Reactive Powder Concrete Microstructure and Particle Packing

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Comparing reactive powder concrete's physical, mechanical, and durability properties with those of HPC/UHPC shows that reactive powder concrete possesses better strength (both compressive and flexural) and lower permeability than HPC.

dispersed composition strength concrete cement

1. Introduction

The disadvantages of high-performance concrete (HPC) and ultrahigh-performance concrete (UHPC) are the binder's high absolute and specific consumption per strength unit. HPC and UHPC have achieved the maximum compressive strength in their existing components' structure. However, with a further increase in the load, the coarse aggregate becomes the weakest part of the concrete. The only solution is to remove the coarse aggregate to increase the compressive strength of concrete even further. The next step in increasing the compressive strength of the concrete is to remove the coarse aggregate. Coarse aggregate is absent in reactive powder concrete [1].

The use of steel and polypropylene fibers improves the strength characteristics of all types of concrete and dispersed reinforcement. Therefore, the hack-characteristics of concrete can be further analyzed without taking into account the reinforcement [2][3][4].

A promising direction for reactive powder concrete production is the use of self-compacting concrete (SCC) [5][6][7]. The self-compacting concrete mix should be characterized by high viscosity and fluidity; there should be no water separation and delamination. The use of superplasticizers of the polycarboxylate type, finely dispersed mineral materials, viscosity modifiers, set retarders, and hardening accelerators provides such characteristics.

For low yield stress, the self-compacting concrete mixture includes an increase of up to 0.5 quota of sand in a concrete mixture, a decrease of up to 3–10 mm in the maximum size of a coarse aggregate, and a low water content. High fluidity and self-compacting of the concrete mixture are achieved by reducing contact interactions between aggregate grains, as well as a high content of cement paste [7][8][9][10].

Concretes with a high cement content have an increased heat release [11]. For this reason, the fixation of the newly formed particles of hydrate phases during structure formation occurs due to molecular selection, mainly in the position of the weak flocculation [12][13] in the framework of the Derjaguin–Landau–Verwey–Overbeek (DLVO) theory [14]. This type of fixation determines an increase in the cement paste's defectiveness, looseness, and microporosity, and a decrease in the building properties of concrete [15].

It is possible to obtain concrete mixtures with a high cement paste content at lower consumption of clinker cement with its partial replacement by highly dispersed mineral additives (finely ground granulated blast furnace slag, fly ash, microsilica, etc.) [16]. However, it is necessary to consider the possible dependence of the parameters (dispersity, content) on the shape and size of the particles of clinker cement using mineral additives. The authors of [17][18][19] discussed the increase in the activity of mineral additives by increasing the specific surface area developed thermodynamic and mathematical models for optimizing the composition of composite mixtures. The main problem of concrete modified with mineral additives is to optimize their dispersed composition, taking into account the spatial and geometric parameters (dispersion of particles, geometry, volume, energy state, the average size of interparticle voids, their fractality, isometrics, etc.) of the clinker component and its pozzolanic activity.

Considering the spatial and geometric parameters of clinker and mineral additives makes it possible to increase the strength of concrete and other structural properties of concrete. When replacing part of the cement with mineral additives, it is necessary to take into account the ratio of sizes (dispersion) of clinker particles and particles of mineral additives. The key factor is using different dispersed mineral additives in one concrete mix. Pozzolanic activity and the energy state of mineral additives also significantly affect the solid phase concentration per unit volume of the concrete mixture [20].

Mineral additive particles of each subsequent more finely dispersed fraction should be placed in between larger particles or grains, providing the maximum possible filling of voids. Small mineral particles with a tessellated distribution on the exterior of clinker particles, large mineral additives, and Coulomb reciprocal action between particles lead to their spontaneous orientation in the space between larger particles. They are hooked with high binding energy in the interparticle voids of a multicomponent system at their hierarchical dispersed granulometric levels of the mix structure. The binding energy increases with decreasing particle size; hence, dispersity can be used to increase the cement paste density. The self-organization of the concrete mixture's structure decreases the disarrangement of the system's component, increasing the particles' potential energy and viscosity. All of this ensures high homogeneity and non-delamination of self-compacting concrete. The volume of the remaining voids in such a system will be minimal [20][21].

Thus, obtaining self-compacting concrete of high strength classes can be ensured only by synthesizing a homogeneous optimized discrete–continuous dispersed-particle size distribution of particles and grains of the solid phase in each hierarchical structural level of the material. The scanning electron microscopy, thermographic, and X-ray phase analysis methods were used to study the structure of the cement paste [21]. It was shown that it is commendable to use clinker particles of several levels of dispersion. The homogeneous optimized approach was proposed to design the balanced content of the concrete mixture with a marked up solid-phase concentration. The approach is based on the rational ratio of highly dispersive mineral and superplasticizers that optimize concrete mixture composition and structure.

The sufficient amount of empirical data on reactive powder concrete microstructure gives possibilities to suggest four commonly used mixture design methods for UHPC [22]. These methods include close packing methods based on dry and wet packing densities [23][24][25], method, based on the relationship between rheological properties of paste and raw materials [26][27], statistical analysis methods [28], and artificial neural network (ANN) models [29][30]. The packing of solid particles is used for mixture design in ceramic processing [31][32][33], asphalt concrete [34], and construction concrete [35][36][37].

2. The Dispersion of Mineral Additives

It can be assumed that there are three cases of dispersion of mineral additives to increase the density of concrete modified with mineral additives:

a. The dispersion of mineral additives is optimum in the sense that the mineral additive particles fill the voids between the clinker particles. In this case, the increase in the cement paste density will be by 8.09% more than without mineral additives.
b. The dispersion of clinker particles and mineral additive particles is the same. The density of the original cement paste does not change if the mineral additive is added.
c. The dispersion of particles of mineral additives significantly exceeds the dispersion of clinker particles. An example of such a finely dispersed mineral additive is microsilica with a specific surface area of 18,000–21,000 m^2/kg. In this case, the increase in the cement paste density could be more than without mineral additives. However, increased mineral additive content could also lead to the formation of large stable aggregates of small microsilica particles with a high binding energy between particles. These large aggregates of mineral additives can lead to the decompaction of clinker particles, an increase in its interparticle voidness, and consequently a negative impact on the properties of concrete. In cement systems of a conglomerate or composite type of structure, especially in the presence of variously dispersed mineral additives, there is a possibility that two or more dispersed particles, i.e., mineral additives, may combine and form a separate aggregate [2][19]. In such microvolumes of cement systems, the pozzolanic reaction practically does not occur. These microvolumes are pseudopores of 5–7 µm (when three particles are combined) and 0.5–1.5 µm (when two particles are combined). With a large number and insignificantly small size of particles and the formation of large aggregates, the particles can be distributed in the interparticle voids of the elementary cells of the matrix component, loosening them. The indicated pseudopores are structural defects and will significantly decrease strength, frost resistance, and deformation characteristics of concrete modified with mineral additives.

The positive and negative influence of mineral additives on the concrete's structure formation and properties requires determining its optimal content in the concrete composition. The rational content of mineral additives for the first case could be 18–25%. The second case with equal dispersion of the clinker component and mineral additives requires 25%, 50%, and 75% content of mineral additives. For the third case, the content of mineral additives is small and is determined experimentally.

Pozzolanic activity of mineral additives affects the degree of hydration of clinker minerals, the nature of the products of hydrate phases, the formation of the properties of the contact zone between the particles of mineral additives and neoplasms, and the integral strength of concrete modified with mineral additives. If inactive mineral additives are used, then the amount of replaced cement decreases, and the content of mineral additives increases. In the case of equivalent replacement of cement with highly active mineral additives and obtaining the strength of concrete modified with mineral additives on their basis higher than the strength of the control composition, the content of cement and mineral additives should decrease in a given ratio in proportion to the increase in strength, thus maintaining the uniformity of the distribution of the particles that form the matrix.

If finely dispersed slag is used as the mineral additive, which is capable of independent hydraulic hardening, then its particles should also be distributed mainly in the interparticle voids of the clinker component. The rational content of slag in the composition of the cement mixture is 35–70% [11]. This content is greater than the volume of interparticle voids of the clinker component. Therefore, it is advisable to use a bimodal particle size distribution or slag or clinker component to obtain a high-density concrete modified with mineral additives of dispersed composition.

The above-proposed physical model of concrete microstructure and particle packing is confirmed by the presented and previous [15][16] experimental results. Thus, the following guidelines are proposed for obtaining self-compacting concrete modified with mineral additives: coarse aggregate should be present in fractions of 5–10 mm. The content of coarse aggregate in the concrete mixture should not exceed a fraction (0.5) of sand to ensure a low level of the ultimate shear stress of the concrete mixture [38]. The fine aggregate should have two or three fractions, for example, a coarse fraction of 0.3 mm in an amount of 80% and a fine fraction of 0.12 mm in an amount of 20%. Such a fractional composition of the fine aggregate provides a decrease in its intergranular voidness and a decrease in air entrainment into the concrete mixture.

In addition, with a high cement content, the total alkali content in various components of the concrete composition could exceed the critical value of 3 kg/m^3. High alkali content requires aggregates containing reactive silica to provide alkaline corrosion of the aggregates. Consequently, using limestone and dolomite flour in concrete modified with mineral additives is less effective than mineral additives containing reactive silica.

3. Conclusions

It is shown that the determining factor in obtaining a homogeneous, highly filled, dense structure of a cement stone with low defectiveness is the use of heterogeneous mineral additives only with a specific surface area and content that are functionally related to the spatial geometric and energy state of the parameters of the particles that form the interparticle voids of the matrix component. With optimal values of geometric and quantitative parameters using mineral additives, the initial interparticle void content of concrete modified with mineral additives is reduced by 12–14% or more, and the strength of concrete is more than doubled. The volume of interparticle voids decreases by 9% or more due to the use of finely dispersed slag.

It is advisable to use particles of the clinker phase of several geometrical sizes, providing an increase in the concentration of the solid phase in a unit volume, a homogeneous course of pozzolanic, and hydration reactions of clinker minerals in all microvolumes of concrete modified with mineral additives. In addition, there is also a significant increase in the density of the cement stone, and the presence of large, strong relics of the particles of the clinker component at a later date, significantly contributing to the integral strength and durability of concrete.

The high efficiency of the complex application of polycarboxylate-type superplasticizers and high-valence hardening accelerator AC has also been established. The optimum content of the hardening accelerator AC is 0.07% of the cement mass as determined taking into account the Schulze–Hardi rule. Using a high-valence hardening accelerator provides a synergistic effect of using the superplasticizer Glenium 430. This makes it possible to additionally reduce water-containing concrete mixtures up to 20%. The introduction of the hardening accelerator into the concrete mixer must be carried out after the plasticizer, 8–10 s before the end of the preparation of the concrete mixture.

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