Mesostructures in 3D Concrete Printing

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ABSTRACT
In concrete design, material performance is typically defined by the composition of the concrete mix (micro scale) and the overall shape and design of building elements (macro scale). However, recent developments in the field of 3D concrete printing (3DCP) are demonstrating that the design of concrete now also can take place at an intermediate scale involving the spatial organization of the material at the level of the printing nozzle. A growing body of work is showing how the additive process can result in novel material configurations through the programming of print paths. This paper specifically examines the relationship between the spatial organization of concrete at the mesoscale and its overall structural performance and presents an experimental procedure for evaluating the load bearing capacity of a selection of generated mesostructures.

Key words: 3D concrete printing, concrete design, mesostructures, testing, concrete performance.

1. INTRODUCTION

1.1 Background

The advancement of concrete as a building material has been predominantly shaped by its use as a casting material. When concrete is poured, it adopts the shape of its mould, and material composition cannot be specified at a more detailed level. Consequently, methods for designing, calculating, and evaluating concrete structures typically treat concrete as a massive and homogenous material with equal properties in every direction.

Conversely, in 3D concrete printing the shaping of concrete takes place at the size of the extrusion nozzle at a level significantly smaller than the object to be manufactured. The deposition procedure follows an additive principle of building up material layer upon layer according to a preprogramed print path. A growing body of work in the field is showing how the possibility to organize the spatial distribution of concrete at the scale of the nozzle opens a new dimension in concrete design at a previously impossible intermediate scale - the meso scale (10^{-2} – 10^{-1} m). The authors have previously shown how organising print paths in three-dimensional patterns can result in complex concrete structures with cavities and intricate surface textures [1]. Apart from new aesthetic possibilities, this newfound ability to design the configuration of concrete at the meso scale also opens new possibilities to modify the material's structural and functional performance. This is especially significant for improving the ability to optimize the use of concrete in building structures by locally adapting the material's structural and functional performance according to design local criteria.

1.2 Scope of the paper

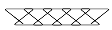
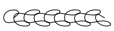
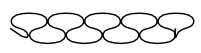
Insofar as concrete properties are typically calculated and specified as a homogeneous isotropic mass, the anisotropic nature of 3D printed concrete requires alternative methods for testing and modelling material performance. This paper specifically describes the design, fabrication and testing of a selection of mesostructures for a comparative study of their load bearing capacity. From this study the authors draw certain conclusions about the impact of the local geometry of the print path on the structural performance of a 3D printed structure. The paper is divided into two main parts. Firstly, an experimental procedure for evaluating the load bearing capacity of a selection of generated mesostructures is presented. Secondly, a discussion of the test results and concluding remarks are provided.

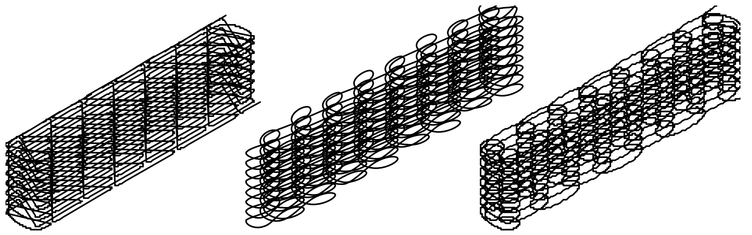
2. EXPERIMENTAL PROCEDURE

2.1 Print pattern generation and fabrication

Three objects with different three-dimensional print patterns were generated with a digital design tool developed at the KTH School of Architecture [2]. To make the patterns comparable they were generated with the same alternating stacking configuration, layer height, amplitude, and wavelength settings to be fabricated with a round 20 mm nozzle. The line types and parameters used are listed in Table 1. The objects were fabricated using an auger-based extrusion tool mounted on a six-axis industrial robot with a Sikacrete-752 3D dry mix with 15% water content by weight [3]. Straight after printing the newly fabricated objects were covered in plastic to prevent rapid loss of moisture and left for 24h on the printing platform before being transferred to an airtight chamber and left to cure for an additional 27 days at 99% humidity and 20ºC temperature.

Table 1. Parameters of print paths

Pattern	Stitch	Line type	Stacking	Layer height [mm]	Nr. of Layers	Amplitude [mm]	Wavelength [mm]	Total length of path [mm]
A	8833		1/1	10	15	40	150	2924
B	0536		1/1	10	15	40	150	3010
C	8204		1/1	10	15	40	150	2315



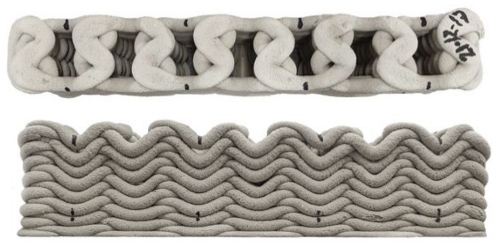


Figure 1. Generated print paths for object A, B, and C. Figure 2. Mesostructure C, top (a) and side view (b) with cut markings for the planned test specimens.

2.2 Extraction and preparation of test specimen

After 28 days the fabricated mesostructures were cut into three equal 150 mm long sections. The top surface of each specimen was flattened using a diamond grinder to facilitate an even distribution of forces during the compression test. The specimens were then weighed, and overall measurements were taken. The areas of the top and bottom surface of each specimen were calculated by first making an ink imprint on paper which was then scanned and measured. The material volume of each test specimen was calculated by using the water displacement method.

2.3 Compressive testing

Compressive tests were carried out after 28 days. The samples were loaded perpendicularly to the print direction under constant displacement control at 0,1 mm/s. 3 mm hardboard plates were placed in-between the compressive plates and the top and bottom concrete surfaces to ensure an even distribution of loads over the flattened areas.

3. RESULTS AND DISCUSSION

The averages of the values obtained for the three mesostructures are listed in Table 2. For the purpose of comparison, a fourth column containing average values of data obtained from cast test specimens have been included.

3.1 Density

The density of standard cast concrete is around 2400 kg/m^3 depending on the concrete mix used whilst densities as low as 800 kg/m^3 can be achieved for non-structural concrete if special aggregate is used. In the case of the fabricated mesostructures two density values need to be considered, both the density of the material itself and the bulk density of concrete at the meso scale, that is the unit weight of concrete over the printed volume. Due to the geometry of the printed patterns the bulk densities of the mesostructures are significantly lower than that of a standard cast concrete and ranged between 1250-1580 kg/m^3.

3.2 Load capacity

Overall, the compressive strength values of the mesostructures were found to be a bit let less than half of that of cast concrete. Although mesostructure C was able to withstand the lowest ultimate loads, it per-formed the best in terms of compressive strength. However, when also taking account the lower bulk density of the pattern (strength/weight) the load bearing capacity of mesostructure C was the most efficient of the three patterns and performed at about 73% of the capacity of cast concrete. The compressive strength of printed tested specimens from the same pattern were found to vary more than that of cast test specimen. This is likely due to local differences in print quality caused by slight variations in the material flow during printing. Test specimens from mesostructure A showed the greatest scatter with ultimate loading ranging from 133,2 kN to 183,4 kN.

Table 2. Comparison of average values of test results

		Mesostructure A	Mesostructure B	Mesostructure C	Solid
Mass	g	3625,9	3442,5	2539,3	4815
Volume	cm^3	1717,1	1607,6	1194,3	1629,1
Length	mm	150,4	150,4	150,2	150
Width	mm	105,1	104,9	96,1	100
Height	mm	144,7	145,3	140,3	150
Area [top]	mm^2	7774	8146	4535	15000
Area [bottom]	mm^2	16466	11092	11873	15000
Max force	KN	151,4	157,8	92,0	800,8
Comp. strength	MPa	19,4	19,5	20,6	53,39
Bulk density	kg/m^3	1580	1500	1250	2140
Strength/weight	MPa/kg	5,34	6,67	8,11	11,1

4. CONCLUSIONS AND OUTLOOK

This paper has shown how the placement of concrete through the programming of print paths can lead to new ways of controlling the bulk density and load bearing capacity of this traditionally massive material. The structural performance of the studied mesostructures were significantly lower than that of cast concrete because of smaller cross sections transferring the loads. Also, different patterns resulted in different stiffness, which can be related to the complex microcracking development along the mesostructures. These findings, of how different mesostructures can influence the mechanical properties of complex 3DCP elements, will form the basis of future research looking at how to optimize print paths according to load bearing criteria in order to minimize the amount of material used in concrete printing. The long-term goal of this research is to establish a library of material structures with associated performances that can become part of the tool palette available to architects and designers.

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