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A 3D PRINTER OF CEMENT MORTARS BASED ON INITIAL DEPOSITION OF DRY MATERIALS

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Abstract
The paper presents the studies of implementation of an equipment for producing mortar elements through a 3D printing process, aiming to demonstrate feasibility and challenges, with the intent of a future upscaling to actual concrete production. The technique for 3D printing is based on the additive method, with an innovative approach in regard to the deposition of materials. Indeed, the cement/sand are deposited by layers into their final positions. After the deposition of each layer, water is sprayed in a controlled manner. When a given set of layers is deposited, compaction is applied to the entire part. This technique has the interesting feature of allowing to differentiate mortar composition at different regions of the produced elements, with possibility of structural optimization of the spatial use of cement. The feasibility of the developed equipment and produced parts is demonstrated, and discussions are held in regard to challenges and future developments.

1. Introduction

The term Construction 4.0, in direct connection with Industry 4.0 concepts, has gained significant attention and momentum in recent years. Amongst the former, one of the most promising fields seems to be the use of 3D printing techniques for digital fabrication of construction elements, or even for entire constructions. An extensive and very up to date recent literature review has been made by Ghafar *et al.* [1], with particular focus on the use of additive manufacturing (AM) technologies, which are defined in such review *as procedures that form layers to create three-dimensional (3D) solid objects from digital models, allowing creatives, engineers, architects and designers to make customised designs in one-step process*.

Several processes have been devised for construction with AM techniques based on extrusion of pre-mixed cement based blends, such as the contour crafting [2], the 'concrete printing' method by the team at Loughborough University [3], amongst other initiatives based on similar principles and applied at laboratory and construction scale by the industry (review in [1]). Even though this is a very interesting idea, the fact that the mix is 'wet' at the stage of deposition, brings many challenges regarding the fresh state material problems, and concerns about printable shapes without the need for specifically tailored support material. However, much less research has been focused on 'dry' deposition of binders, with very few works known on the subject, except for a conceptual discussion by Pegna [4], and the efforts initiated by Enrico Dini with the D-Shape method that relies on such principle with use of binders that require activators [5]. Except for a brief reference at the website of D-Shape [6], and an alternative method based on extrusion of pastes to sand packings [7], no scientific works written in English were found to focus on dry deposition of cement-based materials for 3D printing efforts, which seems to be an important research gap. However, the research team at the Civil Engineering Department at UMinho has dedicated attention to this matter since 2012, with a line of research based on a 3D printer of cement based materials through the dry method. A MSc thesis has been initially developed by Sepúlveda in late 2012 [8], followed by a national conference paper, written in Portuguese [9]. The work has then been continued in a further MSc thesis by Morais [10], which delved further within the acknowledged limitations and challenges. In view of such efforts, the present paper aims to provide an integrated view of the developments achieved, identifying opportunities and challenges.

2. The concept and implementation

2.1 Concept

The concept behind the proposed printing process is relatively straightforward. It relies on the principle that the element to be printed can have an absolutely arbitrary geometry within the printing bounds, and the mixing proportions of the cement-based material can be changed at any given position of the element under construction. In order to materialize these two important performance requirements, the concept is based on mortar printing (cement, graded sand and water) through a dry method. The explanation of the printing method can be understood by observation of the schemes in Figure 1. Three separate containers are attached to the movable printing head: one for cement, one for graded sand, and another for water. The containers of cement and graded sand have their bottom extremity controlled by a computer controlled valve, that allows continuous feed at known rates of sand and cement, which are in turn gathered in a mixing funnel and deposition head. The principle is that this movable deposition head can deposit controlled quantities of each material, allowing to create regions of different mixing proportions in the printed element, according to performance requirements (e.g. structural, tightness or any other). In the regions that are to become hollow, or merely support the printed layers to be placed above (e.g. cantilevered portions), deposition of sand alone is made, so that it can be washed away and reused after the printing process is finished. On the right side of Figure 1, it is possible to see a layer of deposited materials, surrounded by a confining boundary, having respectively: sand deposited in the vicinity of the confining boundary, mortar 1 in the outer regions of the solid to be printed, and mortar 2 (potentially less rich in cement) in the core region. At the present stage of the description, mortars 1 and 2 are not yet watered, so they are mere blends of cement/sand. The controlled watering of these mixtures is then done through an additional printing head, as shown in the left part of Figure 1, which allows finishing the mixing proportions defined by the user, by judiciously spraying water in a potentially differentiated manner throughout the entire layer of dry materials that had previously been deposited. Afterwards, the conceptual principle includes the application of a controlled static compaction weight over the entire recently watered layer, as to promote better final density and material properties.

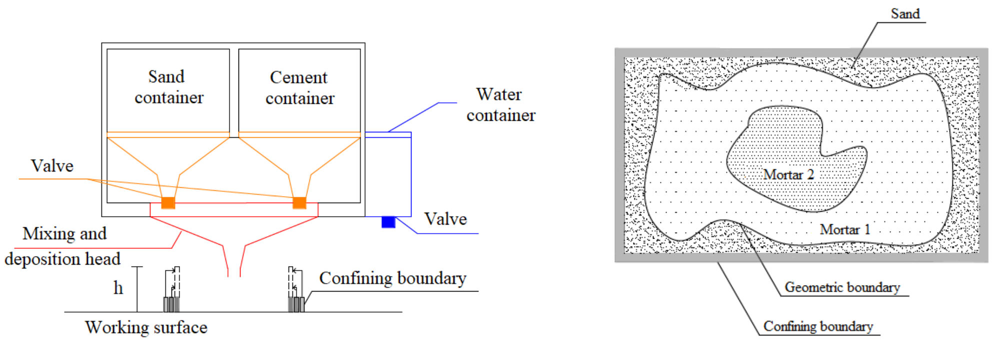


Figure 1: The basic concept of the proposed 3D printing process: cross-sectional view (left); plan view of resulting printing (right). Adapted from [9]

2.2 Implementation

In order to prepare a prototype, the requirements stated above were mostly satisfied, except for the fact that the sand and cement containers were not separated. Instead of that, a single reservoir containing a predefined blend of sand and dry cement was considered. The prototype printer that was developed has a potential field for printing of 1.2 m × 0.6 m in plan, and maximum potential printing height of 0.3m. The frame is depicted in Figure 2a, where the necessary linear guides for the 3 active axes (x, y, z) and corresponding computer controlled step motors can be seen. The dry material dispenser is shown in Figure 2b: it basically consists of a funnel with bottom dispensing diameter of 9 mm, which in turn is filled up to its bottom by a threaded bar. The dry mix for printing (sand and cement) is placed in the funnel, and the threaded bar is acted by a rotary engine (seen in the top part of Figure 2b) that allows controlled deposition of the mix (Archimedes screw principle). The water spraying is made through a standard aerograph, as show in Figure 2c, which is controlled by the central processing unit of the system. For more details on the mechanics and electronics of the system, the reader is directed to [8].

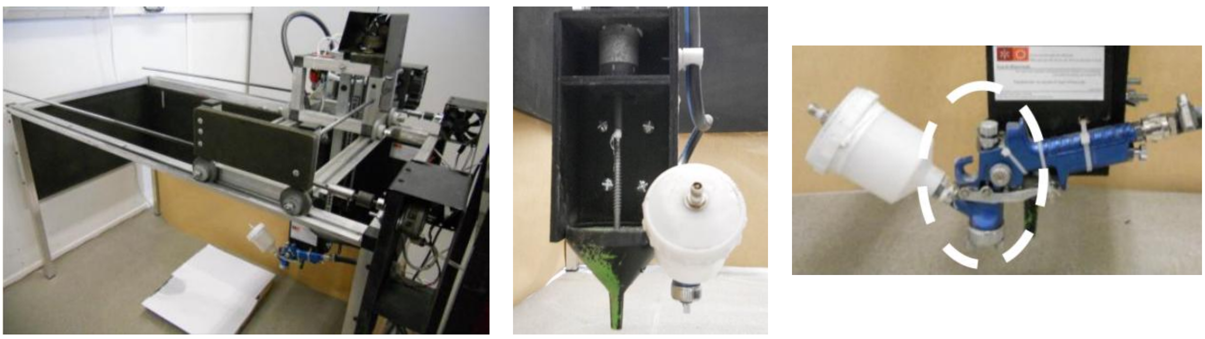


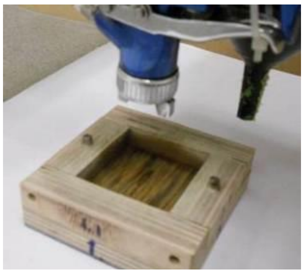
Figure 2: a) The printing frame; b) The dry material dispenser; c) The water dispenser [8]

3. Use of prototype printer and results

3.1 Procedure in effect

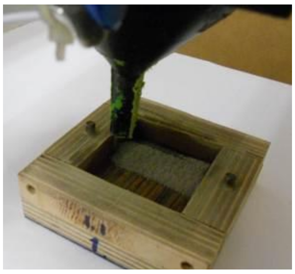
The setup described above has been put under test in a small confined region of 5 cm × 5 cm, which in turn was used to produce test cubes of 5 cm edge. At this point, it was also decided to solely print a single proportion of cement/sand, whereas not allowing the possibility of depositing sand only. This means that the single deposit description of Section 2.2 above also applies here. The lateral confinement for pressure application was guaranteed by wooden moulds of 1.25 cm height, that were cumulatively added to the system as needed for lateral confinement of subsequent printing layers. The process is described with support of Figure 3.

Pre-wetting of mould



a)

Deposition of 1st layer



b)

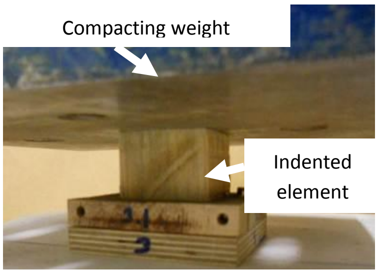
Water spraying

c)

2nd layer deposition (perpendicular to the previous one)

d)

Apply compaction after 5 layers



e)

Final result after printing and curing

f)

Figure 3: The procedure adopted for printing test mortar cubes

Initially, the mould is pre-wetted with water spraying (Fig. 3a), followed by the deposition of the 1st layer in a sequence of parallel lines of deposition (Fig. 3b). Immediately afterwards the 1st layer is finished, controlled water spraying is started, as to attain the desired water-to-cement ratio (pre-calibrated timings of valve opening of water – Fig. 3c). The process is then continued in a similar fashion for the subsequent layers (Fig. 3d). However, every subsequent layer that is deposed, is placed on a perpendicular direction of deposition, as compared to the previous one (attempt to avoid excessive accumulation of fragilities in the interfaces of deposition). The process is followed by water spraying, as done for the 1st layer and sequentially repeated up to the 5th layer. At every five layers, a compacting weight is placed on top of a compacting interface which comes into contact with the specimen (Fig. 3e). This compacting interface is slightly indented at its bottom, as to improve connection between this layer after compaction and the layers that follow. As mentioned before, the lateral confinement parts are added as needed, and the final result of the process described is shown in Figure 3f.

3.2 Systematic experimental program and results

A systematic program of testing has been applied to test both the robustness of the mechanical and electronical parts, as well as the feasibility of the obtained specimens in terms of density and compressive strength. CEM II/B-L 32.5 N was used for the test mortars with fine river sand (maximum grain size ~1 mm). In terms of weight, the following mixing proportions were selected: sand/cement=2:1 and water/cement=0.23. A total of 9 specimens have been prepared with the 3D printing process, with the nomenclature and information provided in Tab.1: 3 specimens compacted with 25 kg weigh and tested perpendicularly to the plan of layer deposition; 6 specimens compacted with 50 kg and tested both in parallel (3) and perpendicular direction (3) to the plan of layer deposition. Additionally, 3 more specimens have been prepared and mixed in a Hobart mixer with the same raw materials and mix proportions (except for the addition of superplasticizer to ensure adequate workability).

All specimens were cured at 20 ºC (sealed conditions) up to the age of testing, at 7 days, in which density and compressive strength were assessed sequentially.

The 3D printer was able to produce all specimens without malfunctioning and exhibiting an apparently robust capacity for repetition of the test procedure.

The results are cumulatively shown in Table 1. It was noticed that the density of specimens made with standard mixing had an average of 2069 kg/m^3, as opposed to the average density of 1720 kg/m^3 for printed specimens compacted with 50 kg and 1660 kg/m^3 for printed specimens compacted with 25 kg. These are significant reductions of ~20% with impact on the average compressive strength. In fact, not only is the f_c of 3D printed specimens significantly lower than the traditionally mixed ones, but it also exhibits a significant dispersion, as shown in Tab.1. This is an indication that the process needs improvements, as to allow, at least a better consistency of the quality of produced specimens. Additionally, to the results shown below, more experiments have been made further to try to increase strength and decrease dispersion [10]. In spite of such efforts, no significant improvements were attained yet. Further studies with potentially better performing mixes (e.g. higher w/c ratio) might pave the way for new developments.

Table 1: Systematic experimental programme

Name	*Size* [mm]	*Compacting weight* [kg]	*Test direction*	*Density* [kg/m^3]	*Compressive strength* [MPa]
P1_25_PER	50×50×50	25	Perpendicular to the plan of the layers	1632,24	4,15
P2_25_PER		25		1682,24	***
P3_25_PER		25		1680,22	6,50
P4_50_PER		50		1725,63	7,66
P5_50_PER		50		1730,86	4,80
P6_50_PER		50		1698,47	8,64
P7_50_PAR	50×50×50	50	Parallel to the plan of the layers	1756,57	3,39
P8_50_PAR		50		1721,83	7,44
P9_50_PAR		50		1733,34	4,05
P10_Standard	50×50×50	-	-	2091,28	11,32
P11_Standard		-	-	2074,48	12,25
P12_Standard		-	-	2041,89	10,75

*** Invalid test result.

3. Conclusions

This paper has presented the underlying concept and development of a fully working prototype of a 3D printer for mortars (additive manufacturing), based on the deposition of dry material (sand and cement) and subsequent spraying of water, followed by compaction. The concept may extend further to allow differentiated mixture deposition and creating arbitrary geometry, without having problems of material support of overhangs (satisfied by printing sand to be removed after printing). The working prototype has demonstrated robustness of its mechanical and electronic parts, but the quality of the produced mortar is still inferior to that which can be obtained with the same raw materials through traditional mixing of constituents. The attained results have demonstrated viability to justify further works following the same line of thought of dry-material deposition in 3D printing of cement-based materials.

Acknowledgements

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