Optimization of granulometric composition of mineral part of fine-grained concrete modified by ultrasound

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Abstract. Ultrasonic methods are widely used in the construction industry as methods of defectoscopy and non-destructive testing of physical and mechanical characteristics of concrete in structures. At the same time, ultrasonic treatment of concrete mix and freshly laid concrete can be used for the purpose of modifying its structure and properties as well. The relevance of the topic is directly related to the consideration of issues related to savings in construction, since it allows you to reduce the cost of introducing expensive cements into the concrete.

1. Introduction
In acoustic ultrasonic field, under the influence of wave pressure, centers of colloidal compaction of cement paste arise and when merging into a solid layer, water is displaced all over the volume with highly dispersed cement fractions suspended in it, which are formed as a result of cavitation destruction of large particles [1,2]. Cavitation activates the forces of internal adhesion between cement and limestone microparticles, which contributes to a compact spatial distribution of solid phase particles and an increase in the number of contacts between the particles – an increase of the coordination number [2].

We should also expect the opposite and positive effect – increasing the efficiency of ultrasonic treatment itself, as it is obvious that the more contacts between the particles and the more rational their relative distribution within the source structure, dependent particularly on the granulometry of the mineral part of concrete, the higher the degree of cavitation. It leads to collapse of micro-bubbles inside the mixture and less defective structure of the concrete mix and the concrete. Moreover, the effectiveness of ultrasonic treatment will also be determined by its parameters (mode and time).

2. Experiment
2.1. The composition optimization modeling
At the first stage of the work, the grain composition of the mineral part of fine-grained concrete (sand concrete) was optimized, on which the effect of ultrasonic treatment was assessed.

In order for the aggregate to fully fulfill its assigned role as a solid skeleton of a fine-grained composite, it is necessary to distribute its particles so that smaller fractions are located in the spaces between the large particles, without pushing them apart. This is possible only if there are at least three sand fractions in the aggregate in an optimal amount, the average sizes of which must be correlated in a certain proportion [3]. Data on the initial granularity of large and medium-sized sands show that the
most effective in terms of technology and sifting costs is the separation of sand into three fractions with particle sizes: 0-0.5 mm; 0.5-1.25 mm; 1.25-3.2 mm, and their mixing in an optimal ratio.

In this work, we determined the area of ratios of the specified sand fractions that provide the most dense packing of aggregate particles, both by theoretical calculations and by experimental method, while the maximum value of the bulk density of the aggregate served as the criterion for dense packing.

The calculation method uses a physical model of the considered mixture of three fractions and attempts to achieve the optimal granulometric composition of the mineral part by calculation.

It is convenient to start consideration of physical models of packaging of bulk materials with systems made up of spherical geometric bodies, so the calculation of a ternary (dry bulk mixture consisting of three fractions) mixture, where the particles of fractions are taken as balls, is given below. In the process of forming bulk filled systems based on several fractions with different diameters of spheres, the fraction with the maximum body size is selected as a skeletal one, which is conditionally filled with a unit of volume of the bulk filled system in the first order. The calculation of the compositions of spherical bulk systems is made with taking into account the phenomena of mutually sliding spheres and filling interspheric voids with spheres of smaller sizes. The volume of solid material per unit volume of spherofraction equal to 0.6, while the void volume is 0.4.

The average diameters of the spheres for the three quartz sand fractions mentioned above are: \( d_1 = 2.725 \) mm, \( d_2 = 0.875 \) mm, \( d_3 = 0.25 \) mm. For the preparation of \( 1 \) m\(^3\) of ternary bulk mixture, the flow rate of each fraction in m\(^3\) is determined as follows.

The volume coefficients of sliding of spheres of large diameter by spheres of smaller sizes are determined and their product is found:

\[
\alpha_1 = \left(1 + \frac{d_2}{d_1}\right)^3; \quad \alpha_2 = \left(1 + \frac{d_1}{d_2}\right)^3; \quad \alpha_3 = \left(1 + \frac{d_3}{d_2}\right)^3; \quad X_1 = \alpha_1\alpha_2; \quad X_1 = \alpha_2\alpha_3,
\]

where \( \alpha_1, \alpha_2, \alpha_3 \) – the volume coefficients of sliding, \( d_1, d_2, d_3 \) – average diameters of the spheres of the specified fractions.

The flow rate of each fraction in m\(^3\) is determined in the following order:

\[
V_1 = 1.m^3 \cdot X_1^{-1}; \quad V_3 = (X_1 - 0.6) \cdot (X_2 - 0.6) \cdot (X_1 \cdot X_2)^{-1},
\]

где \( V_1, V_2, V_3 \) – volumes of the specified fractions, \( X_1, X_2 \) – multiplication of the coefficients of sliding of spheres of larger diameter by spheres of smaller sizes.

The volume of monolithic spheres is determined by the formula

\[
V_{\text{mon}} = V_{\text{bulk}} - V_{\text{bulk}} \cdot V_{\text{void}},
\]

где \( V_{\text{bulk}} \) – flow rate of spherofractions, m\(^3\), \( V_{\text{void}} \) – the volume of voids.

Finally, the bulk volume of the bulk mixture of three fractions in m\(^3\) is equal to

\[
V_{\text{bulk}} = V_{\text{mon1}} + V_{\text{mon2}} + V_{\text{mon3}} + V_3 \cdot V_{\text{void}}
\]

Based on the above calculation, we get:

\[
\alpha_1 = \left(1 + \frac{0.875}{2.725}\right)^3 = 2.306; \quad \alpha_2 = \left(1 + \frac{0.25}{2.725}\right)^3 = 1.302; \quad \alpha_3 = \left(1 + \frac{0.25}{0.875}\right)^3 = 2.126;
\]

\[
X_1 = 2.306 \cdot 1.302 = 3.002; \quad X_1 = 1.302 \cdot 2.126 = 2.768; \quad V_1 = 1 \cdot 3.002^{-1} = 0.333.m^3;
\]

\[
V_2 = (3.002 - 0.6) \cdot (3.002 \cdot 2.786)^{-1} = 0.289.m^3;
\]
Thus, according to the calculation, the optimal granulometric composition, which provides the maximum packing of filler grains, was: 26.7% of the 0-0.5 mm fraction, 23.1% of the 0.5-1.25 mm fraction, 50.2% of the 1.25-3.2 mm fraction.

For experimental selection of the optimal ratio of sand fractions in a fine-grained concrete aggregate, a nonlinear planned experiment was performed with simultaneous variation of the content of these fractions within the limits: the ratio of the fraction 0.5-1.25 mm to the fraction 0-0.5 mm - \( X_1 \) = 0.67...4; the ratio of the fraction 1.25-3.2 mm to the fraction 0-0.5 mm - \( X_2 \) = 1.67...7, and the measurement of the bulk density of the resulting mixtures in the dry state. The plan of the experiment and its results are shown in table 1, and the curves of the bulk density of the aggregate on its fractional composition obtained by mathematical models in the form of lines of equal level are shown in Fig. 1.

Table 1. Matrix of the planned experiment and results of determining the bulk density of mixtures in the dry state.

| № п/п | \( X_1 \) | \( X_2 \) | Bulk density of the mixture of fractions, kg / m³ |
|-------|----------|----------|-------------------------------------------------|
| 1     | 0.67     | 1.67     | 1640                                            |
| 2     | 4.00     | 1.67     | 1590                                            |
| 3     | 0.67     | 7.00     | 1535                                            |
| 4     | 4.00     | 7.00     | 1600                                            |
| 5     | 0.67     | 4.34     | 1585                                            |
| 6     | 4.00     | 4.34     | 1560                                            |
| 7     | 2.33     | 1.67     | 1620                                            |
| 8     | 2.33     | 7.00     | 1590                                            |
| 9     | 2.33     | 4.34     | 1560                                            |

The data obtained allow us to determine the composition of the optimal granulometry mixture corresponding to the highest bulk density, namely: 30% of the 0-0.5 mm fraction, 20% of the 0.5-1.25 mm fraction, 50% of the 1.25-3.2 mm fraction. The theoretical calculations given above are consistent with the experimental values, which indicates the validity of the model used.

A deeper optimization of the granulometric composition of the mineral part of fine-grained concrete can be obtained by introducing various finely – ground additives-fillers in an optimal amount [4]. The influence of fillers on the properties of concretes was considered in previous publications [5, 6], where it was shown that the use of ground limestone cement systems as a filler in combination with a superplasticizer allows purposefully regulating the properties of fine-grained concretes.

2.2. The ultrasonic processing

Based on these assumptions, the task of testing the effect of ultrasonic processing of fine-grained compositions optimized for granularity, in the composition of the finely-dispersed part of which a carbonate micro-filler was introduced in various amounts (as a replace for the corresponding part of cement), on the structure of hardening systems.

The following parameters of ultrasonic processing were used (table 2).

Ultrasonic treatment was carried out in the process of preparation of the mixture (at a frequency of 0.62 MHz as matching the average fraction), and curing of sample cubes 100x100x100 mm of fine aggregate concrete made with this cement-sand mixture (at a frequency of 1.8 MHz corresponding to the level of microparticles). The application of the UDM generator transducer to the sample cube
during its hardening and scanning for the homogeneity of the internal structure of the composite is shown in Fig. 2.

![Figure 1. Aggregate bulk density equal levels diagram in dependence on granulometric composition of aggregate.](image1)

**Table 2.** General parameters and processing conditions (UZ - UDM).

| General parameters and processing conditions (UZ UDM generator) |  |
|---------------------------------------------------------------|--|
| frequency range                                               | 0.62-1.8-2.5-5 MHz |
| Power                                                         | 80-250W |
| Processing time                                               | t=30min |

![Figure 2. Application of the UDM generator transducer to the sample during its hardening and scanning for the homogeneity of the internal structure of the composite.](image2)

Figure 3 shows the waveforms of three samples of fine-grained concrete containing 0, 30 and 50% of the fine-grained part of limestone ground powder with a specific surface area equal to 450 m²/kg (replace for the corresponding part of cement) and superplasticizer SP-1 in a dosage of 0.5 and 0.75% of the mass of the fine-grained part (cement and limestone powder) for dry matter.
Figure 3. Waveforms of ultrasonic scanning of the internal deep structure of concrete samples in order to determine its uniformity with the UDM device at average values of signal power and sensitivity and the maximum range of sound (100 mm), at a frequency of 1.8 MHz.

Figure 3 shows that samples with the content of limestone fine powder in an amount of 50% in the total content of cement and filler and superplasticizer in an amount of 0.5% of the mass of the fine part (cement and limestone fine powder), subjected to ultrasound, have a more homogeneous structure (the gate is selected within 8 percent of the band of the measuring scale). This indicates the contribution of ultrasonic processing to a more uniform distribution of particles over the mass of the composite. There is a cavitation effect of decomposing the mixture at the micro level at the optimal frequency for ultrafine filler particles at the rate of 1.8 MHz. At the same time, we should expect an improvement in the performance properties of such concrete, including crack resistance and durability without significant loss of strength, even in the case of a raw material mixture that is depleted in terms of cement consumption.

Analysis of the results obtained at this stage of research shows that the use of an ultrasonic generator-modifier UDM allows you to purposefully influence the structure of fine-grained concrete in order to improve its performance properties.

3. Conclusions

The mechanism of formation of homogeneous structure of cement stone containing admixture based on microfine limestone powder and superplasticizer at ultrasonic modification, is associated mainly with the process of collapse of gas micro-bubbles during cavitation, which leads to disaggregation of the mixture on micro- and meso-levels.

The joint effect of ultrasound processing and optimization of granulometric composition of the mineral part of the fine aggregate concrete can promote synergies while improving operational properties of fine-grained concrete by enhancing the blend of active centers of microcavities and the most uniform distribution of particles in the volume of the mixture making it more homogeneous, coherent and dense.

References

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