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MODIFICATION OF PROPERTIES OF FRESH MIXTURE FOR 3D PRINTING USING CEMENT-BASED MORTAR

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Abstract. Portland cement is traditional binding material which is applicable for various modern technologies in these days – the 3D printing is one of them. The development of 3D printers using cement-based materials for the manufacturing of structural elements and moreover entire building is novel concept of structural engineering, which combines advanced material solution and high level of automation. This paper is focused on the study of properties of fresh mixture in order to control its consistency and regime of setting time to achieve continual process of 3D printing. The properties of fresh mortar were modified by the admixture accelerating the process of hardening and stabilizing agent. The performed experimental program showed that both applied admixtures could be used for the control of the consistency of fresh mortar to achieve optimal shape of mortar layer after its extrusion.

Keywords: Accelerating admixture, stabilizing admixture, setting time, flow table, concrete 3D printing.

1. Introduction

3D concrete printing is a novel approach in the field of manufacturing of structural elements, alternatively entire buildings, using printing machine and cementitious mixture.

There are available several technical concepts for 3D concrete printing [1–5], however the admixture printing seems to be the most frequently used worldwide. The crucial aspect of additive 3D concrete printing is the soft dosage of chemical admixture into the printing nozzle shortly before an extrusion of printing material [1]. Such a measure allows to control the process of hardening or modification of the consistency, and other rheological properties of fresh mixture to achieve required plasticity in case of using accelerating and stabilizing admixture [6]. Alternatively, could be added mixing water, however that logically leads to the reduction of mechanical properties of hardened mixture, which can be controlled by the use of a plasticizing admixture [7].

The addition of accelerator into the printing nozzle has several advantages. Utilization of this kind of chemical admixture causes an increase of strength development, an increase the temperature of fresh mixture, reduces the consistency, what could lead to the defects during printing [5, 8, 9]. The 3D concrete printing is based on the gradual placing of concrete layer by layer. Thus, the fresh mixture has to exhibit tougher consistency, in comparison with traditional concrete, to load following layers without immense deformation or loss of the stability.

That is why, the stabilizing agents are widely used to modify the consistency of fresh mixture. Usually, these admixtures are integral part of the other admixtures used during mixing, however their application into the printing nozzle could increase the applicability of 3D concrete printing, because the stabilizer increases the loadbearing capacity of freshly layered mixture, thus higher number of layers exhibit vertical stability after the printing.

The process of 3D printing is highly automatic, where the speed of printing, respectively movement of the nozzle, has to respect the shape and dimensions of the final element. The speed of printing could be basically derived according to Equation 1,

$$v \ \leq \ L_L \cdot t_s \frac{N}{60}, \tag{1}$$

where v [m s^{-1}] is the linear movement of the printing nozzle, L_L [m] is length in one layer, t_s [min] is the setting time of extruded mixture, N is the number of following layers exhibiting stability in fresh state. The performed experimental program was focused on the optimization of dosing accelerator and stabilizing agent to maximize the speed of 3D printing.

2. Experimental program

The experimental program was focused on the modification of mixture used using 3D printing of entire concrete structures, Figure 1, which was developed during the collaborating with Podzimek a synové and Strojirny Podzimek Ltd. This type of 3D printer is designed for the printing of larger structures under external conditions. The technology of admixture 3D printing allows to control process of hardening and the consistency of fresh mixture to achieve higher homogeneity of the 3D printing. The sense of the continual control is given by the changing external condition.

Figure 1. 3D printer (Třešť).

2.1. Methods

Initially, the flow rate of the mixtures was quantified. This procedure contains of positioning a metal cone at the center of the shaking table and subsequently filling it with mixture in two stratified layers. Each layer is uniformly compacted using light taps from the choke. Excess mixture is then removed, and the surrounding area is meticulously cleaned. The cone is lifted vertically, allowing the mixture to spread across the table surface through 15 consistent impacts at a fixed frequency. The final flow is measured along two orthogonal axes.

The setting time was determined using the Vicat apparatus. Vicat's ring was filled with a fresh mixture and the setting time was determined using a Vicat needle. For the purpose of this test, a non-standard needle with an enlarged area of 2 mm diameter was chosen, as it was not only the paste (a mixture of binder and water) that was tested, but a pre-prepared industrial mixture of a specific composition. It was necessary to use this modified needle for this mixture as the standard needle did not provide meaningful data. The start of setting time was that takes from the addition of water to the mixture until the Vicat needle remains suspended 3 to 5 mm above the substrate.

2.2. Materials

For the purpose of the experiment, an industrially produced mixture from company Stachema CZ was used. This product is supplied as a dry mixture, which is bagged to protect it from moisture. It is further dosed separately on site and mixed with water to the desired consistency required by the 3D printer. This mixture is composed of Portland cement-based binder, fibers, fillers and admixtures. The specific composition is protected by the know-how of the company.

For the purpose of regulating the setting time and flow, a liquid accelerator was used, which was manufactured by the same supplier, i.e. Stachema CZ. The same manufacturer of the dry mixture and the accelerator ensures the compatibility of both components and their efficient use. The accelerator dosage was gradually increased to monitor changes in the behavior of the mixture. The rest of the composition, including the water dose, was kept constant.

A stabilizing admixture as a viscosity modifying agent was further tested to control the flow without affecting the setting time. This admixture was again manufactured by the same company Stachema CZ for the purpose to achieve compatibility of all components. The tested stabilizing admixture was cellulose-based used in a dry, powdered form. For the purpose of the experiment, the stabilizing admixture was dosed separately along with the priming mixture and water. The dosage of water and mixture was constant, the dosage of the stabilizing admixture was varied.

3. Results and discussion

3.1. Flow rate

The use of the accelerator in smaller doses did not have a negative effect on the flow. A reduction in the flow rate was observed only when the dose exceeded 0.6 % of the cement weight. When this limit was exceeded, the final flow rate decreased with increasing accelerator dose, see Figure 2. The mixture with a 100 mm flow rate exhibited a very stiff consistency that would be difficult to work properly.

Similar results were achieved by I. Dressler et al. [1]. They monitored the rheological properties using initial

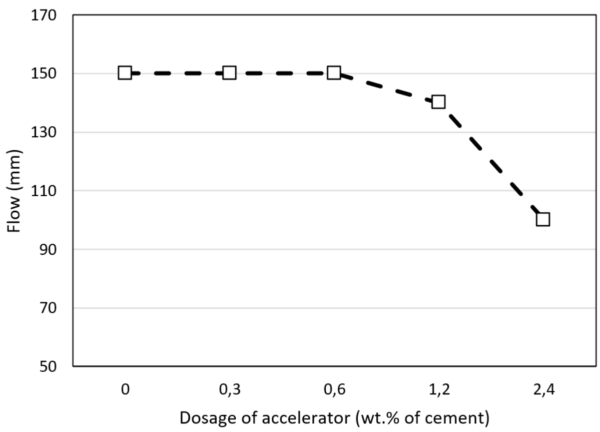

Figure 2. The influence of accelerator on the consistency.

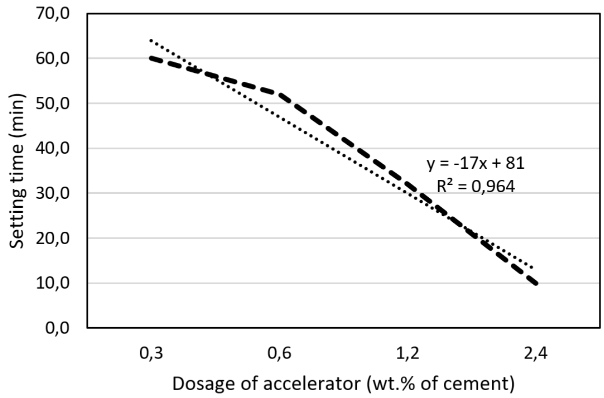

Figure 3. The influence of accelerator on setting time.

yield stress. An increase in accelerator dosage leads to an increase of initial yield stress.

The same trend of decreasing consistency with increasing accelerator content was also observed in the research by S. Ramakrishnan et al. [10]. In this research, the encapsulated accelerator was used into the mixture. The mixtures containing accelerator in dose of 1.5 and 2.5 % by weight of cement showed lower flow than the reference mixture without accelerator. They noted that it could be also due to the presence of large elongated capsules that reduced the cohesiveness of the mix.

Reduced flow can cause discontinuity of the printed trace during the 3D printing process, problems with the transport of the mixture through the device and even complete blocking of the print head. Therefore, this parameter needs to be monitored. The critical flow value will then depend on the final technical design of the device.

3.2. Setting time

The acceleration of the setting time of the mixture with increasing accelerator content was expected result. Up to a dosage of 0.6 % by weight of the cement showed a slower acceleration. After exceeding this dosage, an increased acceleration effect was observed as can be seen in Figure 3.

At a high dose of 2.4 % by weight of the mixture, the setting time was accelerated to only 10 min. However, with such a high ramp-up rate, the flow rate was also significantly reduced. These two factors are interdependent and therefore it is always necessary to monitor and achieve the desired properties in both areas.

This behavior is also described in work by A. U. Rehman et al. [9]. They monitored the setting time using the ultrasonic pulse velocity method (UPV). The result shows that dose of 7.5 % of accelerator demonstrated a sharp increase in the UPV during the first day. The rapid increase in the UPV value indicates a quick transformation of the accelerated mixture from the liquid state to the solid state and enhanced connectivity in its solid particles during the first day.

3.3. Stabilizing effect

The stabilizing admixture is intended, by its very nature, to limit the flow. This effect was confirmed when this admixture was used in the 3D printing mixture. The final flow rate decreased with increasing percentage of stabilizing admixture, see Figure 4. It should be noted that a constant water dose was maintained for all samples in the experiment.

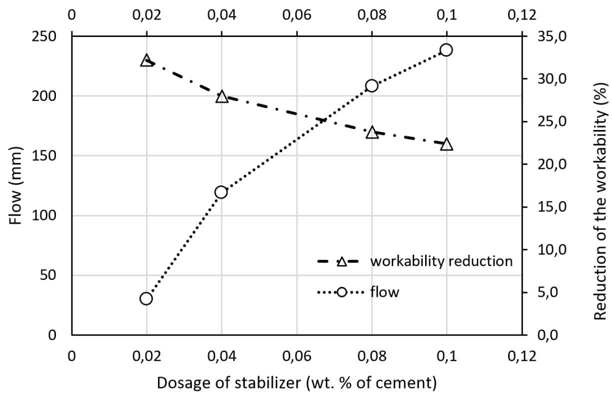

Figure 4. The influence of stabilizing agent on the consistency.

At a dose of stabilizing admixture of 0.02 % by weight of cement, a flow rate of 230 mm was achieved; when the stabilizing admixture was dosed at a high dose of 0.1 % by weight of cement, a flow rate of 160 mm was achieved, which represented a decrease in flow rate of almost 35 %.

C. Brumaud et al. [11] were also noted that the stress level or rigidity of the system is reduced when cellulose ether is added to the paste. This suggests that cellulose ethers have a priori an effect on the contribution of the nucleation of hydrates between cement grains. According to research C. Brumaud et al. [12] the increasing the amount of cellulose ether also increased the viscosity in the distilled water. Among others, this research reports the fact that the specific composition of the viscosity enhancing agents itself has a major influence on the changes in the rheological properties of the cement mixture.

The results show that this type of stabilizing admixture effectively influences the final flow and can effectively control the required final flow with respect to the requirements of the 3D printer.

4. Conclusion

The experimental program dealt with the possibilities of the consistency control using advanced chemical admixtures in relation to concrete 3D printing. Two types of admixtures, which could be added into the printing nozzle were studied. From the results obtained it is evident that the final flow and the setting time can be effectively influenced by the use of the proper admixture. If it is necessary to influence the setting time, accelerator can be effectively used. The importance of using the accelerator is motivated by the printing of smaller elements to ensure load capacity of layered concrete. Along with this parameter, however, the mixture flow rate is also influenced, which must be considered and evaluated if the 3D printer is capable of operating with such flow rates. If we only need to affect the flow, thus the workability, the stabilizing admixture has worked effectively. This admixture allowed to reduce the flow rate by up to 35 % with respect to the selected dose. The final dose will depend on the requirements of the 3D printer itself and the requirements for the final consistency of the printed trace. The combination of both chemical admixtures will be studied in detail during further research.

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