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HARDENED PROPERTIES OF 3D PRINTED CONCRETE – EXPERIMENTAL INVESTIGATION

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ABSTRACT

At the end of the last century, 3D printing of concrete became an innovative method for producing concrete structures. The beginning of the application of 3D printing in the concrete construction industry is referred to the Contour Crafting printing method. In addition to Contour Crafting, other methods such as Fused Deposition Modeling, Shotcrete 3D Printing, and ink printing method, developed and utilized by D-Shape, have been applied in this field. Through the use of these technologies, numerous structures have been successfully created, including one-story and multi-story houses, residential buildings, pedestrian bridges, as well as individual elements like columns, walls, facade panels and outdoor furniture. However, the wider implementation of this technology has revealed various challenges, such as the lack of regulations and standards for the production and testing of these concrete materials as well as the structural analysis of 3D printed structures.

The topic of this research is the investigation of the hardened properties of 3D printed concrete. The focus is on the physical and mechanical properties such as the bulk density of concrete, compressive strength, flexural strength and interlayer bond strength. This paper gives an overview of previous research on these properties, while the experimental part gives insight into the results of own research. Two types of specimen processing were used: full-notch removal (series 1) and printed samples (series 2). Additionally, samples with four or six layers were analyzed.

The obtained values for bulk density were 1964.46 kg/m³ for full-notch removal samples and 1859.62 kg/m³ for printed samples. The compressive strength was 25 MPa for perpendicular and lateral directions, while the bending strength was 5.57 MPa. A significant influence of layering on fracture patterns and results was observed during the bond strength testing. The obtained values ranged from 1.59 to 2.91 MPa, the lowest value was obtained in the axial tension test, while the highest value was achieved in the shear test. The highest uniformity of results was achieved for series 1 samples tested in axial tension and splitting tests.

Keywords: Additive manufacturing; 3D printed concrete; Hardened properties; Mechanical testing; Bond strength

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1. INTRODUCTION

The technology of 3D printing was created in the 1980s as an innovative method of manufacturing various elements based on the idea of Charles Hull [1], [2]. This process, often referres to "Additive Manufacturing" (AM) in the literature, means the gradual deposition of material in layers along a desired path to create complex-shaped elements based on a 3D computer model. Initially applied to metals, polymers, ceramics, textiles, and other composite materials, the technique quickly found applications in various industries [1]–[3].

The application of 3D printing technology using concrete as a printing material is closely associated to Behrokh Khoshnevis from the University of Southern California and his own method Contour Crafting (CC) [3], [4]. Besides CC, other techniques have been utilized in this field. One of them is Fused Deposition Modeling (FDM) [2], [3], where material is extruded in layers based on G-code generated from a CAD model of the element (Fig. 1). Another method is Shotcrete 3D Printing (SC3DP) [5] which involved the continuous spraying of concrete by robotic arm, without clear layering and with potential for reinforcement incorporation (Fig. 2). The Ink Printing Method employs the spraying of a binder onto layers of material intended for printing and has been successfully developed and applied by the company D-Shape (Figure 03) [3], [6].

Fig. 1. FDM technology for 3D printing of concrete. [7]

Fig. 2. 3D concrete printing using the spraying method (SC3DP). [5]

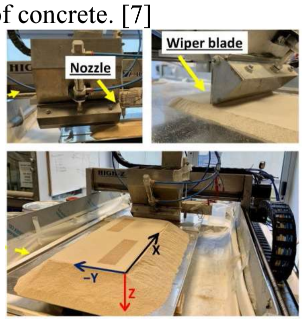

Fig. 3. The Ink Printing Method. [8]

Advantages of 3D concrete printing include faster construction without formwork and material savings, improved safety and potential for sustainable development. However, drawbacks include higher initial costs, skilled labor requirements, material quality concerns, and a lack of design and construction regulations [2], [3], [9]. 3D printing technology has made remarkable strides in the construction industry. It has been successfully applied to build various structures, like residential houses (Fig. 4), multi-story buildings, and pedestrian bridges (Fig. 5). Moreover, individual components like columns and walls have been successfully printed using 3D concrete. Beyond structural applications, non-structural elements like sculptures, planters, urban furniture, and other decorative items have also been produced using 3D printed concrete [2], [3], [9].

Further advancements in 3D concrete printing could be achieved by exploring the integration of reinforcement into the printing process, enhancing the connections between printed elements, and addressing challenges like cold joints [2], [9]. By tackling these issues, 3D printing technology can gain wider acceptance in modern construction practices. Additionally, a promising direction for the future development of 3D printing technology lies in the field of prefabricated construction. The possibility of producing different prefabricated printed elements with the utilization of different printers can potentially change the construction industry, offering faster, more efficient and sustainable building solutions.

Fig. 4. Milestone House [9]

Fig. 5. Pedestrian bridge over the Peelse Loop canal [10]

The objective of this paper is to analyze and investigate the specific hardened properties of 3D printable concrete. A critical review of relevant literature and research in this field has been done. Additionally, an experimental part gives insight into the results of own research regarding bulk density, compressive strength, flexural strength and interlayer bond strength.

2. HARDENED PROPERTIES OF 3D PRINTED CONCRETE: LITERATURE REVIEW

Testing the physical and mechanical properties of a material is a fundamental step on the roadmap for its structural application. In the case of 3D printed concrete, there are no technical regulations and standards that specifically quantify its properties [11], [12]. Similar to ordinary concrete, various properties of 3D printed concrete have been investigated, such as bulk density, compressive strength, flexural strength, interlayer bond strength, shrinkage, flowability, durability parameters, and more [2], [12], [20].

The main difference between ordinary concrete and 3D printed concrete lies in the layer-by-layer construction process, which further increases its anisotropy and heterogeneity. Mechtcherine et al. [11] discuss three main approaches for determining the hardened properties of 3D printed concrete:

1. Testing on specimens obtained by casting fresh concrete into the molds,
2. Testing on specimens obtained by 3D printing concrete directly,
3. Testing on specimens extracted/cut from finished elements produced by 3D printing.

Generally, approach 1 is used to determine whether the fresh concrete mixture is suitable for the printing process or to optimize the concrete mixture. Approaches 2 and 3 allow more realistic assessment of the properties of 3D printed concrete since they consider the layering effect that influences its properties. The printing process leads to the formation of small linear voids between the layers, resulting in anisotropy, which reduces the properties of the printed specimens (approaches 2 and 3) compared to specimens obtained from molds [11], [12].

For ordinary concretes, the testing of bulk density is defined by numerous standards, such as EN 12390-7:2019 [13]. However, for 3D printed concretes, there is currently no standardized process for bulk density testing. Zhanzhao Li et al. [12] provided an overview of how the bulk density of 3D printed concrete is affected by printing parameters like pump pressure, speed, and path shape. Better compatibility between printer head movement, pump pressure, and material flow enhances print quality and ensures high bulk density. Le et al. [14] concluded that good print quality provides lower air voids and higher bulk density rather than traditional mold casting. Similarly, Panda et al. [15] reported that superior print quality through higher extrusion pressure leads to greater bulk density compared to cast concrete. Dey et al. [16] studied the impact of the material deposition method on the hardened properties of 3D printed concrete. Pump-printed samples had fewer voids than screw extruder-printed ones, yielding a higher bulk density. Increasing layer height (10 to 15 mm) reduced bulk density due to decreased layer overlap and macro-voids. Eun-A Seo et al. [17] explored printing environment effects on mechanical properties, finding that air-printed samples had a higher bulk density than underwater ones, while mold-cast samples had a slightly higher density than printed samples. Qian Yu et al. [18]

noted that lower porosity and higher density of lower layer in Z direction are influenced by printer head pressure and upper layer weight.

The compressive strength of ordinary PC concrete is typically tested according to EN 12390-3:2014 [19]. The provided tests examined cubic specimens with length of 40–100 mm, influenced by layer width, aggregate size, and more [11], [12]. Anisotropy and porosity variations in all directions prompt testing 3D printed concrete specimens in three ways: perpendicular, longitudinal, and lateral (Fig. 6) [11], [12]. Zhanzhao and others [12], analyzed influencing factors on compressive strength like mixture composition, print quality, path, and force direction. Shape impact and fiber effects have been studied too. Yilmaz's study [20] assessed the impact of cement on compressive strength using molded samples and it was concluded that cement type has a significant influence on these concrete properties. Dey et al. [16] studied material extrusion and layer number. They showed that pumped samples have fewer voids and higher yield strength compared to mold-cast samples. Also, they noted that increasing of layer height gives lower strength. Pan et al. [7] investigated the influence of path, nozzle size, and speed on the properties of 3D printed concrete. Their main conclusion was that printing path affects fracture patterns while sample size minimally affects strength. Duan et al. [21] explored the addition of metakaolin and proved that metakaolin increases compressive strength and reduces shrinkage. Wolfs et al. [22] examined layer orientation, nozzle height and the effect of time intervals on bonding between layers. The yielding strength of samples was lover for printed ones compared to mold-cast samples. Le et al. [14] showcased high-strength concrete potential, achieving 91-102 MPa, and also straight-line samples had higher strength than curved ones.

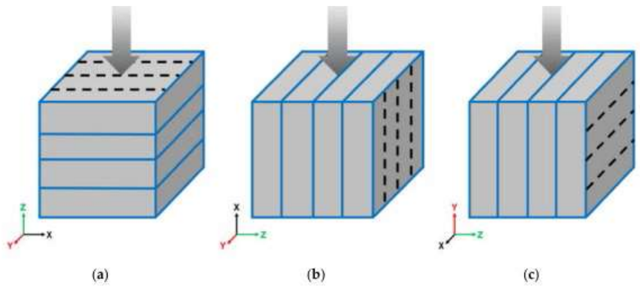

Fig. 6. Directions of applied force in compressive strength test: a) perpendicular, b) longitudinal and c) lateral [12]

The parameters that have influence on compressive strength also affect on flexural strength. Zhanzhao et al. [12] identified six loading directions for flexural strength testing due to anisotropy, aligning with literature recommendations for sample extraction and testing. However, some researchers only determine this property in two or three directions. Also, the sample extraction method from finished elements must consider the layered property. Yielding in perpendicular direction has higher values due to greater compaction in the lower layers. The incorporation of reinforcement in 3D printed concrete is still unsolved. The possibility of using steel and other fibers as reinforcement has been investigated. Yilmaz [20] used molded samples to determine flexural strength of concrete for 3D printing. It was concluded that cement type has significant influence on flexural strength. Dey et al. [16] have achieved the highest values in perpendicular directions and also get lower values for printed samples than molded samples. Rahul et al. [23] investigated concrete mixtures with different additives. They achieved higher longitudinal and perpendicular strengths than molded samples due to reduced porosity in stress areas. Le et al. [14] reported a flexural strength of 13 to 16 MPa for 3D printed samples taken from rectangular elements, higher than molded samples and with the lowest strength observed in lateral directions.

Interlayer bond strength is an important property for 3D printed concrete, because of layers [12], [24]. Widely used tests include axial tension, shear, and Brazilian (splitting) tests. Simplicity and consistency of splitting test make it popular, although the most precise assessment is through the axial tension test [25]. Zhanzhao et al. [12] reviewed factors impacting bond strength in 3D printed concrete. They found that the time gap between layers affects bond strength, and the longer gaps decrease bond strength. Lower printing head speeds or nozzle height increase bond strength, while higher strength is produced by an increased nozzle. Also, nozzle form has an influence on bond strength. Rectangular nozzles reduce voids and lead to larger contact areas between layers than circular nozzles. Viktor et al. [11] outlined bond strength testing guidelines. They considered different sample setups and dimensions, focusing on axial tension and shear tests. Bond strength is lower than layer material strength. Because of this, it is necessary to create a test method for determining interlayer bond strength. Panda et al. [15] studied 3D printed geopolymer bond strength using an axial tension test. Larger time gaps between layers provide lower bond strength, while lower printing speeds and nozzle height increased it. Hager et al. [25] explored the bond strength of a commercial mixture on finished element samples, using axial tension, shear, and splitting tests. The shear test had the highest value but the most variation.

3. EXPERIMENTAL INVENSTIGATION

3.1. Used materials and preparation of fresh mixture

For the printing of samples tested in this study, a fresh concrete mixture was made from a commercial ready-to-use premix called Sikacrete®-751 3D [26], manufactured by Sika. Sikacrete®-751 3D is a one-component micro-concrete specifically designed for 3D printing technology. The main components of this premix are Portland cement, aggregate, and specific chemical additives with the maximum grain size of 1 mm. To obtain a fresh concrete mixture, the premix should be mixed only with water.

The fresh concrete mixture was prepared according to the following recipe: 15 kilograms of the premix were placed into the mixer and dry-mixed for 30 seconds. Subsequently, water was gradually added over a period of 60 seconds. Two different water-binder ratios (0.15 and 0.17) were used for preparing a fresh mixture. Mixing continued for the next 240 seconds, during which the fresh mixture transformed from a dry to a plastic consistency, which is necessary for the 3D printing process. The total mixing time is 330 seconds, or 5.5 minutes.

3.2. The process of 3D printing

The first university 3D printer for concrete in Republic of Serbia [2] has been installed at the Faculty of Civil Engineering, University of Belgrade, in 2022 (Fig. 7). The printer is able to create specimens with maximal dimensions of 600x400x2500 mm. The printer head has a rectangular nozzle with dimensions 40x15 mm, and serves as the outlet for releasing the fresh concrete mixture, with movement along all three axes (X,Y, and Z) and with maximum speed of 6000 mm/min. After the mixing process, the fresh concrete mixture is placed in the loading hopper of the pump and then conveyed through the hose to the printer nozzle. For this purpose, the PFT Swing-M pump was used.

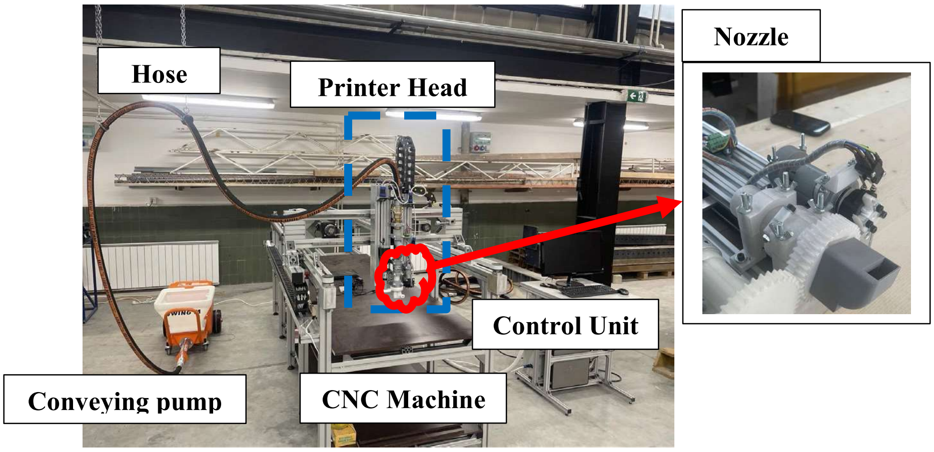

Fig. 7. The 3D concrete printer at Faculty of Civil Engineering University of Belgrade [2]

Traces of approximately 80 cm in length were printed from a fresh concrete mixture, with several layers in height (2, 3, 4, and 7). The printing head speed was set at 500 mm/min, while the pump pressure was maintained at 30 bar. This approach was used to assess the fresh properties, such as extrudability and buildability. The traces were cut to proper size, for making samples necessary for testing the properties in the hardened state.

3.3. The descriptions of samples

Mechanical testing was conducted on samples divided into two series:

Series 1 - Samples with a higher water-binder ratio (0.17) were obtained by surface treatment of the traces, as shown in Fig. 8 below. The samples were extracted from the central part of the trace, resulting in samples with flat and smooth surfaces like mold-cast samples and with full-notch removal between layers.

Series 2 - Samples with a lower water-binder ratio (0.15) were obtained by longitudinally cutting the printed trace. No surface treatment was applied to these samples and layers stayed visible, Fig. 9. This represents the behavior of these concretes with layering characteristics.

A total of 20 samples were used for both series.

Fig. 8. Sample from series 1 after surface treatment

Fig. 9. Sample from series 2 after cutting

3.4. Testing methods

The bulk density was determined for all samples from both series following the EN 12390-7:2019 [13]. Micro ruler was used to determine the average values of all dimensions (length, width, and height) for each sample, which were then used to calculate the sample volume and bulk density.

The compressive strength was determined on samples from series 1. Three samples were subjected to compressive forces applied perpendicular to the direction of the layers, while another three samples were tested with forces applied parallel to the layers (lateral direction). The testing was conducted in accordance with EN 12390-3:2014 [19] on an Amsler press with a capacity of 600 kN. The flexural strength of samples from series 1 was determined by three-point bending test. The testing was conducted following EN 1015-11:2008 [27] on an Amsler press with a capacity of 600 kN.

For testing interlayer bond strength, the following methods were used: axial tension test, shear test and splitting test. The testing of the bond strength using the axial tension method was conducted on samples from both series. The testing equipment was the Shimadzu AT-X universal testing machine with a capacity of 300 kN. Two samples from series 1 and four samples from series 2 were subjected to testing. Among the series, two samples had four layers, while the remaining two had six layers. To prepare the samples for testing, the treated surfaces were bonded to seals with an extension rod, which were then placed in the grips of the testing machine. The rate of force increase during testing was 190 N/sec for series 1 and 50 N/sec for series 2. The shear test for determining the bond strength was performed on samples from both series. However, different testing arrangements were used for each series, as described below:

1. For testing series 1, a specialized tool was used (Fig. 10). One part of the sample was fixed, while the other part was subjected to the force applied through a wedge on the press.

2. For testing series 2, the shear method was utilized, which involves shear between two layers (Fig. 11). For the sample with six layers, the upper surface at the middle layer position was leveled and smoothed to facilitate loading on the press.

Fig. 10. Fracture of samples from series 1 in shear test

Fig. 11. Fracture of samples from series 2 in shear test

Two samples from each series were tested. The testing was conducted on an Amsler press with a capacity of 600 kN. During the testing, the maximum force at which the sample fractured was measured, and the fracture pattern was observed to determine whether the fracture occurred at the bond interface or within the material. The testing of the bond strength using the splitting test method was conducted on samples from series 1. In this test, a smooth reinforcing rod with a diameter of 6 mm was placed on the joint of two layers, both on the top and bottom surfaces of the sample. The sample was then loaded on an Amsler press with a capacity of 600 kN.

4. TESTS RESULTS AND ANALYSIS

Specimen labels used in the tables below have the following meaning:

I – C – P(T) -6-1

- Number of sample: 1, 2, 3
- Number of layers: 4, 6
- Direction of applied force: Perpendicular (P), Lateral (L), or Test method for bond strength: Axial tension method (T), Shear method (SH), Splitting method (S)
- Type of test: Compressive strength (C), Flexural strength (F), Bond strength (B)
- Number of series: Series 1 – full-notch removal samples (I), Series 2 – printed samples (II)

4.1. Density of concrete

The values of bulk density in the hardened state for series 1 and series 2 are presented in Table 1. For each tested sample, the bulk density was individually calculated. The mean value was then determined based on the individual results.

Table 1. The bulk density of concrete in the hardened state for series 1 and series 2

Label	Width [mm]	Lenght [mm]	Height [mm]	Weight [kg]	Bulk Denstiy [kg/m³]
I-C-P-1	46.06	48.90	47.71	0.21	1954.65
I-C-P-2	43.60	48.76	50.27	0.21	1974.54
I-C-P-3	42.70	46.46	46.78	0.18	1929.00
I-C-L-1	44.18	53.08	49.44	0.23	1949.14
I-C-L-1	45.04	40.94	46.65	0.17	1953.71
I-C-L-1	43.75	47.48	44.37	0.19	2050.61
I-F-P-1	44.51	157.23	47.83	0.65	1930.18
I-F-P-2	47.43	155.54	46.36	0.67	1967.78
I-B-T-1	45.07	93.06	60.05	0.50	1977.54
I-B-T-2	44.07	88.43	59.52	0.45	1957.49
Average value for series 1:					**1964.46**
II-B-T-6-1	46.60	53.00	82.08	0.39	1918.89
II-B-T-6-2	46.58	51.01	83.60	0.37	1873.07
II-B-T-4-1	55.62	62.35	50.10	0.31	1761.53
II-B-T-4-2	45.52	59.11	53.30	0.26	1834.18
II-B-SH-6-1	47.68	70.27	80.06	0.53	1976.32
II-B-SH-6-2	48.36	72.37	79.66	0.50	1793.73
Average value for series 2:					**1859.62**

4.2. Compressive and flexural strength

The compressive strength values for the samples in series 1 are presented in Table 2. The results are shown for two directions: perpendicular to the layers (perpendicular direction) and parallel to the layers (lateral direction). The flexural strength values for the samples in series 1 are given in Table 3. The results are specifically provided only for the perpendicular direction of the layers.

Table 2. The compressive strength for samples from series 1

Label	Area [mm^2]	Ultimate Force Value [kN]	Strength [MPa]
I-C-P-1	2252.09	73.60	32.68
I-C-P-2	2125.94	52.20	24.55
I-C-P-3	1983.84	38.40	19.36
Average value for perpendicular direction:			**25.53**
I-C-L-1	2184.41	53.00	24.26
I-C-L-1	2100.89	56.00	26.66
I-C-L-1	1941.19	47.40	24.42
Average value for lateral direction:			**25.11**

Table 3. The flexural strength for samples from series 1

Label	Width [mm]	Lenght [mm]	Height [mm]	Span [mm]	Ultimate Force Value [kN]	Strength [MPa]
I-F-P-1	44.51	157.23	47.83	105.00	3.20	4.95
I-F-P-2	47.43	155.54	46.36	105.00	4.00	6.18
Average value for perpendicular direction:						**5.57**

4.3. Interlayer bond strength

The strength values of the bond between the layers, determined by using the axial tension test are presented in Table 4 below. The strength values are provided for series 1 samples and series 2 samples with four and six layers. Two samples were tested for each batch. The stress-strain curves for each tested sample can be seen in Fig. 12 below. The bond strength values between the layers, determined by the shear test and splitting test for the samples from series 1 and series 2 are provided in Table 5 and 6.

Table 4. The bond strength by axial tension test for samples from series 1 and series 2

Label	Width [mm]	Lenght [mm]	Height [mm]	Area [mm^2]	Ultimate Force Value [kN]	Strength [MPa]
I-B-T-1	45.07	93.06	60.05	4193.99	10.63	2.53
I-B-T-2	44.07	88.43	59.52	3896.67	10.30	2.64
Average value for bond strength determined for series 1:						**2.59**
II-B-T-6-1	46.60	53.00	82.08	2469.80	5.83	2.36
II-B-T-6-1	46.58	51.01	83.60	2375.79	3.64	1.53
Average value for bond strength determined for Series 2 (six layers):						**1.95**
II-B-T-4-1	55.62	62.35	50.10	3467.32	6.45	1.86
II-B-T-4-1	45.52	59.11	53.30	2690.46	3.56	1.32
Average value for bond strength determined for series 2 (four layers):						**1.59**

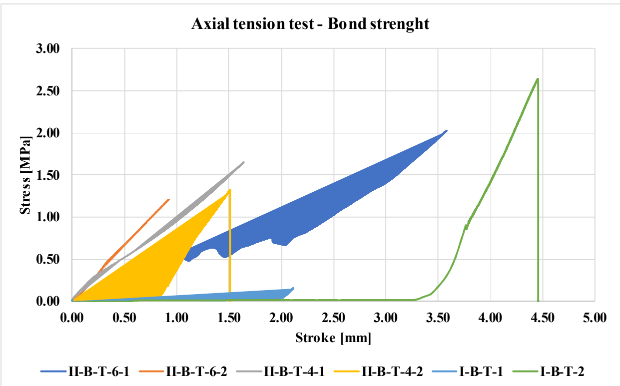

Fig. 12. Stress-Strain Curves

Table 5. The bond strength by shear test for samples from series 1 and series 2

Label	Width [mm]	Lenght [mm]	Height [mm]	Area [mm^2]	Ultimate Force Value [kN]	Strength [MPa]
I-B-SH-1	45.00	87.50	48.00	4200.00	16.20	3.86
I-B-SH-2	45.00	70.00	48.00	3360.00	6.60	1.96
Average value for bond strength determined by the shear test for series 1:						**2.91**
II-B-SH-1	47.68	70.27	80.06	3349.88	11.00	3.28
II-B-SH-2	48.36	72.37	79.66	3499.45	8.80	2.51
Average value for bond strength determined by the shear test for series 2:						**2.90**

Table 6. The bond strength by splitting test for samples from series 1

Label	Width [mm]	Lenght [mm]	Height [mm]	Area [mm^2]	Ultimate Force Value [kN]	Strength [MPa]
I-F-P-1	45.00	87.50	45.00	3937.50	16.20	2.62
I-F-P-2	45.00	65.00	48.00	2925.00	10.00	2.18
Average value for bond strength determined by the splitting test:						**2.40**

5. DISCUSSION

Series 1 samples exhibit similar bulk density values, indicating low variation of results compared to series 2 samples, which show a larger range of values due to surface roughness caused by layering. Due to the smaller voids between the layers and therefore better compactness, samples for series 1 have a higher volumetric mass and bulk density.

Compressive strength test showed that perpendicular direction of force application causes a greater variation in results than lateral direction of force application. A possible reason is a minor damage on samples, which occurred during the its preparation. The fracture pattern (Fig. 13), is similar to the mold-cast samples. By comparing the average values, it can be shown that the material is homogeneous and that layering has a small influence on the compressive strength. The flexural strength testing demonstrated that the full-notch removal samples exhibit behavior similar to samples cast in a mold. Also, the layering doesn't have a significant influence on the results. Fracture occurred at the location of the applied force (Fig. 14), without any delamination or damage to the layers. The similar strength values indicate minimal variation in the results. Additionally, due to larger sample dimensions, higher precision in sample preparation was achieved, reducing the impact of sample quality on the results.

Fig. 13. Fracture of sample in compressive strength test

Fig. 14. Fracture of sample in flexural strength test

For series 1, there was no significant difference in bond strength values. The stress-strain curves from the axial tension test displayed some variation between the curves due to different loading rates. (Fig. 12). However, the low variation in value suggests that the loading rate does not significantly affect the bond strength. Fracture patterns (Fig. 15) indicated that in both samples, the fracture occurred more within the material than at the bond, which indicates material homogeneity and the lower influence of layering on bond strength. For series 2, the results showed cases where fracture occurred through the layer and at the bond between layers. Fracture at the bond (Fig. 16) was associated with defects in the bond or the layer itself, leading to higher variation in the results. By pairing the values based on fracture patterns, the bond strength for series 2 was estimated to be 1.43 MPa with a standard deviation of 0.10 MPa, while the tensile strength of the material was estimated to be 2.11 MPa with a standard deviation of 0.25 MPa. Comparing these values with the bond strength of series 1, it can be concluded that the full-notch removal samples exhibited higher strength compared to the printed samples. This is expected due to the fact that series 2 had rough connection between layers. Additionally, series 2 had a lower water-binder ratio, resulting in less fine cement paste for bond filling and reduced homogeneity.

Fig. 15. Fracture of sample from series 1 in axial tension test

Fig. 16. Fracture of sample from series 2 in axial tension test

For series 1, the applied method for determining interlayer bond strength is unsuitable for this material, which can be seen in the fracture occurring at location that were not expected (Fig. 10), resulting in significant variation in results. The obtained values for both samples from series 2 were approximately similar. Despite the challenges in comparing results due to different test configurations and factors, both series showed the same bond strength value of 2.90 MPa. The testing of the interlayer bond strength using the splitting test showed similar values for both samples, indicating low variability in the results, as supported by the standard deviation value of 0.22 MPa. The average bond strength obtained is 2.40 MPa, which refers to the relationships between strengths according to Eurocode 2 [28] for ordinary cementitious concretes. It is approximately 10 times lower than the compressive strength and 10% higher than the axial tensile strength. The fracture pattern of the sample demonstrates that the crack opened precisely at the location of the applied force, which is the area between two layers. It was an asymmetric fracture pattern (Fig. 17 and 18), indicating that the fracture did not occur purely along the layers but also affected material from both sides with good homogeneity and connection between the layers.

Fig. 17. Fracture of sample in splitting test

Fig. 18. The segments of the samples after reaching the ultimate load

6. CONCLUSSIONS AND DIRECTIONS FOR FURTHER RESEARCH

Based on a review of literature and provided experimental research, the following significant conclusions can be drawn:

1. Currently, specific standards and regulations for testing the fundamental properties of 3D printed concrete are lacking. However, this study successfully applied the testing methods used for conventional concrete to this new type of concrete. The choice of sample type and shape, including samples cast in molds and extracted from 3D printed layers with and without processing, must be considered to gain a comprehensive understanding of these properties and the impact of layering. The application of standardized testing methods and regulations will further enhance the development and implementation of 3D printed concrete in practical applications.
2. Printing procedure that includes printing speed, nozzle shape, height and preassure has a significant influence on the mechanical properties of 3D printed concrete. It was shown that samples printed with better quality achieved higher mechanical properties than molded samples.

3. Samples from series 1 exhibit smaller voids between the layers and greater compactness compared to series 2. Therefore, higher bulk density with low variation of results was obtained - 1964.46 kg/m^3 for series 1 compared to 1859.62 kg/m^3 as a mean value for series 2.
4. The compressive strength test showed that the material is homogeneous and that layering has a small influence on the strength. Similar values of strength were achieved for both considered directions (about 25 MPa), but with a higher variation of result in the perpendicular than the lateral direction. The fracture pattern is similar to the mold-cast samples.
5. The full-notch removal samples from series 1 behave like mold-casted samples. In this case, the layering doesn't have a significant influence on the results because of the homogeneity of the material and the good connection between the layers. It was obtained a value of 5.57 MPa for flexural strength with low variation of results.
6. The highest value of 2.91 was obtained in the shear test with the note that in both series 1 and series 2, the fracture did not occur at the bond, but within the material. The lowest value of 1.59 was obtained in the axial tensile test, which can be considered the realistic value of bond strength. Based on these conclusions, the splitting method can be recommended as the best choice for testing the bond strength between layers.
7. The material used for printing exhibited a bulk density of approximately 1980 kg/m^3, a compressive strength of 25 MPa regardless of layer orientation, a tensile strength of 2.1 MPa, and a flexural strength of 5.50 MPa. The bond strength between layers was found to be 1.43 MPa. Full-notch removal samples from series 1 closely resembled samples cast in molds, demonstrating high material homogeneity and bond quality between layers. On the other hand, printed samples from series 2 exhibited potentially new fracture points due to layer defects or bond issues. High bond quality resulted in fractures that occurred within the layer material, further confirming the homogeneity of concrete mixture.

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