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Rheological behaviour of earthen materials for 3D printing

3D printing is an emerging method of construction and is a process that can be used with a large variety of materials to design and build complex shapes. Shapes can be adapted to the climatic conditions the building is subject to, to constraints present in the walls or to the need to reduce seismic susceptibility [1] [2] [3].

The dimensioning and use of a 3D printer requires control of the rheological properties. During the printing process, the material must be able to flow into the device, but once the material has been deposited, it must be stiff enough to support its own weight and the weight of subsequent layers. This behaviour is characterized by yield stress measurements. The main parameter that has an impact on the rheological behaviour of an earthen material is its water content. Indeed, earth has three states that are a function of its water content: liquid, plastic and solid. The first means that there is enough water for the earth to flow without the use of any force. The second characterizes a material behaviour that requires applying pressure to make the material flow. Finally, the third describes the state where the material breaks when force is applied [4] [5] [6].

In general, the study of the rheology of building materials is carried out using rheometers [7] [8]. However, this method requires a material with a low yield stress. Because the hardening of earth materials is primarily a function of their rate of drying, one should ideally work with mixtures with a low water content, but these exhibit a higher yield stress than can be measured with a rheometer.

To this end, a squeeze test can be undertaken in the laboratory to characterize a material. The test applies a force at a controlled speed to a material placed between two parallel plates and measures the force applied as a function of the height of the sample to calculate the yield stress. This test, however, requires specific equipment such as a press equipped with a suitably sensitive detector and the protocol must be adapted to each material [9] [10] [11].

Instead, a classical and practical test was proposed to determine the yield stress of earthen materials by measuring the penetration distance of a falling plunger in a material as the function of the plunger weight. The yield stress is then calculated as the ratio between forces and the surface engaged. This test can easily be conducted in the field next to the printer [12].

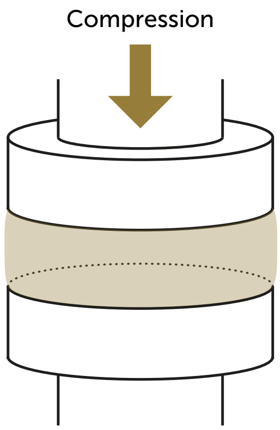
Using these two methods, the yield stress was measured for two raw earth samples across a broad range of water content levels. The squeeze test served as a reference and the weighted plunger test was evaluated against it. The findings provided the basis for a discussion on how to use the weighted plunger test for 3D printing facilities.

Materials and methods

Materials and samples preparation

An earth plaster mortar from the "Briqueterie deWulf" in France and a natural Romainville earth from the Parisian basin have been selected for the current study. The first is composed of less than 10% clays and the second of about 53% clays [13].

Mortars composed of earth and distilled water were prepared with a planetary mixer. The mixing process comprises two phases: an initial mixing phase of 60 s at 67 rpm and a second of 30 s at 125 rpm. Before testing, the mortars were allowed to rest for at least 48 hours. Both earths were tested across a broad range of water content levels.



01 Schematic setup of the compression of an earth sample

Squeeze test

The squeeze test is a rheological test used to measure the yield stress of materials at laboratory scale. It entails the compression of a sample between two parallel plates (Figure 1). For the experiments, a Shimadzu AUTOGRAPH AGS-X press equipped with a 1 kN force detector was used. The radius (R) of the plates was 19.31 mm and the height of the samples was about 20 mm. The compressive force was applied at 1 mm/s and the force applied (F) was measured as a function of the distance between the plates (h).

The squeeze test is a well-documented experiment [11] [14] and the yield stress was calculated using the following equation. It corresponds to the reduced compression load force (F*) as a function of the ratio between h and R.

$$F^* = \frac{F * h}{\pi * R^3} = \frac{2K_a}{\sqrt{3}} * \left(\frac{h}{R}\right) + \frac{2K_b}{3}$$

The yield stress appears in the slope part of the equation (K_a) and corresponds to the bulk material. It can also be calculated from the intercept part (K_b) and is representative of the behaviour of the material at the interfaces with the plates. The yield stress from the slope part was used as it is more significant.

Weighted plunger test

The weighted plunger test is inspired by the NF EN 413-2:2017 standard [15] which evaluates the consistency of mortars. The principle involves releasing a plunger from a height of 100 mm and allowing it to fall on the tested mortar. The penetration distance is then measured.

02 Using the weighted plunger test to ascertain the yield stress of the earth sample

For our modified weighted plunger test, the plunger is released directly from the surface of the material. The distance of penetration is then measured as a function of the plunger weight (Figure 2). Finally, the yield stress is calculated as the slope of the total forces engaged – the sum of the plunger weight and the buoyancy – as a function of the penetration surface. Detailed equations have been presented in full in a previous paper [12].

Results and discussion

The yield stress was measured for both earth samples, the earth plaster mortar and the Romainville earth. Firstly, the squeeze test was used as a reference test. Then, our newly developed weighted plunger test was undertaken. Figure 3 presents the yield stress obtained using the squeeze test and the weighted plunger test as a function of the water content of the mixes.

We can see that data from both tests overlap. This show that the weighted plunger test returns similar results to the squeeze test. A detailed explanation of the test procedure of the weighted plunger test was presented in a previous research paper [12].

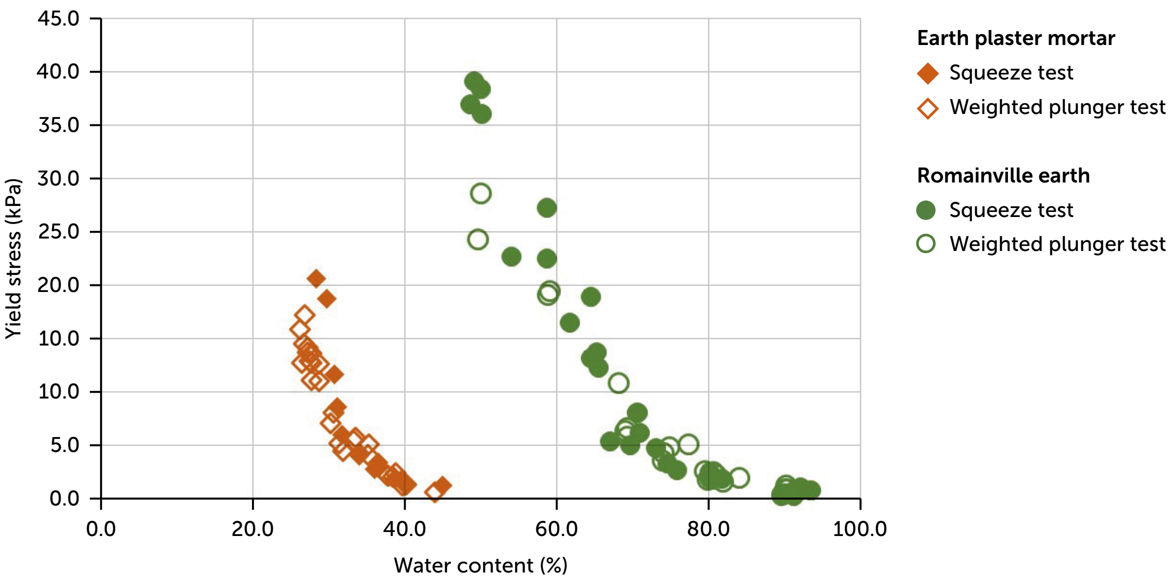
Moreover, we can note the wide range of behaviour that these two experiments make it possible to measure. The lower yield stress was measured with the weighted plunger test. It is about 0.67 kPa at a water content of 44% for the earth plaster mortar and about 0.46 kPa at a water content of 90% for the Romainville earth. By contrast, the higher yield stress is measured with the squeeze test. It is about 20 kPa at a water content of 30% for the earth plaster mortar and about 40 kPa at a water content of 50% for the Romainville earth.

The development of the weighted plunger test aims to make it possible to measure the yield stress of earth materials during a 3D printing process. The process requires a mix that can flow in the printer and, at the same time, is stiff enough to not flow under its own weight or under the layers deposed.

Two steps are therefore necessary before 3D printing with earthen materials. The first is to choose the composition of the earth by making a scale of the yield stress that can be reached. The second is to confirm before printing that the prepared mix corresponds to the desired yield stress, so that it can be corrected if necessary. For both steps, the weighted plunger test can provide quick and easy results.

The squeeze test, by contrast, is a laboratory test that requires specific equipment because the compression device has to have a sensitive detector and the protocol needs to be adjusted for each earthen material. The weighted plunger test can be performed next to the printer simple equipment and the measurement can be conducted easily on many earthen materials.

03 Yield stress of the two earth samples as a function of the water content measured using the squeeze test and the weighted plunger test



Conclusion

The main purpose of this work was to propose a method for measuring the yield stress of earth materials for 3D printing. The dimensioning and use of a 3D printer requires control of the rheological properties. During the printing process, the material must be able to flow into the device, but once the material has been deposited, it must not flow under its own weight or under the weight of subsequent layers.

Two tests were performed for the yield stress measurements of two raw earths. The squeeze test was used first as a reference test. As it requires specific equipment and time to master the experiment, it cannot be used in the field. Then the weighted plunger test, a classical and practical test, was proposed to measure the yield stress of earthen materials. This test can be undertaken quickly and easily in the field, next to the printer.

To conclude, a wide range of yield stresses was measured for two earths using two tests: one for use in laboratory conditions and the other for use directly on site. A discussion on how to use the weighted plunger for 3D printing facilities then followed.

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