

Research Article

Durability and Cracking Defects in 3D-Printed Concrete

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This article explores the durability and cracking defects associated with 3D-printed concrete, a rapidly emerging technology in construction. As the demand for innovative building techniques grows, understanding the long-term performance of 3D-printed structures becomes crucial. The most important properties of these products are the resistance to freezing and thawing and the possibility of cracking during maintenance. A fine-grained concrete mixture with expanded perlite additive was tested on strength, freezing–thawing resistance, and the reasons for cracking were analyzed during maintenance. Some differences between the results from standard concrete specimens and the results from 3D-printed concrete were obtained experimentally. During the research, 3D-printed concrete specimens were produced with industrial equipment, the density and compressive strength were determined, the mass loss of concrete specimens after freeze/thaw cycles was tested. By reducing the water-to-cement ratio to 11%, the strength of concrete with expanded perlite additive increased from 68.2 to 71.1 MPa. For concrete with W/C equal to 0.47 after 28 freeze/thaw cycles, the mass loss of 3D-printed specimens reaches 2.09 and 56 freeze/thaw cycles 9.17 kg/m², and large surface defects were obtained. An analysis of the origin and recommendations for preventing cracks from occurring in 3D-printed products were carried out. The findings underscore the need for optimized mix designs and printing parameters to enhance durability.

Keywords: 3D printing; compressive strength; concrete; cracking; density; freezing–thawing resistance; perlite

1. Introduction

3D concrete printing (3DCP) is a highly flexible, automated, and ecologically friendly technology. It has significant benefits in the construction of street furniture, infrastructure, and buildings and in the construction of low-rise and remote-area infrastructure.

3DCP in construction can have a positive environmental impact by using low-embodied energy raw materials, such as construction and industrial waste. Compared to traditional construction methods, 3D printing can help minimize material waste and dust generated during the building erection process. Mierzwiński et al. [1] explored the growing use of 3D printing in the construction industry, highlighting its

benefits such as reduced labor costs and waste, while noting the need for further development and optimization based on case studies and literature analysis. This can contribute to a cleaner and more efficient construction process [2–4]. The progress of 3D-printed concrete regarding workability, mechanical properties, and building plan design is being reviewed to optimize its practical applications [5].

Researchers and manufacturers are exploring ways to optimize the fresh-state properties of concrete to make it suitable for printing. This includes the use of fine aggregates, testing of fiber reinforcements, and the incorporation of shrinkage-reducing admixtures to enhance printability and prevent cracking [6, 7]. It is also important to remember that the extrusion-based 3D printing process presents 3D printing

technology that has the potential to reduce construction materials by up to 60%, construction time by 50%–70%, and labor costs by 50%–80% [6]. Researchers [8] compared the properties of 3D-printed samples with those made on a vibrating platform. Experimental results demonstrated that the potential under compaction of fine-grained mixtures produced via 3D printing, and the associated reduction in properties, can be offset by incorporating hardening activators and superplasticizer additives.

The rheological properties of concrete play a crucial role in the printing process. Managing the change in viscosity of the material during printing is essential to ensure proper extrusion and layer deposition [9, 10]. The researchers investigated the influence of different water–cement ratios on the fresh behavior of cement paste and rheology parameters to describe the strength parameters of cement mortar [11]. Different aggregate-to-binder content can influence the flow conditions of concrete pumping. Plastic viscosity and yield stress parameters were observed with an increase in aggregate volume fraction [12].

Another critical parameter of 3D printing quality is the investigation of freezing–thawing resistance and shrinkage on concrete properties. Assaad, Hamzeh, and Hamad [13] evaluated the bond strength between layers by subjecting the 3DCP specimens to multiple freeze/thaw cycles. This allowed it to be possible to assess the durability and performance characteristics of materials under difficult conditions [13]. Spurina et al. [14] carried out an experiment exposing 3DCP to freeze/thaw cycles, which allowed the determination of the mass loss of each sample after freeze/thaw cycles.

Researchers investigated the influence of thinner and thicker filaments on the cracking of 3D-printed elements with different cross-sectional layers. They found that thin filament-printed concrete elements crack during concrete shrinkage [15, 16]. Moelich, Kruger, and Combrinck [16] developed a novel experimental method to determine plastic shrinkage cracking with which they were able to evaluate the free shrinkage of 3DPC samples.

The article presents a novel study on how the freeze/thaw cycles affect printed concrete samples, compared to cast samples of the same concrete mix, and the influence of various factors on the shrinkage and cracking of printed concrete. The research innovatively uses various antievaporation agents, including paraffin, siloxane, and acrylates, in order to reduce cracking and improve the concrete's resistance to environmental stress. Additionally, the study reveals the specific shrinkage characteristics of 3D-printed concrete and offers new insights into preventing cracks in printed structures by analyzing water-to-cement ratios and the role of mineral additives in detail.

2. Materials and Methods

2.1. Materials

2.1.1. Cement. Cement CEM I 42.5 R confirming the requirements of EN 197-1 was used as a binder for 3D-printed concrete mixture. The physical and mechanical properties of cement are presented in Table 1.

TABLE 1: Physical and mechanical properties of cement.

Property	Value
2-day compressive strength (MPa)	35
28-day compressive strength (MPa)	55
Fineness by Blaine (m^2/kg)	490

2.1.2. Fine Aggregate and Mineral Additives. Sand with a fraction of 0/2 and a fineness modulus of 2.6 was used as a fine aggregate. The sand confirms the requirements of the EN 12620 standard.

Expanded perlite with a particle-specific density of 1.1 g/cm^3 was used as a mineral additive for 3D-printed concrete. The chemical composition of perlite is presented in Table 2.

The aim of applying perlite in mortar is to reduce the shrinkage and cracking of 3D-printed concrete as it cures. Its porous structure absorbs water, leading to more controlled water release during curing, which can help reduce the internal stresses that cause cracks.

The granulometric composition of sand, perlite, and cement is presented in Figure 1.

The density of compacted concrete under air-dry conditions and its compressive strength were tested by forming samples in the laboratory using 3D printing technology. The composition of concrete mixtures is presented in Table 3.

2.2. Testing Methods

2.2.1. Mixing Procedure. The mixing of the concrete mixture for the formation of samples began with the dosing and mixing dry components (sand, cement, and mineral additives) in a forced-type concrete mixer (mortar) with a capacity of about 50 l for about 5 min. This was followed by adding water with a superplasticizer, followed by the rest of the water with an accelerator and liquid glass. Mixing of all components was continued for another 2 min. The mixed concrete (mortar) is unloaded into a 12-l plastic container.

2.2.2. Sample Forming and Curing Procedure. After about 15 min, the mixed concrete (mortar) was formed into plywood panel molds $100 \times 100 \times 100 \text{ mm}$ using a cylindrical construction mortar syringe with a nozzle of about 2 cm in diameter (Figure 2). After filling the mold with a pile, the plywood panel mold was easily rolled onto the floor for uniform distribution of the concrete mixture throughout the entire volume of the mold by analogy with the production tests with the technological equipment in the factory.

Concrete samples formed were taken out of molds on the second day and hardened for 27 days in 20°C – 2°C water (in standard conditions).

2.2.3. Printing Technology for 3D Concrete Products. Printing products from concrete mortar using a 3D printer within a factory setting involves several sequential steps. First, a suitable mortar mix is formulated for optimal layer deposition, and then loaded into the printer's material reservoir. A digital model is created using CAD software and processed through slicing software to set parameters like layer height and extrusion rate. The 3D printer deposits the mortar layer

TABLE 2: Chemical composition of the active mineral additive (perlite).

Components	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	TiO ₂
Perlite (%)	70–75	12–15	0.5–2	0.5–1.5	0.2–0.7	3–4	3–5	—

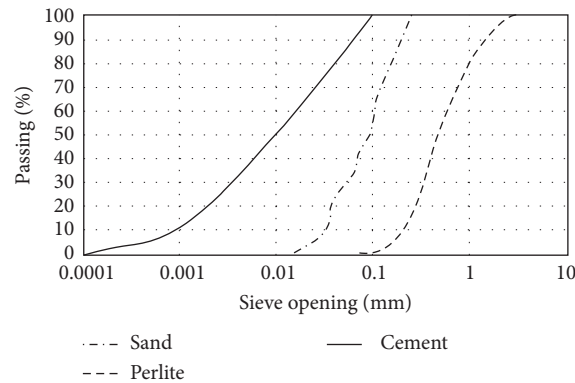


FIGURE 1: Granulometric composition of sand, perlite, and cement.

TABLE 3: 3D-printed concrete composition (with perlite), kg/m³.

Specimen number	Cement (kg)	Perlite (kg)	Sand (kg)	Water (kg)	Superplasticizer (kg)	Liquid glass (kg)	Accelerator (kg)	W/C
S1	660	88	1034	308	10.56	2.20	6.60	0.47
S2	740	60	930	308	11.1	2.20	6.60	0.42



FIGURE 2: Concrete (mortar) samples forming.

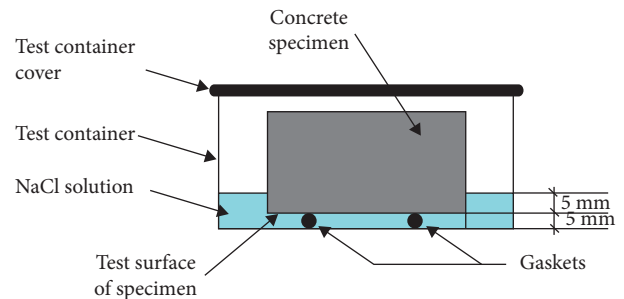


FIGURE 3: Freezing/thawing testing of concrete (mortar) samples.

by layer, allowing each to cure before applying the next to ensure adhesion and structural integrity. Environmental controls, such as temperature and humidity, are maintained to optimize curing and minimize defects.

2.2.4. Hardened Concrete Tests. Standard test methods were used to determine the density and compressive strength of the formed and hardened concrete samples. Five samples were tested from each composition (S1 and S2) for compressive strength evaluation, while three samples from composition S1 were utilized for assessing freezing–thawing resistance. Concrete density was determined according to EN 12390-7 and compressive strength according to EN 12390-3.

The freezing–thawing resistance test of hardened specimens was carried out according to the methodology of the modified standard CEN/TS 12390–9 CDF method. According

to CEN/TS 12390-9, the surface scaling of CDF is evaluated. The main idea of the test is to determine the amount of scaled material after exposing the concrete surface to 56 freeze/thaw cycles, where the tested concrete surface should be in contact with a 3% NaCl solution. The testing procedure begins by cutting the concrete cubes in half and using the sawn surface to come into contact with 3% NaCl solution. For each specimen (half concrete cube), a 5 mm thickness of 3% NaCl solution should be placed in contact with the testing surface and placed in the freezer to start the freeze/thaw cycles, as shown in Figure 3. Each freeze/thaw cycle includes 6 h of cooling, 6 h of freezing at -20°C , 6 h of thawing, and 6 h at $+20^{\circ}\text{C}$ (Figure 4). After a specified number of freeze/thaw cycles, up to 56 cycles, the scaled material is collected from the tested surface and weighed, the higher the weight, the higher the scaling [17].

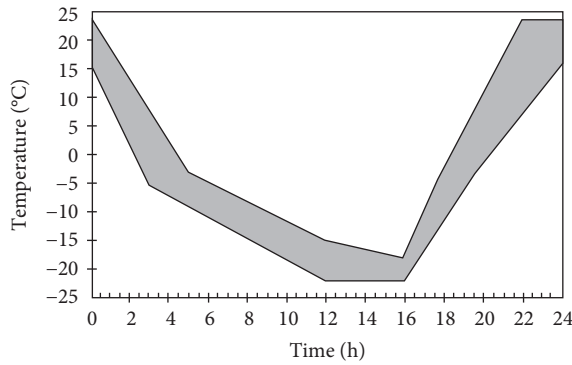


FIGURE 4: Temperature range for freezing/thawing resistance.

TABLE 4: Density and compressive strength of 3D-printed concrete.

Specimen number	Density (kg/m ³)	Compressive strength (MPa)
S1	2116	68.2
S2	2197	71.1

The weights of the specimens were recorded before and after the test. The mass loss of the samples was determined after 7, 14, 21, 28, 38, 48, and 56 cycles.

For each specimen calculation, the cumulative amount of scaled material per unit area after n cycles S_n , in kilograms per square meter, was calculated by the following equation:

$$S_n = \frac{m_{s,n}}{A} \cdot 10^3, \quad (1)$$

where S_n is the mass of the scaled material related to the test surface after the n cycle in kg/m²; $m_{s,n}$ is the cumulative mass of dried scaled material after the n freeze/thaw cycle; and A is the total area of the test surface, calculated from the length measurements rounded to the nearest 100 mm².

The mean value and the individual values for each specimen after 56 cycles are used to evaluate the scaling resistance.

3. Results and Discussion

3.1. Density and Compressive Strength of Hardened Concrete. The density of hardened concrete (air-dry conditions) and the compressive strength of concrete were tested by forming samples in the laboratory according to the 3D printing technology, as described in Section 2.2.1. The composition of concrete is given in Table 3.

The test results for the density and compressive strength of 3D-printed concrete after 28 days of curing under standard conditions are given in Table 4.

The results obtained show that the density of concrete with the addition of expanded perlite in the dry state ranges from 2166 to 2197 kg/m³. The results obtained are analogous to the concrete density results obtained during 3D printing production tests.

The compressive strength of concrete after 28 days of curing under standard conditions ranges from 68.2 to

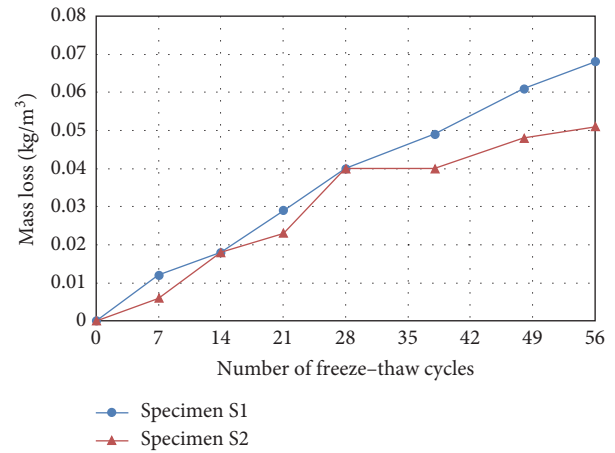


FIGURE 5: Mass loss of concrete molded specimens after 56 freeze/thaw cycles.

71.1 MPa depending on the W/C ratio and is suitable for manufacturing structural and decorative products. The results obtained are analogous to those previously obtained for the compressive strength of concrete during production tests.

3.2. Freezing–Thawing Resistance Test. The results of the concrete freezing–thawing resistance (mass loss from the test surface) after 56 cycles are presented in Figure 5. The deterioration of the concrete surface was determined by a view of the surface tested after the freeze/thaw cycles presented in Figure 5.

In Figure 4, we can see that the resistance to freezing–thawing of concrete (mass loss from the test surface) after 56 cycles is 0.07 kg/m² for concrete with W/C equal to 0.47 and 0.05 kg/m² for concrete with W/C equal to 0.42. The tested surface of the concrete is in good condition with small defects which are presented in Figure 6.

As we can see in Figure 7, the mass loss from the test surface of 3D-printed specimens after 28 and 56 cycles for concrete with W/C equal to 0.47 after 28 freeze/thaw cycles, the mass loss of 3D-printed specimens reached 2.09 and 56 freeze/thaw cycles 9.17 kg/m².

Figure 8 shows the appearance of 3D-printed specimens after 56 freeze/thaw cycles. The tested surface of 3D-printed specimens after 56 freeze/thaw cycles is destroyed, especially the corners of the specimens.

Compared to molded concrete mass loss and surface defects (Figure 5), the 3D-printed specimens have higher values of mass loss and larger surface defects (Figure 7).

Several studies have attempted to quantify the durability of 3D-printed concrete. Nodehi et al. [18] conducted accelerated aging tests to evaluate the long-term performance of 3D-printed structures under various environmental conditions. Their findings indicated that while 3D-printed concrete exhibits promising initial strength, it is susceptible to environmental degradation over time. This is echoed in the research of El Inaty, Baz, and Aouad [19], who emphasized the need for durability-focused design parameters specific to 3D printing technologies.

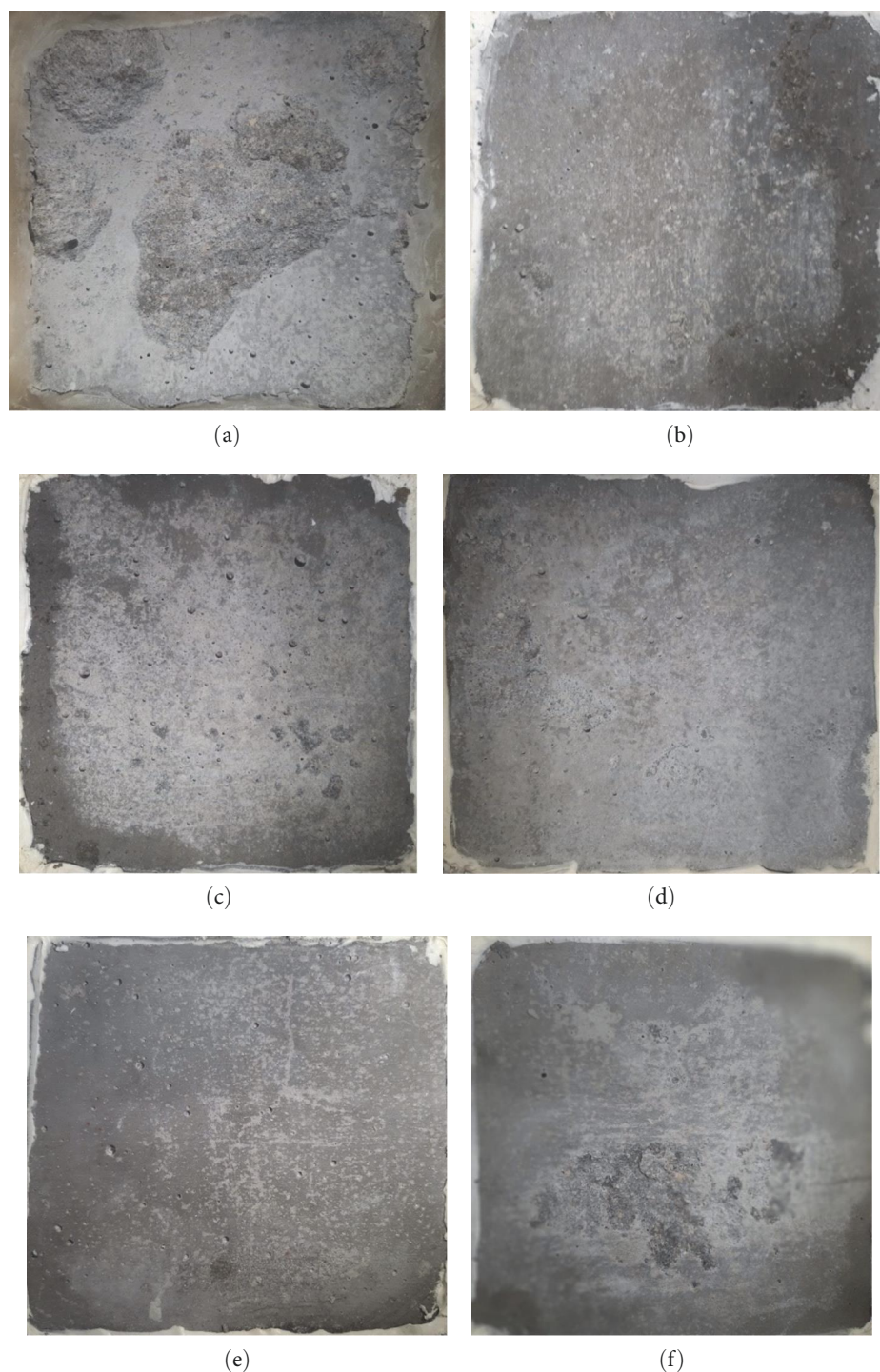


FIGURE 6: The surface of hardened concrete mortar cubes modified with perlite after 56 cycles of freeze-thaw: (a–c) specimens S1; (d–f) specimens S2.

3.3. Analysis of the Origin of Cracks in Products and Recommendations for Prevention. Cracks in a larger length 3D-printed product occur in a newly formed layer when a new layer is formed on a rough (concrete, wooden, previously formed layer, or other) substrate (Figure 9). A new product can be formed only on a sliding surface, for example, on a clean polyethylene film. Do not extend the formation of

the product (larger dimensions) on the hardened layer of the product, especially after a longer break.

To solve the problem of cracking 3D-printed concrete units, it is recommended to cover (spray) the entire surface of the product, both from the outside and from the inside, with a paraffin, siloxane, or acrylates-based water antievaporation agent after forming the product. Some materials that inhibit water

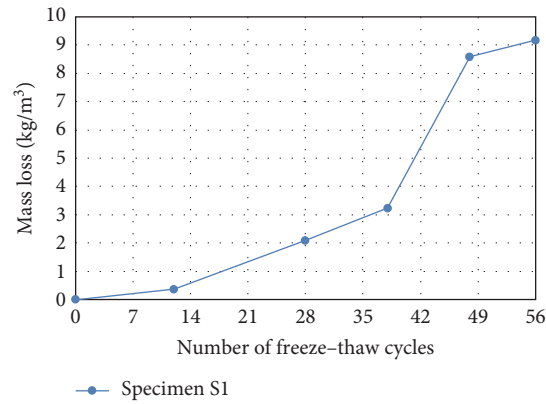


FIGURE 7: Mass loss of 3D printed concrete specimens after 56 freeze/thaw cycles.

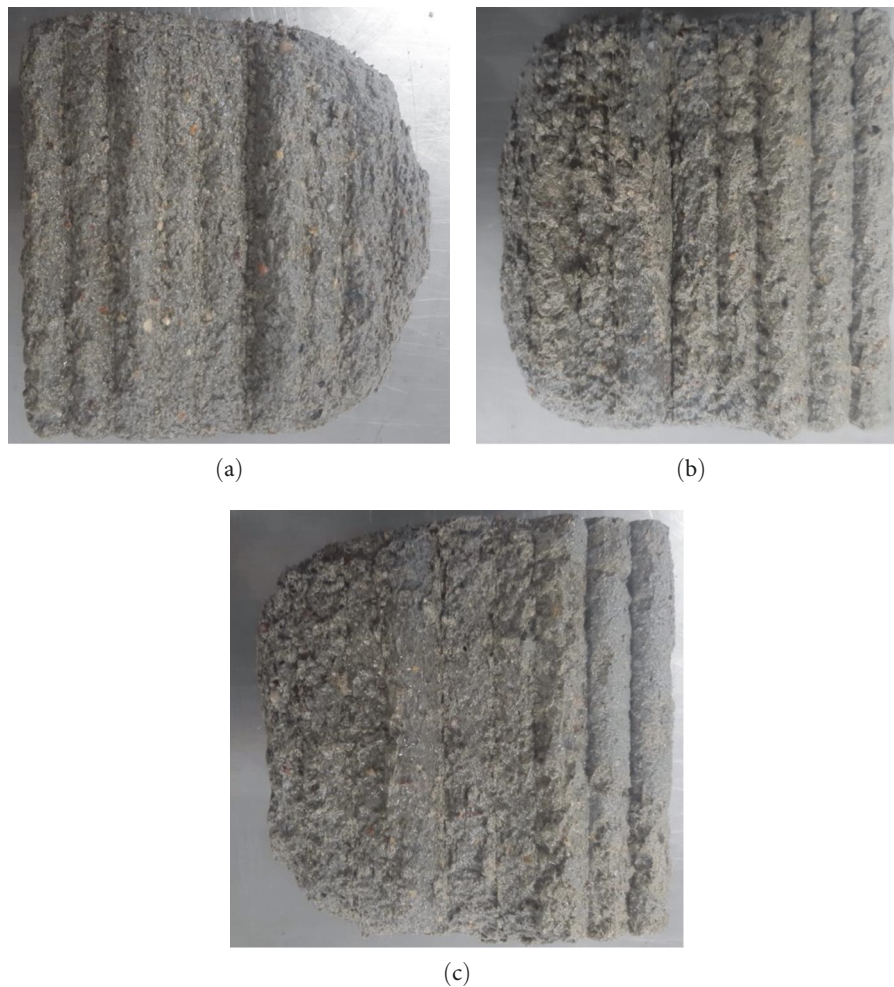


FIGURE 8: The surface of hardened concrete product modified with perlite after 56 freeze/thaw cycles: (a)–(c) specimen S1.

evaporation from concrete can change the surface of concrete (whiten, cause staining). Therefore, before using such materials to cover finishing surfaces, they should be tested.

3D molded products in round or spherical profile units with a poured concrete bottom (Figure 8), continuous vertical cracks appear on the surface, which can only be found in

the lower part of the product (Figure 9). The reasons for the appearance of such cracks are as follows:

- a. Significantly higher water content in the concrete mixture used for 3D printing (about 300l of water per 1 m^3 of concrete mixture) than in the bottom concrete



FIGURE 9: Cracking results of concrete products 3D printed. (a) Continuous slit in a product with a round cross-section with a bottom. (b) Continuous slit (in the lower part) in a hollow product with a bottom.

mixture of the product (about 200 l of water per 1 m³ of concrete mixture).

- b. Rapid evaporation of water on both sides of the walls of the 3D-printed unit.
- c. Approximately three times the longitudinal shrinkage of the unit walls (wall length) than the radial shrinkage of the unit bottom (diameter of the concrete bottom).

These circumstances cause a sudden rupture of the product wall when the tensile strength of the concrete exceeds the tensile strength of the concrete under circumstances that cause intense evaporation of water from the concrete. Such circumstances can include placing the product in the sun and wind, especially after the product is intensively wet during rain.

Cracking in 3D-printed concrete can arise from several mechanisms, including thermal shrinkage, hydration stresses, and improper layer adhesion. According to Shahmirzadi et al. [20], thermal gradients during the curing process can lead to differential shrinkage, which is a primary cause of early-age cracking. Their findings align with those of Fu et al. [21], who emphasized the need for controlled curing environments to mitigate such effects. The relationship between the layer thickness and print speed is also crucial. Huang et al. [22] noted that adjusting these parameters can influence the occurrence of cracking significantly.

During 3D printing, many types of shrinkage (drying, autogenous, chemical, and plastic) act on the concrete mixture, since the structure is thin-walled and under the influence of gravity from its own weight. As moisture evaporates, the volume shrinks concrete. Drying occurs most rapidly near the surface due to the short distance the water must travel to escape and more slowly from the interior of the concrete due to the increased distance from the surface. The shortening per unit length associated with the reduction in volume due to moisture loss is termed shrinkage. A nearly linear relationship exists between the magnitude of the shrinkage and the water content in the mixture for a particular value of relative humidity.

4. Conclusions

According to the experimental results, the following conclusions can be drawn:

1. 3D-printed concrete with a W/C ratio from 0.47 to 0.42 and an expanded perlite additive can achieve compressive strength up to 70 MPa with a density of 2150–2200 kg/m³.
2. The freezing–thawing resistance of 3D-printed and tested concrete using standard methodology can be achieved up to about 0.05–0.07 kg/m² scaling value after 56 freeze/thaw cycles with only small defects on the concrete surface.
3. For concrete with W/C equal to 0.47 after 28 freeze/thaw cycles, the mass loss of 3D-printed specimens reaches 2.09 and 56 freeze/thaw cycles 9.17 kg/m². Therefore, a new specialized methodology must be developed for 3D-printed concrete.
4. 3D molded products in round or spherical profile units with a poured concrete bottom continuous vertical crack appear on the surface due to significantly higher water content in the concrete mixture used for 3D printing, rapid evaporation of water on both sides of the walls of the 3D-printed unit and about three times more the longitudinal shrinkage of the unit walls than the radial shrinkage of the unit bottom.

Data Availability Statement

Data are available upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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