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COMPOSITE FOR ADDITIVE MANUFACTURING INCLUDING FLAX BYPRODUCTS AND QUARRY FINES

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Abstract

This study work focus on the development of self-standing insulating wall elements using 3D printing technology. Additive manufacturing is promising for the construction industry as it allows complex geometry exploration but also prevent the need for formwork as it is in the traditional building techniques. In this research work, flax and quarry fines with a clay-like behavior are integrated in the mix design to obtain environment-friendly wall elements. Short flax fibers and quarry fines are mixed along with a high-content blast furnace slag cement to obtain the structural part of the wall. Effects of flax fibers inclusion into the material are investigated through mechanical tests and plastic shrinkage. Hollows of the 3D printed elements are then filled with a foam made up with flax shives and quarry fines. Finally, a 3D printing test session is displayed.

Keywords

Additive manufacturing ; Flax byproducts ; Quarry fines ; Mechanical performances ; Shrinkage

1. Introduction

Growing in the field of construction, 3D printing consists of joining materials layer upon layer to obtain part or all of a building from a 3D model developed by CAD software. The 3D printing allows the building of various and complex shapes. By significantly reducing useful matter to build, 3D printing allows to optimize resources [1,2]. This technique is the subject of several pieces of research including the development of printing materials such as concrete, metal or earth. In building domain, concrete is the most advanced printed material. Earthen materials are studied in some research works such as WASP project in Italy or also the ICAA project Pylos in Spain. Traditional building techniques use the unfired earthen materials for millinerics across the world. This is a mineral resource that can come from to the building site, therefore not requiring transportation. Besides, its energy requirements remain limited.

In most current applications of 3D printing, the printed material serves as the structural part of bearing walls [3,4]. But, to bring thermal or acoustic comfort to the user, a wall must also have insulating performance, which is given by insulating materials. Lightweight concretes can represent a solution to bring insulating performances while being adapted to 3D printing criteria (extrudability and buildability). Lightweight concretes can be obtained by including lightweight aggregates and/or foaming agents [5,6]. A solution derived from eco-construction techniques can be the use, as lightweight aggregates, of vegetable co-products (e.g. straw), which are renewable materials and offer interesting thermal and acoustic behaviour whether on their own or combined with unfired earth materials (e.g. cob) thanks to their multi-scale porosity.

By allowing the use of locally available and inexpensive materials, earth materials and vegetable co-products have a decisive role to play in the development of 3D printing applied to the building sector. Russel [7] demonstrates the great potential of earth materials to be an innovative solution to the

housing shortage the developing world is facing. Among vegetable coproducts, flax represents an interesting resource in the north of France due to a large cultivated area. Each year, 86 621 tons of flax shives and 17 595 tons of short fibers are from the cultivation in the region Hauts-de-France (France). Flax shives can be used as major component in vegetable concretes, largely developed for some years, for their hydrothermal and acoustic performances [8]. Short fibers can replace polypropylene, glass or metallic fibers for the structural reinforcement of mortars and concrete [9-11].

In this context, this research work aims to develop a composite wall with insulating performances and including ecomaterials, for the 3D printing in the building domain. In a fresh state, a satisfying workability and a rapid hardening are targeted to obtain extrudable and buildable materials. One type of mixes is discussed in this paper: mixes with good mechanical performances to be applied as a structural material. Insulating materials have been designed in a previous research work [8]. After the presentation of used components and chosen tests to characterize the mixes, the results on laboratory specimens are discussed then a 3D test is shown.

2. Experimental details

This part describes the materials and the mix proportions chosen for the experimental campaign.

2.1. Materials

The flax products include short fibers and flax shives. Short fibers (F), chosen in the mix design, have a length of 24 mm and have the capacity to absorb 60-70% of their weight in water, after immersion, due to their porosity. Flax shives have particles sizes inferior to 40 mm and a water absorption of 130% after immersion.

The earthen materials are quarry fines (QF) coming from aggregates washing. The quarry fines include limestone ($\approx 62\%$), kaolinite ($\approx 12\%$), illite ($\approx 7\%$), quartz ($\approx 11\%$), goethite ($\approx 3\%$) and dolomite ($\approx 5\%$). The size of the particles ranges from 0.1 and 100 μm . The quarry fines are defined as Ap (low plastic clay) according to the USCS classification.

Two types of hydraulic binders are associated to quarry fines according to the type of mix. For the structural mix, a blast furnace cement (C) is chosen to its high rate of blast furnace in order to promote waste re-use and referenced CEM III/A 52.5 L CE PM-ES-CP1 NF. The insulating mix includes natural prompt cement.

To control the setting time, a retarder is included in the mix design of the structural mix. This additive also plays the role of plasticizer. For the insulating material, a foam agent is chosen.

2.2. Fabrication process

Two types of mixers are used (5 litre mortar mixer or 100 litre planetary concrete mixer) with a common introduction sequence of components. First, all the dry elements (dry powders and flax products) are put in the bowl or tank. Water is introduced progressively for 30 s, once the mixer is turned on, to avoid the loss of powders. Retarder or foam agent is poured at the same time. The mixing continues for 90 s then the mixer is stopped. Once the mixer is stopped, the workability of the mix is tested or the mix is cast into molds for tests in the hardened state.

2.3. Mix design of structural mixes

All the studied structural mixes, shown in this paper, are shown in Table 1. The mixes mainly include quarry fines (QF) and cement (C). DM (dry minerals) corresponds to the sum of quarry fines and

cement quantities. Some tests are performed with and without flax fibers (F) to evaluate their influence on mechanical performances and shrinkage. The influence of the retarder (R) is also measured in doing tests on mixes with and without this additive.

Table 1. Compositions of studied mixes

	QF/DM (%)	R/C (%)	Fibers/DM (%)
QF-C-1	70	0	0
QF-C-2	80	0	0
QF-C-R-1	70	0.8	0
QF-C-R-2	80	0.8	0
QF-C-R-F-1	70	0.8	1.1

The water content is chosen to have a sufficiently fluid mix for a correct extrudability or filling while allowing a rapid hardening. To satisfy these criteria, workability tests are shown in the next section.

3. Laboratory tests

This part describes all the tests procedures (type of equipment, test parameters) and the results.

3.1. Workability and hardening

After mixing, the fresh behaviour is studied up to the hardening of the materials. For structural materials, fall cone tests are performed to follow the evolution of consistency. Based on previous tests with validation by printing tests, a range of depth penetration [18 ± 2 mm] is targeted to have a satisfying extrudability without problems of buildability. This range corresponds, in soil mechanics, to the liquid limit of soils. Simultaneously, a Vicat test is carried out (NF EN 480-2). Table 2 shows the water content of each mix, as well as the measurements performed just after fabrication until the initial setting. The two first mixes have a rapid initial setting and a rapid increasing of their consistencies. With the retarder, the time range with satisfying consistency (TR_{SC}) is larger and their initial setting time (T_{Vicat}) is later than those of mixes without retarder. For QF-C-R-F-1, no results have been obtained due to the flax fibres which obstruct the test proceedings. Its water content has been fixed to 35.5%, in considering the value of the mix without fibers and the water adsorption of fibers.

Table 2. Water contents and measurements at fresh state

	W/DM (%)	TR_{SC} (min)	T_{Vicat} (min)
QF-C-1	37	0'-31'	190
QF-C-2	37	0'-28'	205
QF-C-R-1	34	13'-70'	650
QF-C-R-2	37	35'-140'	870
QF-C-R-F-1	35.5	-	-

3.2. Compressive strengths

During the preparation of samples, the material is not vibrated. Samples are kept in their mold until their hardening, then are unmolded and are stored in a climatic room (20°C, 50% RH). The

mechanical performances have been measured by compressive tests on prisms (area $1.6 \times 10^{-4} \text{ m}^2$). Tests are done using an electromechanical testing machine with a force capacity of 50 kN. The loading velocity for the compressive test is 1.27 mm/min. This level of load velocity has been chosen in several research works [12,13] on hemp concrete or earthen materials to avoid to obtain incorrect values due to bad distribution of the load inside the samples. The five mixes have been tested after 28 days of curing under plastic film and the compressive strengths for two of them have been followed according time and two curing mode (table 3): samples directly in contact with the ambient air (AA) and samples, protected from hydric exchanges, under plastic film (UPF).

The results show a high difference between mixes including 70% and 80% of quarry fines in dry minerals. The compressive strengths at 28 days are divided by around 2.4 in increasing the rate of quarry fines. Besides, the adding of retarder does not influence the mechanical behaviour. In opposition, the curing mode seems to be a influent parameter. Without protection, hydric exchanges happen between the samples and the air in storage room. Compressive strengths decrease in comparison to protected samples. The evolution of compressive strengths according time is similar between the mixes QF-C-R-1 and QF-C-R-F-1. Short fibers do not improve the results, even if no decreasing of the compressive strength is observed between 10 and 28 days.

Table 3. Compressive strengths of fives mixes for 28 days (left) – Evolution of compressive strengths of two mixes according time (right)

Mixes	Rc _{28d} (MPa)	Curing time (days)	Rc (MPa)			
			QF-C-R-1		QF-C-R-F-1	
			AA	UPF	AA	UPF
QF-C-1	15.1					
QF-C-2	6.5					
QF-C-R-1	17.3	1	1.05	1.05	1.02	1.02
QF-C-R-2	6.9	3	4.24	4.23	4.0	3.14
QF-C-R-F-1	15.5	10	10.1	12.6	7.5	9.3
		28	8.8	17.3	11.4	15.5

3.3. Shrinkage measurements

Linear shrinkage is followed on prisms equipped of shrinkage plugs from just after unmolding to the stabilization of shrinkage evolution. Specimens are stored according two types of cures: in ambient air (20°C – 50% H.R.) with or without plastic film to preserve humidity conditions. This test highlights the huge effect of drying on specimens (Fig. 1). As for compressive tests, the short fibers do not improve results.

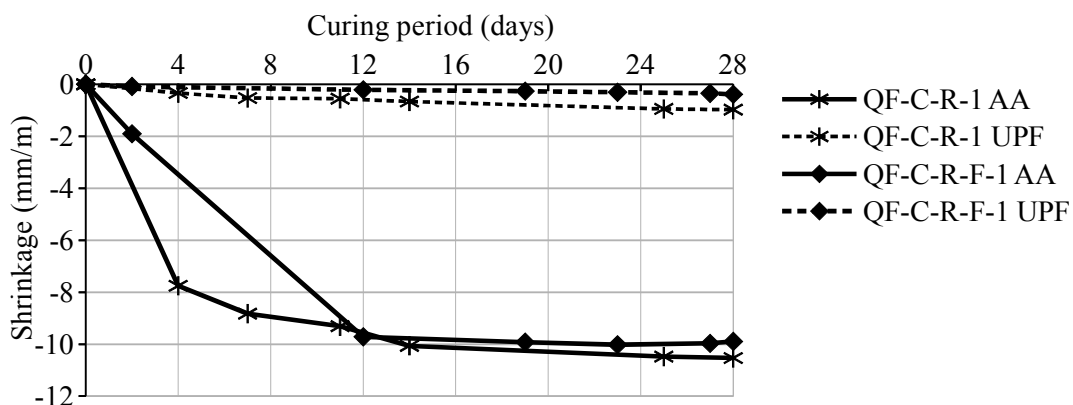


Figure 1. Shrinkage evolution according time of four mixes

4. 3D printing test

In the framework of a research project called Matrice, 3D printing test has been performed to verify the adequacy between our mixes and this building technique through a six axis manipulator that operates a nozzle (Fig. 2) connected to a pipe for material deposit. Architects designed different types of walls in following principles of funicular surfaces (Gaudi), minimal surfaces (Otto) and constant slopes surfaces. With geometric data included in a CAD model, a slicing of the surface (Gcode) was performed. Then, trajectory generation of the tip of the nozzle was controlled in position and orientation, in parallel to the flow rate control of the material through an external concrete pump.

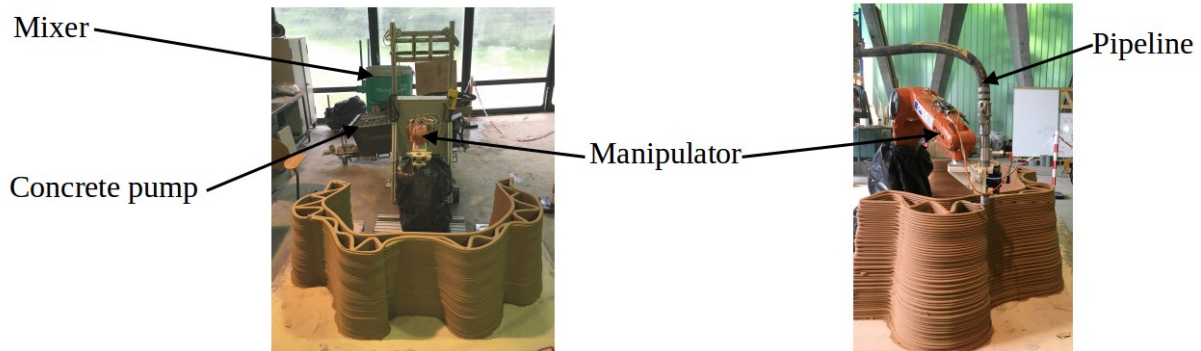


Figure 2. Printing process (left) – Printing test in progress (right)

The structural part of walls was made up mixes with QF-C-R-1 because of its properties at fresh state allowing to benefit large time to print it. Some tests was performed with various forms of walls to verify the compatibility with the mix developed in laboratory. The structural part was filled handly with the PC QF1 mix which has been chosen for its better thermal performances [8]. The concrete pump was not able to pump the insulating material due to its low density. The auger induced a tunnel effect in moving the material to the hopper sides without being able to send it in the pipe. An other type of pump will be tested in further studies.

The sides of the structure had a slight slope. A first test has been done without filling the structure. For a height of 21 cm, the structure has crumbled (Fig. 3) due to its own mass, the slope of the structure and the absence of internal support (zigzag) traditionally used in 3D printing. On the bottom right of the Fig. 3, the form without filling is observable with two of its sides joined due to the collapsing. A new test has been completed; the structure has been filled with PC-QF1 every 15 cm. After filling, the printing of structural material restarted. During the following printing phases of structural material, the PC-QF1 mix hardened and acted as a support to the structural material (Fig. 3). The printing reached 55 cm without collapse of the element. This height was the final height fixed in the CAD file.



Figure 3. Shapes with and without insulating material

In a building site, the manipulator could include two printing devices, one for the structural material and another for the insulating material. Ten days after printing, cracks on the structural part were observed due to the drying shrinkage. Further studies will be led to solve this problem in modifying the type of binder.

5. Conclusion

This research works aims to develop mixes for building a composite wall by 3D printing. The composite wall is compounded of a structural part filled by an insulating material. The designed mixes include flax products and quarry fines on the principles of traditional building techniques. The evolution of the cement proportion in the mix design of structural materials is significant. With a cement proportion of 30% in dry minerals, the compressive strength at 28 days reaches a higher level than the requested level for the two floor house per example. However, laboratory tests and printing tests show high shrinkage due to a sensitivity to drying. In the following of the study, others binders will be tested.

Acknowledgments

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