Assessment method for fresh concrete spreadability

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Abstract. The results of studies of the fresh concrete spreadability using 3D printing of construction products are presented. The 3D printer is an automated device for the construction of buildings and erections, the manufacture of specific structures and products by the method of three-dimensional printing of fine-grained fiber-reinforced concrete with special additives, sand concrete, geopolymer concrete, etc. Assessment methods for the concrete consistency occurring during installation are considered. The applied methods for assessing the spreadability of fresh concrete take into account only its own mass of concrete and do not reflect dynamic processes. The use of the ultrasonic method allows mass testing of products of any shape repeatedly, to continuously monitor the growth or decrease in strength. The disadvantage of this method is the error in the transition from acoustic characteristics to strength. The spreadability of the concrete mixture is estimated depending on the amplitude-frequency characteristics. The dependences of the amplitude of vibrations and accelerations of the paver hopper on the density of the concrete mixture are given. Particular optimization of vibration accelerations by the amplitude of the oscillations of the hopper walls, the amplitude of the oscillations of the charge layers and the stiffness of the vibration dampers is performed.

1. Introduction
Currently, there is a great interest in the use of additive technologies (three-dimensional printing) in various areas of production. Due to the possibility of using a 3D printer in the design and manufacture of objects of various geometric shapes and sizes, the manufacture of prototypes of products to assess assembly safety and functionality, this technology is being successfully used in the modern construction industry in the most developed countries of the world.

The 3D printer is an automated device which makes it possible to reduce the impact of the human factor and the percentage of production defects while manufacturing individual structures and products, buildings construction by 3D printing. This ultimately allows to reduce financial costs of production and shorten the time of construction work, which is necessary for economic efficiency.

One of the main problems of the active introduction of three-dimensional printing in the construction industry in Russia is the selection of special additives for concrete mixtures, which allows to obtain the necessary consistency, degree of spreadability, level of strength, solidification time and ability to hold the mold, which will meet the all necessary requirements for this technology. In connection with these requirements, the development of the composition and improvement of the production technology of concrete mixes for 3D technology is the main task of applying three-dimensional printing in the construction industry in Russia.

The manufacturing process by three-dimensional printing is influenced by a large number of factors, some of which arise directly during operation. Currently, there are several different methods for
measuring and quantifying the quality of 3D printing objects. Non-destructive quality control is especially relevant in the manufacture and operation of construction sites and their parts, at the same time non-destructive testing methods are indirect, each of them has limitations in use due to its weaknesses and advantages. Studies on this issue were carried out by different authors, in whose works some methods of quality control of manufactured products were proposed for use in the construction industry as a whole [1,2,3,4] and for the manufacture of concrete structures in particular [5,6,7,8 ].

Existing methods for assessing the consistency of concrete that occur during paving take into account only the own mass of concrete, not reflecting dynamic processes. One of the most common non-destructive methods for controlling the quality of fresh concrete is the ultrasonic method, based on the connection between the speed of ultrasonic waves in concrete and its density, dynamic modulus of elasticity and strength. Depending on the location of the sensors during the tests, through and surface ultrasonic sounding are distinguished. This method allows to obtain data on strength in the surface and deep layers of concrete. It is applicable for mass testing of objects of any shape and continuous monitoring of the increase or decrease in strength. The error in the transition from acoustic to strength characteristics is a disadvantage of the ultrasonic method.

Using the vibrational method of forming products, the “consistency” test is carried out indirectly according to the amplitude-frequency characteristics, since fresh concrete is in the plastic state during transportation, when mixed and compacted - in the liquid state, and sometimes in both. This method is especially suitable for concrete from soft to very fluid consistency, but not for very dry and dry concrete. [9]

The objective of the work is to develop a method for assessing the spreadability of fresh concrete in 3D printing.

2. Methods and materials
Figure 1 shows the 3D printing equipment of the vibration type.

![Figure 1. The control process of the spreadability of fresh concrete monolithic beam: 1 – monolithic beam; 2 – sliding formwork; 3 – frequency counter; 4 – hopper.]

When the paver moves, the mixture from hopper 4 enters sliding formwork 2 under the influence of the driving force arising from the operation of the vibrator 5. The spreadability of the fresh concrete was determined by the accelerometer indirectly according to the amplitude-frequency characteristics of the vibration equipment (figure 1). In this case, the driving force of the vibrator varied. The measurement accuracy is about ± 2%. The measurement range of the accelerometer covers frequencies from 800 to 50,000 min – 1, which corresponds to approximately 14–833 Hz.

The spreadability of a monolithic beam depends on the composition of the concrete mixture. Table 1 shows the classes of spreadability and compaction of concrete mix depending on the category of concrete.
3. Results

During the operation of the vibrator, there are vibrations of the hopper walls, which are transmitted to the charge layers of concrete mixture. By adjusting the size of the disturbing force of the vibrator, the optimal vibration mode was selected, as well as the effect of vibration on the auto-excitation of the hopper and the sliding formwork. The hopper walls are made of sheet metal material. It allows to provide oscillations of the concrete mixture and, accordingly, to compact it in the process of forming products. The amplitude of the oscillations of the charge layers depends on the amplitude of the oscillations of the hopper walls, and therefore on the placement of the vibrator on the hopper. Studies of the process of forming a monolithic beam by 3D printing showed that the maximum amplitude of the charge oscillations is observed from the side of the wall on which the vibrator is mounted. Figure 2 shows the experimental dependences of the amplitude of oscillations of the hopper walls at a frequency of oscillations created by the vibrator: 30, 40, 50 and 100 Hz.

![Figure 2](image-url)

The largest amplitude of vibrations of the hopper walls occurs at a frequency of 40 Hz. Using a vibrator with an industrial frequency of 50 Hz allows to get the amplitude of the oscillations of the hopper walls up to 0.3 mm. This is enough to transmit vibration to the concrete mixture charge. Therefore, the oscillations of the concrete mixture charge were investigated during the operation with a vibrator at a vibration frequency of 50 Hz.

The oscillation amplitude of the walls of the hopper is described by the equation

$$A = -0.0011f^2 + 0.13f + 0.43$$

| Concrete category according to consistency | Spreadability classes | Compaction classes |
|-------------------------------------------|-----------------------|---------------------|
|                                           | Spreadability value mm| Class | Compaction degree v |
| very dry                                  | -                     | C0       | ≥ 1.46              |
| dry                                       | F1                    | C1       | 1.45 – 1.26         |
| ductile                                   | F2                    | C2       | 1.25 – 1.11         |
| soft                                      | F3                    | C3       | 1.11 – 1.04         |
| very soft                                 | F4                    | -        | -                   |
| fluid                                     | F5                    | -        | -                   |
| very fluid                                | F6                    | -        | -                   |

Table 1. Characteristics of concrete.
where \( f \) is the oscillation frequency.

The influence of the driving force of the vibrator on the amplitude of oscillation of the hopper walls is shown in Figure 3.

![Figure 3](image)

**Figure 3.** The dependence of the amplitude of the oscillations of the hopper walls on the driving force of the vibrator: 1 - when the hopper is not loaded with a mixture; 2 - when the hopper is loaded with a mixture.

With minimal debalance, the amplitude decreases towards the middle of the wall; the ends - the corners of the hopper, vibrate more, which makes it possible to more compact the mixture at the edges of the frame and thereby equalize the strength of the product. With a driving force of 2.4 and 5.2 kN, respectively there is a leveling of density throughout the sliding formwork.

According to the height of the concrete column, the amplitude of the oscillations of the charge layers decreases with increasing distance from the installed vibrator. The smallest oscillations of the charge are observed on the opposite side of the vibrator. The maximum amplitude of the oscillations of the charge is 0.27 mm. It is observed at the level of the installed vibrator. The minimum oscillation amplitude in the same layer is 0.27 mm. Thus, in the process of its oscillations the charge is moving in the opposite direction from the vibrator.

### 4. Discussion

When determining the rational parameters of vibration dampers, the local optimization method was used. At this stage, a particular optimization of vibration accelerations was performed depending on the design parameters of the equipment and the charge density. As an optimization criterion, the condition was adopted to reduce the level of vibration without loss of quality of the equipment due to the absorption of part of the energy and the redistribution of the internal damping energy inside the system itself.

Individual optimization of vibration accelerations according to oscillations amplitude of hopper walls and oscillations amplitude of the charge layers and the stiffness of the vibration dampers was carried out using the Excel program editor. The level of vibration acceleration 3D printer was adopted as the optimization parameter. The initial optimization conditions are given in Table 2.

**Table 2.** Initial optimization conditions.

| Vibration acceleration \( \dot{Y}, \text{m/s}^2 \) | Amplitude of oscillation of the hopper walls \( A_h, \text{mm} \) | Amplitude of oscillation of the charge \( A_c, \text{mm} \) | Stiffness of the shock absorber, \( C_1, \text{kN/m} \) |
|---|---|---|---|
| 3 | 0.3 | 0.28 | 100 |
| 2 | 0.23 | 0.21 | 100 |
| 0.75 | 0.1 | 0.09 | 100 |
| 2.75 | 0.4 | 0.38 | 10 |
| 0.5 | 0.05 | 0.04 | 10 |
The regression equation of vibration acceleration:

\[ \ddot{Y} = -0.6381 + 78.7383A_{\text{h}} - 73.714A_{\text{ch}} + 0.0027C \]

where \( A_{\text{h}} \) - the amplitude of the oscillations of the hopper walls; \( A_{\text{ch}} \) - the amplitude of the oscillations of the charge layers; \( C \) - the stiffness of the vibration dampers.

5. Conclusions

The results of studies of the process of spreadability of fresh concrete have shown that with the vibration method of molding construction products, the consistency of the mixture depends on the amplitude-frequency characteristics and power of the vibrator. With increasing density of the concrete mixture, vibration acceleration and the amplitude of the hopper oscillations decrease. With increasing time of vibration, accelerations increase slightly, not exceeding the standard sanitary and hygienic values. Rational oscillation frequency \( \omega \) is 50 Hz.

The amplitude of the oscillations of the walls of the hopper varies linearly depending on the action of the driving force of the vibrator and non-linearly on the frequency of vibrations of the vibrator. The largest amplitude of vibrations of the walls of the hopper of a vibration molding machine occurs in the range of oscillation frequency 40 - 50Hz. Using a vibrator with an industrial frequency of 50 Hz allows to get the amplitude of the oscillations of the walls of the hopper up to 0.3 mm

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