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# Development of a stabilized natural fiber-reinforced earth composite for construction applications using 3D printing

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**Abstract**. The application of additive manufacturing technologies to the construction industry has a wide range of advantages from the economic, social and design flexibility point of view. However, most of up to date research studies have been performed using ordinary Portland cement (OPC)-based mortars and concretes. Therefore, the objective of this article is to explore the development of an eco-friendly earth composite reinforced with natural sisal fibers and chemically stabilized with a hydraulic binder. Analysis of the workability by shear vane tests was performed on fresh earth samples to find the optimum water content in sisal fiber-reinforced earth stabilized with OPC. Afterward, the effect of the addition of OPC on the hardening process was evaluated through shear vane and Vicat needle tests from 0 to 180 min after mixing. The results indicate that water content, fiber addition and OPC replacement have a strong influence on the shear yield strength. Furthermore, the presence of chemical stabilizers as OPC accelerates the hardening process allowing a faster layer-by-layer deposition. This low cost and eco-friendly preliminary earth-based composite can be used for 3D printing applications in the construction industry.

## 1. Introduction

3D printing was defined by the American Society of Testing Materials (ASTM) as the manufacture of objects by depositing material using a print head [1]. The literature indicates that materials used for 3D printing applications for construction should be designed according to the particular characteristics of the printing system [2] and should ensure flow ability with a balance between a self-compacting mixture and a non-slump mixture [3]. During the printing process, this material must satisfy specific conditions of extrusion, shape retention, capacity to control deformation to withstand successive layers and good adhesion [4–6].

From a material, economic and environmental point of view, earth has proven to be a suitable alternative building material that properly used can provide safe solutions that are also thermally and acoustically efficient [7–9]. However, compared to other traditional building materials (e.g. concrete or fired clay), untreated raw earth has several limitations and disadvantages. Some of its negative points are its low resistance to compression and tensile loads, vulnerability to water erosion, low resistance to dynamic loads and high cracking during the drying process [7 – 10]. Chemical stabilizers and fiber reinforcement have been actively investigatedfor modifying this material obtaining earth-based composites with improved compressive, tensile and flexural strength [11] and enhanced durability [12]. Aerial binders such as quick lime and slaked lime [13], hydraulic binders such as OPC

[14], geopolymers such as fly-ash-based geopolymers [15] and pozzolana-based geopolymers [16] and biopolymers such as alginate [11], carrageenan [17] and chitosan [18] have been used as chemical stabilizers of earth-based construction materials. In the case of natural fiber reinforcement, a wide range of natural plant and animal fibers were employed in earthen buildings materials [9, 11, 19].

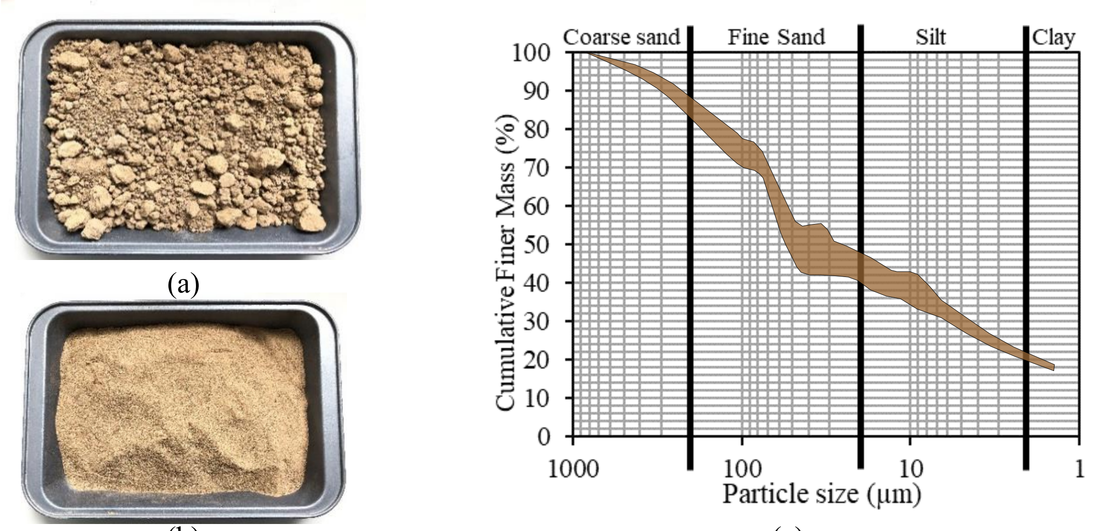
3D printing projects for construction such as Contour Crafting (CC) [20], the 3D concrete printing project of Loughborough University [21], D-shape [22]and the proposal for large-scale 3D printing of high-performance concrete developed by Gosselin et al. [23]stand out in this area. All of these projects have been designed with OPC-based mortars or concretes. There are limited applications related to the use of earth as a building material for 3D printing applications. Perrot et al. [24] used stabilized earth with alginate biopolymer for the generation of an extrudable material. The use of this agent significantly increased the gain rate of the yield strength allowing a stable layer-by-layer deposition. On the other hand, the Italian company Wasp3D presented in 2018 the first printed house built with stabilized earth and reinforced with rice residues [25]. The material used to build one-story modular houses was composed of 25% earth (30% clay, 40% silt and 30% sand), 65% rice residues and 10% lime. Therefore, the objective of the present research is to explore the development of a new earth-based composite composed of earth, natural sisal fibers and OPC for 3D printing applications. A detailed description of the followed methodology based on the analysis of the workability and the hardening process to obtain an earth-based composite adequate for 3D printing applications is presented.

## 2. Materials and experimental plan

### *2.1. Description of raw materials*

Earth used in this study was soil extracted from Callao (Peru). As shown in Figure 1a, this raw material was inadequately for 3D printing applications due to the high content of gravel and lumps. Therefore, the material was passed through ASTM sieve No.20 to remove particles larger than 0.875mm obtaining a ratio of the maximum particle size to the diameter of the delivery system pipe of 1/29 (less than the recommended maximum ratio of 1/10).This process allowed obtaining the sieved earth shown in Figure 1b that exhibited a particle size distribution envelope given in Figure 1c. The granulometric analysis of the earth was performed following the statements of UNE-EN ISO 17892-4:2019 [26] and indicated a d90= 250 μm, d50=25 μm and d20=1.8 μm. Approximate average contents of coarse sand, fine sand, silt and clay of 15%, 41%, 21% and 23%, respectively, were defined and demonstrated that this material fulfilled the recommendation of a maximum content of gravel and sand of 80% given by Lecompte& Perrot [27].

In addition, the sieved earth was subject to a physical characterization campaign following the standard UNE-EN ISO 17892-12:2019 [28] (see Table 1). The earth presented a liquid limit of 29.6%, a plastic limit of 19.9%, and a plasticity index of 9.7. Based on these results, the earth was classified as inorganic clay soil. Finally, the moisture content and apparent specific gravity of the raw material were measured at 3.4% and 2.6, respectively.



(a)

(b)

(c)

**Figure 1.** Raw material: (a) Raw earth; (b) Sieved earth; (c) Particle size distribution envelope of sieved earth.

**Table 1.** Physical properties of sieved earth.

| Liquid limit (%) | Plastic limit (%) | Plasticity index | Moisture content (%) | Specific gravity |
|---|---|---|---|---|
| 29.6 | 19.9 | 9.7 | 3.4 | 2.6 |

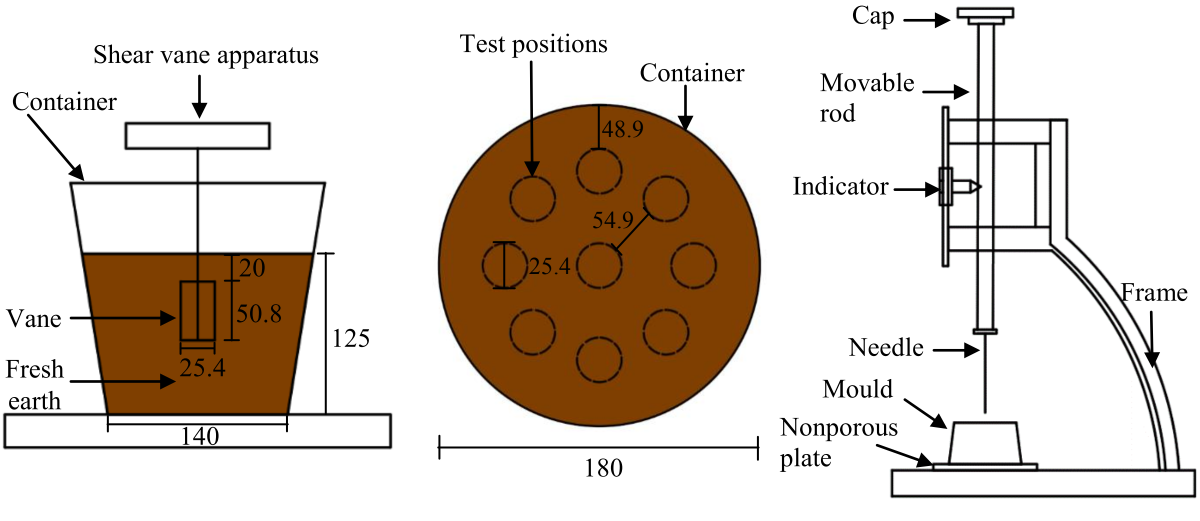
Natural sisal fibers were used as short-random reinforcement of the earth-based material. Sisal fibers present a density of about 1.30-1.45 g/cm$^3$ [29] and are composed of around 58-63% cellulose, 20-24% hemicellulose, and 7-9% lignin by weight[30]. In the present research, sisal fibers were obtained from commercial products (ropes) and cut to a length of approximately 10 mm. The average diameter of sisal fibers was calculated around 137 μm (aspect ratio l/d of 73), measured with a Mitutoyo dial thickness gauge (model 7301).The tensile strength of sisal fibers was investigated by direct tensile tests carried out with an MTS Exceed 42.053 machine with 5kN at a displacement rate of 6 mm/min. Sisal fibers showed a tensile strength, E-modulus and elongation capacity of 508 MPa, 27 GPa and 2%, respectively.

OPC is a fine-grained material produced by gypsum and clinker inter grinding. Clinker, the major component of cement (95%), is a pyro processed hydraulic material mainly composed by tricalcium silicate ($C_3S$), dicalcium silicate ($C_2S$), tricalcium aluminate ($C_3A$) and tetracalcium aluminate ($C_4AF$), where both calcium silicates compounds are the most important for earth stabilization[14]. For this research, Portland Cement SOL type I was used as a chemical stabilizer of the fiber-reinforced earth-based composite.

### *2.2. Characterization of the fresh properties on earth-based composites*

Trial mixes of earth-based composites were subjected to shear vane tests to evaluate their suitability for 3D printing applications. As Le et al. [31] stated, shear vane tests can provide more valuable and scientific information regarding workability than conventional methods as slump, compacting factor and flow tests. A Humboldt H-4227 field shear vane set with vanes with a diameter: height ratio of 2, as specified by ASTM D2573/D2573M−18 [32], was employed to perform the workability assessments of all earth-based composite mixtures. Due to the relatively low shear stresses presented by the material immediately after mixing, a 25.4 x50.8 mm vane (conversion factor of 0.5) was used during workability analysis. All shear yield strength measurements were performed immediately after mixing in a container with the dimensions shown in Figure 2a. Large dimensions of the container allow taking nine measurements per test avoiding boundary effects as shown inFigure 2b.

An evaluation of the shear yield strength gain overtime was performed to study the effect of the OPC on the hardening process of the earth-based composites. The tests were performed at 0, 30, 60, 120 and 180 minutes after mixing. In this stage, in addition to 25.4 x 50.8 mm vane, 20x40 mm and 16x32 mm vanes (conversion factor of 1 and 2, respectively) were used to study the fiber-reinforced earth-based composites stabilized with OPC due to the high shear stresses registered from 30 minutes. The hardening evaluation was complemented with Vicat needle tests (Figure 2c). Measurements were taken from 0 to 180 minutes after mixing in intervals of 10 min in a sample poured in a truncated cone mold with a dimension of 70x60x40 (base diameter x top diameter x height).



(a) (b) (c)

**Figure 2.** Experimental procedure diagrams: (a) Side view of shear vane tests; (b) Plan view of shear vane tests with measuring points; (c) Vicat needle tests.

### *2.3. Preparation of samples*

Earth-based matrix (EM), fiber-reinforced earth-based matrix (FEM) and fiber-reinforced earth-based matrix stabilized with OPC (CFEM) were prepared to study their effect on the workability and hardening process of earth-based composites. Earth, sisal fibers and OPC were dry-mixed to ensure homogenous distribution. After that, tap water was gradually added and mixed until a homogenous paste was obtained. All mixing process was executed using a mortar mixing machine UTG-0130 (UTEST) with a capacity of 10 L. Once pouring the fresh earth-based composite in the container for shear vane tests and truncated cone mold for Vicat needle tests, samples were kept under room temperature and relative humidity of 18 °C and 74 %, respectively.

Different contents of water were studied for EM, FEM and CFEM (a summary of all trial mixtures is presented in Table 2). The water content is expressed in terms of the weight ratio (wt.%) of water to the total composite (earth + water + OPC). Water content was varied for the three earth-based composites to reach suitable workability in terms of the shear yield strength for 3D printing applications. For this research, a maximum shear yield stress of 2.2 kPa was defined based on the recommendations given by Perrot et al. [24] for an extrusion machine with a maximum working pressure of 20 bar. Fiber addition and OPC replacementat1% (wt. %) of fibers to the total solids (earth + OPC) and 13 % (wt. %)of OPC to total solids, respectively, were used for the reinforcement and chemical stabilization of EM. OPC replacement value was chosen on the basis of the recommendation given by UNE 41410:2008 [33] that stated a maximum of 15% of stabilizers in earth-based materials.

**Table 2.**Summary of mixture proportions used for the preparation of earth-based composites.

| Earth-based composites | N° | Water content (wt. % of the total composite) | Fiber addition (wt. % of solids) | OPC replacement (wt.% of solids) |
|---|---|---|---|---|
| Earth-based matrix (EM) | 1 | 18.0 | 0 | 0 |
| | 2 | 19.0 | | |
| | 3 | 20.0 | | |
| Fiber-reinforced earth-based matrix(FEM) | 4 | 18.0 | 1 | 0 |
| | 5 | 19.0 | | |
| | 6 | 20.0 | | |
| | 7 | 21.0 | | |
| | 8 | 21.5 | | |
| | 9 | 22.0 | | |
| Fiber-reinforced earth-based matrix stabilized with OPC (CFEM) | 11 | 20.6 | 1 | 13 |
| | 12 | 21.5 | | |
| | 13 | 22.5 | | |
| | 14 | 24.3 | | |

## 3. Results and discussion

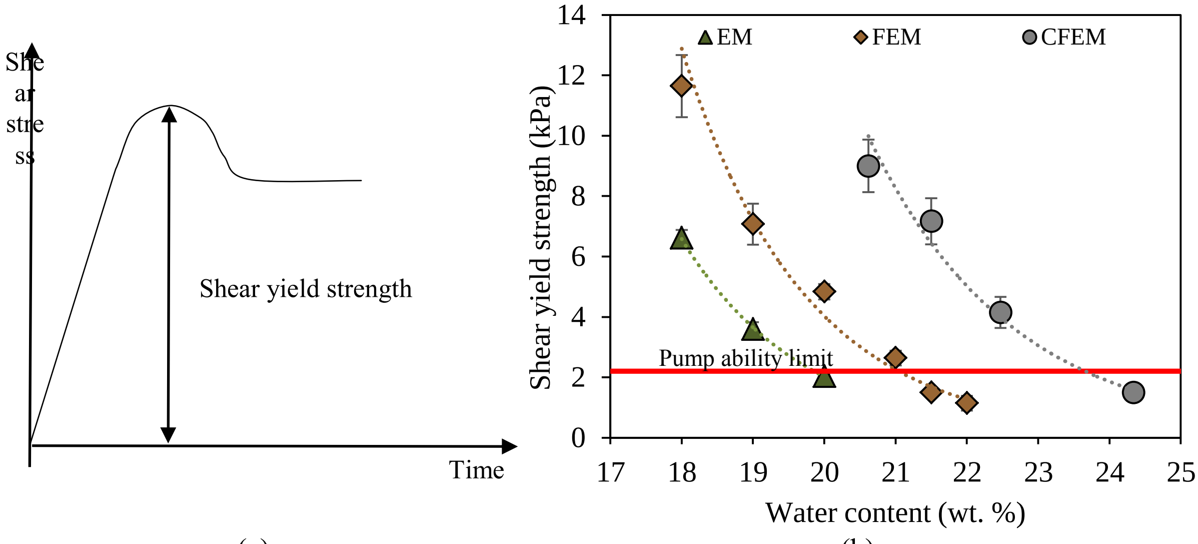
### *3.1. Evaluation of the workability of earth-based composites*

Stress growth experiments were performed using a shear vane apparatus to obtain the shear yield strength of all earth-based composites immediately after mixing. During stress growth shear tests, the material is subjected to a constant strain rate at low rotational speeds (Figure 3a). It is important to execute the tests at low speeds since the conversion from maximum torque to yield strength is valid only for low rpm. The conversion from torque to yield strength is obtained with equation (1) for a vane with H/D=2 [32]:

$$\tau_y = \frac{6\mathrm{T}}{7\pi\mathrm{D}^3} \times 10^6 \tag{1}$$

Where T is the maximum torque, $\tau_y$ is the yield strength while H and D are the height and diameter of the vane, respectively. The conversion factors are expressed with respect to a standard vane of 20 x 40 mm.

The results of shear vane tests on earth-based composites are shown in Figure 3b. The results indicate that the water content has an indirect exponential relationship with the shear yield strength for all the three earth-based composites. In the case of EM, the water content necessary to obtain a yield strength of less than 2.2 kPa was 20%. When sisal fibers were added, for constant water content, the shear yield strength significantly increased since sisal fibers have a water absorption capacity of 125% and also high surface area due to its high aspect ratio (L/D = 74). Therefore, a water content of 21.5% in FEM was used to obtain a shear yield strength of 1.5 kPa. Finally, an OPC replacement at 13% (wt. %) again affect severely the shear yield strength of the material, an increment of 380% was observed for a water content of 21.5%. This increment of the yield strength caused by the replacement of earth by OPC can be explained by the significantly lower specific surface area of OPC by its finer particle size (usually from 0.5 to 50 um) that increases the water demand. Consequently, the water content necessary to obtain a CFEM for printing applications using an extrusion machine of 20 bar was 24.3% (wt. %).

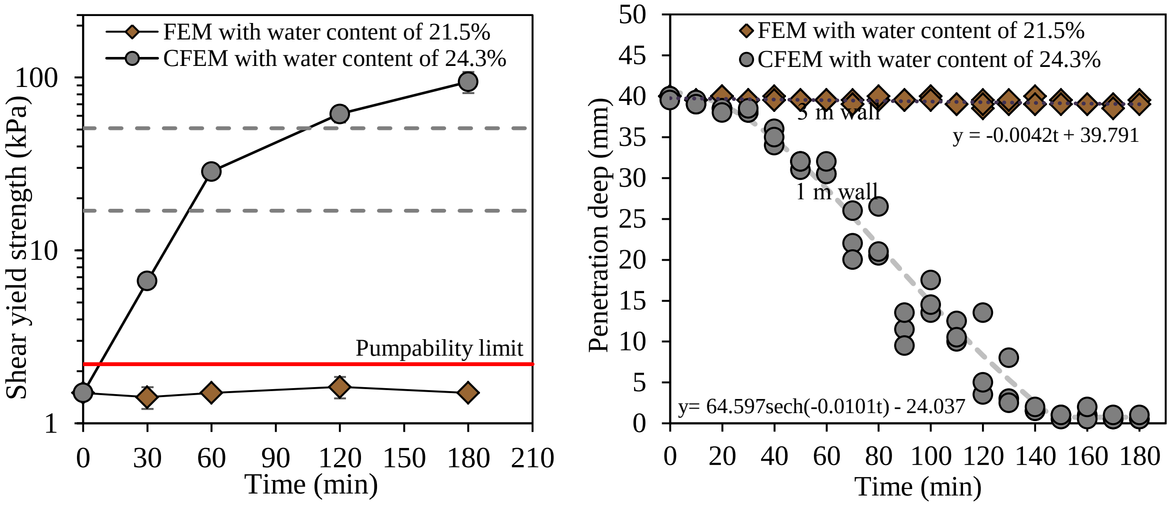


(a) (b)

**Figure 3.** Shear vane tests: (a) Scheme of the stress grow tests; (b) Influence of the water content in the shear yield strength for EM, FEM and CFEM.

### *3.2. Evaluation of the hardening process of earth-based composites*

The hardening process was evaluated on FEM with a water content of 21.5% and CFEM with a water content of 24.3% through shear vane tests at 0, 30, 60, 120 and 180 min and the results are displayed in Figure 4a. The results indicate the great influence of the hydraulic binder presence on the hardening process. After 60 minutes, the stabilized earth-based composite (CFEM) reached a yield strength of 29 kPa. Wangler et al. [34] stated that the vertical compression load applied to a given layer by a printed structure is equal to ρgH where ρ is the density in the fresh state of the printed material (1730 kg/m$^3$ for this research), g is the gravity constant and H is the height of the printed structure above a given layer. Therefore, the developed CFEM is able to support the weight of a 1 m high wall after 1 hour. After 120 min, the stabilized earth-based composite is able to sustain a 3 m high wall. However, this rapid gained of yield strength can be undesirable if the material cannot be extruded in a few minutes, a concept defined as open time or printability window. On the other hand, FEM did not exhibit major evolutions on its shear yield strength. This can be explained due to the hardening of earth-based materials without chemical stabilizers is based on free water loss, which is a very slow process, especially at high relative humidity environments (e.g. 70%). On the contrary, hydraulic compounds of OPC as $C_3S$ and $C_2S$ can set and harden in contact with water and produce calcium hydroxide crystals responsible for cation exchange and flocculation and agglomeration, and calcium silicate hydrate (C-S-H) that bring strength to the earth matrix [14]. In addition, ettringite, which is the first hydrate product to crystalize (1 hour after mixing), contributes to stiffening and setting during early ages[35]. The results of shear vane tests are compatible with Vicat needle tests, a conventional method to evaluate the setting time of OPC pastes. As in the case of shear vane tests, the earth-based material with no OPC replacement (FEM) did not exhibit stiffening up to 180 min. However, the addition of OPC at 13% (CFEM) alter the penetration resistance to the Vicat needle of the earth-based composite. Furthermore, the data of the latter are well fitted to a hyperbolic secant curve (see Figure 4b). This trend is in accordance with Knudsen [36]who proposed linear and exponential hyperbolic models for the hydration of cement-based materials.



(a) (b)

**Figure 4.** Evaluation of the hardening process of earth-based composites: (a) Shear vane tests; (b) Vicat needle tests.

## 4. Conclusions

This article was aimed to analyze the workability and hardening process of earth-based composites in the context of 3D printing for construction applications. An earth-based material with a water content of 24.3% (wt. %) reinforced with 1% (wt. %) of sisal fiber sand chemically stabilized with 13% (wt. %) of OPC was developed. This building material has a shear yield strength immediately after mixing of 1.5 kPa, making it suitable for 3D printing applications using an extruder with a minimum working pressure of 20 bar. Furthermore, the analysis of the hardening process allowed to demonstrate that a layer of this new earth-based composite can sustain a 3 m wall after 120 min. This enhanced hardening of the earth-based material is fundamental to achieve high-speed construction processes.

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