High-strength lightweight concrete with internal curing for 3D-printing in construction

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Abstract. In the global information space there is a positive trend in the number of publications devoted to the technology of building 3D-printing. As functional additive for internal care of concrete superabsorbent polymer (SAP) can be used. It was found that the mobility of high-strength lightweight concrete mixtures with SAP is decreased in contrast to cement pastes. The decrease of the spread diameter of the concrete mixture with an increase of the SAP content to 2.3 % by weight of Portland cement is to 20 %. The SAP content of less than 1.5 % by weight of Portland cement provides the required mobility of the concrete mixture and the average density of high-strength lightweight concrete. Taking into account the requirements for the strength of the studied concrete, the optimal content of SAP is 1.0-1.5 % by weight of Portland cement. The efficiency of the use of solutions of superabsorbent polymers for reducing shrinkage deformations of the concrete in contrast to granular SAPs is proved. This is especially actual for concrete used in adverse hardening conditions of Portland cement, for example in 3D-printing in construction. It was shown that the concentration of SAP less than 1.5% by weight of Portland cement allows to ensure the mobility of the mixtures and preservation of concrete strength.

1. Introduction
In the global information space there is a positive trend in the number of publications devoted to the technology of building 3D-printing [1...8]. In fact, the technological feature of such technology can be called a combination of the manufacturing principles of non formwork and monolithic constructions. On the one hand compositions with desired viscous-flowing properties are used and on the other, a massive continuous volume of concrete mix is molded directly at the construction site (figure 1). However, this approach makes difficult to care concrete because environmental protection is lack.
The production of concrete structures by extrusion directly at the construction site is associated with the appearance of an open surface area of the finished product. The lack of external care under such conditions creates unfavorable background for the hydration of Portland cement. Intensive loss of moisture due to evaporation leads to a lack of water for structure formation and subsequently to decrease in concrete density and strength, resistance of shrinkage and cracking.

Providing a reserve of water in the particles of the porous aggregate for can reduce the effect of the indicated disadvantages. This approach is known in lightweight concrete technology [9…11]. Pre-saturation of the aggregate by water until the preparation of lightweight concrete allows to reduce the risk of cracking in the early stages of structure formation due to shrinkage. The use of lightweight concrete for 3D printing technology is justified not only by technical and economic efficiency [12] but also by the ability to ensure the functionality of printed constructions due to high operational properties [14…15]. The low average density of high-strength lightweight concrete is an additional advantage to reduce the load on freshly extruded structures from the upper layers during 3D printing. However, the use of hollow microspheres as a lightweight aggregate in such concrete limits the possibilities for internal curing. The lack of open porosity of the microspheres limits the use of special additives.

As functional additive for internal care of concrete superabsorbent polymer (SAP) can be used [16…18]. As a rule, SAPs are microsized granules or fibers capable to absorb water up to 50 times from original volume. Preservation of moisture in the volume of concrete in the early stages of hardening reduces the shrinkage from 12 to 70 % [19…22]. The greatest effect of inhibition of shrinkage appears at the age of 28 days. However, the SAP absorption requires the excess water up to 20 % to keep the mobility of the concrete mixture [20]. Additional porosity leads to a decrease in concrete strength by 10-35 % [21, 22] due to the large W/C and a decrease in the volume of SAP particles after desorption.

Thus, the combined solutions for building "inks" for 3D-printing with hardening under adverse conditions can be the modification of high-strength lightweight concrete on hollow microspheres by superabsorbent polymers. In this case the use of solutions of acrylate polymers with changeable polymerization rate should be used as an additive for internal care that reduces concrete shrinkage.

2. Material and methods
In this paper, the influence of a solution of a superabsorbent polymer on the properties of high-strength lightweight concrete is studied. The concretes were made in accordance [23] using Portland cement CEM I 42.5 “Lipetskcemment”, silica fume MK-85 with a particle size of 1-100 microns, quartz sand 0.16-0.63 mm and quartz sand flour with a specific surface of 700-800 m²/kg, water and polycarboxylate plasticizer “Melflux 1641F”. Hollow glass microspheres “ForeSphere 3000” with a
particle size of less than 0.2 mm and a strength of more than 20 MPa were used as a lightweight aggregate to reduce the average density of concrete.

The multi-component acrylate composition “Renovir hydrogel” used for injection drainage of structures, it is proposed to use as SAP. The SAP solution is obtained by mixing water (W) with the three components of the polymer part (ΣA = A1 + A2 + A3) and catalyst (B). The component “A1” is acrylic acid (propenoic acid CH2=CH–COOH) or salt (sodium polyacrylate [-CH2–CH(COONa)]n). The component “A2” is a crosslinking agent in which poly-saturated compounds are widely used. The component “A3” is an initiator from peroxides, hydroperoxides, hydrogen peroxide, persulfates, azo compounds or redox systems.

The mobility of cement mixtures was determined by the diameter of the spread from a truncated cone. The study of the physico-mechanical properties of cement stone was carried out at the age of 28 days after hardening under adverse conditions (temperature – 30±1.0°C, humidity – less than 10±2.5 %) using prism samples 40×40×160 mm according to the table 1.

### Table 1. The ratio of the components of SAP in concrete composition

| Ratio | Value |
|-------|-------|
| W/C   | 0.24  |
| B/A1  | 0.06  |
| W/ΣA  | 95.0  |
|   -   | 47.0  |
|   -   | 23.0  |
|   -   | 15.0  |
| SAP/C, % | 8.5 |
|   -   | 0.4   |
|   -   | 0.8   |
|   -   | 1.5   |
|   -   | 2.3   |
|   -   | 3.9   |

Note. Ratio A2/A1 = 0.02 and A3/A1 = 0.08.

The relative deformation of shrinkage was determined using a longitudinal horizontal comparator IZA-2 as the ratio ε = Δl/l, where Δl is the change of the distance between the benchmarks at the age of 28 days, l is the base distance between the benchmarks at the age of 2 hours. Acoustic emission signals were recorded using the “Malachite AS-15A” acoustic emission system during mechanical testing of concrete. The device includes receivers, a preliminary and main amplifier, a bandpass filter (20 and 96 kHz), an analog-to-digital converter (192 kHz), and a noise suppression circuit.

### 3. Results and discussion

The ensuring of mobility of the mixture and high strength of the composite after extrusion is an important condition for the development of materials for 3D printing. The use of SAP solutions with controlled time of polymerization should provide is designed rheological properties of the mixture in contrast to granular superabsorbent additives. The results of the study of high-strength lightweight concrete (average density is 1400 kg/m^3) with a SAP solution of various concentrations are presented in table 2. It was found that the mobility of concrete mixtures of high-strength lightweight concrete with solution of SAP is decreased in contrast of effect on cement pasts. The spread diameter of the mixture is decreased by 20 % at the increasing of the polyacrylates concentration more than 2.3 % by weight of Portland cement. This consistent pattern may be associated with a significant contribution of the plasticizer to ensure the rheological properties of such compositions.

### Table 2. Rheological properties of the mixtures and physical and mechanical properties of cement stone with SAP

| W/ΣA | ΣA/C, % | D_sp, mm | ρ, kg/m^3 | R_f, MPa | R_com, MPa | ε, mm/m |
|-------|---------|----------|-----------|----------|------------|---------|
| 1     | –       | 225      | 1370      | 5.50     | 45.3       | 12.2    |
| 2     | 95      | 0.4      | 212       | 1360     | 5.60       | 45.2    | 11.6   |
| 3     | 47      | 0.8      | 199       | 1360     | 5.80       | 47.8    | 10.2   |
| 4     | 23      | 1.5      | 181       | 1355     | 6.85       | 47.6    | 10.0   |
| 5     | 15      | 2.3      | 180       | 1355     | 6.35       | 44.2    | 9.5    |
| 6     | 8.5     | 3.9      | 170       | 1325     | 6.00       | 37.1    | 8.9    |

Notes: D_sp is a spread diameter, ρ is the average density, R_f is the flexure strength, R_com is the compressive strength, ε is the relative deformation at the age of 28 days.
One of the possible reasons of decreasing in the mobility of the concrete mixture may be the poor compatibility of the plasticizer and SAP components. However, a study of the surface tension of plasticizer solution with different concentrations of SAP shows the compatibility of these additives. (table 3).

**Table 3.** The dependence of the surface tension of the plasticizer solutions on the content of the acrylate part of the SAP

| State of the SAP          | Concentration of SAP solution, W/ΣA |
|---------------------------|------------------------------------|
|                           | 0 | 95.0 | 47.0 | 23.0 | 15.0 | 8.5 |
| Before polymerization     | 47.5 | 44.5 | 44.4 | 43.7 | 43.4 | 42.5 |
| After polymerization      | 45.2 | 45.0 | 44.6 | 44.5 | 43.0 |

Note. Concentration of plasticizer solution (Melflux 1641F) is 0.04 %.

It was found that each of the components of the solution (polycarboxylate plasticizer and acrylate SAP) reduces surface tension, regardless of the degree of SAP polymerization. This indicates the mutual compatibility of the plasticizer Melflux 1641F and SAP components and the possibility of their effective combination for mixtures and products of high-strength lightweight concrete.

The table 2 shows that the studied compositions have sufficient mobility of the mixture ($D_{ap} > 150$ mm) to perform technological operations. In this case both the laying and the shape preservation can be ensured (Figure 2). The rational concentration of SAP in the compositions of mixtures for 3D-printing should not exceed 1.5% by weight of Portland cement.

![Figure 2. An example of extruded layers of high-strength lightweight concrete with SAP](image)

As shown in [16...22], the use of granular SAP leads to a decrease in the strength properties of cement composites. This is due to the formation of additional porosity in the structure of the material after desorption of water from the polymer additive. Therefore, the use of SAP solutions to reduce shrinkage deformations can be justified by maintaining of the mechanical characteristics. The dependences of the flexural and compression of high-strength lightweight concrete on the amount of SAP are presented in table 2. It was found that the use of the SAP solutions in an amount of 0.50-1.0% by weight of Portland cement provides the smallest decrease in concrete strength. After hardening under adverse conditions (temperature – 30±1.0°C, humidity – less than 10±2.5 %) for 28 days such concrete has the flexural strength in the range 5.5-5.8 MPa and compressive strength 45.3-47.8 MPa.

The acrylate content of up to 2.3 % by weight of Portland cement in the concrete composition provides an increase in flexural strength up to 17 %. This can be explained by the reinforcing effect of polymer films or fibers in the structure after desorption. Moreover, an increase in the concentration of more than 1.5% by weight of Portland cement leads to a decrease in the compressive strength by 8.5%.
Hence, the allowable amount of SAP in the concrete is limited to 1.0-1.5 % by weight of Portland cement.

The study of shrinkage deformation of high-strength lightweight concrete was carried out after exposure for 28 days under conditions of intense moisture loss in a ventilated climatic chamber. The use of SAP solutions allows to reduce the shrinkage strain of high-strength lightweight concrete by 25 % including at low concentrations (up to 0.25 % by weight of Portland cement). The maximum decrease in shrinkage compared with the control composition is achieved at the SAP concentration of 2.3 %. Given the changes in the rheological and physico-mechanical properties, the varying the SAP concentration in the range of 0.8-1.5 % by weight of Portland cement provides the best amount of shrinkage.

Figure 3 shows the acoustic emission energy curves of high-strength lightweight concrete with SAP. Each curve has stages with different intensity. The changes in the intensity for studied compositions are characterized close limits. However, the composition of high-strength lightweight concrete with a maximum acrylate content of 3.9% by weight of Portland cement is an exception. Stage III occurs at a lower external load. This characterizes early destruction of the material compared with the rest of the compositions and indicates the negative effect of the SAP solution in such concentration.

![Figure 3](image)

**Figure 3.** The dependence of the AE energy of high-strength lightweight concrete on the load at the varying the SAP concentration

Thus, AE studies of high-strength lightweight concrete with SAP allow that the solutions of acrylate polymer have a minor effect on the defectiveness of the composite. It was found that the limit concentration of SAP solutions is 3.9 % at which a shift in the AE energy curve is observed.

### 4. Conclusions

It was found that the mobility of high-strength lightweight concrete mixtures with SAP is decreased in contrast to cement pastes. The decrease of the spread diameter of the concrete mixture with an increase of the SAP content to 2.3 % by weight of Portland cement is to 20 %. The SAP content of less than 1.5 % by weight of Portland cement provides the required mobility of the concrete mixture and the average density of high-strength lightweight concrete. Taking into account the requirements for the strength of the studied concrete, the optimal content of SAP is 1.0-1.5 % by weight of Portland cement.

The efficiency of the use of solutions of superabsorbent polymers for reducing shrinkage deformations of the concrete in contrast to granular SAPs is proved. This is especially actual for
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References
[1] Zhang Yu, Zhang Yu, She W, Yang L, Liu G, Yang Yo 2019 Construction and Building Materials 201 pp 278-285
[2] Vatin N I, Chumadova L I, Goncharov I S, Zyкова V V, Karpenya A N, Kim A A, Finashenkov E A 2017 The construction of unique buildings and structures 1 (52) pp 27-46
[3] Jayathilakage R, Rajeev P, Sanjayan J G 2020 Construction and Building Materials 240 pp 17989
[4] Mechtherin V, Nerella V N, Will F, Nather M, Otto J, Krause M 2019 Automation in Construction 107 pp 102933.
[5] Inozemtcev A S, Korolev E V, Duong T Q 2018 IOP Conference series: Materials science and engineering 365 pp 032009.
[6] Nerella V N, Mechtherine V 2019 3D Concrete Printing Technology pp 333-347
[7] Panda B, Singh GVP B , Unluer C, Tan M J 2019 Journal of Cleaner Production 220 pp 610-619
[8] Marchment T, Sanjayan J 2020 Automation in Construction 109 pp 102992
[9] Zou D, Li K, Li W, Li H, Cao T 2018 Construction and Building Materials 163 pp 949-959
[10] Cusson D, Hoogeveen T 2008 Cement and Concrete Research 38 (6) pp 757-765
[11] Browning J, Darwin D, Reynolds D, Pendergrass B. 2011 ACI Materials Journal 108 (6) pp 638-644
[12] Inozemtcev A S, Duong T Q 2019 E2S Web of Conferences 97 02010
[13] Shatornaya A M, Chislova M M, Drozdetskaya M A, Ptuhina I S 2017 The construction of unique buildings and structures 9 (60) pp 22-30
[14] Inozemtcev A S 2014 Magazine of Civil Engineering 51(7) pp 31-37
[15] Inozemtcev A 2015 IOP Conference Series: Materials Science and Engineering 71(1) pp 012028
[16] Dang J, Zhao J, Du Z 2017 Polymers 9 (12) pp 672
[17] Shan J, Guo Sh 2015 International Symposium on Material, Energy and Environment Engineering (ISME 2015) pp 154-157
[18] Mignon A, Snoeck D, Dubruel P, Vlierberghe S V, Belie N D 2017 Materials (Basel) 10 (3) pp 237
[19] Klemm A J, Almaid F S R, Sicora K S 2016 CPI – International Concrete Production 4 pp 44-52
[20] Schröfl Ch, Mechtherine V, Gorges M 2012 Cement and Concrete Research 42 (6) pp 865-873
[21] Wang F, Yang J, Hu S, Li X, Cheng H 2016 Cement and Concrete Research 81 pp 112-121
[22] Liu H, Bu Y, Sanjayan J G, Nazari A, Shen Zh 2016 Construction and Building Materials 112 pp 253-260
[23] Korolev E V, Inozemtcev A S 2012 Patent RF 2515450 p 3