



# 3D printing of earth-based materials: Processing aspects

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## HIGHLIGHTS

- Using a fast setting binder, it is possible to print an earth-based mortar.
- Alginate is an efficient binder to enables earth printing.
- 3D printing can make an earth-based material with compressive strength in the same order of conventional cob earth.
- Young modulus and yield stress evolution of the material govern the maximum printing rate.

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## ABSTRACT

Due to its low environmental impact, earth construction has received much consideration in recent years. Nevertheless, its development remains limited due to low production rate. Recent developments have been made to improve earth-based materials mix-design and processing methods. Simultaneously, digitally based construction methods have been introduced in the field of construction especially for cement-based materials application. Among these new techniques, the so-called 3D printing by extrusion deposit has been the most intensively studied. In this study, we assess the possibility of adapting this technique to earth-based material. After making the earth's rheological behaviour suitable for 3D printing, a laboratory-scale printing has been carried out and the printed samples have been mechanically tested.

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## 1. Introduction

Earthen construction has recently regaining much attention in the building industry due to its low environmental impact and recyclability [1–4]. Nevertheless, the development of earthen construction is still limited because of the price, insurability difficulties and bad durability due to high water sensitivity. The high price is mostly due to the labour cost and to the time required for the material to harden and by a slower production rate than that of the concrete industry. At the present time, it is difficult to have a mix-design that allows for both fast casting and sufficient strength in the dry state. In order to address both problems and to improve mix-design of earth-based material, a recent trend has been to apply scientific knowledge and expertise developed by the concrete industry to earthen construction (Gnanli et al., 2014) [4–8].

Some attention has been paid to the possibility of simulating the cement setting by using biopolymers such as alginate [9–11] or using a combination of hydraulic binders and admixtures [8,12].

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Moreover, unconventional processing methods have been recently introduced and studied to improve the simplicity of building with earth and accelerate the building rate. For example, extrusion [13,14], self-compacting clays [15] or hyper compaction [16] have been developed for that purpose.

A recent trend in construction is to introduce digitally based construction method such as 3D printing in order to accelerate the production rate, improve the security of workers, and provide design freedom to architects. Cement-based materials 3D printing is beginning to be well documented [17–24]. Among the developed techniques, extrusion-based additive manufacturing methods have been the most studied [17–21]. In this technique, the successive layers of concrete are deposited by a robot to build a complete structure. It is important to note that the success of this process is based on a competition between the material structural build-up rate and the construction rate [21,23]: the deposited material must be hard enough to support the increasing load induced by subsequently deposited layers of the “in process” construction. It follows that the fast development of so-called green strength of the cement-based material is required to ensure fast production and structure stability; this problem has required an accurate

description of the evolution of the cement-based material with time [25–28].

The basic aim of this paper is to show that it is possible to print a structure with an earth-based material. It is a great challenge to attempt to mix the world oldest construction material with the newest construction processing techniques. To achieve this objective, alginate seaweed biopolymer has been added to earth in order to provide fast development of the earth's green strength, such fast hardening is here studied and described. This method allows the computation of the maximum building rate of the structure. The elastic rigidity of the freshly mixed earth has also been evaluated using the penetration method. To our knowledge, it is a first study dealing with earth 3D printing, however some clay-based systems have already been printed at small-scale in the ceramics industry [29–32]. In this paper an example of laboratory-scale printing of an earth structure is presented and the subsequent mechanical testing of the final structures.

## 2. Materials and methods

### 2.1. Materials

The tested material was a raw earth coming from Saint-Sulpice-La-Forêt (Ille et Vilaine, France). It was a fine soil with a particle size distribution (PSD) showing 60% particles finer than 10  $\mu\text{m}$ ; the  $d_{50}$  diameter was equal to 8  $\mu\text{m}$ . The clay particles were a mixture of quartz, kaolinite, illite and smectite (these results were obtained by XRD analysis of the natural material, material after thermolysis at 550  $^{\circ}\text{C}$ , and material treated with ethylene-glycol). The plasticity index of this soil was 21 with a liquid limit of 48% and a plastic limit of 27%. The tested water content was 45%. In order to assess the workability, the material yield stress was measured with a Anton Paar Rheolab QC device in a vane tests configuration (stress growth procedure at constant strain rate of 0.05  $\text{s}^{-1}$ , cup radius 50 mm, vane diameter 11 mm and vane height of 40 mm; see [33] for more details in the procedure). At such a low shear rate, viscosity effects are negligible and yield stress could be computed from the measured torque peak value at flow onset. The vane geometry used in this study consisted of four blades around a cylindrical shaft. The measured yield stress value is 1.5 kPa which makes the material consistency close to the liquid state [34] which is expected to be helpful to ensure earth pumpability.

The raw earth used in the study has been used on cob construction site. A 1 mm mesh sieve has been used to remove the largest particles. The particles size distribution should not present too large particles (a typical ratio of pipe to maximum particles diameter should be around 10). Moreover, the amount of sand and gravel should be limited (less than 80 percent the random packing fraction [25]) in order to avoid frictional behaviour and to ensure pumpability. This is the case for the tested material.

A commercial alginate was used in this study. Alginate is a family of seaweed biopolymers which are alginic salts obtained from the cell walls of brown seaweed. The alginate used was a white powder of alginic salt Cimalgin HS3<sup>®</sup> supplied by Cimaprem (Redon, France). This product is designed to make high strength gel for arts and molding applications. The HS3 product was mostly composed of alginate salt with “on demand” calcium release agents that allowed the monitoring of the duration of alginate gel network creation. Alginate can form a cross-linked isotropic insoluble gel when a soluble form of alginate nucleates with divalent metal cations like  $\text{Ca}^{2+}$  that can be found in earth-based materials. Chains of alginate make junctions by intercalating divalent cations creating a sort of egg-box connection [35]. In order to improve the dispersion of alginate within the earth material, the HS3 powder was firstly mix with an equal mass of water.

Alginate is not the only possible admixture, cement or hydraulic binders can be also used to induce a fast structural build-up of earth.

The earth was prepared using high capacity Hobart mixer. Dry earth was first introduced into the bowl and water was then added, the quantity being that to attain a water content of 45%. The mixing procedure consisted of a 4 min low velocity mixing stage, followed by a high velocity mixing stage of 5 min. Between these two stages, the bowl was scrapped in order to ensure that no unmixed material remained adhered to the bowl. Eight 8 kg batches of the mix of water and earth were prepared and put in a 100 L container for 24 h for homogenization.

The alginate solution was prepared just before the printing and was mixed with the wet earth (water content of 45%) using a mortar hand mixer for 4 min.

The material composition was summarized in Table 1.

### 2.2. 3D printer

The 3D printer consisted of the combination of a 6-axis industrial robot designed by Staübli robotics (load capacity of 195 kg) with a TP5 Giema electric pump designed for mortar/render application (maximum pressure of 20 bar, maximum flow rate of 40 L/min).

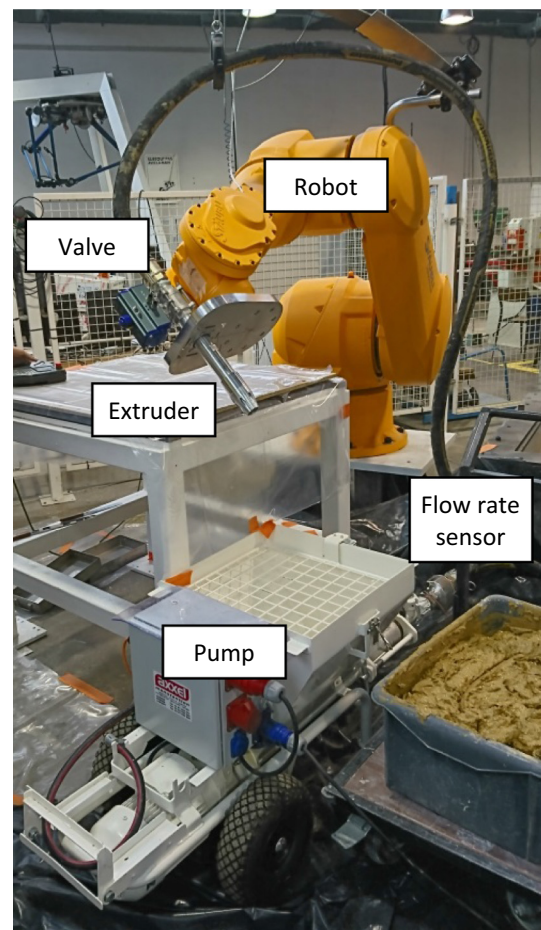


Fig. 1. 3D printer for earth-based material.

Table 1  
Materials mix design – component mass/earth mass ratio.

	Earth	Water	Cimalgin HS3
With Cimalgin	1	0.45	0.03
Without Cimalgin	1	0.45	0

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