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Valorisation of stranded *Laminaria digitata* seaweed as an insulating earth material

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A B S T R A C T

In Normandy, the marine macroalgae become a large problem when the retreat of the tide leaves large quantities of stranded seaweed on coast. These stranded seaweeds can be toxic during their degradation in addition to creating odor problems. Consequently, their elimination has become a major problem and their recovery an emergency. In this work, we proposed to use the stranded seaweed in the building construction at a large scale. We investigated in particular the performance of insulated walls based on lightened earth incorporating reed and stranded *Laminaria digitata* seaweed at different substitution level. The compressive strength and the hygro-thermal properties of the earth insulated walls specimens were carried out. Our results show that the incorporation of seaweed in lightened earth improves both its heat storage capacity and its level of insulation without compromising its compressive strength. The most efficient seaweed content for improving the thermal insulation of the material seems to be 20%. Indeed, the addition of 20% of *Laminaria digitata* decreased the thermal conductivity by 34% at 20 °C in comparison with standard cob. For this mixture, the specific heat capacity value is around 800 J.kg⁻¹.K⁻¹ at 20 °C, which are very high compared to that of the only earth-fiber specimen (400 J.kg⁻¹.K⁻¹). These increases in mechanical and hygrothermal performance of insulating cob material incorporating seaweed will lead to a reduction of the cob walls thickness and therefore to the development of sustainable energy efficient building materials with a low environmental impact.

1. Introduction

Seaweed are organisms living in aquatic environments and are known for their ability to photosynthesize [1,2]. However, marine macroalgae become a problem when the retreat of the tide leaves large quantities of stranded red, green and brown seaweed on the coasts [2]. They create odor problems in Normandy coasts (Nord-west of France) and under certain rare conditions, they can also be toxic during their degradation [3]. The stranding of seaweed and the rafts they can create by remaining on the surface of water represent a recurring problem for Normandy shellfish farming activities but also a danger for nautical activities [3]. The BOREA group from the University of Normandy has extensively worked on this phenomenon on the last 8 years through PhD research on the species quality composition and recurrence of stranding. The project named VARECH, funded by the Government of Normandy

Region, lead by the BOREA group in collaboration with ALGAIA SA is looking at biochemical composition and valorization potential of those cast seaweed. Currently, the only solutions to this problem are the elimination of seaweed stranding and not to prevent mass deposition from occurring since no solution has been found to date. For example, the seaweed can be pushed back to the sea before it dries out, or it can be collected by farmers and used such as compost for the agricultural sector [4]. According to the Center for the study and the valorization of algae (Centre d'Etude et de Valorisation des Algues, CEVA), the Normandy coastal localities observe an increase of mudflats on the coast as well as the more frequent stranding. Between 50,000 and 100,000 m³ (corresponding to an average of 44,640 tons) of seaweeds are collected and treated annually by the concerned local authorities [5]. This activity generated a total cost of about 1.7 million euros per year on the coast from Basse-Normandie to Ile de Ré [5]. Thus, this represents an annual

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cost of 20 euros per m^3 [5]. The studies based particularly on the invasive seaweed such as *Sargassum muticum* and carried out on a small geographical area between Coudeville and Bricqueville sur Mer in Normandy, have shown that the proliferation of this seaweed can reach very large quantities and especially in the summer when the stocks can reach 2,200 tons in July, corresponding to approximately 4000 m^3 [5]. Thus, it can be estimated that these quantities are sufficient to be exploited on a large scale [4]. As the authors, in a 3-year project named SNOTRA and co-funded by Normandy Region, have estimated annual average quantities of 12.000 Tons (corresponding to approximately 24000 m^3 of fresh *Sargassum muticum*, [6]. A follow up project of SNOTRA looking at valorization ways of this invasive species, the project SAVENT, co-funded by ADEME Normandy and lead by ALGAIA SA, is investigating also the potential use of seaweed fibers for insulation. These quantities of *Sargassum muticum* are indeed quite substantial as they represent one sixth of the total volumes of seaweed collected in France per year.

Earth construction is one of the oldest and most widely used building techniques [7]. It is found in many parts of the world and has been the main building material in the ancient civilisations [7]. Earth has the ability to maintain higher thermal mass potential and indoor humidity than most alternative building materials [8]. Earth construction is the most economically feasible way to solve the current housing problem with low resource demands. Therefore, the incorporation of seaweed minerals or seaweed ash in the earth construction can be explored. Seaweed is an environmentally friendly material because it is naturally occurring and stores carbon. These seaweeds also contribute to limiting ocean acidification and deoxygenation as well as other impacts related to global climate change [4]. The incorporation of seaweed (powders, fibers and co-products) into soil could lead to the reuse of waste materials, limit environmental contamination and at the same time reduce the cost of earth and its impact on the environment while maintaining or improving the properties of the soil [9]. Indeed, earth is subject to differential settlement, high compressibility and low shear strength and must be stabilized to improve its properties. The chemical stabilization method is the most recent technique for this purpose [10]. Historically, the first uses of seaweed in construction were in Denmark on the island of Laeso [11]. Dating back to the 19th century, only about 20 of these seaweed-roofed houses remain, classified as national heritage [11].

Seaweed are composed of 90% water, so when dried, they become mainly composed by minerals. Indeed, on the remaining 10% of the total mass, minerals represent 6 to 30% for green seaweed and over 36% for brown seaweed [12]. In addition, the alginate contained in these seaweeds can influence the pigmentation of the seaweeds [12]. Alginate is an algal polysaccharide found in the cell walls of brown algae such as *Laminaria digitata* and which represent between 20 and 60% of the dry matter [13]. Alginate is a block copolymer of β -D-mannuronic acid and α -L-guluronic acid residues, highly suited to a wide range of stabilization and gel-forming applications [14] in textile dyes, food, pharmaceutical and printing industries. All these industries share a common property: the gelling and texturizing capacity of this natural product [14].

Only few studies have been conducted on the use of seaweed or alginate as a stabilizing additive for earth construction. In the field of construction and engineering, some studies and patents have been approved on the use of seaweed in the construction field. For example, [15] showed the ability of biocomposite prepared from seaweed fiber to reinforce building materials. [16] referred to the use of seaweed fiber in unfired adobe blocks. In all of these studies, details about the seaweed products used are limited. In addition, no information about the chemical composition and the origin of the seaweed products are given. [17] investigated the effect of adding a natural animal fiber to earth and alginate matrix. Their results showed that the samples prepared with alginate generally have the lowest density. In addition, the highest compressive strengths were obtained for samples with animal fiber and soils mixed with alginate.

[18] studied the effect of alginate as a binding agent on the

manufacture of unfired earth bricks. Their results showed that the *Laminaria hyperborea* stem product improved the compressive and flexural strength of the earth bricks.

The most detailed studies on the use of alginates in earth construction are those conducted by [19] and [20]. In these studies, the authors fabricated clay bricks incorporating natural fibers as reinforcing elements and alginate polymer as a binder. Alginate stabilization of clay is attributed to the ability of alginate polymer to form reversible cross-linked matrices in the presence of divalent calcium cations originating from clay. The addition of alginate and reinforcement with wool fibers lead to double the compressive strength of the clay brick. The best performances were obtained with a smaller amount of wool. Furthermore, the earth materials in all previous studies have been tested only in relation to structural and mechanical performance. The investigations into other properties of the earth product with seaweed such as hygrothermal performance and moisture absorption have never been studied so far.

Earth can be applied directly to build walls or used in the form of building blocks. The common earth construction techniques are cob, rammed earth, Daub, and compressed earth [21]. In Normandy region (France), the common earth construction technique used is Cob. Cob is a traditional building technique using hand-formed clods of earth mixed with sand and fibers such as straw and reed [22]. Fibrous materials such as reed are typically used to reduce drying shrinkage in earth material and to provide it with the best thermal performance.

Different studies show that lightweight earth mixes have a strong ability to interact with moisture [22,23]. Earth-straw and earth-hemp mixtures are among the insulating materials with the highest level of water buffering value (ability of a material to regulate the humidity of a room). Moreover, the hygrometric regulation felt by the occupants depends on the finishing coat [24,25]. A mixture of light earth completed with a highly hygroscopic finishing coat (based on seaweed alginate for example) is a solution of insulation with a very strong water regulation capacity.

In this paper, we studied the hygroscopic, thermal and mechanical performance of insulated earth wall based on lightened earth incorporating reed fiber and *Laminaria digitata* seaweed at different substitution level. The cob materials are prepared using a technology similar to that used in standard cob construction. Experimental studies of the compressive strength and the hygrothermal properties of cob specimens were carried out. In addition, the composition of *Laminaria digitata* were examined.

2. Materials and methods

2.1. Materials and samples preparation

2.1.1. *Laminaria digitata* seaweed

The species of stranded seaweed explored in this study is *Laminaria digitata* type. Wild *Laminaria digitata* seaweeds (Fig. 1a) were collected at low tides from the coast of Courseulles sur Mer in Normandy, France.

The raw *Laminaria digitata* seaweed were dried in oven at least for 24 h at 40°C and then grounded to powder through $63 \mu\text{m}$ sieve (Fig. 1b). The raw seaweed has a water content around 78 wt%. The drying temperature of 40°C resulted in a color change. Indeed, the brown color of *Laminaria digitata* became "green" (in terms of lightness, chrominance and hue color space). This phenomenon is attributed to a higher oxidation rate of the seaweed pigments with temperatures [26].

The average protein content of *Laminaria digitata* was evaluated by using a nitrogen-to-protein factor, which is $7.9 \pm 1.3\%$. The *Laminaria digitata* alginate content was quantified according to the method developed by Kennedy and Bradshaw [27]. The principle is to use polyhexamethylbiguanidium chloride in order to precipitate alginate. The amount of alginate in the *Laminaria digitata* estimated at $29.3 \pm 2.4\%$ of the dry weight of the biomass.

The measured thermal conductivity of *Laminaria digitata* is 0.073 W/

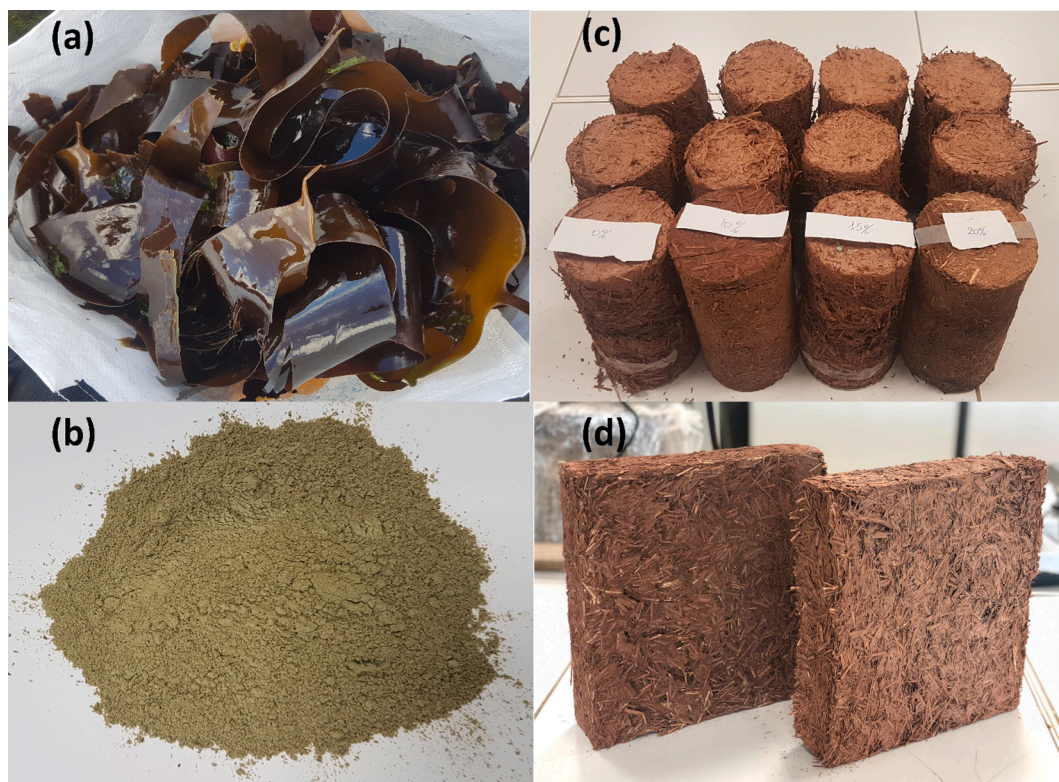


Fig. 1. (a) Raw *Laminaria digitata*. (b) *Laminaria digitata* powder used as earth substitution. (c) Samples used for mechanical tests ($\varnothing 11$ cm \times 22 cm) and (d) samples used for thermal analysis ($30 \times 30 \times 4$ cm³).

m.K at 20 °C. Metal composition of *Laminaria digitata* were achieved using ICP-MS Xseries 2 and ICP-OES (ICP equipped with Optical emission spectroscopy) was used for the measurement of Ca, Na, K and Mg using a Perkin Elmer Optima DV4300. The major four metal cations in *Laminaria digitata* are K, Na, Ca and Mg with the following order: $K > Na > Ca > Mg$ followed by Sr, Fe, Al, Zn and As with trace of Ba, Cu, Cr, Ni, Pb and Mo. The iodine quantity is close to that of Ca and Mg (Table 1).

2.1.2. Natural fiber

The natural fibers were used as reinforcement and insulating materials. As traditional cob, we used the reed fiber for this study. These fibers have different advantages because they are widely available and inexpensive. Therefore, their valorization could lead to a reduction of the environmental impact compared to polymeric fibers due to their renewable and biodegradable aspects and CO₂ emissions neutrality. The reed fibers used in this study were provided by local farmers. The use of reed are fundamentally suitable as an insulation material. Indeed, the thermal conductivity of reed is close to 0.05 W.m⁻¹.K⁻¹ [28].

2.1.3. Lightened earth

The soil used in this study was collected in Lieusaint carry, Normandy. The soil is composed by illite and kaolinite with trace of chlorite. Kaolinite is responsible, when mixed with water, for the clays moldability [29]. The chemical composition and the mechanical properties of the soil are given in Table 2. The soil was dried in an oven at 105 °C for 48 h to remove the absorbed water and then ground to a fine powder.

The particle size distribution of lightened earth is shown in Fig. 2. The result shows that the earth has a larger particle size distribution. The

Table 1

Laminaria digitata chemical analysis determined by ICP-MS and ICP-OES.

Element	Al	As	Ba	Ca	Cu	Cr	Fe	K	I	Mg	Mo	Na	Ni	Pb	Sr	Zn
mg/kg	63	21	6.3	8731	3.6	0.8	127	35,491	8762	7637	0.3	24,863	0.5	0.4	856	48

Table 2

Physical and chemical properties of lightened earth.

Component rate (%)	Lightened earth
Silicon dioxide (SiO ₂)	59.73
Aluminum oxide (Al ₂ O ₃)	20.25
Ferric oxide (Fe ₂ O ₃)	6.09
Calcium oxide (CaO)	5.33
Magnesium oxide (MgO)	3.16
Sodium oxide (Na ₂ O)	0.1
Potassium oxide (K ₂ O)	2.05
Sulfur trioxide (SO ₃)	less than 0.1
Phosphorus Pentoxide (P ₂ O ₅)	less than 0.1
Cl ⁻	0.18
Loss on ignition	3.10
Physical properties	
Plasticity limit (%)	42.5
Plasticity index (%)	15.3
Absolute density (g.cm ⁻³)	2.73

earth particles with size of less than 2 mm in sintering are about 98% of total particles.

2.1.4. Mixture design

Different mixes were prepared. The reed fibers were cut to the length between 4 and 6 cm. These fibers were then added randomly and mixed until getting a homogeneous composite. According to the usual method [23], the reed content used is 25% and the water content is 100%.

The composition of the mixture are presented in Table 3. After mixing, the cob specimens were filled into cylindrical molds (diameter

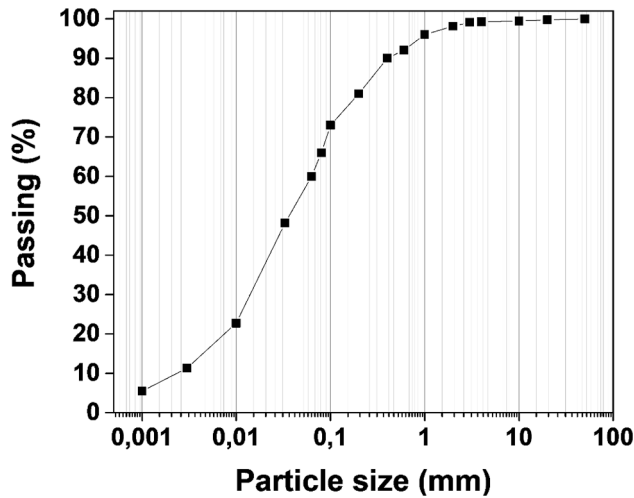


Fig. 2. Soil particle size distribution after crushing.

Table 3

Composition of the cob mixes samples (in wt%). LD for *Laminaria Digitata*.

Formulation	Fiber	Water	Earth	<i>Laminaria digitata</i>
Standard Cob	25	100	100	0
Cob-LD10	25	100	90	10
Cob-LD15	25	100	85	15
Cob-LD20	25	100	80	20

Ø11 cm × height 22 cm) for mechanical analyses and into the prismatic molds (30 × 30 × 4 cm³) for thermal analyses.

The earth and seaweed are first mixed by hand dry. The necessary amount of water is added and mixed with the earth-seaweed until the mixture reaches a liquid state. The fibers are then added gradually in the PROVITEQ Concrete Mixer for 120 s. The lightened earth-seaweed mixture is compacted manually and stored at controlled temperature (20 ± 1 °C) for 24 h. After this 24 h, the mixture is then compacted manually in oiled molds. All mixtures appropriate weights were calculated, in order to obtain a same density. For each sample, we need approximately 700 kg/m³ of dry density and 1.46 kg of dry mixture. Taking into account the quantity of water, the necessary mass to be filled in the mold is then 2.628 kg. The molds are left for 48 h at room temperature (20 ± 1 °C) and then placed 48 h in an oven at 40 °C. The drying process takes 21 days. For each selected composition, three replicates were prepared. After the drying period, the samples are placed a room conditions (20 ± 1 °C and relative humidity of 50%) (Fig. 1c and Fig. 1d). The characterizations of samples began once equilibrium is reached, i.e. when the mass difference between two daily weightings is less than 0.1%. In general, this equilibrium is reached after 48 h. It is important to notice that no cracking was observed and the shrinkage remains very low (less than 1%) for all specimens after 28 days.

The measured specific gravity of the mix is between 643 and 697 kg.m⁻³. For comparison, we prepared the standard cob insulating material, corresponding to that studied in the CobBauge project [22]. The composition of the studied cob mixes is given in Table 3.

2.2. Characterization techniques

The thermal conductivity was analyzed using a system of Heat Flow meter NETZSCH (Model HFM 436 Lambda). The test sample, with prismatic dimensions of 30 × 30 × 4 cm³, is placed between the cooling plate and the heater plate; the heat flows from the heater plate through the sample to the cooling plate from where it is carried off. The cooling and heater plate temperature are adjusted by a Peltier cryostat to establish a temperature gradient from the heater plate across the

specimen of 10 ÷ 40 °C.

Specific heat capacity (C_p) characterizes the ability of a material to store thermal energy. C_p measurements are performed with a Differential Scanning Calorimetry technique (DSC, NETZSCH STA 449 F3) according to the standard ISO 11357-4. Data are collected from -20 °C to 30 °C continuously with heating rate of 1 °C.min⁻¹.

The specific surface area of the cob specimens was determined following the BET method [30] and the absolute density was determined by using a Helium pycnometer (Accupyc II 1340).

Earth plasticity is determined through the Atterberg limits according to the standard NF P94-051.

Prismatic samples were used for bending strength. Mechanical strengths were obtained using a testing machine IGM with a capacity of 50 kN in accordance with AFNOR [NF EN-12390-5] (speed of 0.3 mm/min for bending test) and AFNOR [NF EN 12390-3] (speed of 0.05KN/s for compressive test). The compressive strength at 2 % shrinkage is presented in this study because this value is more representative of the building behaviour [23].

The Raman analyzes of cob mixes were recorded at room temperature using a T64000 spectrometer (Jobin-Yvon, Horiba Group, Kyoto, Japan) equipped with a 514 nm laser as an excitation source. Data was collected over a wavenumber range of 60–1500 cm⁻¹. Raman spectra were recorded at low laser power with an integration time of 30 s.

3. Results

3.1. Moisture sorption isotherm of cob specimens

The moisture sorption curves are similar for all specimens and corresponds to a sigmoidal shape (Fig. 3a). According to the IUPAC classification (International Union of Pure and Applied Chemistry), these curves belong to Type II-isotherm [31] with hysteretic loops. These curves are typical of porous materials, as the investigated earth-fiber mixtures.

The result shows a decrease in the mass difference value from cob specimen to COB-LD specimens. This phenomenon could be attributed to several factors such as the porosity of the specimen. The porosity of the standard cob material and COB-LD specimens are presented in Table 4. The addition of alginate in earthen materials results in the modification of the microstructural properties and physico-chemical interactions with water. The reduction of the pores size through pore-filling is often proposed as a physical mechanism for the gain in strength and in the water-resistance increase. Due to their hydrophilic properties and water retaining, sodium alginates can further reduce the pore size and then enhanced the hygroscopic properties of the materials.

The results show that the porosities of the COB-LD mixes are very low compared to the standard cob insulating material. As seen in Fig. 3b, the moisture of the raw earth, reed fiber and *Laminaria digitata* seaweed were analyzed. The results showed that the seaweeds have a high absorbed moisture in soil-fiber mixtures. Earth-fiber mixtures increase their hygroscopic performances with addition of seaweed. The high absorbed moisture of *Laminaria digitata* is due to the presence of alginate. The amount of alginate in the *Laminaria digitata* is around 29.3% of the dry weight of the biomass. Alginate is considered as a polysaccharide hydrocolloid, which is a very important hydrophilic material due to its capacity to absorb and retain a large amount of water within its structure [32,33]. Fig. 3c presents the typical mass change for adsorption and desorption dynamics at different RH% steps. The particular interest is in at 90% RH, where the mass change for seaweed and for the Cob-LD20 specimen is around 45% and 12%, respectively.

The sorption capacity of *Laminaria digitata* is high and therefore this seaweed will prevent surface condensation (mildew), when it will be added into the soil-fiber mixture.

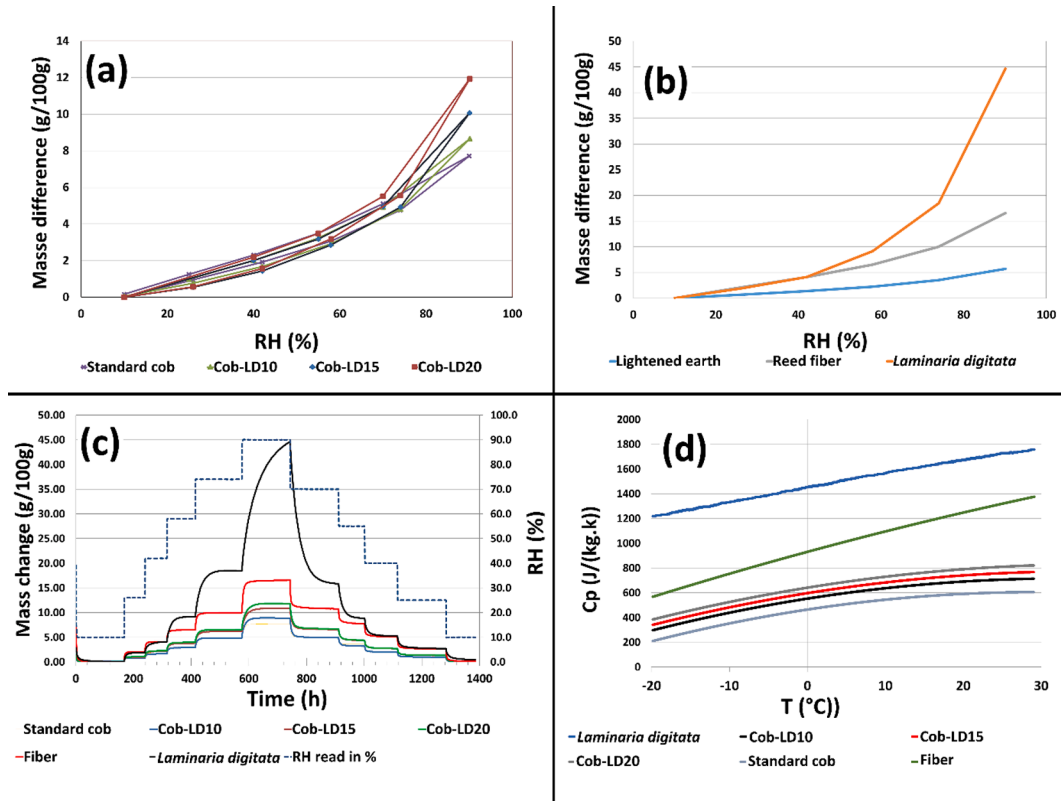


Fig. 3. (a) Moisture sorption isotherm of the cob mixes specimens at room temperature. (b) Moisture sorption isotherm of lightened earth, fiber and PCM. (c) Dynamic vapour sorption of the cob mixes specimens at room temperature. (d) Evolution of the specific heat capacity of cob specimens as function of temperature in heating.

Table 4
Physical properties of the standard cob material and Cob-LD mixes.

Properties \ sample	Standard cob	Cob-LD10	Cob-LD15	Cob-LD20
Compressive strength (MPa)	0.079	0.245	0.115	0.085
Thermal conductivity (W.m ⁻¹ .K ⁻¹)	At 10 °C	0.151	0.134	0.113
		0.157	0.134	0.117
	At 20 °C	0.159	0.141	0.123
		0.164	0.148	0.127
	At 40 °C	0.164	0.148	0.127
Porosity	61%	56%	48%	41%
Density (Kg.m ⁻³)	697	668	657	643

3.2. Thermal conductivity of cob specimens

As can be seen in Table 4, thermal conductivity of the cob specimens made without *Laminaria digitata* seaweed is between 0.151 and 0.163 W.m⁻¹.K⁻¹ for temperature varying between 10 and 40 °C, respectively. For the cob specimens with 10% of seaweed, the values of thermal conductivity range from 0.134 W.m⁻¹.K⁻¹ at 10 °C to 0.148 W.m⁻¹.K⁻¹ at 40 °C. These results demonstrated that the addition of seaweed in earth matrix decreases the thermal conductivity of the cob insulating material. The most efficient *Laminaria digitata* seaweed content for improving the thermal insulation of the material seems to be 20%. Indeed, the addition of 20% of *Laminaria digitata* seaweed decreased the thermal conductivity by 34% at 10 °C and by 29% at 40 °C in comparison with standard cob.

3.3. Specific heat capacity of cob specimens

The specific heat capacity curves of the cob specimens are presented in Fig. 3d. The results showed that the specific heat capacity values increase with the *Laminaria digitata* seaweed content. For the Cob-LD20, the Cp is between 400 and 800 J.kg⁻¹.K⁻¹, which is very high compared to that of the earth-fiber mixture (between 200 and 400 J.kg⁻¹.K⁻¹). In construction applications, a material with a higher specific heat capacity value is required. This confirms that the soil-fiber-seaweed samples have better performance than the standard cob with only a soil-fiber mixture.

Laminaria digitata has a very good calorific capacity with a thermal conductivity (Cp = 1700, λ = 0.073 W.m⁻¹.K⁻¹ at 20 °C) similar to that of thermal insulators based on hemp fiber (Cp = 1400 J.kg⁻¹.K⁻¹, λ = 0.038 to 0.059 W.m⁻¹.K⁻¹ at 20 °C) [34,35].

3.4. Compressive strength of cob specimens

In the compression tests performed on the cylinders, apart from the loss of adhesion between the constituents of the mixture, no breakage of the particles was observed. Therefore, the compressive strength for these ductile materials cannot be the maximum stress observed [9]. Previous research has determined the maximum compressive strength for a percentage of longitudinal deformation ranging from 1.5% to 7.5%. As traditional cob, we chose the corresponding mechanical strength at 2% strain [23]. Our results show an improvement in mechanical strength and thermal conductivity with the increase of seaweed proportion (Table 4).

The results show also that the mixes with the seaweed level of 10% produced the higher strength after 28-day curing compared to that of all cob-building specimens. This can be attributed to the good adhesion between earth, fibers and alginate matrix that prevented the cracks spreading. It is known that lightened earth undergoes differential

settlements and poor shear strength and must be stabilized in order to improve their properties [10]. Alginate stabilization method is one of the recent technique for this purpose. This product originating from brown algae is gaining more importance recently [36].

The Raman analysis of the COB-LD samples after 28 days shows the presence of gaylussite (Fig. 4 in all the COB-LD composites. Gaylussite is a hydrated calcium sodium carbonate with the formula $\text{Na}_2\text{Ca}(\text{CO}_3)_2 \cdot 5\text{H}_2\text{O}$. The most intense band of gaylussite is observed at 1078 cm^{-1} [37]. The internal E_g modes are present at 710 and 1430 cm^{-1} , and the lattice modes occur at 275 and 149 cm^{-1} .

The seaweed contain a high quantity of sodium oxide (Na_2O). The excess of Na_2O reacts with atmospheric CO_2 to form Na_2CO_3 phases. The formation of $\text{Na}_2\text{Ca}(\text{CO}_3)_2 \cdot 5\text{H}_2\text{O}$ as show by Raman analysis, suggests that Ca may have been dissolved from the clay.

In conclusion, the stabilizing effect of the *Laminaria digitata* seaweed in this study is attributed to the ionic bridging between the high sodium alginate within seaweed and the divalent calcium cations originating from the soil, as reported by [20]. This ionic bridging leads to the formation of the double carbonates gaylussite, which is responsible of the high compressive strength obtained for the COB-LD composites compared to standard cob material.

4. Discussion

4.1. Evaluation of performances

In order to evaluate the hygrothermal performances of our developed insulated earth walls, our results have been compared to data found in literature for different earth-fiber materials such as lightened earth and clay of different densities. The measured thermal conductivities, densities, specific heat capacities and maximums isotherm sorption are presented in Table 5.

Despite all the results are all from the same type of material, the hygroscopic values show a wide range of variation for lightened earth. For example, it can be seen that for a dry density between 600 and 702 kg.m^{-3} , the thermal conductivity values vary from $0.113 \text{ W.m}^{-1}.\text{K}^{-1}$ (this study) to $0.20 \text{ W.m}^{-1}.\text{K}^{-1}$ [22]. For a dry density less than 300 kg.m^{-3} , the thermal conductivity is $0.09 \text{ W.m}^{-1}.\text{K}^{-1}$ [38]. This difference in density can partly explain the slightly high conductivity between our composites and those reported in literature [39,40]. Indeed, it is admitted that the thermal conductivity increases with the density [41,39]. Thus, the thermal conductivity values measured in this present study are in the lower range of measured thermal conductivities with the equivalent dry density.

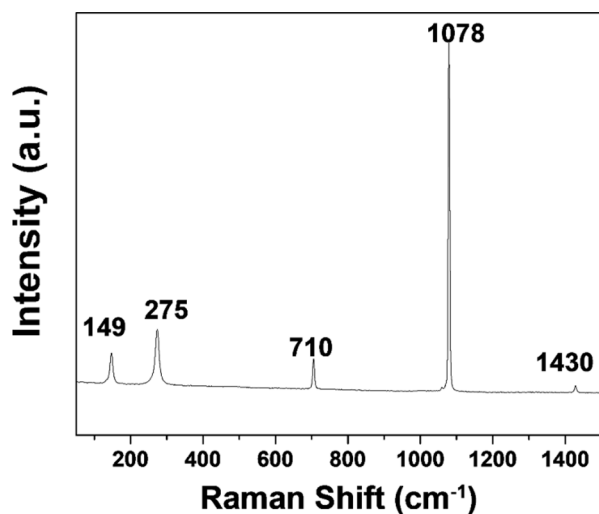


Fig. 4. Raman spectrum of the gaylussite formed on COB-LD20 specimen after 28 days of curing time.

Compared to the work on thermal conductivity, there are relatively few studies on specific heat capacity. The C_p value for our earth-fiber-seaweed composites is lower than the values reported in the literature on earthened earth with hemp fiber or in the presence of PCM, but still higher than that of traditional Cob. The enhancement brought by PCMs is noticeable only near phase change temperature. The difference in C_p between the present earth-based materials and that of Colinart's is due to the high fiber mass content (33.7%). The result shows also a low C_p compared to mud specimens. This phenomenon could be attributed to several factors such as the density, the porosity of the specimen and the differences in the proportion of major constituents (i.e. clay minerals) present in the gravel wash mud sample. Indeed, the higher amount of clay minerals in the material, the higher absorption capacity is expected [42]. Regarding maximum sorption value, lightened earth-seaweed mixtures are more efficient when compared to the literature.

Finally, the enhancement brought by stranded seaweed is noticeable on the sorption of the lightened earth.

4.2. Interests

4.2.1. Cost of drying and processing

The seaweed mix material used in this study is still wet even if the water content tend to be lower than the fresh seaweed species represented in the mix, especially due to the cast situation. However, one of the point of attention in the development of such an application with the material is the pre-processing cost, which requires washing and drying. Washing techniques are current in seaweed processing with low cost impact but the drying technique may be costly, up to 600€ per ton of fresh material, according to ALGAIA. These high costs could affect the development of this application as in parallel, construction materials are highly price conscious. However, the industrial partners have already investigated and tested exceeding heat source from parallel activities such as methanization, which decrease considerably the drying costs down to below 100€ per ton. This type of approach can of course be expanded to other heat production activities in order to offer new prospects for progress in this sector.

4.2.2. Potential advantage of seaweed

The mechanisms of *Laminaria digitata* seaweed stabilization is attributed to the ionic bridging between the high sodium alginate within seaweed and the divalent calcium cations originating from the soil. The earth stabilization is due also to the gelation properties of alginate at room temperature [43]. Sodium alginate present in *Laminaria digitata* is soluble in water, but when exposed to a calcium-rich environment, it forms an insoluble gel [43]. In addition, the sodium alginates originating from brown seaweeds are known to be non-toxic hydrogels with excellent biocompatibility properties that promote their application in the pharmaceutical industry [44]. This indicates the high performance of seaweed in the stabilization and the conservation of earth-based materials. Future work will be conducted to investigate the long-term durability of our composites specimens. Finally, the results obtained in this work clearly demonstrate that stranded seaweeds, which are regarded as wastes have the potential to improve hygrothermal and mechanical properties of earth insulating material. The lightened earth based materials presented in the present study would then be more appropriate for the realization of exterior walls delaying the heat transfer from outdoor to indoor.

Raw earth is traditionally reinforced with biosourced materials such as reed or biopolymers. In this study, different levels of alginate (seaweed) and reed fiber additions were tested to reinforce raw earth. We show that these additions are able to improve the compressive strength and hygroscopic properties of the earth-based materials.

The earthen construction is now receiving new attention because it represents a potential way to set up local value chains with low environmental impact. However, the development of this construction technique, historically present in a major region of France, is still limited

Table 5
hygrothermal properties for different insulated soil-fiber walls.

Soil	Composition	Density (Kg. m ⁻³)	Conductivity (W.m ⁻¹ . K ⁻¹)	C _p (J.Kg ⁻¹ .K ⁻¹)	Sorption max (%)	Reference
Lightened earth	Earth, 25% Reed, 0–20% seaweed	643–697	0.113 – 0.157	400 – 600 at 30 °C	7.8–12	This study [22]
	Earth, 25% Reed (Thermal Cob)	637–664	0.16 – 0.18	x	x	
	Earth, 25% Hemp	654–702	0.18 – 0.20	x	x	[22]
	Earth, 33.7% Hemp	272	0.09	1050 at 40 °C	4.3 – 5.6	[38]
	Earth, 25% Reed, 0–20% PCM (Phase Change Materials)	650–700	0.134 – 0.156	537–2130 at 24 °C	6–7.7	[23]
Gravel wash mud	Mud, 0–6% Straw	1100–1537	0.14 – 0.55	1300–1400 at 40 °C	3.5	[47]
	Mud, 0–6% Hemp	1271–1519	0.25 – 0.55	1500–1600 at 40 °C	3.4	[47]
	Mud, 0–6% Corn Cob	1565–1671	0.35 – 0.55	1500–1600 at 40 °C	3.1	[47]
Clay	Clay, 20–33% Typha <i>Australis</i>	323–586	0.065 – 0.112	x	12.9	[39]
	Commercial Straw-clay	241–531	0.071–0.12	x	12	[40]

due to the high cost and the construction time imposed by the large workforce and the duration of the drying of the material. It could be interesting to make the earth material benefit from the advances made for the formulation of concrete, especially in terms of rheology control. For that, the addition of dispersants and gelling agents (reed fiber and alginates) allows to control the initial rheology and the rapid solidification of the material. It is thus possible to consider producing self-compacted clay [45,46].

4.2.3. Research projects in Normandy

For over ten years, many research projects have been interested in the exploitation of seaweed in Normandy, both on the harvest of certain species present in large quantities and on algoculture. In addition to the companies already installed, especially on the recovery, as for carrageenans or on certain productions such as spirulina, the final conference of the SNOTRA project in December 2019 has allowed to take stock of the projects progress conducted in Normandy as well as the interest of many actors in the territory to turn more to seaweed.

From this observation was born the idea of federating the Normandy actors interested by the exploitation of seaweed from collection or cultivation to marketing, within a structure of associative type or other. The aim of this structure would be to pursue the acquisition of knowledge in the economic, environmental, regulatory, scientific and social fields, to act as a link between the Normandy actors and the French and European seaweed industry, to ensure the links between the different partners, to coordinate the different cooperation projects and to valorize the results with the aim of constituting a perennial seaweed industry in Normandy.

Given the large quantities of stranded algae, this present study shows the possibility of valorizing the seaweed on a large scale. The future studies on the valorization of seaweeds in constructions will concern the *Sargassum muticum* seaweed. The quantities of *Sargassum muticum* are indeed very important since they can represent up to sixth of the total volumes of algae collected in France per year.

5. Conclusions

This study has focused on the mechanical and hygrothermal characterization of insulated earth walls containing *Laminaria digitata* seaweed at different content level. The experimental studies have shown that the addition of seaweed, up to 20%, in the cob matrix improves the performance of the material. The experiments have yielded some promising findings, which are summarized as follows:

- The incorporation of seaweed in lightened earth improves their heat storage capacity, their insulation degree and their compressive strength.

- The valorization of stranded seaweed on a large scale in the earth construction is possible. This valorization will contribute extensively to the achievement of the sustainable development goals and thus the reduction of the financial cost of stranded seaweed management.
- The seaweeds have many advantages: they are environmental friendly. In addition, the energy demand of the future cob houses will be reduced thanks to their thermal properties.
- The increase in compressive strength and the hygrothermal performance of cob material with seaweed compared to standard cob construction materials will lead to a reduction of the cob walls thickness.

These first results highlight the need for a complementary investigation at building scale, in order to propose an optimized architectural design of earth walls with various seaweed sources (powder or fiber) for indoor and/or external walls to achieve good energy efficiency in winter accompanied by a good comfort in summer. The simulation of the energy savings due to the seaweed incorporation into earth for the cob buildings construction should be also evaluated.

CRediT authorship contribution statement

Manal Bouasria:Methodology, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, **Yassine El Mendili:** Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, **Mohammed-Hichem Benzaama:**Validation, Investigation, Formal analysis, Writing – review & editing, **Valérie Pralong:**Validation, Investigation, Formal analysis, **Jean-François Bardeau:**Validation, Investigation, Formal analysis, Writing – review & editing, **Franck Hennequart:**Validation, Formal analysis, Investigation, Data curation, Visualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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