

3D CONCRETE PRINTING: A STUDY OF PRINTED STRUCTURES DURABILITY

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Abstract: The article presents the results of an experimental study of the influence of technological parameters of construction 3D concrete printing (3DCP) on the durability of printed elements of building structures during accelerated model aging in a climatic chamber. The aim of the work was to study the patterns of degradation of multilayer concrete samples printed on a construction 3D printer in various ways (with and without layer bonding, as well as with cold joint modeling) under cyclic climatic influences. For the experiments, an industrially produced composition of the material for additive construction production 3D4Art was used, applied by a workshop construction 3D printer of a portal design. The control group consisted of monolithic samples of similar geometry. The study included a comparative analysis of the degradation kinetics and mechanisms of destruction of samples during 100 cycles of combined exposure to freezing thawing with humidification. The results demonstrate that while maintaining the overall structural integrity of all samples, 3D printed elements exhibit an increased tendency to crack formation in the areas of interlayer contacts, which is especially pronounced in the case of technological defects (cold seam). The obtained data emphasizes the need for further research into the influence of technologically conditioned defects on changes in the mechanical properties of structural elements during aging. The results of the work are of practical importance for optimizing the technological modes of construction 3D printing to increase the durability of erected structures.

Keywords: 3D concrete printing, additive construction production, durability, interlayer adhesion

АДДИТИВНОЕ СТРОИТЕЛЬНОЕ ПРОИЗВОДСТВО: ИССЛЕДОВАНИЕ ДОЛГОВЕЧНОСТИ НАПЕЧАТАННЫХ КОНСТРУКЦИЙ

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Аннотация: В статье представлены результаты экспериментального исследования влияния технологических параметров строительной 3D-печати бетоном (3DCP) на долговечность напечатанных элементов строительных конструкций при ускоренном модельном старении в климатической камере. Целью работы являлось изучение закономерностей деградации многослойных бетонных образцов, напечатанных на строительном 3D-принтере различными способами (с перевязкой и без перевязки слоев, а также с моделированием холодного шва), в условиях циклических климатических воздействий. Для экспериментов использовался промышленно производимый состав материала для аддитивного строительного производства 3D4Art, наносимый цеховым строительным 3D-принтером порталной конструкции. Контрольную группу составили монолитные образцы схожей геометрии.

В ходе исследования проведен сравнительный анализ кинетики деградации и механизмов разрушения образцов в течение 100 циклов комбинированного воздействия замораживания-оттаивания с увлажнением. Результаты демонстрируют, что при сохранении общей структурной целостности всех образцов, 3D-печатные элементы проявляют повышенную склонность к трещинообразованию в зонах межслоевых контактов, особенно выраженную в случае наличия технологических дефектов (холодный шов). Полученные данные подчеркивают необходимость дальнейших исследований влияния технологически обусловленных дефектов на изменение механических свойств конструктивных элементов в процессе старения. Результаты работы имеют практическое значение для оптимизации технологических режимов строительной 3D-печати с целью повышения долговечности возводимых конструкций.

Ключевые слова: 3D печать бетоном, аддитивное строительное производство, долговечность, межслойная адгезия

INTRODUCTION

Recently, more and more attention has been paid to issues of additive construction production, both in Russia and abroad. Thus, for the keyword combination 3D concrete printing in the international Scopus database, 3482 results are available for all time as of June 2025 (sample 1), for the phrase concrete printing - 3916 publications (sample 2). At the same time, not many publications are devoted to durability issues (the complex of words 3D concrete printing + durability was selected to assess the state) (sample 3) - Figure 1.

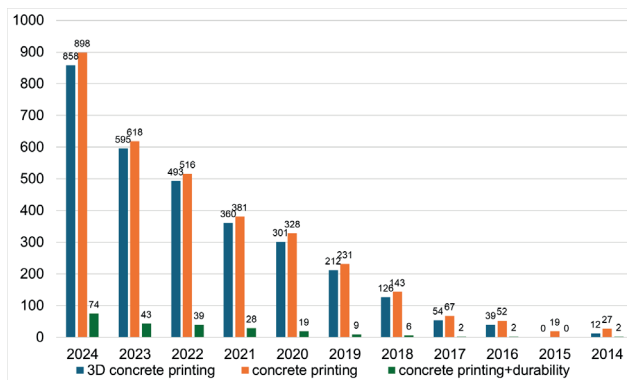


Figure 1. Dynamics of distribution of publications by keywords

The analysis of sample 3 allowed us to conclude that additive construction production or 3D concrete printing is actively developing, but requires solving the problems of interlayer adhesion, anisotropy of mechanical properties and durability. At the same time, considerable attention is paid to sustainable development using 3D concrete printing [1-15], problems of interlayer adhesion [16-25], and issues of anisotropy [26-29]. There are separate publications that pay attention to the durability of printing using geopolymer composites [30-32], but there are no issues of studying durability depending on the printing method yet.

The relevance of studying the durability of 3D concrete printing structures is due to the rapid development of this area in the modern construction industry and the need for scientific justification of

their operational reliability. In recent years, 3D concrete printing (3DCP) technology has demonstrated significant potential for transforming traditional approaches to the construction of buildings and structures, offering such advantages as reduced construction times, reduced waste, and design flexibility, which makes it possible to create complex architectural and space-planning forms. However, the widespread adoption of this technology is hampered by insufficient study of the long-term behavior of printed structures in real operating conditions, especially when exposed to aggressive environmental factors. Of particular importance is the study of interlayer adhesion as a critical factor determining the mechanical characteristics and durability of structures. The durability of structures made of fine-grained concrete, which includes materials for 3DCP, is generally beyond doubt, but it is in the contact zones between successively applied layers that stresses can concentrate and potential destruction sites can form. The existing shortage of experimental data on the behavior of 3DCP structures under cyclic temperature and humidity exposure, typical for cold climate zones, requires comprehensive studies aimed at establishing a correlation between the technological parameters of printing, the structural features of the material and its resistance to external influences during operation. Obtaining such data is important both for improving the additive construction technology itself and for developing a regulatory framework governing the operation of structures manufactured using this technology. In this regard, the purpose of this study is to investigate the effect of the printing method of multilayer products and structures on the nature of degradation under conditions of accelerated model aging.

MATERIALS AND METHODS

The experimental part of the study was carried out using the material for additive construction production 3D4Art. The main physical and mechanical characteristics of the material used were de-

terminated based on the Research Institute of Construction Materials and Technologies of the National Research University Moscow State University of Civil Engineering, considering the requirements of GOST R 59096-2020. The results of standard material tests are presented in Table 1.

Table 1. Results of testing a batch of material used for additive construction production

№	Name of the indicator	Unit of measurement	Test method	Test result
1	Humidity	%	GOST 8735-88 p. 10	0,29
2	Grain size (largest size of filler grains)	MM	GOST 8735-88 p. 3	5
3	Grain size (content of grains of the largest size)	%	GOST 8735-88 p. 3	0,03
4	Bulk density	кг/м ³	GOST 8735-88 p. 9.3	1382,23
5	Mobility by cone flow	MM	GOST R 58277-2018 p. 5	135
6	Water holding capacity	%	GOST R 58277-2018 p. 6	98
7	Start of setting	min	GOST 30744-2001, p. 6	100
8	End of setting	min	GOST 30744-2001, p. 6	110
9	Bending strength	MPa	GOST 310.4-81 p. 2.2	4,1
10	Compressive strength (GOST 310.4)	MPa	GOST 310.4-81 p. 2.2	34,6
11	Effective thermal conductivity (thermal conductivity coefficient)	W/m*K	GOST 7076-99 GOST 12730.2-2020 p. 6.1	0,442
12	Water resistance grade by the "wet spot" method	–	GOST 12730.5-2018 p. 4	W20

To implement the study, control programs were prepared for three types of parallelepiped-shaped products:

1. The first version of the product for printing layers oriented in one direction along one axis.

The height of the finished product was 400 mm, which corresponds to 20 layers with the format of each layer being 50 mm in width and 20 mm in height. The length of each layer reached 450 mm, considering the rotary part (Figure 2).

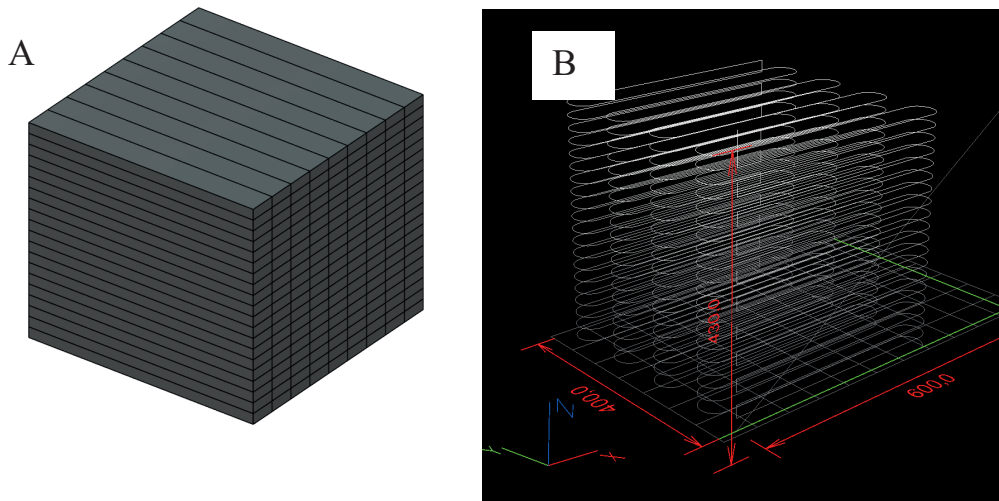


Figure 2. Visualization of the first version of the product. A – 3D model. B – visualization of the control program

2. The second version of the product was also a parallelepiped with the following parameters: height 400 mm, width and length 450 mm. However, in this case, the sequence and direc-

tion of printing layers alternated. Thus, one layer was printed along the X axis, and the next one along the Y axis (Figure 3).

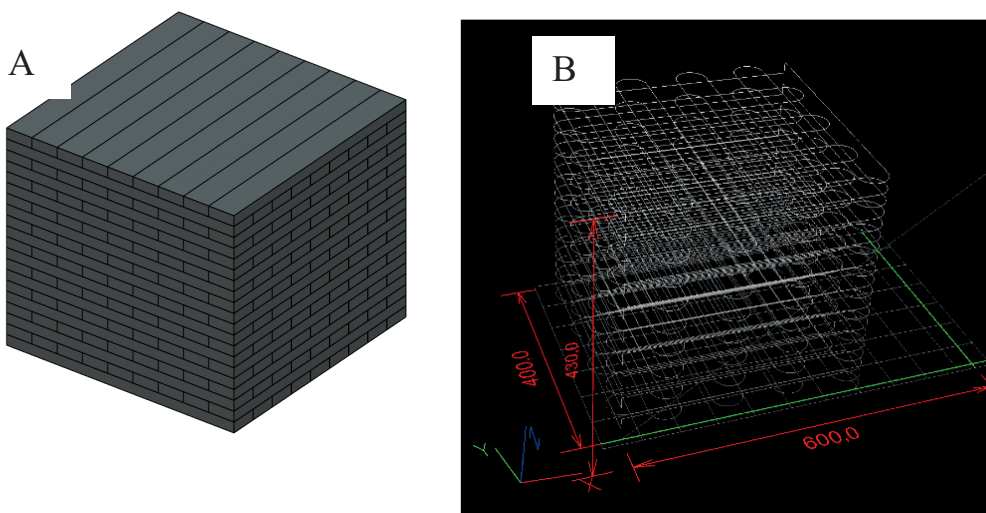


Figure 3. Visualization of the second version of the product. A – 3D model. B – visualization of the control program

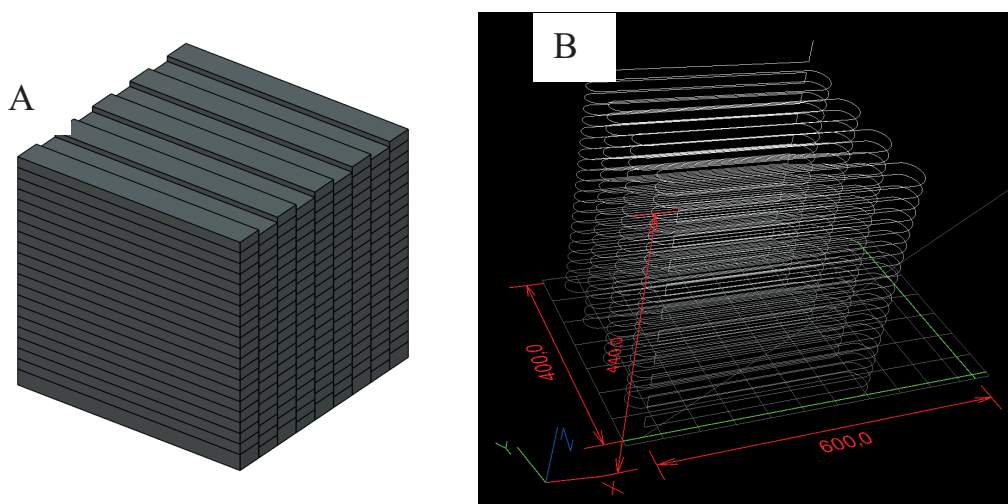


Figure 4. Visualization of the third version of the product. A – 3D model. B – visualization of the control program

The third version of the product is characterized by a variable height of layer printing. Thus, when printing layers in contact with the base of the print field (floor), the layer height alternated sequentially: 3 cm and 2 cm. Subsequent layers were printed with a height difference between adjacent layers (1 cm) formed in this way, but with the same height of each layer (2 cm). This approach ensured a tight fit of adjacent layers to each other in the contact zone (Figure 4).

As a result, three different strategies for forming the geometry of solid products using 3DCP were tested. The first option involved printing layers in one direction, the second - alternating directions, and the third - a variable height of layers to improve adhesion between them.

Despite the fact that in real practice, the technology of 3DCP is mainly used for the construction of permanent formwork for enclosing or (less often) supporting structures with a thickness of, as a rule, one or two layers - studying the durability of such structures requires a special approach that takes into account the specifics of layer-by-layer formation of the material. Since 3DCP involves sequential application of layers, interlayer boundaries become potentially vulnerable zones where stresses can concentrate, microcracks can form, and delamination can occur under the influence of external factors. In this regard, the use of multilayer samples for studying aging processes seems

methodologically justified, since it allows artificially increasing the number of interlayer contacts and thereby accelerating the manifestation of degradation processes under cyclic climatic influences, such as freezing and thawing in combination with sprinkling. Despite the apparent discrepancy between the multilayer structure of the studied samples and the single-layer configuration of most real building elements, the proposed methodology provides a reliable basis for predicting the durability of 3DCP structures, since it allows for a targeted study of the weakest zones of the material and modeling its degradation processes in an accelerated mode.

The 3DCP products were manufactured using a portal-type construction 3D printer. The X axis is the axis along which the nozzle of the construction 3D printer's print head moves during layer-by-layer extrusion of the material. During the optimization of the model for printing multilayer products, the parameters were adjusted so that when laying adjacent layers, their maximum adhesion was achieved without the occurrence of sagging. This considers the selected width of the printed layer and the extrusion speed.

All products were manufactured under identical temperature and humidity conditions corresponding to room temperature and humidity, in the same laboratory room.

The photographs below demonstrate the process of printing a multilayer product in the form of a parallelepiped with layer-by-layer laying of the

mixture in one direction and the appearance of the finished product (Figure 5).



Figure 5. Printing of a parallelepiped-shaped product with layer-by-layer laying of the mixture in one direction and the appearance of the finished product

Similarly, the process of printing a parallelepiped-shaped product with layer-by-layer laying of the mixture in perpendicular directions

is demonstrated below (Figure 6), as well as with different printing heights of the layers (Figure 7).



Figure 6. Printing of a parallelepiped-shaped product with layer-by-layer laying of the mixture in perpendicular directions and the appearance of finished products



Figure 7. Printing of a parallelepiped-shaped product with layer-by-layer laying of the mixture and different printing heights of the layers

In addition to the products printed in one run, an additional series of three products with layer bonding was printed, on which a cold joint was simulated. For this, the product was printed to the middle of the height, after which a pause of at least 6 hours was made, and after this pause the remaining part of the product was printed. This approach is designed to simulate long pauses in the operation of a construction 3D printer that may occur at a construction site. One product with a cold joint serve as a control,

while the other two were coated with a primer based on styrene-acrylic polymer dispersion (Figure 8a) and concrete contact (Figure 8b) using a paint brush to assess the effectiveness of the influence of various methods of cold joint treatment on ensuring interlayer adhesion (Figure 9). In this case, the compositions were applied to one product immediately after printing the first half, and to the others - before printing the second part.



a) applying primer



b) concrete contact application process

Figure 2. Cold seam processing



Figure 9. Printing process over a processed cold seam

In addition, monolithic samples of the same dimensions are manufactured. After reaching the age of 28 days, the products are placed in a large climatic chamber for temperature and humidity loading (Figure 10). Every 10 block cycles of temperature and humidity loading are recorded and the defects that have arisen in the products are described. The tests involve the

application of cyclic climatic effects to the product under test in accordance with the requirements of GOST R 55943-2018. One block cycle (24 hours) consists of two climatic cycles (cycle A and cycle B) each lasting 12 hours (720 minutes) (Figure 11 - Figure 12), following each other.



Figure 3. Placing products in a large climate chamber

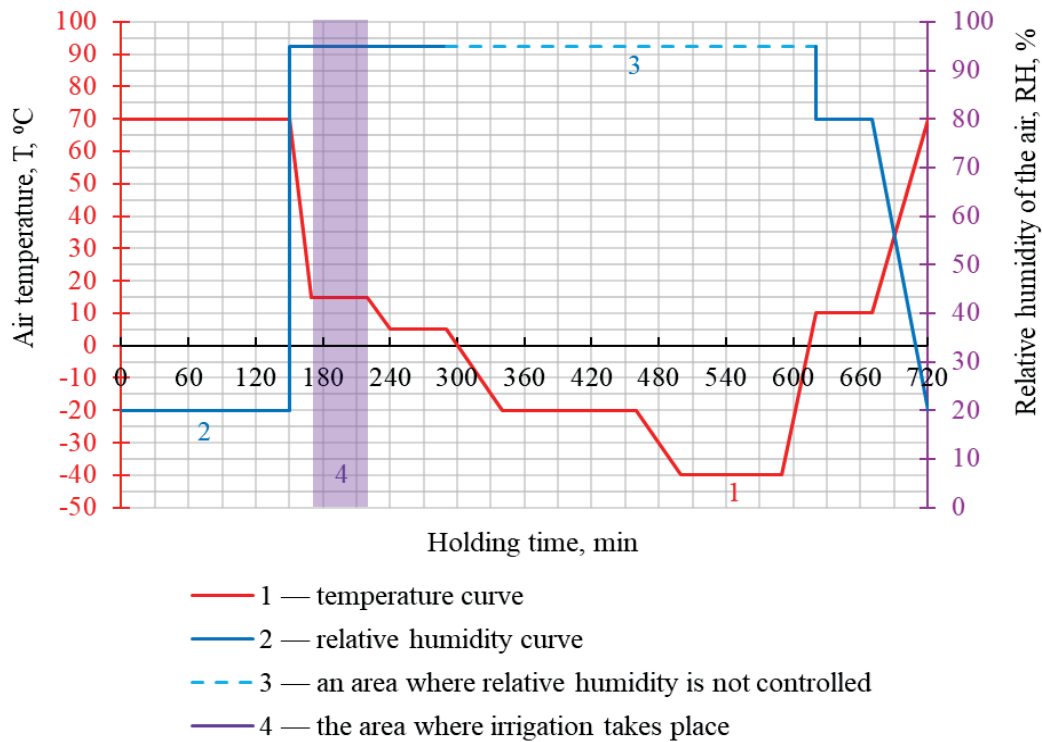
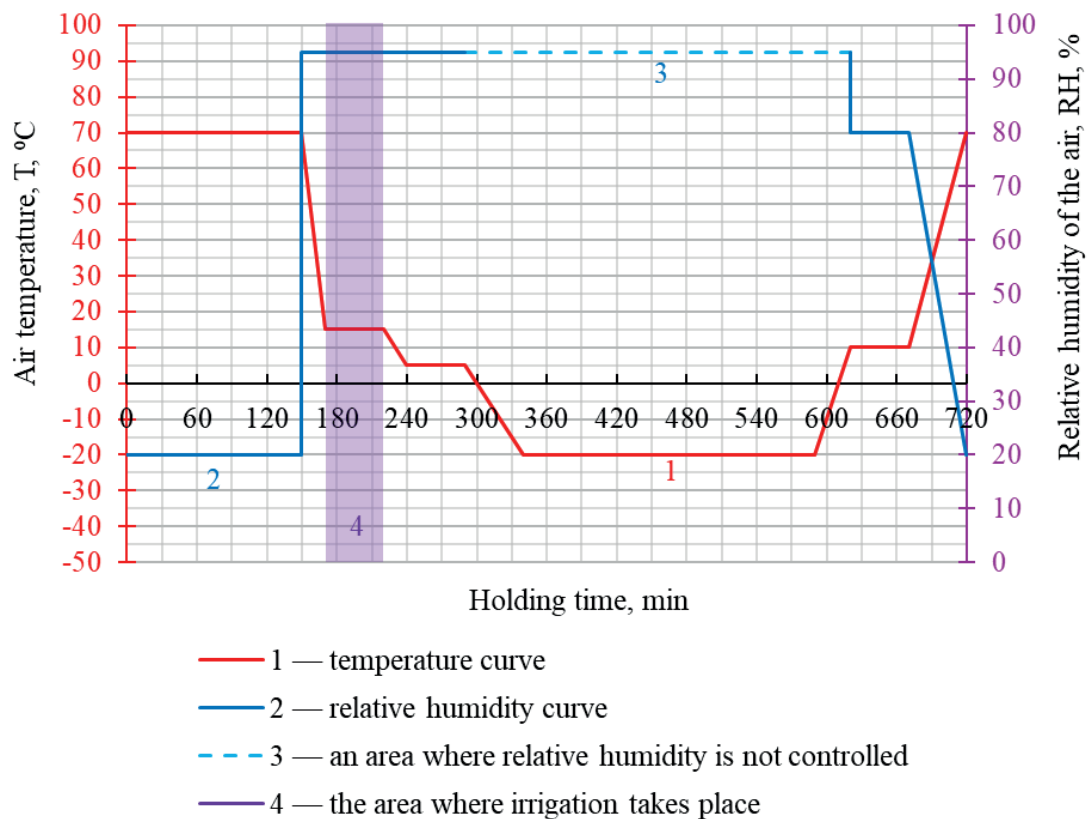


Figure 4. Climate cycle A



RESULTS OF THE STUDY OF THE INFLUENCE OF THE PRINTING METHOD OF MULTILAYER PRODUCTS AND STRUCTURES ON THE NATURE OF DEGRADATION UNDER CONDITIONS OF ACCELERATED MODEL AGING

In the part of the experimental study described in this article, the effect of the printing method for multilayer products and structures on the nature of degradation under accelerated model aging conditions was assessed visually by the

nature of crack development and the width of their opening. The results of the visual assessment of the samples after climatic influences are presented in the form of photographs. Before conducting climatic tests according to GOST R 55943-2018, each of the seven test samples was visually inspected for defects. Visual inspection was carried out on 5 faces with codes A - D (A - front face; B - left side face; B - back face; G - right side face; D - horizontal face above). Each sample was assigned a unique code (Table 2).

Table 2. Codes assigned to samples

Sample name	Sample code
Control sample of 3D printing with a cold seam	1
Monolithic sample	2
Sample of 3D printing with a cold seam with primer applied before printing the second part	3
Sample of 3D printing with a cold seam with primer applied im-	4

mediately after finishing printing the first part	
Sample of 3D printing with different layer heights	5
Sample of 3D printing with cross layers	6
Sample of 3D printing with cross layers	7

Based on the results of the inspection prior to the climatic tests, it was established that:

- the 3D printing sample with a cold seam with code 1 has one horizontal crack in the layer in the center of face A with pigmentation (Figure 13); isolated vertical cracks on faces B and C; there are no defects on faces G and D;
- the monolithic sample with code 2 has: a vertical crack 12.5 cm long, a horizontal hairline (less than 0.1 mm) crack 4 cm long in the center of the face, a diagonal hairline crack 7 cm long and a horizontal interlayer hairline crack 5 cm long on face A; face B was not inspected due to lack of access; a vertical hairline crack 12 cm long in the center of face C; there are no defects on faces G and D;
- the 3D printing sample with a cold seam with primer applied before printing the second part with code 3 has multiple vertical cracks in the layers along the edges of faces A, B and G (Figure 14); there are no defects on faces B and D;

- the 3D printing sample with a cold seam with primer applied immediately after finishing printing the first part with code 4 has single vertical cracks in the layers along the edges of faces A, B and G; there are no defects on faces B and D;
- the 3D printing sample with different layer heights with code 5 has multiple vertical cracks in the layers of the edges of faces A, B and G; single vertical cracks in the layers along the edges of face B; there are no defects on face D;
- the cross-layer 3D print sample with code 6 has: multiple vertical cracks in the layers of faces A, B, C and G (Figure 15); there are no defects on face D;
- the parallel-layer 3D print sample with code 7 has multiple vertical cracks in the layers of the edges of faces A, B and G; single vertical cracks in the layers along the edges of face B; there are no defects on face D.



Figure 13. Horizontal crack with pigmentation



Figure 14. Vertical cracks along the ribs

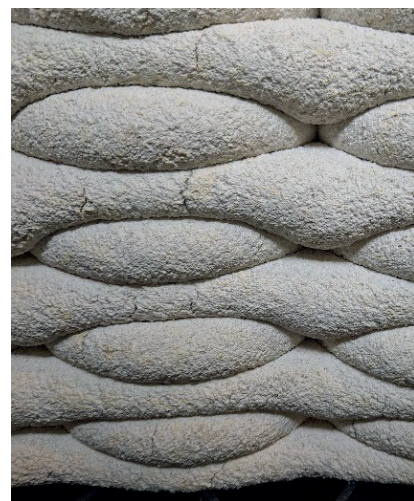


Figure 15. Vertical cracks

After the inspection, the climatic effects were activated. The first intermediate inspection was carried out after one block cycle of climatic effects. Then the inspection and photo recording of the samples was carried out every 5 block cycles, until the result of 100 block cycles was achieved. According to the results of the inspec-

tion after the first block cycle, it was found that the samples with markings 1, 3 and 4 in the wet state are covered with numerous hair cracks forming a "spider web", which is not observed in the dry state, no other defects were found. After 5 block cycles, the "spider web" was found on all samples (Figure 16 - Figure 17).



Figure 16. Multiple hairline cracks "spider web" on sample with code 5

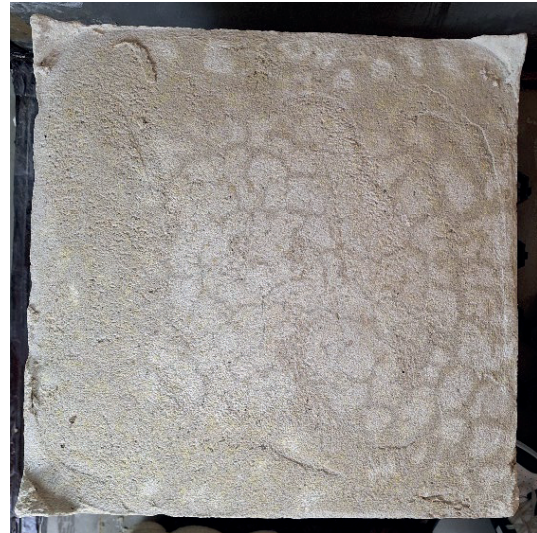


Figure 17. Multiple hairline cracks "spider web" on sample with code 2

In addition to hairline cracks after 1 block cycle, a vertical crack was found in the middle of face G on sample code 3, with its transition to face D (Figure 18).

As a result of the tests, samples were photographed every 5 cycles. Below is a general assessment of the development of defects in samples with different codes.

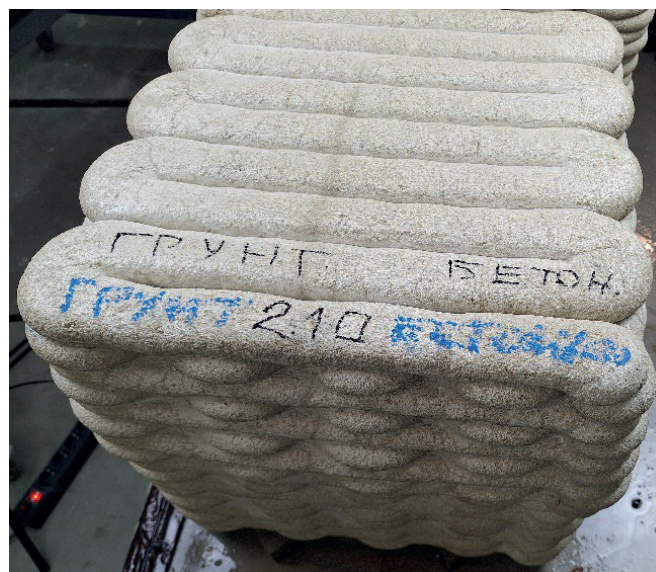


Figure 18. Vertical crack along faces G and D

Sample code	Evaluation of defect development	Conclusion based on the results of 100 cycles of model aging
1	In the period from 1 to 100 block cycles of climatic impacts: after the 5th block cycle, the appearance of a crack with an opening of more than 0.1 mm is observed, passing along the middle of the faces G and D; after 15 block cycles, yellow-red efflorescence was noticed on all faces of the sample; from the 15th to the 100th block cycle, the appearance of new visible damage was not observed, but more significant efflorescence was noticed with a change in the color of the sample and a greater opening of the crack along the faces G and D to a thickness of more than 0.1 mm	The sample has: one horizontal layer crack in the center of face A with white and reddish efflorescence along the edge and multiple hairline cracks; single vertical layer cracks and multiple hairline cracks along faces B, C and G; one crack in the middle of face D with white efflorescence along the edge; yellowish-reddish efflorescence and significant color change
2	In the period from 1 to 100 block cycles of climatic influences: after the 5th block cycle, the appearance of a "web" of hairline cracks is observed; after 10 block cycles, yellow-red efflorescence was observed on all edges of the sample; from the 10th to the 100th block cycle, the appearance of new visible damage was not observed, but more significant efflorescence was observed with a change in the color of the sample	The sample has a vertical crack 12.5 cm long, a horizontal hairline crack (less than 0.1 mm) 4 cm long in the center of the face, a diagonal hairline crack 7 cm long and a horizontal interlayer hairline crack 5 cm long on face A; face B was not inspected due to lack of access; a vertical hairline crack 12 cm long in the center of face C; there are no defects on faces G and D; yellowish-red formations and significant color change
3	In the period from the 1st to the 100th block cycle of climatic impacts: after the 40th block cycle, yellow-red efflorescence was observed on all faces of the sample; after the 65th block cycle, a crack was found in the lower part of face A, which is a continuation of the crack formed after the 1st block cycle; after the 75th block cycle, the appearance of a vertical crack in the middle of face B with an opening of more than 0.1 mm is observed; from the 75th to the 100th block cycle, the appearance of new visible damage was not observed, but more significant efflorescence was observed with a change in the color of the sample and a greater opening of the crack along faces G and D to a thickness of more than 0.1 mm (Figure 19 - Figure 20).	The sample with the application of primer before printing the second part has multiple vertical cracks in the layers along the edges of faces A, B, C and D; a crack with an opening of more than 0.1 mm along faces A, B and D; one crack on face D with an opening of more than 0.1 mm, adjacent to the edges of faces B and D; yellowish-red formations and a significant change in color
4	In the period from 1 to 100 block cycles of climatic impacts: after 10 block cycles, one	The sample with the application of the primer immediately after the

Sample code	Evaluation of defect development	Conclusion based on the results of 100 cycles of model aging
	crack is observed in the middle of faces A and D, extending to the cold joint; after 15 block cycles, yellow-red efflorescence was observed on all faces of the sample; from 15 to 100 block cycles, the appearance of new visible damage was not observed, but more significant efflorescence was observed with a change in the color of the sample and a greater opening of the crack along faces G and D to a thickness of more than 0.1 mm.	end of printing of the first part with the code 4 has single vertical cracks of the layers along the edges and multiple hairline cracks on faces A, B and G; multiple hairline cracks along the entire face B; one crack on face D with an opening of more than 0.1 mm and multiple hairline cracks; yellowish-red formations and a significant change in color.
5	In the period from 1 to 100 block cycles of climatic influences: after the 5th block cycle, the appearance of a "web" of hairline cracks is observed; after the 35th block cycle, yellow-red efflorescence was noticed on all edges of the sample; from the 35th to the 100th block cycle, the appearance of new visible damage was not observed, but more significant efflorescence with a change in the color of the sample was noticed.	The sample has: multiple vertical cracks in the layers of the ribs and multiple hairline cracks on faces A, B and D; single vertical cracks in the layers along the ribs and multiple hairline cracks on face B; multiple hairline cracks on face D; yellowish-red formations and significant color change
6	In the period from the 1st to the 100th block cycle of climatic impacts: after the 5th block cycle, the appearance of a "web" of hairline cracks is observed; after the 20th block cycle, the appearance of a vertical crack along face A with white efflorescence is observed, and yellow-red efflorescence is also noted on all faces of the sample; from the 20th to the 100th block cycle, the appearance of new visible damage was not observed, but more significant efflorescence was noted with a change in the color of the sample and a greater opening of the crack along face A to a thickness of more than 0.1 mm with more significant white efflorescence.	The sample has multiple vertical cracks in the layers of faces A, B, C, D and E; one vertical crack in the middle of face C with white efflorescence along the edge and an opening of more than 0.1 mm; two vertical cracks in the middle of face D with white efflorescence along the edge and an opening of more than 0.1 mm; yellowish-red formations and a significant change in color
7	In the period from 1 to 100 block cycles of climatic impacts: after the 5th block cycle, the appearance of a "spider web" of hairline cracks is observed; after 15 block cycles, yellow-red efflorescence was observed on all edges of the sample; from the 15th to the 100th block cycle, the appearance of new visible damage was not observed, but more significant efflorescence with a change in the color of the sample was noted.	The specimen has multiple vertical cracks in the layers of the ribs and multiple hairline cracks on faces A, B and D; single vertical cracks in the layers along the ribs and multiple hairline cracks on face B; multiple hairline cracks on face D; yellowish-reddish precipitates and significant discoloration

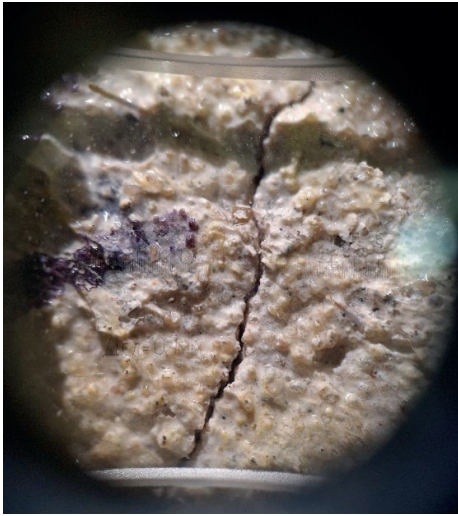


Figure 19. Crack on face D after 30 cycles

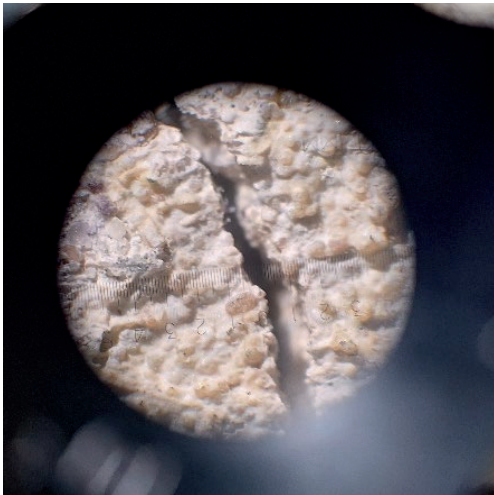


Figure 20. Crack on face D after 100 cycles

Summary results of visual assessment of samples after climatic impacts

The conducted studies revealed significant differences in degradation of 3D-printed samples and a monolithic analogue under cyclic climatic influence. The key differences are in the features of crack formation, the dynamics of defect development and resistance to external influences. The monolithic sample (code 2) demonstrated the least tendency to crack formation. Despite the presence of hairline cracks and single defects, their development during testing was minimal. In contrast, all 3D-printed samples, especially with a cold seam (codes 1, 3, 4), showed intense crack formation, mainly in the zones of interlayer contacts. The most pro-

nounced defects were observed in samples with a cold seam, where cracks reached an opening of more than 0.1 mm, and were also accompanied by the formation of efflorescence.

Samples with cross-layer stacking (code 6) and variable layer height (code 5) showed better stability compared to samples printed in one direction (code 7). However, even they were inferior to the monolithic sample in terms of resistance to climatic influences. This confirms that interlayer boundaries remain a weak link in 3D-printed structures, despite the optimization of printing strategies. The use of a primer and concrete contact to improve adhesion in the cold joint zone (codes 3, 4) did not lead to a significant increase in durability. On the contrary, in some cases the treatment even contributed to an increase in the number of cracks, which may be due to additional stresses at the layer interface. During the removal of samples that had undergone 100 cycles of accelerated model aging from the climatic chamber, it was established that all samples for which the creation of a cold seam was modeled (codes 1,3,4) did not have interlayer adhesion and were freely separated in the zone where the cold seam was modeled (Figure 21).



Figure 21. Free separation of the sample by the cold seam modeling zone after 100 cycles of accelerated model aging in a climatic chamber

CONCLUSIONS

The conducted study allowed us to obtain several conclusions that may be relevant for the further development of 3DCP technology and assessment of the durability of structures created in this way. In particular, the obtained results demonstrated that monolithic samples manufactured in the traditional way have a significantly higher resistance to cyclic climatic effects compared to 3D-printed analogues. This confirms that the layer-by-layer formation of the structure is a critical factor determining its durability. Accelerated model aging in a climatic chamber shows that it is the interlayer contact zones that become the main sources of degradation, where stresses are concentrated and cracks develop. At the same time, none of the developed printing methods (parallel, cross-laying of layers, variable layer height) allowed us to completely neutralize this effect, although cross-laying showed slightly better results. The use of a primer and concrete contact to improve adhesion in the technological break zone did not give the expected positive effect. In some cases, this even led to an increase in the number of defects, which requires a revision of existing approaches to the processing of interlayer connections. The data obtained indicates that solving the problem of durability of 3DCP structures requires simultaneous optimization:

- composition of building mixtures (with an emphasis on improving adhesion characteristics);
- technological printing parameters (extrusion speed, temperature conditions);
- design solutions (stress distribution in interlayer contact zones).

This study has identified several promising areas for future research:

- development of new methods for assessing interlayer adhesion at the construction site;
- study of long-term behavior of structures under real operating conditions;
- creation of specialized regulatory and technical documents for assessing the durability of

building products and structures manufactured using 3DCP technology.

The findings obtained are of fundamental importance for understanding the degradation processes of layered building materials, as well as of practical value for the industry, indicating the need for further improvement of additive construction production technologies. The solution to the identified problems will facilitate a wider implementation of 3D printing in construction practice while ensuring the required level of reliability of the structures being erected.

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