Mechanical Performance of 3D Printed Concrete: Comparing Cast and Printed Concrete Materials

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Abstract. An innovative solution to address challenges surrounding housing needs and labour productivity is the use of 3D concrete printing (3DCP), which has emerged as an innovative construction approach in North America. Despite the rapid increase in use of the technology, questions remain surrounding the mechanical performance of 3DCP materials, including the influence of coarse aggregate and the inter-layer behaviour in tension. This paper aims to address some of these gaps and conducts mechanical testing on 3DCP materials, including materials with and without coarse aggregate to evaluate their strength. Tests are also conducted on both cast and printed specimens to better understand how the in-situ properties, including the effect of layering on compressive strength and modulus of rupture. Results of the study demonstrate that 3D printed concrete with coarse aggregate has improved structural performance in terms of compressive strength and modulus of rupture when compared with 3D printed mortar. Furthermore, failure in tension was found to initiate at layer interfaces but to propagate through the concrete material, resulting in similar strengths between cast and printed specimens. The implications of the work for the additive manufacturing industry and the research needs in this area are also discussed.

Keywords: additive construction, concrete, mortar, material testing.

1 Introduction

North America is faced with growing pressures to increase the supply of housing to keep pace with population growth and combat rising housing costs. In Canada, there is a goal to double the pace of housing construction over the next decade (Government of Canada, 2026), while the province of Ontario has set a more specific target to build 1.5 million homes over the next decade (Government of Ontario, 2025). While demand for new housing construction rises, labour productivity by some estimates has stagnated or declined over the last two decades (HICC, 2025), which is partially attributed to its low rate of adoption of new technologies. Consequently, there is an ongoing need to develop innovative technologies to improve the speed and efficiency of construction.

Historically, the construction industry has been slow to adapt to the digital age and many repetitive tasks on construction sites continue to be predominantly done by human labourers. A promising solution to these challenges is the use of 3D concrete printing, commonly referred to as 3DCP. Falling within the umbrella of additive manufacturing, 3DCP has emerged in recent years and there are now several companies using the technology to build homes in North America, including in Canada. For example, recent notable Canadian projects include the construction of a multi-unit residential building in Windsor, ON (Campbell, 2022) and the construction of four supportive housing units in Siksika First Nation, AB (Coulter, 2023). While these projects highlight the potential of the technology, significant research gaps remain surrounding its structural performance both at varying scales and under different loading conditions.

While 3DCP is a comparatively new technology, there has been a significant amount of research on its material performance, which has been summarized in several state-of-the-art reviews (Zhang et al., 2019; Heidamezhad and Zhang, 2022; Cai et al., 2024). Past work includes research into the mix designs and rheological properties of 3DCP cementitious materials, including concrete without coarse aggregate (Wagner et al., 2024), fibre reinforced concrete (Hou et al., 2021; Ding et al., 2020), and ultra-high performance concrete (Gosselin et al., 2016, Arunothayan et al., 2023). However, there have been comparatively few studies studying the performance of 3DCP with coarse aggregate (defined as maximum aggregate size less than 4.5 mm) (Cai et al., 2024), which limits the feasibility of 3DCP because use of coarse aggregate would reduce cement content, and enable the possibility to print directly from a ready-mix truck, thereby avoiding the need for an on-site batch plant.

This paper aims to address some of these gaps and presents results from mechanical testing on 3DCP materials to evaluate their strength and add to the existing literature in this area. The specific objectives of this paper are to:

1. Compare the compressive strength of 3DCP materials with and without coarse aggregate.
2. Evaluate the modulus of rupture of 3DCP materials with and without coarse aggregate, including the inter-layer cracking behaviour in tension.
3. Compare the mechanical properties of printed concrete (i.e., samples taken from large-scale assemblies) to those from traditional mold cast specimens.

2 Experimental Program

2.1 Material Composition

Two different materials were evaluated as part of this research, which included a 3DCP without coarse aggregate, here after referred to as mortar, and 3DCP with coarse aggregate, hereafter referred to as concrete. Typical cross-sections of each material type are shown in Figure 1. The mortar and concrete materials used in this study were proprietary to the manufacturing company, and thus, detailed mix designs are not available. However, generally the mixes included a cement content from 400-600 kg/m^3, fine aggregate, superplasticizer, accelerator, and a hardener at the nozzle. The mortar and concrete had maximum aggregate sizes of <2 mm and 6.4 mm, respectively. The materials were also air entrained (6-8 %) and included synthetic monofilament microfiber to reduce plastic shrinkage cracking.

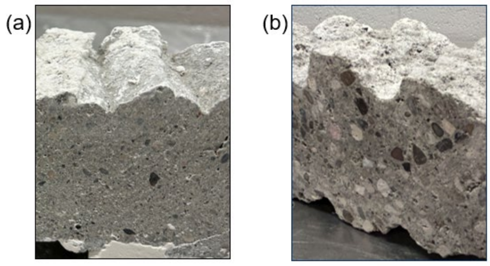

Fig. 1. Comparison of 3DCP materials tested in this study: (a) mortar, (b) concrete.

2.2 Test Specimens

An objective of this work was to evaluate compressive strength and modulus of rupture using conventional test methods from mold cast concrete and to compare them with samples taken directly from a 3D printed element. To accomplish this objective, specimens were fabricated both by saw cutting samples from a 3DCP wall as well as casting samples in formwork. Figure 2 shows the samples from which the printed specimens were cut, both during the printing process and after curing. It is noted that cast sampled were prepared on the same day as the printed specimens and the concrete material was taken directly from the printer head, such that it would have material properties that were as close as possible to the printed material. The walls were printed as part of a large-scale construction project, and the printer speed was approximately 100 mm/s, which resulted in a layer time of approximately 12 minutes.

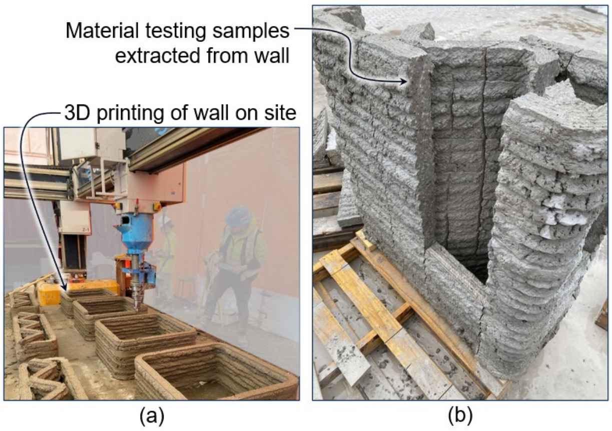

Fig. 2. (a) 3D printing of wall assemblies, (b) typical sample removal from printed wall

Table 1 summarizes the test matrix. The naming convention used for the specimens includes first the mechanical property being evaluated (C – compression and R – modulus of rupture), followed by the material type and fabrication method (CC – cast concrete, CP – printed concrete, MP – printed mortar). As noted in Table 1, 5-10 repeated tests were conducted, as noted in Table 1.

Table 1. Summary of test specimens

Name	Material	Fabrication Method	Test Type	No. Tests
C-CC	Concrete	Cast	Compression	10
C-CP	Concrete	Printed	Compression	10
R-CC	Concrete	Cast	MOR	10
R-CP	Concrete	Printed	MOR	10
R-MP	Mortar	Printed	MOR	5
R-MP	Mortar	Printed	MOR	5

Figure 3 highlights the different specimen types tested in this research. Because of the lack of standardization for 3DCP material characterization, a broad range of test methods have been used to evaluate its properties in the literature (Cai et al., 2024). While the ISO/ASTM 52939 standard (ISO/ASTM, 2023) outlines quality assurance guidelines for construction using additive construction methods, it does not prescribe specific material testing requirements, something that will be crucial for the long-term viability of 3DCP, but for this reason a range of specimen dimensions were employed.

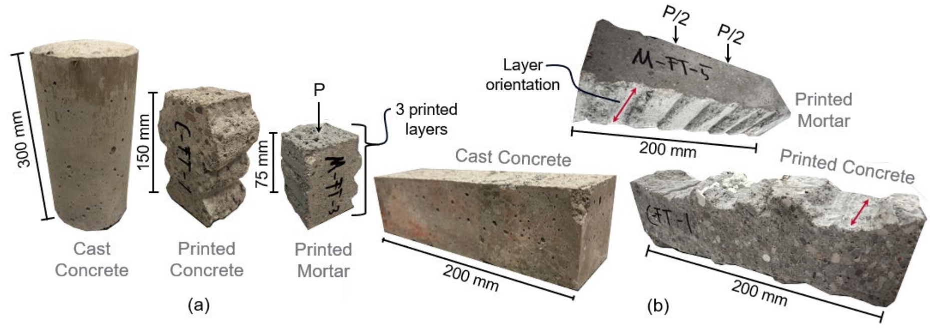

Fig. 3. Comparison of test specimens: (a) compression, (b) modulus of rupture.

The dimensions of the compression specimens, shown in Figure 3(a), followed the requirements of ASTM C39/C39M for the cylinders while no standard exists for 3DCP prisms. The cylinders for compression testing had dimensions of 150×300 mm. To evaluate compressive strength of the printed materials, prisms consisting of three printed layers in height were tested (shown in Figure 3). The layer thickness for the concrete and mortar prints were 50 mm and 25 mm, respectively, resulting in overall prism heights of 150 mm and 75 mm, respectively. The cross-section of the compression prisms were approximately 50×50 mm on average, which was equal to the print layer width, however, there was variability in the dimensions of the specimens because of the printing process, and the specific dimensions of each specimen were recorded.

The modulus of rupture specimens followed the guidelines outlined in ASTM C78/C78M and the cast concrete prisms were 80×80×280 mm. For the printed concrete and mortar, saw cut prisms from larger walls (Figure 2) had average dimensions of 50×50×240 mm, however, this was once again variable because of the printing process.

3 Experimental Results and Discussion

3.1 Compression Testing

Figure 4 summarizes the compression tests conducted on cast concrete cylinders, printed concrete prisms, and printed mortar prisms. Overall, the results show that concrete had a higher compressive strength when compared to the printed mortar, however, both materials met the minimum strength requirements in CSA A23.3. Comparing cast and printed prisms, the printed material had a compressive strength that was on average 32 % lower than the cast cylinders, something that has been noted in past research by Wagner (2025), who observed an average 46 % decrease in strength between cast and printed specimens on average.

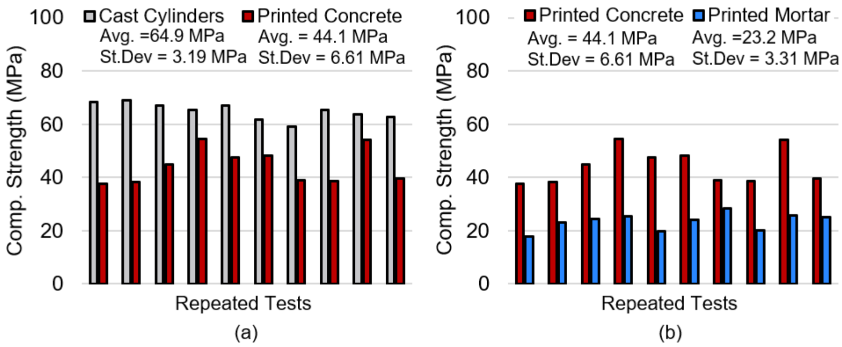

Fig. 4. Comparison of compressive strength results: (a) cast versus printed concrete, (b) printed concrete versus printed mortar

Figure 5 shows the commonly observed failure mechanism in the compression testing, which often involved vertical splitting crack developing through the section of the 3DCP at the interface between the central 'core' portion of the prism and surrounding layers, as noted in the figure.

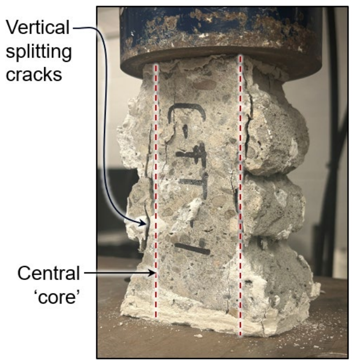

Fig. 5. Typical observed failure mode in printed concrete prisms

3.2 Modulus of Rupture

Figure 6 summarizes the modulus of rupture test results for the materials tested in this study. Notably, the modulus of rupture of the cast and printed concrete (T-CC and T-CP specimens) did not vary significantly as the average modulus of rupture in the cast concrete prisms was 5.97 MPa (SD = 0.52 MPa) compared to 5.68 MPa (SD = 0.97 MPa) in the printed mortar prisms. While the averages are similar, there was more variation in the results from the printed concrete, which is attributed to the variation in the cross-section of the prisms along their length. The printed mortar had an average modulus of rupture of 3.15 MPa (SD = 0.61 MPa), which was lower than the printed material, however, this was expected as the material had a lower compressive strength.

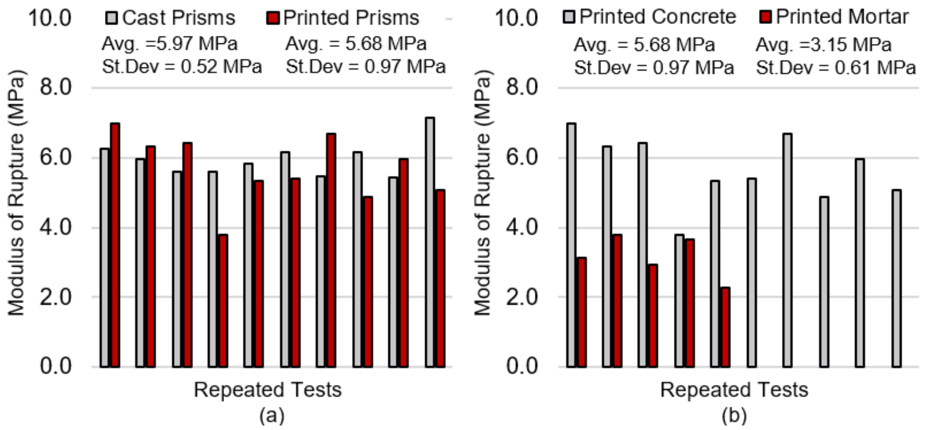

Fig. 6. Comparison of modulus of rupture results (a) cast versus printed concrete, (b) printed concrete versus mortar

Figure 7 shows the typical observed failure mode in the printed concrete and mortar prisms from the modulus of rupture tests. One of the concerns regarding the behaviour of 3DCP is the influence of its layers and the potential implications for cracking. The results in Figure 7 show that while the failure crack does have a tendency to initiate at the interface between concrete layers, the failure propagates through the concrete material (i.e., matrix and aggregate) as opposed to failure along the interface between layers. These results suggest that for the printed concrete tested in this study, the layer and setting time were sufficient for the inter-layer bond strength to exceed the strength of the concrete material, while maintaining buildability, which is the ability of the 3DCP material to support its own weight as well as the weight of overlying layers.

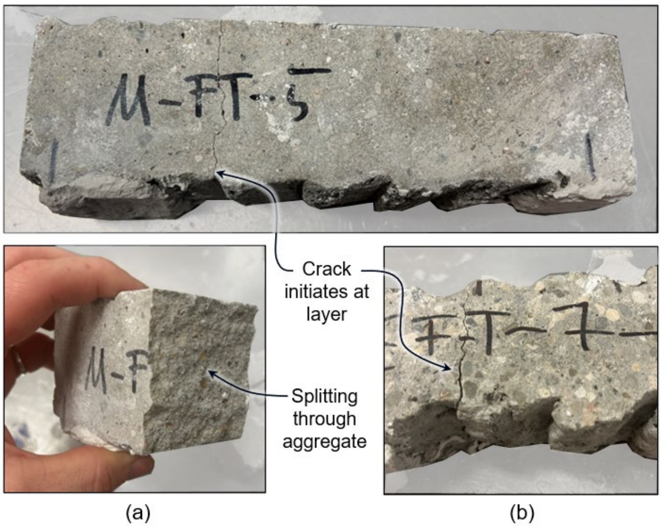

Fig. 7. Typical observed failure modes in modulus of rupture tests: (a) printed mortar, (b) printed concrete

4 Conclusions

This paper presented results on the mechanical testing of 3DCP materials with and without coarse aggregate and compared the strength of printed materials to traditional mold-case specimens. Specific conclusions of this work include:

1. Printed concrete prisms in compression were found to have a 32 % lower compressive strength when compared to cast concrete cylinders, matching previous research available in the literature (Wagner et al., 2025).
2. The modulus of rupture of mold-cast concrete prisms and prisms extracted from a full-scale wall assembly were found to have similar modulus of rupture.
3. Cracking in modulus of rupture tests initiated at the interface between concrete layers, however, cracking extended through the concrete matrix.

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