Proceedings of the Seventeenth International Conference on
Civil, Structural and Environmental Engineering Computing
Edited by: P. Iványi, J. Kruis and B.H.V. Topping
Civil-Comp Conferences, Volume 6, Paper 4.3
Civil-Comp Press, Edinburgh, United Kingdom, 2023
doi: 10.4203/ccc.6.4.3

Mechanical performance of stiffening-controllable concrete using a two-component system

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Abstract

To control the stiffness of 3D printable concrete, a two-component system (twin-pipe pumping) has been devised. This system involves pumping a cement-based mixture (without an accelerator) and a limestone-based mixture (with a high dosage of the accelerator) separately, which are then combined through a helical static mixer before being extruded. As these two mixtures pass through the helical static mixer, the accelerator present in the limestone-based mixture interacts rapidly with the cement in the cement-based mixture, resulting in a swift stiffening process. This research aims to investigate how the mechanical properties of printed elements are affected by the number of mixing baffles (ranging from 6 to 30) employed in the helical static mixer. To evaluate the printed elements, flexural, compressive, and tensile strength were measured using prismatic, cubic, and cylindrical specimens extracted from printed wall elements. The experimental findings reveal that the printed specimens exhibit anisotropic behavior. Furthermore, an increase in the number of mixing baffles from 6 to 30 enhances the mechanical strength gradually due to improved mixing homogeneity.

Keywords: digital fabrication, 3D concrete printing, twin-pipe pumping, mechanical behavior, helical static mixer, limestone powder

1 Introduction

Unlike traditional mold-cast concrete, digital fabrication using concrete, also known as 3D printable concrete, demands a rapid stiffening rate without the need for formwork [1, 2]. Conversely, a slow stiffening rate is necessary to ensure smooth pumping operations. However, reconciling these conflicting requirements remains a significant challenge in the realm of 3D concrete printing [3]. To tackle this obstacle, a stiffening control system (twin-pipe pumping) has been devised. In this system, a cement-based mixture (without accelerator) and a limestone-based mixture (without cement but with a high dosage of the accelerator) are delivered separately using two pumps and then merged through a helical static mixer just before extrusion. During the pumping process, the cement-based mixture is formulated to have an open time exceeding 2 hours, while the limestone-based mixture is expected to have an indefinite open time due to the absence of cement. When these two mixtures are combined in the helical static mixer, the accelerator present in the limestone-based mixture rapidly reacts with the cement in the cement-based mixture, resulting in a significant acceleration of the stiffening rate. This enables the attainment of excellent shape stability for 3D printed elements [4].

Past studies have demonstrated the anisotropic characteristics of hardened 3D printed concrete, which can be attributed to the relatively weak interlayer bonding between adjacent printed layers [5, 6]. Regarding the mechanical properties of elements fabricated through the twin-pipe pumping system, additional weak regions have been identified. Specifically, inadequately mixed limestone striations were observed [7]. Furthermore, it was demonstrated that the utilization of a helical static mixer with an increased number of mixing baffles can enhance the mixing homogeneity [8]. Nevertheless, the impact of the number of mixing baffles on the mechanical properties of printed elements using the twin-pipe pumping approach has not been explored. Therefore, this study focuses on printing straight wall elements utilizing a helical static mixer with varying numbers of mixing baffles (6, 12, 18, 24, and 30). Subsequently, specimens were extracted from these wall elements and subjected to flexural, compressive, and tensile testing. The resulting data allowed for the evaluation of the mechanical strength in relation to the number of mixing baffles.

2 Methods

The mixture compositions of the cement-based mixture and the limestone-based mixture are shown in Table 1. The cement-based mixture comprises silica sand (0-2 mm), ordinary Portland cement (Holcim CEM I 52.5 N), water, and superplasticizer (BASF Master Glenium 51). The limestone-based mixture consists of sand (0-2 mm), limestone powder (Carmeuse), water, superplasticizer (BASF Master Glenium 51), and accelerator (Sika Sigunit 49-AF). Both mixtures maintain a sand-to-cement/limestone powder ratio of 1.2 and a water-to-cement/limestone powder ratio of 0.35. More details about the materials and mixture design can be found in [7].

Using a pan mixer with a 50-liter capacity and a constant rotational speed of 60 rpm, a total of 40 liters of the cement-based mixture and 20 liters of the limestone-based mixture were prepared. The mixing process involved the following steps: (1) manually mixing water and superplasticizer for 10 seconds, (2) dry mixing sand and cement for the cement-based mixture or sand, limestone powder, and accelerator for the limestone-based mixture for 30 seconds, and (3) adding water (containing the superplasticizer) to the dry materials and mixing for 3 minutes. The overall mixing time for both mixtures amounted to approximately 220 seconds.

Subsequently, the cement-based mixture and the limestone-based mixture were introduced into two pumps (Rudolf STROBOT 407) and transported through two pipes (with an inner diameter of 25.4 mm and a length of 3 meters). A total of 5 static mixers were employed, each with a varying number of mixing baffles (6, 12, 18, 24, and 30). Each mixing baffle had an inner diameter (D) of 32 mm and a length (L) of 45 mm. As the cement-based mixture and the limestone-based mixture passed through the helical static mixer, the mixing baffles progressively combined the two mixtures. Within a single flow cycle, the streams encountered two mixing baffles that rotated in different directions. To manipulate the movement of the helical static mixer and the nozzle located immediately after it (with an outlet width of 40 mm), a robotic arm (ABB IRB 6650) was employed. Further information regarding the twin-pipe pumping system used in this research can be found in a previously published paper by the authors [9].

The printing process maintained a constant speed of 200 mm/s, with each layer having a thickness of 10 mm. A total of 5 straight wall elements were printed, each measuring 800 mm in length, 40 mm in width, and 180 mm in height. These wall elements were produced using the helical static mixer, with different configurations of mixing baffles. Subsequently, at a 1-day age, prismatic specimens (measuring $40 \times 40 \times 160$ mm^3), cubic specimens (measuring $40 \times 40 \times 40$ mm^3), and cylindrical specimens (with a diameter of 25 mm and a height of 40 mm) were extracted from the printed wall elements. For further information regarding the specific extraction positions, please refer to the provided source [7]. After that, the specimens were cured in a climate room with a constant temperature of 20 °C and a relative humidity of 95%.

Mixture	Sand	Cement	Limestone powder	Water	Superplasticizer	Accelerator
Cement-based	1076	896.7	0	313.8	4.5	0
Limestone-based	1034	0	862	302	6.5	125.5

Table 1: Mixture composition of two constituent mixtures (kg/m^3).

The mechanical tests were conducted after 28 days. The loading orientations for flexural, compression, and tensile tests can be observed in Figure 1. For the assessment of flexural strength, prismatic specimens were subjected to three different loading directions (F1, F2, and F3). Additionally, cubic specimens were tested in two loading directions (C1 and C2) to determine compressive strength, while cylindrical specimens, used for measuring tensile strength, were solely tested in one loading direction (T1). In the flexural test, three specimens were examined for each series, whereas six specimens were utilized for each series in both the compressive and tensile tests. The standards NEN-EN 12390-5, NEN-EN 12390-3, and NBN-EN 1542 served as reference guidelines [10-12]. More details about the testing protocol can be found in [9].

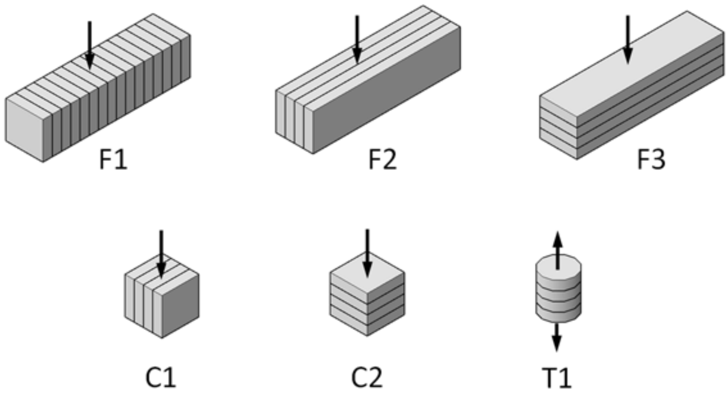

Figure 1: Loading directions in flexural, compression, and tensile tests.

3 Results

The flexural strength of the prismatic specimens under different loading directions is shown in Figure 2. The obtained values demonstrated a reliance on the loading direction, revealing anisotropic behavior. For instance, when utilizing 6 mixing baffles, the flexural strength of the specimen under loading direction F1 (0.5 MPa) exhibited a significant decrease compared to the values obtained for the other two loading directions (8.2 and 5.7 MPa). This discrepancy can be attributed to a fracture occurring in the weaker regions composed of limestone-based materials under loading direction F1, where a scarcity of cement resulted in the limited formation of hydration products. Furthermore, an increase in flexural strength was observed as the number of mixing baffles increased for each loading direction. In the case of loading direction F3, the flexural strength rose from 5.7 MPa to 12.4 MPa as the number of mixing baffles increased from 6 to 30. A similar trend was observed for the other two loading directions. As the cement-based mixture and the limestone-based mixture traversed the helical static mixer, the mixing baffles continuously blended the two streams, resulting in improved mixing homogeneity and enhanced mechanical integrity [9].

The compressive strength of the cubic specimens is shown in Figure 3. Anisotropic behavior was also evident in the compressive strength, with dependency on the loading direction. The compressive strength for loading direction C2 was significantly higher compared to the values observed for loading direction C1. For instance, when employing 12 mixing baffles, the compressive strength for loading direction C2 (48.1 MPa) was nearly double the value obtained for loading direction C1 (27.2 MPa). Interestingly, a marginal enhancement in compressive strength was observed as the number of mixing baffles increased from 12 to 30. This phenomenon differed from a recent study where calcium sulfoaluminate cement was utilized instead of ordinary Portland cement, and no such limitations were observed [9]. Under those circumstances, the compressive strength for loading direction C2 exhibited a gradual increase with an increase in the number of mixing baffles. The underlying factors for this phenomenon could be attributed to variations in mixture compositions or disparities in the initial rheological properties of the two streams being blended. More specifically, achieving better mixing homogeneity is facilitated when combining two streams with lower yield stress or viscosity. This aspect warrants further investigation to gain deeper insights.

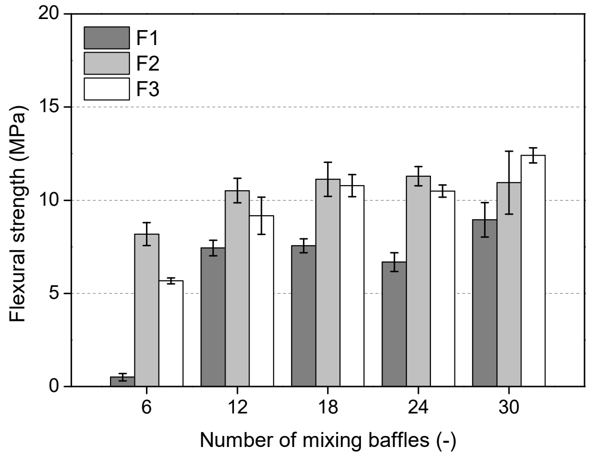

Figure 2: Flexural strength results (error bars represent the standard error, n=3).

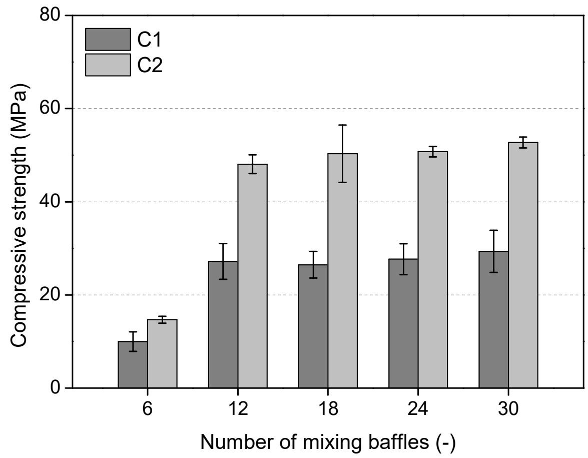

Figure 3: Compressive strength results (error bars represent the standard error, n=6).

The tensile strength of the cylindrical specimens is shown in Figure 4. By increasing the number of mixing baffles from 6 to 12, the tensile strength exhibited an improvement from 0.1 MPa to 1.1 MPa. Similar to the findings in the flexural and compression tests, the tensile strength displayed minimal changes as the number of mixing baffles increased from 12 to 30. This suggests that 12 mixing baffles are sufficient to attain satisfactory mechanical integrity for the cement-based mixture and limestone-based mixture utilized in this study. However, it is important to note that the situation may vary when different mixtures with alternative compositions are employed.

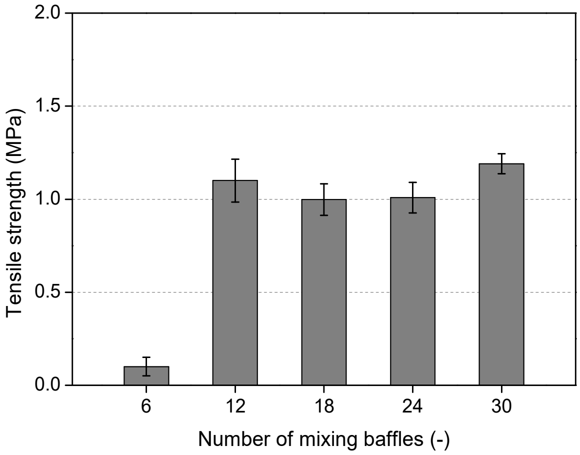

Figure 4: Tensile strength results (error bars represent the standard error, n=6).

4 Conclusions and Contributions

This study focuses on investigating the mechanical characteristics of twin-pipe printed concrete. The printing process involves the separate delivery of a cement-based mixture (without accelerator) and a limestone-based mixture (without cement but with a high dosage of accelerator). These two mixtures are combined using a helical static mixer just before extrusion. Based on the experimental findings and subsequent discussion, the following two conclusions can be drawn. On the one hand, the twin-pipe printed specimens exhibited anisotropic behavior when subjected to flexural and compression loads. On the other hand, the strength of the printed specimens can be enhanced by incorporating a greater number of mixing baffles in the helical static mixer, particularly in cases where the fracture occurred in weaker limestone-based regions.

Acknowledgements

The authors acknowledge the financial support provided by the Ministry of Science and Technology of China (No. 2021YFE0114100).

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