Methodological approaches to optimization of grain composition of heat-resistant concrete

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Abstract. Heat-resistant concrete of fine-grained structure attracts special attention of refractory applications manufacturers. The task of optimizing the grain size composition of heat-resistant concrete fillers on the basis of by-products and related products of silicon carbide (SiC) production and waste products of abrasive tools production on a ceramic bond of fine-grained structure is of research and practical interest. It is proposed to use grain size compositions of gapped grading for a fine-grained cement system of heat-resistant concrete. The analysis of methodological approaches in the calculation of the grain size composition of concrete fillers allowed us to determine the Fuller formula as an optimal one from a practical perspective. Due to the use of gapped grading of the grain component of the concrete composition, an optimal ratio between the size of the grains of quartz sand and the waste of abrasive production was achieved. Balanced distribution of the filler in concrete mix made it possible to obtain intimate contact between their grains, which resulted in dense, “well-packed” concrete structure, and will further enable 5-10% saving of the cement binder. The compressive strength of samples with gapped grading filler was 38.7 MPa, the thermal resistance (water, 800°C) amounted to 16 thermal cycles.

1. Introduction

The issues of energy and material saving have always been and are still urgent, and they are the decisive factor in the sustainable development of the construction industry in the conditions of its economic growth [1-3]. One of the directions of solving the problems of resource saving in the construction industry is the use of secondary material resources in the production of building materials and units. All of the above fully applies to the technology of heat-resistant concrete on Portland cement, where heat-resistant properties of cement stone are imparted not only by the matrix modification, but also by the use of heat-resistant filler based on man-caused waste of engineering and metallurgical industry of the region, taken as the focal area.

Replacement of piece refractory materials with heat-resistant concrete compositions provides an acceleration of construction rates by 20-40%, a reduction in labor costs by 2-3 times, an increase in the service life and productivity of thermal units, a reduction in cash costs for current and capital repairs.

Heat-resistant fine-grained concrete attracts special attention of refractory products manufacturers due to improved workability and formability of products of such structure. These properties of concrete heat-resistant compositions are important in the manufacture of thin-walled and densely reinforced structures due to high resistance to tension stresses. Disadvantages of fine-grained concrete,
such as increased water demand, a significant consumption of cement leading to an increase in the concrete shrinkage, reducing crack resistance, are eliminated by modifying the cement matrix with mineral and organic additives. The use of industrial waste as additives is most relevant in economic and environmental terms.

2. Relevance and scientific merit of the subject
When manufacturing the refractory building structures and structures for various purposes, trends in the development of production of efficient and economical building materials based on Portland cement with extensive use of industrial waste are gaining their relevance.

Introduction of high-temperature core on the basis of by-products and related products of silicon carbide (SiC) production and waste production of abrasive tools on a ceramic bond into the heat-resistant compositions formulation can increase the compressive strength by 12%, and bending strength by 36%. Thermal resistance increases in 3 times. Introduction of double superphosphate modifier in the amount of 0.2% by weight of the cement to the heat-resistant composition allowed to increase the thermal stability of the compounds up to 20 thermal cycles (water, 800°C) [4,5].

Fine-grained heat-resistant concrete gives a full sense of the advantages of such a composition in terms of forming its structure. The possibility of refusal from the expensive coarse aggregate, and creating a homogeneous structure of cement stone with obtaining high-quality surfaces of the products when molding by methods of compressing, vibration compressing, and vibratory casting is provided. And in this regard, the task of optimizing the grain size formulation of compositions for making heat-resistant concrete, which should provide minimal voidage, the possibility of dense stacking of filler grains on the basis of man-caused waste, becomes urgent [6-11].

The task of optimizing the grain composition of aggregates and fillers of heat-resistant concrete on the basis of by-products and related products of silicon carbide (SiC) production and waste products of abrasive tools production on a ceramic bond becomes crucial. Optimally selected granulometric composition of the filler provides concrete with improved physical and mechanical characteristics with minimum binder consumption. Properties of heat-resistant concrete depend very heavily on the type and ratio of the filler components. Evaluation of the influence of grain composition, particle size limit, shape and nature of grain surface, their mineralogical composition on the technological and operational properties of heat-resistant concrete has a certain research and practical interest and scientific value [12-15].

3. Research objective and theoretical part
The properties of the heat-resistant composition on Portland cement depend both on the ratio of the mixture components and the properties of the materials used, and to a greater extent on the processes of forming the structure of the concrete system [16,17]. Granulometric composition of initial materials and, in particular, aggregates and fillers, occupying up to 80% of the volume in concrete, can be considered a determining factor in reducing the consumption of cement. Optimally selected grain composition of aggregates and fillers of concrete contributes to the formation of a rigid skeleton of a strong and heat-resistant material, helping to reduce the deformation of structures under load, increase the strength and modulus of concrete deformation [18].

A filler of cement compositions creating a "hard non-metallic frame" is the basis for the concrete structure formation that can withstand the full range of operational impacts, both at the first stage of its formation, and in the future when exposed to high temperatures during operation. The resulting surface forces reduce the mobility of the cement system and reduce the period of its structure formation. What is more, it should be noted that the higher the content of the filler and its specific surface area, the greater its impact. The filler significantly affects the conditions of hardening of cement stone, as the constant interaction of concrete with water contributes to the gain in strength, hardening occurs in the layers between the grains of the filler. This significantly increases the water-holding capacity of the cement paste, limits shrinkage deformation, facilitates the formation of the
crystal frame of the cement stone, and affects the temperature and humidity in the hardening cement stone [19].

Noting the significant role of the filler as an inert component of the structure only filling the volume of the cement system, it should be noted its significant structure-forming role as the main structuring component that determines the rheological properties of the concrete mixture. The filler of the cement system that regulates the nature of adhesion contacts through the processes of hydration of the binder and the structure formation of materials serves as a base in the initial period of hydration solidification. In this case, the crystallochemical structure and properties of the aggregate and filler materials determine its behavior in the processes of contact formation and the properties of the obtained materials [16,17].

Considering the structure of heat-resistant fine-grained concrete, we can talk about the integrated effect on the processes of structure formation of fine aggregate and filler due to their large specific surface area. Along with the contacts "cement paste - coarse aggregate" there are contacts "fine aggregate - binder" and "micro-aggregate - binder", the strength of which depends on the physical and mechanical interaction of minerals on the surface of the aggregates and the binder particles. From these positions, by-products and related products of silicon carbide (SiC) production and waste products of abrasive tools production on a ceramic bond are most interesting both from the standpoint of their granulometric composition, and from the standpoint of mineralogy and chemical composition of materials. It is possible to trace deeper influence of fillers and small fractions of aggregates on the basis of production wastes on structure formation of cement concrete. Moreover, cyclone dust (SiC 92-90%) of air aspiration units of industrial premises, having a fraction of silicon carbide particles of 0.04 mm, can be classified not only as a filler of a concrete heat-resistant system, but also as a mineral additive of technogenic nature [4,5,20-22].

At the stage of hardening of the cement binder and in the process of heating the concrete to operating temperature and further during operation, the basic properties of heat-resistant concrete are formed during the course of physical and chemical processes. In concrete with a fine-grained structure, the intensity of all physical and chemical processes, especially those occurring at high temperatures, will be significantly higher, since the intensity, other conditions being equal, is determined by the magnitude of the contacting surface. For fine-grained concrete exposed to high temperatures, the most important thing is dispersion of the concrete structure which is determined by the optimal ratio between the filler fractions and the upper limit of grain size. Increasing the density of packing of filler grains of concrete system can be achieved by calculation and selection of rational granulometric composition of the mix of filler and aggregate [18,23,24].

The grain composition of heat-resistant concrete can be considered the most important variable factor, adjusting which the properties of concrete can be varied. It can be said that the upper limit of grain size of the aggregate, depending on the chemical and physical nature of the refractory material, can be varied for fine-grained concretes from 0.5 to 5 mm [25,26].

When designing the optimal granulometry of the heat-resistant concrete composition, the grain composition is selected from the maximum density of grains packaging of fillers of different diameters. To fill the void formed by grains of large diameter with grains of smaller diameter in heat-resistant concrete, grains with a discrete granulometric composition are often used in order to obtain a denser package per unit volume. In this case, the material with higher strength is used.

Heat-resistant concretes on fine aggregate have a more favorable structure with evenly distributed pores which ensures their high strength at high temperatures. It should also be noted that the optimal ratio of grains of different fractions provides vibrorheology characteristics of the concrete mass, contributing to the creation of low-porosity and solid structure of concrete in the molding process, and under the influence of heat treatment. The maximum concrete mass compaction through the selection of granulometric composition can be achieved using the distribution curves of Furnas, the Fuller, Andreasen and Bolomey equations [19,27]. Grains of the same size and spherical shape take the most close-packed spatial arrangement. The hexagonal packing of the particles has the maximum density.
In the work [20] the dependences of bulk density were found for free backfilling and backfilling under shaking conditions for multi-fraction mixtures of quartz sand. Comparison of the results of the experiment and calculations of the optimal composition of the bulk system according to the known packaging models showed that the closest approximation to the experimental optimal grain composition from the criterion of maximum bulk density was obtained by calculations based on the Funk/Dinger formula.

The equations of optimal sifting curves give only an approximate composition of the maximum packing of the filler grains, which can be explained by the different shape of the grains of the real bulk system. The above equation describes the "ideal" sifting curve for systems with a spherical shape of grains and does not take into account possible deviations from this shape for real systems. It is believed that this factor can be taken into account using the grain shape coefficient, which is defined as the ratio of the surface area of the ball to the surface area of the grain of the equal volume. The coefficient of the ball shape is one. Thus, the more the shape of the grains differs from the ideal spherical shape, the greater share of a smaller fraction should be in the grain size composition [26].

Experimental verification of the packing models of real dispersed systems along with theoretical analysis and generalization of the experimental results allowed the authors [26] to propose an improved formula of the "ideal" sifting curve obtained on the basis of the Funk/Dinger formula taking into account the shape factor of the particles.

The above methods of selection of the optimal granulometric composition of the raw mixture of fillers, which consist in finding the best ratio between the components by mixing, which ensures the minimum emptiness of their mixture, are used in practice each separately or in their combination. In addition to the modified Funk/Dinger equation, there is always a possibility to choose and use several other "ideal" sifting curves (Fuller's, Andreasen's and Bolomey's), which significantly expands the possibilities of using computer programs.

4. Results obtained in experimental studies

The considered methods of calculation of granular mixtures of aggregate are acceptable for the compositions of fine-grained concrete. A mandatory requirement for the selection of grain composition for fine-grained concrete is the presence in it of a sufficient amount of fine fraction of the filler with a grain size of 10 ... 5 mm. This size of the filler will provide the creation of a stone frame from its grains in concrete, and the possibility of introducing a filler fraction with a grain size equal to or greater than the size of the voids formed between the grains of a larger filler. For fine-grained cement system of heat-resistant concrete, it is proposed to use grain size compositions of gapped grading based on by-products and related products of silicon carbide (SiC) production and waste products of abrasive tools production on a ceramic bond.

Table 1. The grain composition of the crushed material of waste of the abrasive tool on a ceramic bond and its mineralogy.

| Size of screen opening, (mm) | Partial/full residual, (%) | Grain mineralogy |
|-----------------------------|-----------------------------|------------------|
| 1,25                         | 9,8/9,8                     | 100% clusters of white grains of electrocorundum and bond, hardly could be destroyed |
| 0,63                         | 24,6/34,4                   | 99% clusters of white grains of electrocorundum and bond, hardly could be destroyed |
| 0,315                        | 39,6/74,0                   | 98% aggregates of 2–4 grains of white electrocorundum glued by ceramic bond |
| 0,16                         | 15,2/89,1                   | 98% separate grains of white electrocorundum, grains are hard, couldn't be crushed, matte grain of bond could be split |
| less than 0,16               | 8,9/98,0                    | 100% grains of white electrocorundum, grains are hard, couldn't be crushed |

Fineness modulus is 2,1
Reduction in size of waste of the abrasive tool on a ceramic bond is performed mechanically or by thermal shock followed by grinding of the obtained lump material using grinding equipment (mills, crushers). Mineralogical analysis of the abrasive tool obtained after grinding on a ceramic bond and its sieving on a standard set of sieves is presented in Table 1. It is proposed to use by-products and related products of silicon carbide (SiC) production as filler and a finer fraction of the grain mixture of heat-resistant concrete, the material composition of the fractions is presented in Table 2 [4,21].

| Name of the material                                      | Analyte, (%)      |
|-----------------------------------------------------------|-------------------|
|                                                           | C     | SiC  | Fe₂O₃ | Si   | Al₂O₃ | CaO  | SiO₂ |
| Silicone carbide, grade less than 500 µm                  | 0,07  | 93,9 | 0,64  | 0,79 | 0,25  | 0,20 | 4,11 |
| Silicone carbide sinters, grade less than 1000 µm         | 15,6  | 42,8 | 0,40  | 3,59 | 1,58  | 0,59 | 35,3 |
| Silicone carbide, grade less than 50 µm                   | 17,1  | 72,6 | 0,45  | Less than 0,3 | 0,24 | 0,10 | 8,7  |
| Silicone carbide, grade less than 800 µm                  | 0,05  | 96,4 | 0,85  | 0,3  | 0,35  | 0,69 | 1,35 |
| Silicone carbide, cyclone dust, grade less than 40 µm     | 0,20  | 72,1 | 1,4   | 3,5  | 2,7   | 1,1  | 13,4 |

For fine-grained heat-resistant concrete, we use fractions of several sizes: silicon carbide and abrasive tool waste, as well as quartz sand. We use Fuller formula (1) for calculations for obtaining more dense structure of concrete mix.

\[
S = 100\left(\frac{d}{D}\right)^{1/2}, \tag{1}
\]

where: \( S \) – weight of each filler fraction size in the total mixture, %; \( d \) – maximum size of the filler granule in each fraction, mm; \( D \) – is the maximum particle size of the filler of quartz sand, mm.

Substituting the values of grain size of materials in the formula (1), we obtain a solution in the form of % of the content of each fraction in the concrete:

- Fraction – 0,0-0,05 mm – 2 – 0 = 2% silicon carbide (Table 2);
- Fraction – 0,05-0,1 mm – 14 – 2 = 12% silicon carbide (Table 2);
- Fraction – 0,315-0,63 mm – 35 – 14 = 21% waste of the abrasive tool (Table 1);
- Fraction – 0,63-5,0 mm – 100 – 35 = 65% of quartz sand;
- The total component of grain materials in concrete is 100%.

Specimens of concrete (70x70x70) were made from Portland cement of CEM I 42,5H grade (manufacturer is OAO "Sebryakovcement"). A mixture of fractions of crushed waste of abrasive tools on a ceramic bond and SiC materials (Table 1-2), V/C 0,55, superplasticizer C-3 [20] was used as a filler of heat-resistant concrete composition. The compressive strength of specimens with gapped grading filler was 38,7 MPa, the thermal resistance (water, 800°C) amounted to 16 thermal cycles

5. Conclusions

Thus, due to the gapped grading of the grain component of the concrete composition, an optimal ratio between the different sizes of the grains of quartz sand and the waste of abrasive production was achieved. Balanced distribution of the filler in the mix will enable intimate contact between their grains, which will cause a dense, "well-packed" concrete structure and will allow saving cement binder by 5-10%.
The use of wastes of abrasive production as a high-temperature component of fine-grained concrete aggregate will expand the functionality of cement concrete transferring it to the category of heat-resistant.

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