Influence of Nozzle Diameter on the Anisotropy of Compressive Strength – Measured on 3D Printing Concrete Designed with Recycled Fine Aggregates

Yeakleang Muy[1], Luc Courard[1], David Bulteel[2,3], Sébastien Rémond[4], Maria Taleb[2,3], Khadija El Cheikh[5] and Julien Hubert[1]

[1]University of Liege, Urban and Environmental Engineering, Building Materials, Quartier Polytech 1, Allée de la découverte 9, B-4000 Liège, Belgium

[2]IMT Nord Europe, Institut Mines-Telecom, centre of Materials and Processes, F-59000 Lille, France

[3]Univ. Lille, Institut Mines-Télécom, Univ. Artois, Junia, ULR 4515 - LGCgE – Laboratoire de Génie Civil et géoEnvironnement, F-59000 Lille, France

[4]Univ Orléans, Univ Tours, INSA CVL, LaMé, EA 7494, Rue Léonard De Vinci, 45072 Orléans, France

[5]Concrete Technology Laboratory, Buildwise, Avenue P. Holoffe 21, 1342 Limelette, Belgium

yeakleang.muy@uliege.be

Abstract. 3D printing concrete (3DPC) is an innovative method in the construction sector, eliminating the need for traditional formwork. This study introduces a mortar mixed design with recycled fine aggregates (RFA) where d_{max} < 2 mm. The mortar was printed with two different printers, each equipped with nozzles of different diameters (2 cm and 4 cm). The layers were printed and pressed to widen the string to the chosen width of 6 cm. The primary objective is to study the influence of nozzle diameters on the mechanical properties as well as the anisotropic behavior of 3DPC. The investigation was conducted through mechanical testing on different orientations of printed layers, parallel (oz) and perpendicular (ox) to the printing direction. Results reveal a significant drop of compressive strength in the orientation (oz) when using a 2 cm nozzle compared to a 4 cm nozzle from the same mix design. This is attributed to the intense compression of each layer during deposition to ensure controlled spreading of the material path consequently creating damage in the outer parts of the printed concrete.

Keywords: 3D printing concrete; Nozzle dimension, Anisotropy compressive strength, Interlayer bond strength

1 Introduction

In recent years, the construction industry has witnessed the development of a new building technology driven by innovations in additive manufacturing technologies, commonly referred to as 3D printing (3DP). This technique is considered a cornerstone of industrial 4.0. Three-dimensional printing is an innovative technique that entails the sequential deposition of layers, pioneered in 1986 by C. Hull for prototyping purposes [1]. Compared with traditional concrete (cast-in-situ), 3DPC presents several advantages such as the freedom of design, formwork-free fabrication, waste minimization and mass customization [1-2].

3D printing concrete (3DPC) is being explored as part of the construction industry's shift towards more sustainable and eco-friendly building solutions. While the technology offers improved material efficiency [3-4], challenges persist due to the significant use of cement and sand [4]. To address this, incorporating recycled materials into 3DPC formulations shows promise for reducing environmental impact and promoting a circular economy.

In addition to mix design, printing parameters such as nozzle geometry [5], nozzle distancing [6-7], printing speed [7-8], and printing time-gap [9] also influence the performance of printed concrete, particularly the interlayer bond strength, which may lead to issues such as "cold joint" [10].

Despite extensive research on various parameters affecting the mechanical strength of 3DPC, the influence of nozzle diameter on mechanical strength has not been addressed elsewhere. This paper investigates this issue, including an examination of the failure patterns of interlayer bond strength using direct tensile testing.

2 MATERIALS AND METHODS

2.1 Materials

The recycled aggregate from the recycling of all-mixture concrete, denoted as recycled sand (RS), originates from the Tradecowall recycling center in St-Ghislain, Belgium. This RS possesses a maximum grain size of 2 mm with a density of 2.39 tons/m^3 and exhibits a water absorption rate of 5.31%. The cement employed in this mix is categorized as type CEMI 52.5N with a density of 3.16 tons/m^3, procured from VICAT's manufacturing facility in Créchy, France. The plasticizer Polycarboxylate (PCE) and the viscosity modifying admixture (VMA) used in this research were supplied by Chryso company.

2.2 Mixture proportion and sample implementation

For the mix preparation, the composition is listed in Table 1 and the mixing procedure is initiated by mixing the first third of the materials, including sand, cement, and water, for a period of 2 min. This is followed by the inclusion of the second portion, in which the admixtures are added to the water, which is similarly mixed for 2 min. Lastly, the third portion is introduced and blended for an additional 11 min.

Table 1- Mixtures proportions of mortars (kg)

	Cement	Sand	Water	Plasticizer	VCA	W_{eff}/C
RSM/NSM	905,00	995,60	313,52	22,63	1,81	0,29

Specifically, "S"-shaped elements were continuously printed up to 6 layers with a printing speed of 100 mm/s. Subsequently, these elements were covered with plastic film and left for 24 h before being cured in a humid chamber (maintained at a relative humidity of 95±5% and a temperature of 20±2°C).

2.3 EXPERIMENTAL METHODS

Compressive strength test. Compressive strength R_c evaluations were executed following the protocols outlined in the established standard NBN EN 196-1 [11]. Test prisms with dimensions of 40 × 40 × 160 mm³ were sawed from the “S” shaped elements and tested at intervals of 28, 56, and 91 days for samples printed with a 2 cm nozzle and exclusively at 28 days for samples printed with a 4 cm nozzle.

All extracted samples at each designated time were tested following two distinctive loading directions: (ox) and (oz), as shown in Figure 1.

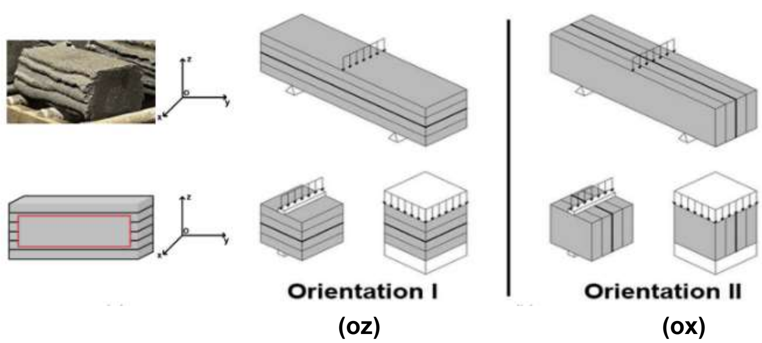


Figure 1- Printing samples and orientations of loading direction [12-13]

Direct Tensile test. Tensile strength R_t was evaluated following the guidelines outlined in the established standard NBN B15-211 [14]. Cylindrical specimens, measuring 50 mm in diameter and 50 mm in height, were drilled from the S shaped elements and tested at intervals of 28, 56, and 91 days for cast samples and exclusively at 91 days for printed samples. All samples were vertically drilled perpendicularly to the printed layers from the printed "S" shape element. The outline of the layers was then traced approximately based on the visible interface on the printed element. The experimental procedure was executed using an INSTRON instrument with a pulling rate set at 0.10 ± 0.05 MPa/s.

Porosity and bulk density measurements. Porosity ε and bulk density ρ_d of the mortar were evaluated following standard NF P18-459 [15]. Cube-shaped samples extracted from the printed "S" element, measuring 40 x 40 x 40 mm³, were employed for these measurements, and both cases of sample printing with 2 cm and 4 cm nozzle. The assessment was conducted at specific time intervals: 28 and 56 days.

For the microstructural comprehension, a complementary investigation was conducted on the inner and the outer parts of the printed sample, as shown in Figure 2 resulting from the printing with 2 cm and 4 cm nozzle at 270 days and 210 days of curing respectively.

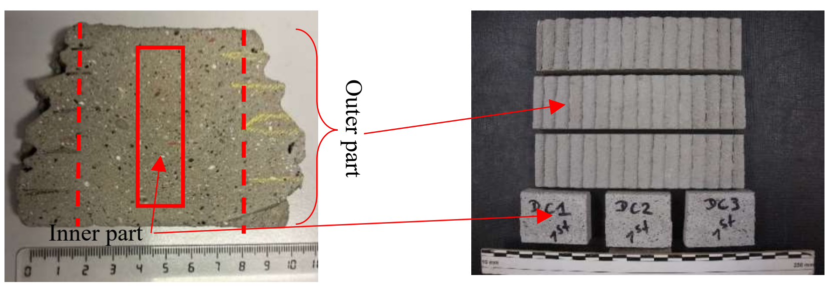


Figure 2- Sample preparation for complementary results for the porosity test

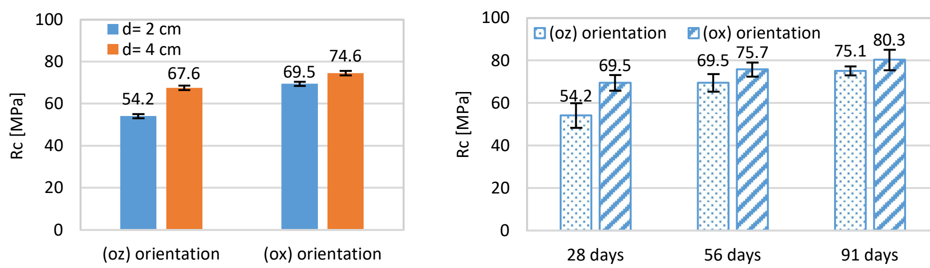
3 RESULTS AND DISCUSSION

3.1 Effect nozzle diameter on the anisotropy of compressive strength of mortar

Figure *3* illustrates the printed bench within the context of the CIRMAP research project [16]. This achievement was accomplished by printing the bench in multiple segments and assembling them afterward. Consequently, each segment exhibits a non-planar configuration, requiring the nozzle to move to different levels during printing, ultimately resulting in the pushing down of the filament.

Figure 3- Printed segment assembled as a bench in the framework of CIRMAP project [16]

Figure 4(a) depicts the compressive strength at 28 days of printed samples using 2 cm and 4 cm nozzle diameters. When applying load in the (oz) orientation, a significant reduction in Rc of approximately 19.8% was observed, decreasing from 67.6 MPa to 54.2 MPa when using a 4 cm and 2 cm nozzle respectively. The samples produced with a 2 cm nozzle diameter tend to exhibit a weak lateral surface (outer part, as shown in Figure 2), which contributes to lower compressive strength in the direction (ox) compared to (oy), as indicated by the satisfactory theoretical failures of the cube's compressive strength [17]. The action of pushing down the string to achieve a 6 cm string width resulted in damage to the lateral printing surface, ultimately leading to dehydration of the lateral surface and simultaneously limiting the hydration of cement. However, after sufficient curing in the chamber with relative humidity (HR) greater than 95%, the compressive strength (R_c) tends to significantly increase due to the development of cement hydration, as depicted in Figure 4(b). These results reflect the mechanical behavior of the actual printed element shown in Figure 3.



(a) (b)

Figure 4- R_c of the printed sample with a 2 cm and a 4 cm nozzle at 28 days (a) and R_c of the printed sample using a 2 cm nozzle at 28, 56, and 91 days

3.2 Effect nozzle diameter on the microstructure of mortar

Table 2 presents the results of the porosity and bulk density of printed samples using a 2 cm nozzle and a 4 cm nozzle at 28 and 56 days. Overall, the porosity of the printed samples using a 2 cm nozzle is higher than those using a 4 cm nozzle, with a difference of 0.7% and 1.4% at 28 days and 56 days respectively. This higher porosity is primarily caused by the level of damage to the lateral surface, as described in Section 2.3. This damage results in excessive drying of the lateral surfaces and may potentially disrupt hydration. Additionally, the difference between the porosity of the outer and inner parts is generally greater for samples printed using a 2 cm nozzle compared to those printed using a 4 cm nozzle, as illustrated in Table 3. Unlike porosity, there is no remarkable change in bulk density between the inner and outer parts of the printed sample.

Table 2- Porosity and bulk density of printed sample using a 2 cm nozzle and a 4 cm nozzle at 28 and 56 days

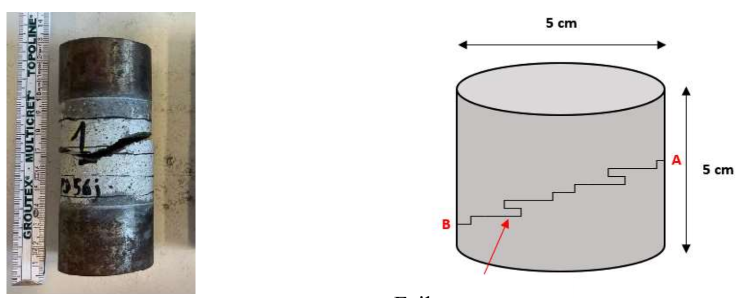
	d= 2 cm		d= 4 cm	
	Porosity [%]	Bulk density [kg/m^3]	Porosity [%]	Bulk density [kg/m^3]
28 days	18.3 ± 0.4	2003	17.6 ± 0.4	2002
56 days	18.2 ± 0.1	2004	15.8 ± 0.1	2014

Table 3- Porosity and bulk density of inner part and outer part of the printed sample using a 2 cm nozzle and a 4 cm nozzle

	d= 2 cm at 270 days		d= 4 cm at 210 days	
	Porosity [%]	Bulk density [kg/m^3]	Porosity [%]	Bulk density [kg/m^3]
Inner part	17.8 ± 0.2	2045	17.2 ± 0.1	2024
Outer part	18.5 ± 0.2	2018	17.7 ± 0.4	2032

3.3 Bonding properties between layers of printed mortar

The direct tensile strength (Rt) at 28, 56, and 91 days of the samples printed with a 2 cm nozzle are 2.51, 2.69, and 2.25 MPa respectively. The investigation focused on the failure pattern of direct tensile strength. As depicted in Figure 2, there was no visible trace observed between layers on the vertical cutting surface. This absence can be attributed to the minimal time gap allocated for printing each layer (50 s per layer). A similar result was reported in the research conducted by Tay et al. [9]. The minimal time gap between layers does not allow the interlayer surface to form a cold joint. Consequently, the failure pattern does not exhibit weakness between the layers, as the failure originates diagonally, as depicted in Figure 5.



(a) (b)

Figure 5- Failure pattern of printed specimens after tensile test

4 CONCLUSION

This research study has illuminated various critical aspects related to 3D-printed mortar, particularly focusing on the impact of using different nozzle sizes on the mechanical behavior and microstructure of mortar containing 100% Recycled Fine Aggregates (RFA). The conclusions can be summarized as follows:

- A minimum compressive strength of 54.2 MPa was achieved with 100% RFA at 28 days.
- Anisotropy in compressive strength was observed, with greater strength when compressing the sample perpendicularly to the layer's deposition. This strength was found to be 19.8% higher compared to compression parallel to the layer deposition.
- Using a 2 cm nozzle diameter created a weaker lateral surface (outer part) compared to that when using a 4 cm nozzle diameter. The smaller the nozzle diameter, the greater damage was observed. It is recommended to use a nozzle diameter as close as possible to the desired string width to avoid the need for widening it by compressing the layers together. This pressure tends to damage the lateral surface which compromises the structural stability of the entire string.
- The porosity of the samples printed with a 2 cm nozzle diameter is 0.7% and 1.4% higher than that of the samples printed with a 4 cm nozzle diameter at 28 and 56 days respectively.
- The porosity of the outer part of the printed sample is typically higher than that of the inner part. Specifically, the difference in porosity between the inner and outer parts was observed to be 0.7% when utilizing a 2 cm nozzle diameter and 0.5% when employing a 4 cm nozzle diameter.
- Given the minimal time gap, the failure of tensile strength is not affected by the interface between layers, as the rupture occurs randomly. These findings challenge traditional assumptions regarding the existence of a weaker interface between layers of 3D-printed materials and underscore the need for further research.

These results highlight additional parameters that may influence the performance of 3DPC, in addition to those identified in previous research. However, further research is needed to ensure the statistical accuracy of these results.

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