Construction Technology of Enclosing Structures by Means of 3D Printing with One-Stage Polystyrene Concrete

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Abstract. Today, layer-by-layer printing of enclosing structures with a 3D printer is the formation of a permanent formwork from a cement-sand mixture, followed by concreting and thermal insulation of the structure using standard technologies and widespread use of manual labor. Despite the use of robotization, 3D printing is only partially involved in the construction process and does not solve the issue of increasing labor productivity. This, and other disadvantages, hinders its widespread use in construction. 3D printing with one-stage polystyrene concrete is devoid of many traditional printing disadvantages, which allows forming a layer of heat-insulating and structural material over the entire wall width in one pass during the construction process. It was possible to overcome the inhomogeneity of a wall thermal conductivity due to the "cold bridges", lower layers spread that did not have time to grab and ability to work only at high temperatures. The approbation of the technology is demonstrated its feasibility and opportunities for improvement.

1. Introduction

3D printers and additive technologies development opened up new, unusual opportunities for various industries within the construction one. Layer-by-layer build-up of material by a computer-controlled 3D printer can dramatically reduce manual labor amount, total labor costs and increase productivity in general. Finally, an opportunity opened up to cope with the long-standing disease of construction - low labor productivity [1 - 4].

However, builders stopped at extruding the mortar on a cement binder through a printing press head with one nozzle and a round die, 16 years after Behrokh Khoshevnis proposed a robotic system for automated construction [5], came up with various designs of printers and print heads and tried cement mortars, clay, sand and polyurethane for these purposes. Controlled by a computer, the print head squeezes layer by layer onto the substrate a pasty strip with a circular cross-section of 30 ÷ 50 mm diameter [6]. But, it is difficult to create an insulated enclosing structure in one pass with such a tool. Therefore, builders everywhere came to 3D printing technology of monolithic fixed formwork of enclosing structures, which must be filled with structural concrete and thermal insulation, using manual labor. (Figure 1).
The task was only partially completed. At the same time, new problems were highlighted.

1. Settling and spreading of laid, but not set layer enough under the weight of new layers on its top. This problem forces the builders, after several passes, to stop giving the solution time to lose mobility. Declared pace of construction is falling. Extending captures in order to increase the time to deposit a new layer is limited by the printer reasonable size. The introduction of hardening accelerators is fraught with the setting of the solution in the system of its supply.

2. Temperature limits. The rate of the cement-sand composition setting and the strength sharply acquisition decreases with a temperature decrease in the ambient. 3D printer also slows down. We have to close the entire construction site with a greenhouse and heat inner space. All this complicates and increases construction cost in general. Continuation work is impossible at minus air temperatures, or it becomes many times more complicated.

3. "Bridges of cold". Facade and inner part of the wall, formed by 3D printer will simply fall apart, when insulating concrete is placed between them and even more the structural concrete without connecting elements. Today, fiberglass screeds are used as connecting elements, which are laid by hand, or more often - "snakes" from the same cement-sand mortar, extruded with the same print head. For even temperate climates, heat loss will be significant through the "cold bridges".

It is known that, the processes of cement hydration are accelerated as the temperature rises. The time for onset of setting is reduced, and cement-sand mixture loses its mobility faster [7]. An increase in the temperature of the cement-sand mixture during its laying can seriously affect adhesion of the laid layer during 3D printing and reduce or prevent its settlement and spreading of the laid layers altogether.

A product made of a hot mixture on a cement binder accumulates more heat energy than a structure made of cold material, cools for a longer time and, due to high temperatures, gains strength more intensively, especially in the initial period of hardening [8]. This means that it is possible to carry out 3D printing work without sheltering and heating the object under construction with sufficient massiveness, even in cold climates.

The experience of using "warm" concrete (gas and foam concrete) shows that walls of solid concrete provide good thermal protection with the required strength and do not require design solutions that subsequently form "cold bridges" with a known thermal conductivity.

Thus, in order to overcome the obstacles that arise, it seems reasonable, to use a hot mixture of heat-insulating concrete in 3D printing of enclosing structures, laid over the entire width of the wall with the maximum possible volume.

Confirm or refute this assumption, possibly by solving the following tasks:

1. Select heat-insulating concrete suitable for heat treatment and 3D printing.
2. Investigate the heat treatment - time modes, temperature, heater power and speed of the print head, providing 3D printing.
3. Design and test 3D printer head suitable for heating the mixture.
2. Mathematical processing of the research result

2.1. Polystyrene concrete 3D printing technology

One of the solutions that ensure the fulfillment of the assigned tasks is 3D printing, based on the technology of one-stage polystyrene concrete. The technology essence lies in mixing the components of the cement-sand mixture with granules of non-foamed polystyrene, preparing the components. Granules have the same density order as the solution. Therefore, they are evenly distributed throughout the volume in the mixing process. Furthermore, the granules under the action of the isopentane contained increase in volume by 20 ÷ 30 times with forced heating of the mixture, converting the cement-sand mortar into a structural and heat-insulating material - polystyrene concrete which products and structures are formed from. Moreover, you can easily adjust the strength and thermal conductivity of the material by changing the amount of polystyrene.

The technology developed at NSUACE (Sibstrin) was developed with the advent of additive technologies thirty years ago. It has been suggested that:

- polystyrene concrete, as a material with good strength and thermal insulation properties, will relieve it of the "cold bridges" typical for traditional 3D printing of enclosing structures simultaneously forming the body of a wall across its entire width;
- forced electric heating of the polystyrene concrete mixture at the laying up place to the swelling temperature of beaded polystyrene granules of 80 ÷ 85 °C will provide a rapid loss of its mobility and prevent sedimentation and spreading of the layer under the upper layers weight;
- polystyrene concrete heated to 80 ÷ 85 °C will intensively increase its strength, and it will cool for a long time with high heat capacity, increasing the hardening time to critical strength and thus will allow working without greenhouses;

A print head was designed to work with polystyrene concrete in order to implement the technology. The print head moves along the wall (Figure 2). A cement-sand mixture with corrective additives and uniformly distributed non-foamed polystyrene bead granules from an extruder is squeezed onto the substrate or a previously formed layer which is part of the print head, through a nozzle with a die in the shape of a rectangle, which large side is equal to the width of the wall being erected. The mixture entering the wall is held by two parallel metal spatula electrodes from lateral spreading, which are supplied with an alternating current of industrial frequency during the print head movement. A reactor is formed between electrodes, the wall surface to be erected and the pressing dielectric spatula, which determines the thickness of the layer to be laid, where the cement-sand mixture with non-foamed polystyrene granules is converted into polystyrene concrete. This is due to the rapid increase in the temperature of the mixture caused by its forced electric heating.

An experimental model of the 3D printer's print head was made, layer-by-layer forming the enclosing structure with polystyrene concrete in order to test the technology operability in laboratory conditions (Figure 3).

The studies were carried out on the strength, thermal conductivity and uniformity of expanded polystyrene granules distribution by weight of polystyrene concrete, obtained by extrusion to assess the feasibility of using polystyrene concrete and forced heating for 3D printing of heated buildings’ walls. The warm-up time, electrical power during heating and the speed of the print head were also investigated.
Figure 2. Print head of 3D printer for extruding polystyrene concrete mixture, a - general image of the print head; b - schematic diagram of the print head operation, where: 1 - extruder; 2 - preliminary heating system of the binding material; 3 - binder material supply system; 4 - outlet nozzle; 5 - spatula electrodes; 6 - cables for power supply of electrodes; 7 - electrical network; 8 - pressing spatula; 9 - non-foamed polystyrene concrete mixture; 10 - foamed polystyrene concrete mixture; 11 - formed layer of polystyrene concrete.

Figure 3. Testing the 3D printer's print head, printing with polystyrene concrete. a - general image; b - testing.

2.2. Strength and heat engineering characteristics of polystyrene concrete, obtained by 3D printing

The main parameters of polystyrene concrete as a material for arranging the heated buildings’ walls are strength, thermal conductivity and stability of thermal insulation properties - the uniformity of insulation granules distribution over the volume.

The strength characteristics of the material were investigated on cube specimens with an edge 70 mm long cut in accordance with GOST 10180-2012 “Concrete. Methods for determining the strength of control samples” from a polystyrene concrete layer with a thickness of 70 mm, formed by the print head. A series of three samples for testing were made in the period of 3, 7, 14 and 28 days for polystyrene concrete of two densities D700 and D1200. Central compression tests were carried out on a PSU-50 laboratory press. The test results are shown in Table 1.
Comparative analysis shows that the strength of medium density polystyrene concrete D700 corresponds to and exceeds the average compressive strength of aerated concrete (3.62 MPa at D550), and the strength of medium density polystyrene concrete D1200 corresponds to the strength of expanded clay concrete (10.54 MPa at D1300).

| Average density, kg / m$^3$ | Compressive strength of polystyrene concrete (MPa) in the period of |
|----------------------------|---------------------------------------------------------------|
|                            | 3 days | 7 days | 14 days | 28 days |
| D1200                      | 3.95   | 7.57   | 9.03    | 12.90   |
| D700                       | 2.66   | 5.17   | 5.98    | 7.84    |

Thermal conductivity of polystyrene concrete with density D700 and D1200 was determined using a device for measuring thermal conductivity PHTh-2 (HS 4276-155-56835627-10) according to a standard technique on samples 250 × 250 mm thick 50 mm collected from layers of polystyrene concrete, formed by the 3D printer’s print head with careful fitting and sealing of joints with cement-sand mortar. The test results are shown in Table 2.

| Average density, kg / m$^3$ | Thermal conductivity of polystyrene concrete (W / (m × K)) for samples |
|----------------------------|---------------------------------------------------------------|
|                            | №1 | №2 | №3 | average |
| D1200                      | 0.1950 | 0.1961 | 0.1958 | 0.1957 |
| D700                       | 0.1269 | 0.1268 | 0.1277 | 0.1271 |

An important parameter for polystyrene concrete is the uniformity assessment of the polystyrene granules distribution over the volume of the material. The studies were carried out using the PHTh-2 device, by measuring the thermal conductivity of flat samples cut from the D700 and D1200 molded by 3D printer for medium density. The test results are shown in Table 3.

| Average density, kg / m$^3$ | Thermal conductivity of polystyrene concrete (W / (m × K)) for samples | Layering, % |
|----------------------------|---------------------------------------------------------------|--------------|
|                            | №1 | №2 | №3 |                     |
| D1200                      | 0.1950 | 0.1961 | 0.1958 | 3.65 |
| D700                       | 0.1269 | 0.1268 | 0.1277 | 1.53 |

Preliminary studies of the strength, heat engineering characteristics of 3D printed polystyrene concrete and its homogeneity show the satisfactory quality of the material for load-bearing enclosing structures in low-rise buildings and for self-supporting walls in high-rise construction.

2.3. Technology parameters
A feature of 3D printing technology with polystyrene concrete is forced heating in contrast to standard 3D printing with cement-sand mortar. The polystyrene concrete mixture getting from the extruder into the thermoreactor becomes a conductor with a function of an electric current possessing. In this process the release of thermal energy occurs faster or slower and the material heats up, depending on the electrical resistance of the mixture. Polystyrene softens, heated to a temperature of 80 ÷ 85 °C, and changing the material properties under the action of isopentane bead polystyrene boiling in the pores the granules swell.

Optimal heat treatment parameters are required for a reasonable print speed and efficient use of energy: warm-up time and rate, associated with electrical power heated, as well as the speed of the print head. Experiments of warming up a standard cement-sand mixture in a printhead reactor at an allowable voltage of 150V showed a very low rate of temperature rise, unacceptable for the required pace of construction. In order to change the resistivity, as well as to accelerate the setting, technical
potassium carbonate $\text{K}_2\text{CO}_3$ (potash) was introduced into the mixture in an amount of 2.4% of the cement mass. As a plasticizer, a mineral additive PP100 was used, developed specifically for operation at high temperatures, in an amount of 0.8% and 1.6% of the cement mass. The compositions of the mixtures are shown in table 4.

Table 4. Compositions of polystyrene concrete.

| № Compositions | Portland cement M500, kg / m$^3$ | Sand, kg / m$^3$ | Water, l / m$^3$ | Expanded polystyrene (APG), kg / m$^3$ | $\text{K}_2\text{CO}_3$, (potash) % of m cement | PP100, % of m cement | Liquid soap, % of m cement |
|----------------|----------------------------------|-----------------|-----------------|----------------------------------------|----------------------------------|-----------------|---------------------|
| 1.             | 720                              | 370             | 247             | 17.4                                   | -                                | -               | -                   |
| 2.             | 720                              | 370             | 247             | 17.4                                   | 2.4                              | 0.8             | 0.8                 |
| 3.             | 720                              | 370             | 247             | 17.4                                   | 2.4                              | 1.6             | -                   |
| 4.             | 720                              | 370             | 247             | 17.4                                   | 2.4                              | -               | -                   |
| 5.             | 720                              | 370             | 247             | 17.4                                   | 2.4                              | -               | -                   |
| 6.             | 720                              | 370             | 247             | 17.4                                   | 2.4                              | -               | -                   |

The rate of temperature rise (Figure 4) changed significantly with the additives addition. The time from of the heating start to the beaded polystyrene granules opening was reduced to 8 ÷ 10 minutes, which became acceptable for the production of works.

Figure 4. Graph of the temperature rise in the heated mixture for different compositions of polystyrene concrete.

At the same time, the consumed current changes, depending on the combination of additives (Figure 5), which can serve as a good guide, control the heat treatment of concrete and the speed of the print head movement. The given dependences indicate the wide possibilities of controlling the mixture heating rate in the print head, the speed of its movement and the consumption of electricity by introducing corrective additives into the composition.

Figure 5. Graph of changes in the nature of current consumption during the mixture heating for various compositions of polystyrene concrete.
The study obtained results of the temperature rise, the loss of the mixture mobility and the complete expansion of beaded polystyrene granules made it possible, in a first approximation, to estimate the maximum possible speed of the print head depending on the mixtures compositions used and technological parameters.

\[ v_{m,g} = \frac{l_{heat.el.}}{v_{t.rise.} + t_{pol.f.}}; \]

\[ v_{m,g} = \frac{l_{heat.el.}}{T_{pol.f.} - T_{start.} - t_{pol.f.}}; \]

Subject to the condition

\[ T_{pol.f.} \cdot T_{start.} \cdot v_{t.rise.} + t_{pol.f.} \geq t_{full.f.}; \]

where:

- \( T_{pol.f.} \) - temperature of polystyrene transition to a viscous-flowing state and the beginning of beaded polystyrene granules foaming, \( T_{pol.f.} = 80-85^\circ C \);
- \( T_{start.} \) - temperature of the mixture before the electric heating start (mixture temperature in the hopper);
- \( v_{t.rise} \) - rate of temperature rise by the mixture;
- \( t_{full.f.} \) - complete time expansion of polystyrene granules in the mixture, \( t_{full.f.} = 6 \text{ min} \);
- \( l_{heat.el.} \) - heating element length, in the developed design of the print head the electrode spatulas length \( l_{heat.el.} = 40 \text{ cm} \);
- \( t_{full.f.} \) - complete loss time of the mixture mobility.

### 3. Results

1. 3D printing modern practice of buildings’ enclosing structures has come to the layer-by-layer molding of a cement-sand mortar, a permanent formwork of walls, which requires the subsequent filling of the formed cavities with structural reinforced concrete and insulation according to the traditional technologies with high costs of manual labor.

2. Layer-by-layer of a cement-sand mortar with a print head with a round die is complicated by the spread of the laid layer before setting under the pressure of the above-laid layers, a decrease in the rate of strength acquisition at low positive and even more minus temperatures, as well as the appearance of connecting elements between the outer and inner parts of the wall "Cold bridges".

3. 3D printing of enclosing structures with one-stage polystyrene concrete with forced electric heating of the mixture provides a uniform heat-insulating structure of the material and the robotic device possibility of the wall at once for its entire width, without "cold bridges" rapid loss of the layer mobility before laying the next one and creates conditions for the accelerated acquisition of strength without additional cover and heating.

4. 3D printing with polystyrene concrete allows you to obtain a monolithic wall with good structural and thermal insulation properties with minimal labor costs, which are easily controlled by the amount of polystyrene in the mixture.

5. The developed printer’s print heads can form a wall of a predetermined width, and the corrective additives can adjust the speed of movement and thus the construction pace.

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