistance increase. For *Ulva sp.* a moderate  
375 improvement of mechanical resistance is observed for the freeze-dried extract and  
376 polysaccharides (ulvan), with a compressive strength between 1.5 MPa and 2.5  
377 MPa. Best results are observed with the addition of polysaccharides of *S. muticum*  
378 (alginate) and *S. chordalis* ( $\iota$ -carrageenan), which improve significantly the  
379 compressive strength at similar dry density, from 1 MPa on average for soil  
380 reference specimens to almost 4 MPa for *S. chordalis*. This phenomenon is also  
381 observed in the same range for *S. muticum* freeze-dried extract whereas *S. chordalis*  
382 freeze-dried extract does not allow to increase compressive strength. This could be  
383 explained by the very low carrageenan concentration in the *S. chordalis* freeze-  
384 dried extract. For *S. muticum* and *S. chordalis*, the compressive strength seems to  
385 increase with the polysaccharides' concentration in the mixture. Several studies  
386 have demonstrated a stabilizing effect of alginates on raw earth construction [33,  
387 47] attributed to the ionic bridging which takes place between the alginate polymer  
388 and divalent calcium cations contained in the soil. A soluble form of alginate is  
389 converted to insoluble gel through the addition of divalent metal cations such as  
390  $\text{Ca}^{2+}$ . This gel forming mechanism is described by the "egg box model". This  
391 involved cooperative binding in water where interactions between the G blocks of  
392 the negatively charged alginate polymer and the positively charged ions create  
393 chain to chain associations. This is due to the formation of junction zones between  
394 two or more chains where the cations sit within the buckled parts of the molecule,  
395 like eggs in an egg box [48] (Fig. 3). During the gelation process, the number of  
396 chain to chain associations increases, eventually leading to the formation of a  
397 continuous network [34]. This network could act like a secondary network that  
398 would reinforce the structure created by the clay particles arrangement and their  
399 interactions with water molecules and could explain the efficiency of *S. muticum* to  
400 increase the mechanical strength. Some measurements still must be conducted to  
401 prove the presence of divalent metal cations in the studied quarry waste that  
402 composes the clayey part of the studied earth to confirm this assumption.

403

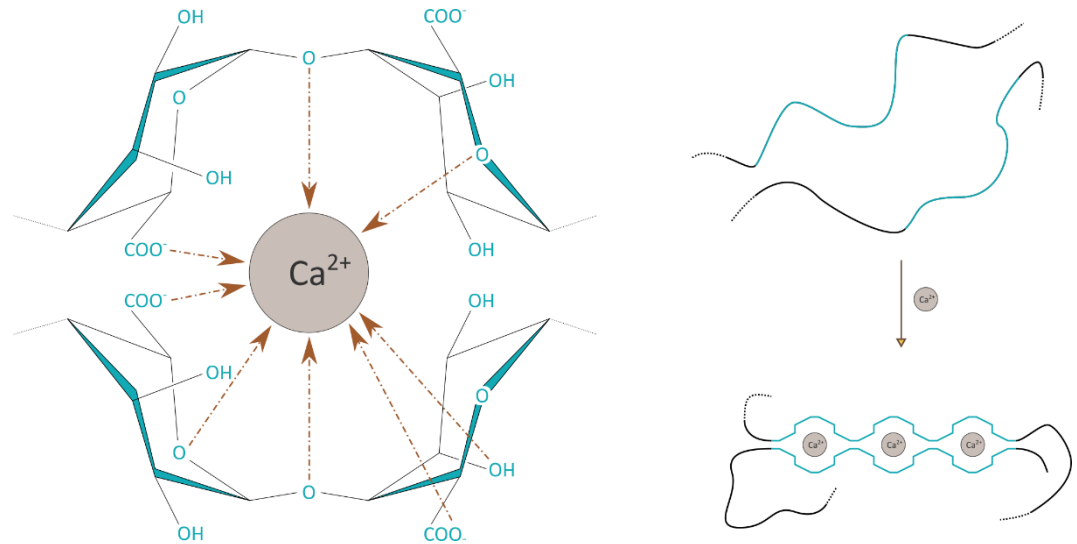




404

405 **Fig.2:** Compressive strength as a function of the dry density for raw earth dry specimen with and  
 406 without seaweed extract additives (- = Soil; ■ = PP - purified polysaccharides 0.25%; □ = PP-  
 407 purified polysaccharides 0.5%; ◆ = FDE - freeze dried hot water extract 0.25% eq.; ◇ = FDE -  
 408 freeze dried hot water extract 0.5% eq.; ▲ = RM -raw material 0.25% eq.; △ = RM -raw material  
 409 0.5% eq.)

410  $\iota$ -carrageenan and  $\kappa$ -carrageenan also have the ability to create interaction and  
 411 binding with metal cations.  $\iota$ -carrageenan forms a threefold, parallel double helix  
 412 in the presence of calcium ions [49]. Calcium ions and water molecules, connected  
 413 to peripheral sulfate groups of  $\iota$ -carrageenan are holding the helices tight.  
 414 Rheological studies on  $\iota$ -carrageenan, gels suggest that calcium is more effective  
 415 compared to monovalent ions like potassium or sodium.



416  
417  
418

**Fig. 3:** Formation of an alginate gel: Egg-box model:  $\text{Ca}^{2+}$  attaches itself into the G bloc structure[48]

419 On the contrary,  $\text{K}^+$ ,  $\text{Cs}^+$  and  $\text{Rb}^+$  are much more effective in stabilizing  $\kappa$ -  
420 carrageenan helices than monovalent cations and divalent cations such as  $\text{Ca}^{2+}$  and  
421  $\text{Mg}^{2+}$ . As calcium ions are often present in large quantity in earthen materials, this  
422 could explain the good efficiency of *S. chordalis* extracts on compressive strength  
423 increase, by its capacity to create a strong and tight secondary network. In  
424 comparison *P. lancifolius* extracts would be less effective with a less dense  
425 network. Ulvan exhibits also good capacity to bind with metal ion through covalent,  
426 electrostatic or redox reactions but the affinity is less important with  $\text{Ca}^{2+}$  than  
427 other metal cations such as  $\text{Cr}^{3+}$  or  $\text{Cu}^{2+}$  [30]. Ulvan demonstrates different  
428 affinities toward various ions, such as  $\text{Al} > \text{Cu} > \text{Pb} > \text{Zn} > \text{Cd} = \text{Mn} > \text{Sr} > \text{Mg} = \text{Ca}$  [50].  
429 Thus, the efficiency of *Ulva sp.* extracts on compressive strength improvement  
430 could be slightly lower than the efficiency of *S. muticum* or *S. chordalis* extracts.

### 431 3.1.2. Tests on wet specimens (after a 5 min immersion in water)

432 Visual observations on reference soil specimens showed that these specimens  
433 partially disintegrated after 5 min of immersion in water, making it impossible to  
434 perform compression strength test. However, the core of the brick remained dry, as  
435 presented in Fig. 4.

436 All the tested polysaccharides and freeze-dried extracts have allowed to keep the  
437 shape of the brick after 5 minutes immersion in water, whereas only *Ulva sp.* raw  
438 extract has allowed to avoid the brick partial disintegration (Fig. 4).















Sample reference	Seaweed extract type	Compressive strength (MPa)	Strength retention ratio
<b>Pp0.5</b>	<i>P. lancifolius</i> PP	0.03	0.02
<b>Sp0.25</b>	<i>S. chordalis</i> PP	<b>1.07</b>	<b>0.39</b>
<b>Sp0.5</b>	<i>S. chordalis</i> PP	<b>1.00</b>	<b>0.27</b>
<b>SI0.5</b>	<i>S. chordalis</i> FDE	0.02	0.015
<b>Up0.5</b>	<i>Ulva sp.</i> PP	0.09	0.04
<b>UI0.25</b>	<i>Ulva sp.</i> FDE	0.08	0.05
<b>UI0.5</b>	<i>Ulva sp.</i> FDE	0.07	0.03
<b>Ua0.25</b>	<i>Ulva sp.</i> RM	0.08	0.05
<b>SAp0.25</b>	<i>S. muticum</i> PP	0.29	0.15
<b>SAp0.5</b>	<i>S. muticum</i> PP	<b>1.41</b>	<b>0.47</b>
<b>SAI0.25</b>	<i>S. muticum</i> FDE	<b>1.52</b>	<b>0.55</b>
<b>SAI0.5</b>	<i>S. muticum</i> FDE	<b>2.35</b>	<b>0.78</b>
<b>SAa0.25</b>	<i>S. muticum</i> RM	0.24	0.19

439

**Table 3:** Results for compressive strength tests on wet specimen

440 The core of the specimen remained dry for *S. chordalis* and *S. muticum* extracts  
441 (polysaccharides and freeze-dried extracts) but was totally wet for *P. lancifolius*  
442 and *Ulva sp.* Compressive strength tests were done on the bricks which have kept  
443 their shape. The results are summarized in table 3. Due to loss of shape and sample  
444 disintegration, no compressive strength test could be performed on wet reference  
445 soil specimens. Their compressive strength after 5 minutes immersion in water is  
446 therefore considered to be zero. Only *S. muticum* freeze-dried extract and  
447 polysaccharide and *S. chordalis* polysaccharide allowed to obtain significant results  
448 with compressive strength higher than 1 MPa. *S. muticum* and *S. chordalis*  
449 polysaccharides acted as water repellents, with a sort of waterproofing effect that  
450 prevented water to penetrate in the core of the specimen. This effect is particularly  
451 visible on specimens containing *S. muticum* extracts. On the contrary, *P. lancifolius*  
452 and *Ulva sp.* extracts have accelerated water diffusion in the center of the specimen  
453 compared to soil reference specimen. This could be due to the gel formation kinetic  
454 or by the different binding behaviour between polysaccharides and water. The  
455 hypothesis can also be made that the formation in a first step of a gel at the specimen  
456 surface, with a specific network structure allows to maintain the shape of the

457 specimen and prevents its disintegration. But a much longer immersion in water  
 458 could lead also to specimen disintegration.

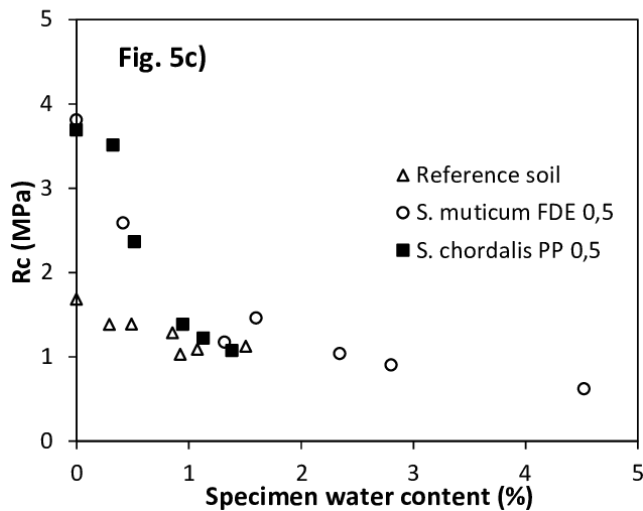
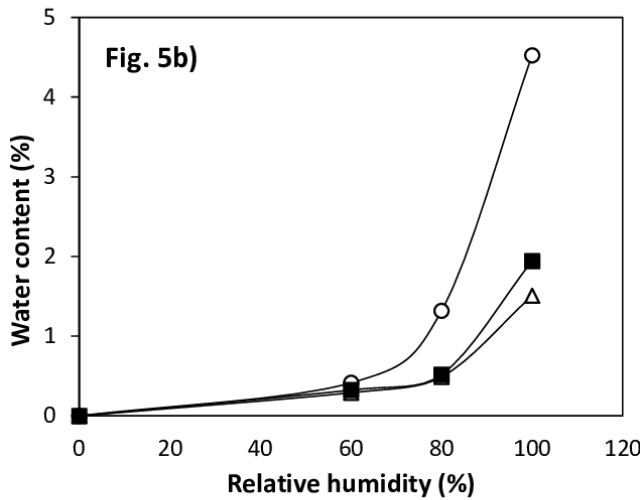
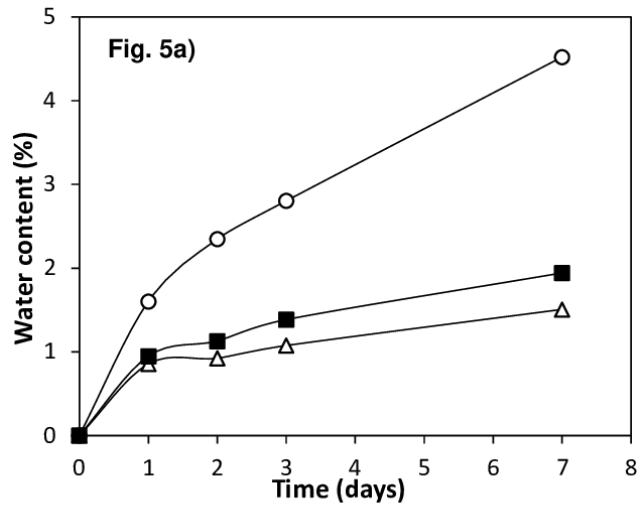
Type of seaweed	Type of extract		
	Raw material RM	Freeze dried hot water extract FDE	Purified polysaccharide PP
<i>P. lancifolius</i>			
<i>S. chordalis</i>			
<i>Ulva sp.</i>			
<i>S. muticum</i>			
No addition			

459  
 460 **Fig. 4:** Visual aspect of specimens after 5 minutes immersion in water

461 **3.2. Study on *S. muticum* and *S. chordalis***

462 Following the results obtained during the preliminary study, *S. chordalis*  
 463 polysaccharides ( $\iota$ -carrageenan) and *S. muticum* freeze-dried extract (containing  
 464 alginate) were selected to continue the study *S. muticum* polysaccharides (alginate)  
 465 gave satisfactory results but the quantity extracted was insufficient to perform more  
 466 tests. Fig. 5a represents the evolution of specimen water content with time for

467 specimens maintained in an atmosphere saturated with humidity. The evolution is  
 468 quite similar for the reference soil and specimen containing *S. chordalis*  
 469 polysaccharide, with a rapid increase of water content until 1% the first day then a  
 470 slower increase the following days to reach less than 2% after 7 days.  
 471 Water content increases more rapidly for specimen containing *S. muticum* freeze-  
 472 dried extract to reach 4.5% after 7 days.



473

474 **Fig. 5:** 5a) Evolution of specimen water content with time in saturated atmosphere; 5b) Specimen  
475 water content evolution with storage room relative humidity. Storage time was 5 days at 60%, 7  
476 days at 80% and 7 days at 100%; 5c) Evolution of compressive strength with specimen water  
477 content (*S. muticum* freeze-dried extract; *S. chordalis* purified polysaccharide)

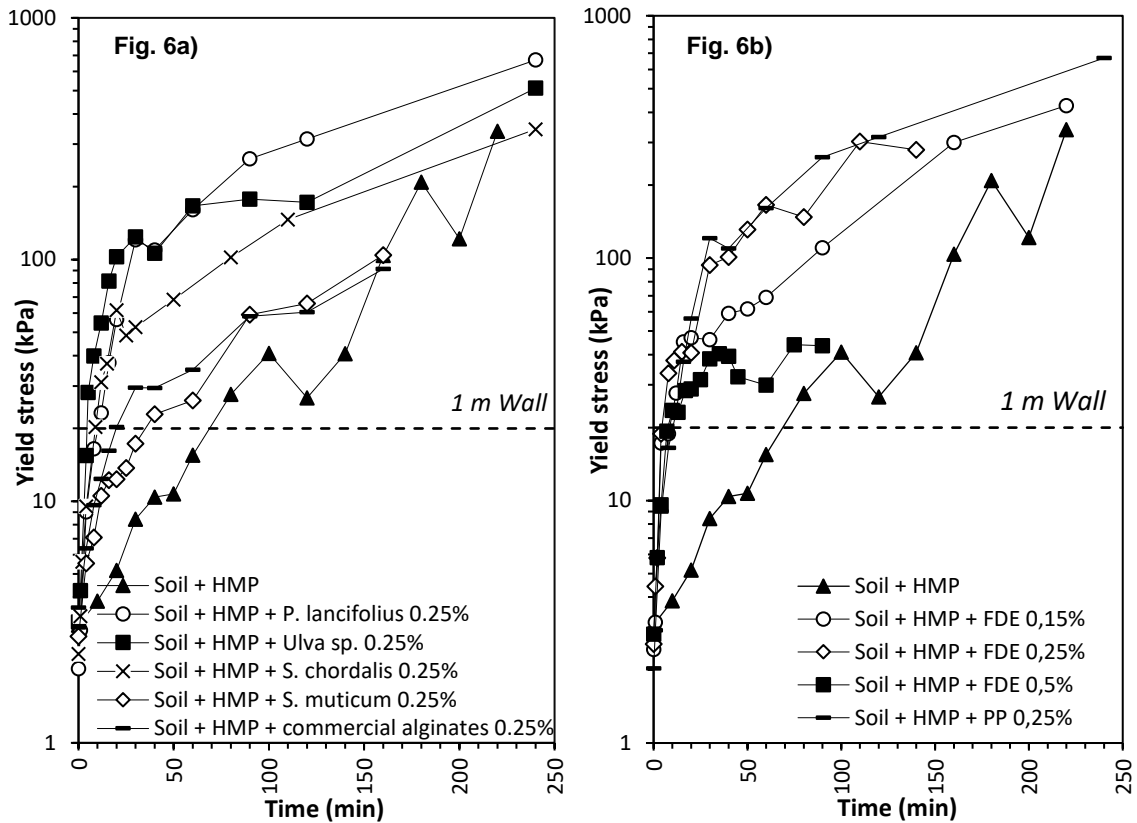
478 This could be due to the form of the extract which is a freeze-dried extract. It  
479 contains material other than polysaccharides and was added in larger quantities in  
480 the mixture. It tends to rehydrate with water vapor contact. Therefore, the amount  
481 of water absorbed will be greater for the freeze-dried extract than for the pure  
482 polysaccharide. A test with pure alginate should be done to determine if the high-  
483 water content of specimen with *S. muticum* freeze-dried extract is explained only  
484 by the extract form or also by the polysaccharide capacity to absorb water.

485 After 7 days in the room at 80% relative humidity, reference soil specimen and  
486 specimen containing *S. chordalis* polysaccharide reach a water content of  
487 approximately 0.5%. The water content of specimen with *S. muticum* freeze- dried  
488 extract is 1.3% (Fig. 5b). Again, the difference of behavior between *S. chordalis*  
489 and *S. muticum* specimens could be due to *S. muticum* extract form. The evolution  
490 of the compressive strength with specimen water content for reference soil, earth  
491 containing *S. chordalis* polysaccharide and *S. muticum* freeze-dried extract are  
492 plotted in Fig. 5c. At dry state, specimens with *S. chordalis* polysaccharide and *S.*  
493 *muticum* freeze dried extract present much higher compressive strength than the  
494 reference soil (4 MPa against 1.7 MPa), that confirms the previously obtained  
495 results.

496 Even if compressive strength rapidly decreases with water content for specimens  
497 containing seaweed extract, seaweed extract addition allows to maintain a higher  
498 compressive strength for a water content lower than 1%. It means that addition of  
499 *S. chordalis* and *S. muticum* extracts allows to increase compressive strength in  
500 indoor conditions and that *S. chordalis* polysaccharide ( $\iota$ -carrageenan) allows also  
501 to increase the mechanical resistance in an atmosphere having a relative humidity  
502 of 80%. Additional test should be done on *S. muticum* polysaccharide (alginate) to  
503 check if pure alginate allows also to increase the compressive strength in an  
504 atmosphere having a relative humidity of 80%.

505           **4. Structural build-up test: influence of seaweed**  
506           **extracts**

507   The structural build-up speed is an important parameter for the development of raw  
508   earth construction. The faster the material becomes firm, holds its shape and can  
509   sustain weight on top, the faster it will be possible to stack the layers and build a  
510   wall. Construction time can then be reduced. This is valid for vernacular  
511   construction techniques such as rammed earth or cob, but also for new processes  
512   such as poured earth or 3D printing. This parameter is particularly important for 3D  
513   printing where layers of material are stacked quickly. A compromise should be  
514   found between the printing speed and the structural build-up of the deposited layer  
515   to sustain its own weight and the weight of the layers above [51]. The evolutions of  
516   the apparent yield stress with time of earth without seaweed extract and earth  
517   containing 0.25% of different seaweed polysaccharides are plotted in Fig. 6a, as  
518   well as the stress induced by a wall of 1 m high [52]. The evolution of yield stress  
519   for the mix soil-HMP was quite linear, mainly due to drying, whereas the evolution  
520   for the mixtures containing polysaccharides were highly non-linear, with a strong  
521   increase of yield stress during the first 20 minutes. *S. chordalis*, *P. lancifolius* and  
522   *Ulva sp.* polysaccharides were the most efficient to obtain a fast-structural build-up  
523   of the earth, with a yield stress at 20 minutes around 100 kPa, which is similar to  
524   earth after 160 minutes. The structural build-up was therefore 8 times faster with  
525   polysaccharides addition. After only 5 minutes, earth containing these  
526   polysaccharides reached sufficient strength to support the weight of a 1 m high wall,  
527   whereas it took 70 min for the earth without polysaccharide. *S. muticum*  
528   polysaccharide was slightly less efficient and the result was comparable to the one  
529   obtained with the commercial alginates.



530 **Fig. 6:** 6a) Evolution of yield stress with time of earth with and without seaweed polysaccharides  
 531 addition (PP); 6b) Evolution of yield stress according to seaweed extract form and concentration  
 532 for *P. lancifolius* (FDE or PP)

533

534 Tests with different forms of *P. lancifolius* extract (polysaccharide and freeze-dried  
 535 extract) and different concentrations of *P. lancifolius* freeze-dried extract show that  
 536 the efficiency on the structural build-up seems to be quite independent of the extract  
 537 concentration in the mixture, and that freeze-dried extract and polysaccharide  
 538 efficiencies were similar (Fig. 6b).

539 Results show that a low concentration of seaweed extract is sufficient to have a  
 540 good efficiency and increase the build-up rate. The seaweed extracts incorporation  
 541 procedure was important to obtain significant results. The dry seaweed extracts in  
 542 powder form were added to the mixture “soil + water” at the last moment. It can be  
 543 of interest to develop processes where seaweed extracts are added when it is needed  
 544 like accelerators at the level of printing head for 3D printed concrete [53]. The aim  
 545 was that the gelation of the polysaccharides occurred directly in the material in the  
 546 mould and not during the preparation phase. Some tests were carried out by first  
 547 mixing the seaweed extracts with water, waiting for gelation and then mixing this  
 548 sirup with the soil. But on one hand this procedure required a larger amount of water



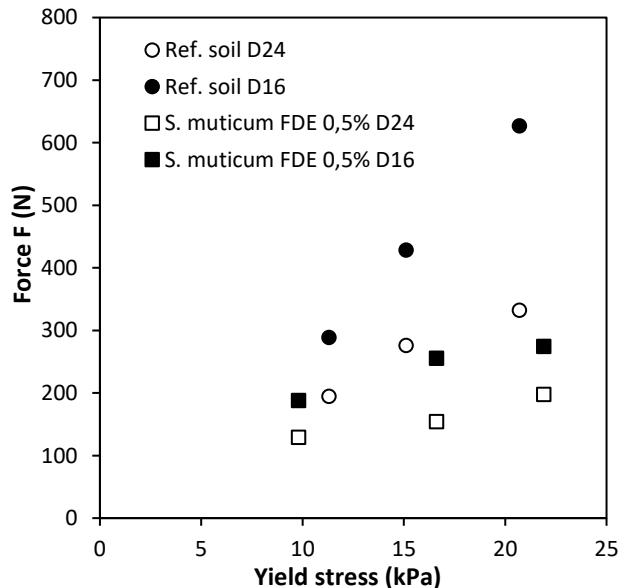
549 to get a workable mixture, and on the other hand the results were not significant.  
550 As the gelation process occurred in the water prior to mixing, no mechanism except  
551 drying allowed to reduce the structural build-up time once the mixture was in placed  
552 in the mould. The formation of a gel in situ, with the creation of bonds between the  
553 polysaccharides and water molecules and metal ions already present in the mixture,  
554 allows to obtain quickly a harder mixture with high yield stress. Once the gelation  
555 process is complete, the yield stress of the mixture increases slowly, mainly due to  
556 drying.

## 557 **5. Extrusion: effects of seaweed extracts**

558 Extrusion is a manufacturing process in which a plastic material is compressed and  
559 forced through a die whose cross-section has the shape of the part to be supplied.  
560 The extrudate is continuously formed. Extrusion is used in particular for the  
561 production of fired earth bricks. 3D printing is also based on the extrusion process.  
562 The development of this technique on raw earth requires precise rheological  
563 properties to have a smooth extrudate, without asperities, and to avoid the  
564 phenomena of drainage and consolidation of the material [44]. All the tested  
565 seaweed extracts allowed to reduce the required force to begin extrusion process  
566 compared to the reference soil (Table 4), and this for both die orifice diameters. The  
567 seaweed extract that allowed to obtain the minimal force to start the extrusion  
568 process is *Ulva sp.* freeze-dried extract, with a required force divided by 2 compared  
569 to the soil reference. *S. muticum* freeze-dried extract allowed also to greatly reduce  
570 the force required for extrusion. A low force to start extrusion means less stress on  
571 the material to be extruded and on the tools. It could be noted that the extrusion  
572 force is the combination of the friction force at the interface between the material  
573 and the extruder wall and the shaping force that is needed to change the diameter  
574 of the extruder in the die area and is proportional to the shear yield stress [45, 46].  
575 It could be assumed that the seaweed extracts act as lubricants and help to reduce  
576 the friction force on the extruder surface as the shear yield stress remains constant  
577 for each material presented in Table 4. Fig. 7 represents the evolution of the required  
578 force to start the extrusion process for reference soil and mixtures with *S. muticum*  
579 freeze-dried extract at different consistencies, for different yield stresses.

	<i>Ref.</i>	<i>P. lancifolius</i>	<i>S. chordalis</i>	<i>Ulva sp.</i>	<i>S. muticum</i>
	<i>soil</i>	<i>PP 0.5%</i>	<i>PP 0.5%</i>	<i>FDE 0.5%</i>	<i>FDE 0.5%</i>
<b>Measured</b>					
<b><math>\tau_0</math> (kPa)</b>	<b>15.1</b>	14.5	15.1	14.4	16.6
<b>Force (N)</b>					
<b>D24</b>	<b>276</b>	169	200	129	154
<b>Force (N)</b>					
<b>D16</b>	<b>428</b>	350	340	199	256

580 **Table 4:** Required force to start the extrusion process at a yield stress ( $\tau_0$ ) of 15 kPa for die orifice  
581 of 24 mm and 16 mm



582

583 **Fig. 7:** Evolution of the required force to start the extrusion versus yield stress for reference soil  
584 and mixtures containing *S. muticum* freeze-dried extract

585 The required force to start the extrusion process strongly increases with the yield  
586 stress for the reference soil, in particular for the 16 mm die orifice, whereas it grows  
587 more slowly for mixture with *S. muticum* freeze-dried extract (Fig. 7). The addition  
588 of *S. muticum* freeze-dried extract helps to maintain some ease of extrusion for  
589 different consistencies, especially when the mixture contains less water. A figure is  
590 available in supplementary material and presents the evolution of the total extrusion  
591 force versus the remaining billet length for reference soil and mixtures containing  
592 seaweed extract on the first 60 mm extruded. On each curve, the strong increase  
593 corresponding to material compaction is visible on the right part.

594 For reference soil, no decrease of the force in the second part of the curve can be  
595 observed, the total extrusion force remaining almost constant or slightly increases.

596 This could indicate the presence of drainage and consolidation phenomena in the  
 597 material, and friction force remain important despite the frictional surface reduction  
 598 during the extrusion process. These observations lead to the conclusion that it is  
 599 impossible to have a correct extrusion with the reference soil. This phenomenon  
 600 can also be observed for mixture containing *Ulva sp.* freeze-dried extract. Even if  
 601 *Ulva sp.* freeze-dried extract allows to reduce the initial force required to start the  
 602 extrusion, it does not allow to have a correct extrusion behaviour over time. For  
 603 mixture containing *S. muticum* freeze-dried extract, a first decrease can also be  
 604 observed then the required force for extrusion remains almost constant. For mixture  
 605 containing *P. lancifolius* polysaccharide, for both die orifices, the curves are quite  
 606 smooth and decrease regularly, even if for die orifice of 24 mm, an increase of the  
 607 require force is observed at 65 mm.

	<i>Ref.</i> <i>soil</i>	<i>P. lancifolius</i> PP 0.5%	<i>S. chordalis</i> PP 0.5%	<i>Ulva sp.</i> FDE 0.5%	<i>S. muticum</i> FDE 0.5%
<b>K<sub>w</sub> (kPa)</b> <b>D24</b>	-	9.17	2.60	12.37	9.13
<b>K<sub>w</sub> (kPa)</b> <b>D16</b>	-	4.54	3.82	13.43	14.58

608 **Table 5:** Average friction stress values Kw at a yield stress of 15 kPa  
 609 The profile of the curves suggests that the addition of *P. lancifolius* polysaccharide  
 610 could improve the ability to extrude the material. For mixture containing *S.*  
 611 *chordalis*, the curves decrease very slowly on the first 60 mm extruded. Table 5  
 612 summarizes the friction stress values Kw obtained with equation (2) for a yield  
 613 stress of 15 kPa. It was not possible to determine a friction stress value for the  
 614 reference soil. Friction stress values vary with the die orifice diameter. Friction  
 615 stress values are higher for the 16 mm die orifice, except for mixture containing *P.*  
 616 *lancifolius* polysaccharide. The mixture containing *S. chordalis* polysaccharide has  
 617 the lowest friction stress value, whereas mixtures with *Ulva sp.* freeze-dried extract  
 618 and *S. muticum* freeze-dried extract have higher friction stress values. To conclude,  
 619 some seaweed extracts seem to have a real impact on the ability to extrude earth  
 620 material. But some additional tests are necessary to better understand the  
 621 parameters affected.

622

## 6. Conclusion

623 The results obtained in this study demonstrate a certain effectiveness of parietal  
624 polysaccharides extracted from certain invasive Brittany seaweeds in improving the  
625 mechanical and rheological properties of raw earth-based material. The ι-  
626 carrageenan extracted from *S. chordalis* and the alginate extracted from *S. muticum*  
627 thus allowed to increase the compressive strength of raw earth specimens in dry  
628 conditions and in wet conditions until a relative humidity of 80%. All the tested  
629 polysaccharides were able to significantly accelerate the structural build-up rate,  
630 thus allowing to reduce processing times during building erection or the  
631 development of 3D printing with raw earth. And visual observations on the impact  
632 of the alginate extracted from *S. muticum* shows that this extract seems to improve  
633 the rheological properties of the raw earth material to obtain a material which is  
634 more easily extrudable than raw earth alone. These results represent a base,  
635 additional tests must be conducted to have a better understanding of the mode of  
636 action of these polysaccharides and to determine the best procedure for adding these  
637 compounds to the mix soil and water. Additional tests must also be conducted on  
638 other types of soil, with different clay content and calcium content.

639 In order to industrialize the process in the future, the polysaccharide extractions  
640 were carried out with as few steps as possible. Some results with freeze-dried  
641 extracts containing other molecules than polysaccharides showed that high purity  
642 is not necessary. However, the polysaccharides precipitation required the use of  
643 absolute ethanol, and the freeze-dried extracts used during these tests have three  
644 main disadvantages, they require higher water additions to obtain a good  
645 consistency, are less concentrated in polysaccharides as they still contained the  
646 algal residues and the freeze-drying process is a rather high energy consumer  
647 process and operates in batch. Other production processes could be considered to  
648 obtain an extract with a high polysaccharide concentration. After the first step of  
649 polysaccharide extraction with hot water, a second filtration step to separate the  
650 solid residues could be carried out, followed by a atomization drying step. The final  
651 goal would be to obtain an algae extract by the cleanest and most-efficient process.

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