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MANUFACTURING SMALL ARCHITECTURAL FORMS WITH 3D PRINTING

Olga Vladimirovna Rudenko[1], *Darya Kamilyevna Anop[1], Vladimir Fedorovich Shevlyakov[1], Valeriy Yuryevich Chernavin[1]

*[1] School of Architecture, Civil Engineering and Energy, D. Serikbayev East Kazakhstan Technical University, Kazakhstan

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ABSTRACT: Additive technologies are currently distributed in the construction sector in many countries worldwide. Analysis of data from previous studies have shown that the manufacturing process model and selection of the composition of the concrete mixture for additive technologies should correspond to various critical conditions that are directly related to the 3D printing methodology. In addition, they do not provide a clear picture of the complete cycle of manufacturing 3D-printed concrete products, especially non-standard configurations, from the development of composition to the printing of finished products. The purpose of this work is to model the process of manufacturing small-architectural-form products via 3D printing, use technogenic mineral formation (TMF) as part of concrete, and create a digital model for printing. As a result of the conducted research, a digital model to produce prototypes was created, a mixture composition for printing on a 3D printer was selected, and small-architectural-form products were produced. The optimal amount of filler to be replaced by industry-related mineral formation is 27%, which provides the required mobility of the mixture for 3D printing, preserves and even increases the strength characteristics (up to 13%). These results demonstrate the effectiveness of technology-related mineral formation in replacing natural sand in the production of 3D-printed concrete products with complex configurations. They present good prospects in the construction industry for the creation of sustainable construction materials with positive environmental impacts, which may be of practical value to both researchers and manufacturers in the construction industry.

Keywords: 3D Printing, Additive Technologies, Concrete, Sustainability, Technogenic Mineral Formation

1. INTRODUCTION

Additive technologies such as AM (Additive Manufacturing) and AF (Additive Fabrication) are technologies of layer-by-layer synthesis or layering products for digital 3D models. 3D printing or "additive production" is the process of creating one-piece three-dimensional objects of almost any geometric shape based on a digital model and sequentially applying layers that display the contours of the model. The main production tool is a 3D printer. An analysis of literary data has shown that the use of additive technologies in the construction sector is highly relevant and has several advantages [1-3].

The main advantage of this technology is that production does not require formwork. It can create complex and non-traditional forms of structures. Printing with a 3D printer based on a digital model provides high-quality products that subsequently do not have to be refined. All elements in the composition retain their integrity and have high physical and mechanical characteristics. The use of a computer model of the future printing product enables one to make adjustments and immediately start production [3] very quickly. The concrete mixture for 3D printing does not contain coarse aggregates and must have good plasticity, which creates good prerequisites for the use of fine-fraction technogenic mineral formations (TMFs). Due to the large number of fine fractions, several tasks can be fulfilled using TMF: industrial waste utilization, decrease in production cost and increase in manufacturing quality. This approach is also consistent with sustainable building principles [4].

The use of industrial waste in the construction industry is highly relevant and widely used [5-11]. The application of rice husk ash to improve the strength properties of concrete has been studied [5]. To improve the durability and compressive strength of non-load-bearing concrete (hollow blocks), recycled fibres from soft drink cans were used as reinforcements [6]. Studies aimed to determine the effects of steel-fibre-reinforced concrete tires and crumb rubber on high-strength concrete [7]. The authors also provide a detailed overview of the use of waste and by-products to produce concrete blocks [9].

Various authors have investigated the use of industrial waste as a substitute for both binder and aggregate in the development of mixtures for 3D printing [12-15]. However, these works lacked information about creating a digital model. Other studies cited research on 3D modeling but lacked information on 3D printing [15].

Earlier studies on the construction of 3D printer revealed various problems in the creation of digital models and development of concrete mixture compositions for printing [16]. The construction of a 3D printer does not directly work with three-dimensional layouts. To send a print file, one must first convert the STL file to mindable for the 3D printer format. In addition, there are several restrictions on geometric parameters (distances between the lines of structures, angles, turning radii) [17]. The selection of a mixture for additive printing is complicated. It is necessary to select a mixture so that the hardening is not started earlier than the stamp ends (i.e., the entire volume of the boot device will be used). Next, hardening should quickly occur to apply the next layer. It is necessary to design products and structures so that the upper layers do not deform the lower layers (sufficient strength is not required).

One of the major challenges in 3D printing concrete is determining the required mixing properties such as the extrudability, assembly, flowability, and release time. Moreover, in a well-printed structure, each layer should have identical height and width and should not exhibit extensive deformations or discontinuities.

Thus, to create high-quality products via 3D printing, it is necessary to solve problems with the selection of mixture composition, printing accuracy and structural integrity of printing plates, and creation of a digital model for printing. This is the focus of the current study. This study presents a complete cycle from the selection of a mixture composition with technogenic mineral formation to create a digital model and print small architectural forms.

2. RESEARCH SIGNIFICANCE

The small architectural forms created in this study, which consider various critical conditions and address the gaps of previous studies, have demonstrated their viability and sufficient physical, mechanical, and performance characteristics.

This study confirms the validity of the decisions taken and extends the available research on 3D printing of construction products to a full-cycle research, from the selection of a mixture composition using industry-related waste to the creation of a digital model and printing small architectural forms.

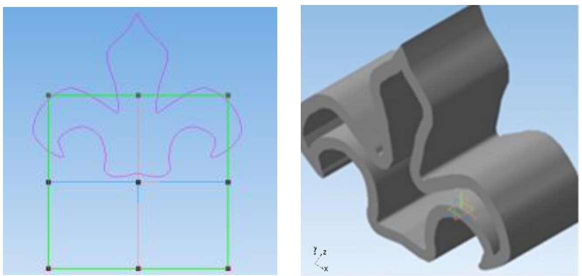
The results of this study may not be limited to the presented type of waste and can be used for future research on 3D printing and the creation of sustainable construction materials. This study will help reduce waste, improve the environmental situation, reduce production costs, and improve product quality.

3. METHODS AND MATERIALS

3.1 Methods

To create a flat model in three-dimensional modelling and assemble a three-dimensional model, we made special subprograms of 3D compass, the solid-state models of which were stored in files with the * M3D extension files. Since the sketch was built in a standard plane of projections, for its construction, a graphical document creation environment was used, such as the geometry toolbar and parametrization tool (Fig. 1, a). The data were set at a one-to-one scale.

A flat model of the three-dimensional object was created by extriving the contour (sketch). The contour was performed according to the type of "basic" line: it should not have intersection points and should not intersect with another outline or overlay lines, which is a very important point. The reason is that the 3D printer will not print if there are intersection points. The working window received an image in the form of a frame, for which the halftone image and orientation of the XYZ isometry (Fig. 1, b) were installed.



(a) (b)

Fig. 1 Example of a small-architectural-form image: (a) Environment of three-dimensional modelling in the compass. (b) Creating a three-dimensional model

To convert the created virtual model to the "Clear" object, the Mach3 software package has been used for a 3D printer, which works on a PC and turns it into a cost-effective control station. Mach3 and its parallel port driver connect to the 3D printer equipment through a parallel port (printer port).

A suitable mixture was modelled to print the obtained digital model, which corresponded to critical conditions that are directly associated with the 3D printing methodology. To select the optimal composition, the following factors were considered: the final strength of the concrete for compression; mobility of the concrete mixture; ability of the composition to preserve the specified form after the distribution of the nozzle; the setting speed; ability to provide sufficient adhesion of the previous and subsequent layers.

Some of the presented criteria contradict one another, and the main goal in modelling the composition of the mixture is to balance all listed parameters. Simultaneously, the following was taken into account: an increase in compressive strength invariably implies a decrease in indicator of the W/C ratio in the composition; however, the reduction in water content under normal conditions reduces the plasticity of the mixture. Importantly, the composition is sufficiently fluid at the exit of the nozzle of one layer, and after its release, the form is retained, and the subsequent layers are retained. Moreover, after the distribution, the composition should be captured as quickly as possible while ensuring adhesion with the subsequent layer.

To prepare fine-grained concrete for printing, the dry ingredients (cement, sand and TMF (technogenic mineral formation)) were first mixed together in a mixer until the mixture was completely homogeneous. Aqueous mortar with a plasticizer (1% of cement weight) was prepared in advance. Aqueous solution was added to the prepared dry mixture and stirred for 3 minutes. Then, the resulting concrete mixture was loaded into a 3D printer for printing.

3.2 Materials

The pre-compositions for 3D printing were calculated using the method of absolute volumes. When selecting the composition of mixture, one must consider the absence of the coarse aggregate that provides the strength of heavy concrete. Therefore, CEM42.5 high-grade cement without additives was used.

Tables 1 and 2 show the chemical and mineralogical compositions of cement, respectively.

Table 3 shows the physical and mechanical characteristics of cement. The plasticizer and hardening agent called Master Rheobuild 1000 was used as a chemical additive.

This chemical additive is a plasticizer, and a hardening agent, and is a high-quality material in the market of Kazakhstan (Bukhtarma cement company).

Class-II sand was used as the filling aggregate. Table 4 shows the physical and mechanical characteristics of the sand. Table 5 shows the characteristics of the water.

A coefficient that corrects for the reduced quality of the filler was used to model the composition. Table 6 shows the TMF characteristics.

Table 1. Chemical composition of the cement

Clinker (Kazakhstan)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3
Content of oxides, %	19.95	5.58	4.98	63.07	4.50	0.36

Table 2. Mineralogical composition of the cement

C_3S	C_2S	C_3A	A_4AF	Mg_2O	K_2O	p.p.p
59.10	12.30	6.30	15.10	0.03	1.02	0.87

Table 3. Physical and mechanical characteristics of the cement

Indicator name	Actual indicator value	Compliance with the characteristics
Compressive strength at the age of 2 days, MPa	14.3	In compliance, min 10
Compressive strength subclass	Normally hardening	Determined according to compressive strength at the age of 2 days
Compressive strength at the age of 28 days, MPa	45.6	In compliance, min 42.5 and max 62.5
True density, g/cm^3	3.1	Value not standardized
Bulk density, g/cm^3	1.5	Value not standardized
Normal consistency of cement paste, %	25.5	Value not standardized
Initial set, min	168.0	In compliance, no earlier than 60
Final set	265.0	Value not standardized
Flow rate, mm	113.0	Value not standardized

Table 4. Physical and mechanical characteristics of the sand

Indicator name	Actual indicator value	Compliance with the characteristics
Gradation factor	2.4	In compliance with the fine grade, min 2.0 and max 2.5
True density, g/cm^3	2.2	Value not standardized
Bulk density, g/cm^3	1.4	Value not standardized
Clay content in lumps, mass percent	0	In compliance, max 0.5
Dust and clay content, %	0.5	In compliance max 5, max 7 is permissible

Table 5. Characteristics of the water to mix concrete ingredients

Indicator name	Actual indicator value	Compliance with the characteristics
Soluble salt content, mg/l	480	In compliance, max 2000
SO^{-2}_4 ion content, mg/l	265	In compliance, max 600
Cl^{-1} ion content, mg/l	110	In compliance, max 500
Suspended particles content, mg/l	17	In compliance, max 200
Hydrogen value of water (pH)	7	In compliance, min 4 and max 12.5
Availability of film created by petroleum products, fats, oils	none	In compliance
Colouring impurities	none	In compliance

Table 6. Characteristics of technogenic mineral formation

Parameter name	Actual parameter value	Compliance with characteristics
Fineness modulus	1.2	Corresponds to very fine sand from 1.0 until 1.5
Sieve residue mass percentage (mesh No. 063)	13.8	Does not conform to the norm until 10
Content of grains exceeding 10 mm, in mass percentage	0	Corresponds to very fine sand maximum 5
Content of grains exceeding 5 mm, in mass percentage	0	Corresponds to very fine sand maximum 15
Content of grains exceeding 0.16 mm, in mass percentage	6.2	Corresponds to very fine sand maximum 20
2.5 mm sieve residue, in mass percentage	1	---
1.25 mm sieve residue, in mass percentage	11.3	---
0.63 mm sieve residue, in mass percentage	13.8	---
0.315 mm sieve residue, in mass percentage	17.3	---
0.16 mm sieve residue, in mass percentage	73.8	---
<0.16 mm sieve residue, in mass percentage	100	---
Content of lumpy clay, in mass percentage	4	---
Content of fines and clay particles, %	8	Does not conform to the norm maximum 5, maximum 7 is admissible
Pour density under normal conditions, kg/m^3	1240	---
Humidity, %	1.0	---
Real density in Le Chatelier bottle, g/cm^3	2.7	2.0 – 2.8
Volume of intergranular openings, kg/m^3	54	---

The concrete composition was selected based on the average strength level. However, since there are no data on the actual homogeneity of concrete and average strength level, the coefficient of variation was assumed to be 13.5%.

When modelling the composition of the concrete mixture for 3D printing, to ensure the most significant criteria such as the viscosity, the form, mobility, compressive strength and open operation time were preserved with the composition by five compositions. TMF was introduced to replace parts of the cement and sand. Compositions No. 1 and No. 2 were based on cement. Technogenic mineral formation (TMF) was used to substitute for cement (9%) for composition No. 3, replace sand (27%) in composition No. 4 and replace cement (9%) and aggregate (27%) in composition number 5. Dry materials were used for the experiments.

After the experiments were conducted under laboratory conditions, the test damps were adjusted: the amount of water in composition No. 1, the amount of water and plasticizing additive in composition No. 3, and number of plasticizing additives in compositions No. 4 and No. 5.

For the experimental printing, the consumption of material was calculated for one mixture of the construction bunker 3D printer, and the water-cement ratio and mobility of the mixture were determined. Table 7 shows the material consumption for one batch of the construction hopper 3D printer.

The manufacturing process of small architectural forms was modeled at the East Kazakhstan Technical University, which was named after D. Serikbaev, using the construction 3D printer of the S-6045 brand (Fig. 2). The printer was adapted to create small architectural forms, elements of houses, landscape products and structures of various shapes. The different layout of supports and carriage increases the speed of printing with stable quality.

The S-6045 printer is an improved model of small-format printers of the S series. It was developed based on the S-6043. It enables printing with various concrete compositions, including the cement of series 500 and use of mixtures with mineral additives and fibrofibres. In the basic configuration, the printer is equipped with three print heads to print with different compositions.

In this work, a 3D printer uses extrusion technology, where each new layer of building material is squeezed out of the printer on top of the previous layer. The lower layers are gradually compacted, which makes it possible to withstand an increasingly increasing weight of the design.

The equipment was designed for a high load, which opened new opportunities for small businesses in the construction industry.

Formwork is not required; moreover, the design printed using a construction 3D printer S-6045 is a formwork for further construction. This is a self-sufficient mechanism that can connect electricity literally at a naked place to create a finished product (Fig. 3).

Table 7. Material consumption for one bunker building 3D printer

Component name	Consumption of components for Composition 1	Consumption of components for Composition 2	Consumption of components for Composition 3	Consumption of components for Composition 4	Consumption of components for Composition 5
Portland cement CEM42.5, kg	10.34	12.73	11.58	12.73	11.58
Sand, kg	36.37	36.37	36.37	26.55	26.55
Technogenic mineral formation, kg	-	-	1.15	9.82	10.97
Water, kg	6.33	8.43	7.30	8.66	7.18

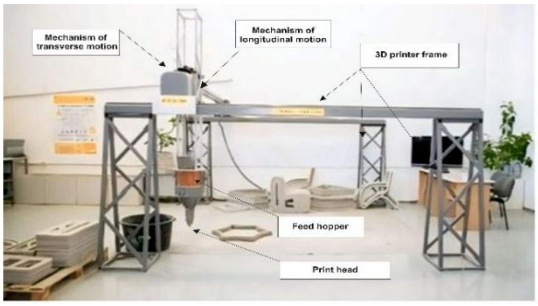


Fig. 2 Construction 3D printer of the S-6045 brand at the VKTU named D. Serikbaev

(a) (b)

Fig. 3 Printing a small-scale architectural structure with the S-6045 3D printer: (a) printing process and (b) type of layers in the finished product

4. RESULTS AND DISCUSSION

The first task was solved by creating a model for 3D printing: a flat model was built based on the knowledge about the original object; simultaneously, the question of the size, configuration and position in the space created architectural form was resolved. When a model is created, one should consider that it will be a physical object and not a virtual one. Then, the object visualization is performed. Here, a three-dimensional object was created from the flat model, which showed us a complete picture of the future object-origin. Solving this task created a digital model to print a 3D printer.

When an object is created for printing, several digital models are created, and an attempt is made to output them into a 3D printer. As a result, not all digital models can be physically printed.

Experimentally, a viable digital model for 3D printing in AutoCAD software complexes and compass-3D can be created only under the following conditions: the line must be single and avoid sharp angles; the minimum distance between adjacent horizontal lines should be 4 mm; data should be introduced to a fairly flat drawing; the created three-dimensional object is a solid body (three-dimensional models must be bodies and objects of the real world) and has a scalable dimension (1 mm in the model should be 1 mm in real life); all sizes are important.

Three-dimensional printing systems do not directly perceive digital files but understand the machine language (G-code). Each machine or supplier commonly uses its own language, so when the model is converted into G-code, there may be loss of model quality. With volume printing, one should always check that the loss of quality remains within the allowed limits.

An important factor that enables printing on a 3D printer is the mobility of the concrete mixture. The required mobility of printing mixtures should be 8-10 cm.

The study results of the compositions of the concrete mixture for additive printing are shown in Tables 8 and 9. Table 9 shows the strength characteristics of the concrete mixture for additive printing. Fig. 4 shows the determined concrete strength.

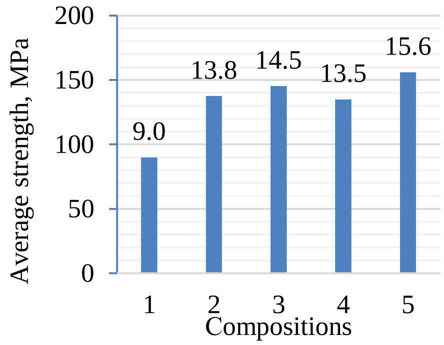


Fig. 4 Results of the concrete strength determination

From Tables 8 and 9, with sufficiently optimal W/C ratio (0.62) and cone precipitation (9 cm), the maximum strength of the concrete was 156 kgf/cm^2 which was achieved by replacing 27% of the aggregate with technogenic mineral formation.

At the final stage of research, at the site of additive technologies for the Center for Competence and Transfer Technologies in the field of construction and building materials of D. Serikbayev East Kazakhstan Technical University, small architectural forms were printed using a 3D printer S-6045.

Table 8. Concrete mix characteristics

Parameter name	Test result of composition 1	Test result of composition 2	Test result of composition 3	Test result of composition 4	Test result of composition 5
Water-cement ratio	0.61	0.66	0.63	0.68	0.62
Mobility	P2	P2	P2	P2	P2
Cone slump, cm	8.00	9.00	7.00	9.00	9.00

Table 9. Strength characteristics of the concrete mix

Parameter name	Test result of composition 1	Test result of composition 2	Test result of composition 3	Test result of composition 4	Test result of composition 5
Average strength, MPa	9.0	13.8	14.5	13.5	15.6

Products were printed according to constructed models from the composition containing 27% of technogenic mineral formation (composition No. 5). During the printing process, the following pattern was revealed for this 3D printer: the height of the structure should not exceed five layers at any time. A larger number of layers destroyed the form.

The small architectural forms that were installed on the territory of the university during operation (4 years) showed good mechanical strength, frost resistance, and moisture resistance. Fig. 5 shows the current types of products.

5. CONCLUSION

The presented work provides practical evidence for the application of additive technologies in construction. The main conclusions are as follows:

- Recommendations are provided to create a digital model for 3D printing, which will enable an ordinary engineer to create digital models to print structures of any configuration.

- The possibility of using a technogenic mineral formation (TMF) is confirmed when creating small architectural forms on additive technology. The optimal amount to replace the filler in a technogenic mineral formation is 27% for 3D printing, which will maintain or even increase the strength characteristics by up to 13%.

- When printing structures on a 3D printer model S-6045, the maximal number of layers to simultaneously print is five.

As a result of research on the created digital model, small architectural forms were manufactured using the technogenic mineral formation (TMF) as part of concrete, which showed good performance.

Studies on further applications of the TMF for 3D concrete mixes will be considered in relation to load-bearing building structures.

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(a) (b)

(c) (d)

Fig. 5 Small architectural forms made using 3D printer model S-6045: (a), (c), (d) examples of manufactured benches. (b) examples of manufactured vases

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