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**CLASSIFICATION AND COMPARATIVE ANALYSIS OF THE  
EFFECTIVENESS OF FINELY DISPERSED FILLERS.**

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**Abstract:** This article presents a classification of finely dispersed mineral fillers used in cement system technology, taking into account their origin, chemical-mineralogical composition, and reactivity. A comparative analysis of the influence of the most common types of aggregates - microsilica, fly ash, metakaolin, and limestone flour - on the physical-mechanical and operational characteristics of cement composites was conducted. Special attention is paid to the consideration of binary systems in which the combination of two different fillers allows achieving a pronounced synergistic effect. It has been shown that the rational combination of active (pozzolan and hydraulic) and inert (carbonate) additives ensures not only the optimization of the granulometric composition and an increase in the packing density of particles, but also improves the structural homogeneity and durability of the cement stone. It is emphasized that the application of binary mineral systems is an effective direction in the development of energy-saving and environmentally friendly cement materials of a new generation.

**Keywords:** cement systems, finely dispersed fillers, binary systems, microsilica, ash-discharge, metakaolin, limestone flour, synergistic effect, microstructure.

**Introduction.** The diversity of finely dispersed aggregates used in cement systems necessitates their systematization. Classification allows for understanding the potential capabilities and limitations of each material and making informed choices for specific technological tasks.

**Classification of fillers.** Micropellants can be classified according to several criteria:

**1. By origin:**

o Natural: diatomites, tripoli, opocs, volcanic ash, limestones.

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o Technogenic (secondary): fly ash (Fly Ash), granulated blast furnace slag (GGBFS), microsilica (Microsilica).

**2. By chemical composition:**

- o Siliceous: microsilica, diatomite (high SiO<sub>2</sub> content).
- o Clay earths: metakaolin (high Al<sub>2</sub>O<sub>3</sub> content).
- o Mixed composition: abrasive ash, slags (containing SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, CaO).

**3. By reactivity:**

- o Inert: finely ground quartz sand (acts only as a microfiller).
- o Active:

Pozzolanes: microsilica, metakaolin, F-class ash (reacts with Ca (OH) 2).

Latent-hydraulic: granulated blast furnace slag (requires activation with alkalis).

Carbonate: limestone flour (participates in the formation of carboaluminates) [1].

**Comparative analysis of popular fillers**

- **Microsilica (MC):** An ultradisperse material with exceptionally high pozzolan activity. Provides a sharp increase in strength (especially early), significant compaction of the structure, and an increase in durability. The disadvantage is high water demand.
- **Metacaolin (MCL):** A highly active artificial pozzolan. Significantly increases strength and sulfate resistance, effectively suppresses the alkaline-silicate reaction. Like MK, it increases the water demand of the mixture.
- **Absorbed ash (AB):** A widely used technogenic filler. In early stages, it can slow down strength gain, but in later stages (90-360 days), it ensures its significant increase due to the slow pozzolan reaction. Effectively reduces heat loss during hardening.
- **Limestone flour (LF):** Inert or weakly active filler. The main advantages are increased early strength due to the nucleation effect, reduced water consumption, and reduced cost of the mixture. At high doses (>15%), it can reduce final strength.

Table 1

Comparative influence of aggregates on the properties of cement stone

Indicator	Microsilica (MC)	Absorbed ash (AB)	Metacaolin (MCL)	Limestone flour (LF)
Early strength	↑↑	↓↓	→	↑↑
Latent strength	↑↑	↑↑	↑↑↑	→
Water demand	↑↑↑	↑↑	↑↑	↓↓
Sulfate resistance	↑	↑	↑↑	↑↑
Heat release	→	↓↓↓	→	→

The modern technology of cement composites has undergone a profound evolution, finally moving beyond the traditional three-component system of cement,

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water, and aggregate. Currently, the development of cement system compositions is a complex scientific and engineering process aimed at creating multicomponent binders with predetermined operational characteristics. This transition is necessitated not only by increasing the strength and durability of materials but also by addressing environmental, resource-saving, and economic challenges related to the decarbonization of the construction industry [2].

One of the most promising directions for the development of materials science is the integrated use of finely dispersed mineral fillers of various nature and functional purpose. In recent decades, cement composite design technologies have evolved from monosystems to binary, triple, and more complex multicomponent systems. Such an approach allows achieving a synergistic effect, in which the combined result of the interaction of components significantly exceeds the sum of their individual influences.

The combined use of several fillers with different mechanisms of action contributes to the mutual elimination of their shortcomings and the enhancement of the positive properties of each of them. Thus, the combined use of finely ground carbonate and active silica additives creates optimal conditions for the formation of a complex set of operational characteristics. Limestone, due to its pronounced filling effect and ability to accelerate the hydration of aluminates, provides an intensive early strength gain, which is especially important in the first stages of cement stone hardening. Simultaneously, active additives, such as microsilica, react with calcium hydroxide in a pozzolan reaction, forming additional C-S-H phases, which increase the strength and durability of the material in the later stages of hardening [3].

Based on these theoretical provisions, the hypothesis of the need for targeted management of the microstructure of cement composites through the rational combination of finely dispersed mineral fillers, differing in their chemical nature and surface activity level, is scientifically substantiated. This approach allows for the formation of a multi-mode structure where particles of different sizes and reactivity perform complementary functions [4].

According to the postulates of V.I. Salomatov's theory of composite building materials, the synergistic effect of multicomponent systems is realized through the combination of two interconnected processes.

Firstly, the creation of crystallization centers and acceleration of hydration are achieved by introducing fillers whose surface activity is equal to or exceeds the activity of the binder ( $F_n \geq F_v$ ). Microsilicon and metakaolin particles act as additional nucleation centers, contributing to the intensive growth of hydrate phases and the formation of a dense, homogeneous structure [5].

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Secondly, the ordering of the structure and the reduction of deformation stresses are carried out by introducing fillers with a lower surface activity ( $F_H < F_B$ ), such as finely ground limestone or quartz sand. These materials contribute to the compaction of the phase boundaries, the reduction of internal stresses, and the formation of a more stable microstructure, which minimizes the risk of microcracks and increases the durability of the composite.

Thus, the modern concept of cement system design is based on the principles of multi-level structural regulation, where the main tool is the controlled interaction of components of varying dispersity and chemical activity. This allows for a shift from empirical composition selection to scientifically based engineering of new-generation cement composites with predictable properties and increased operational efficiency.

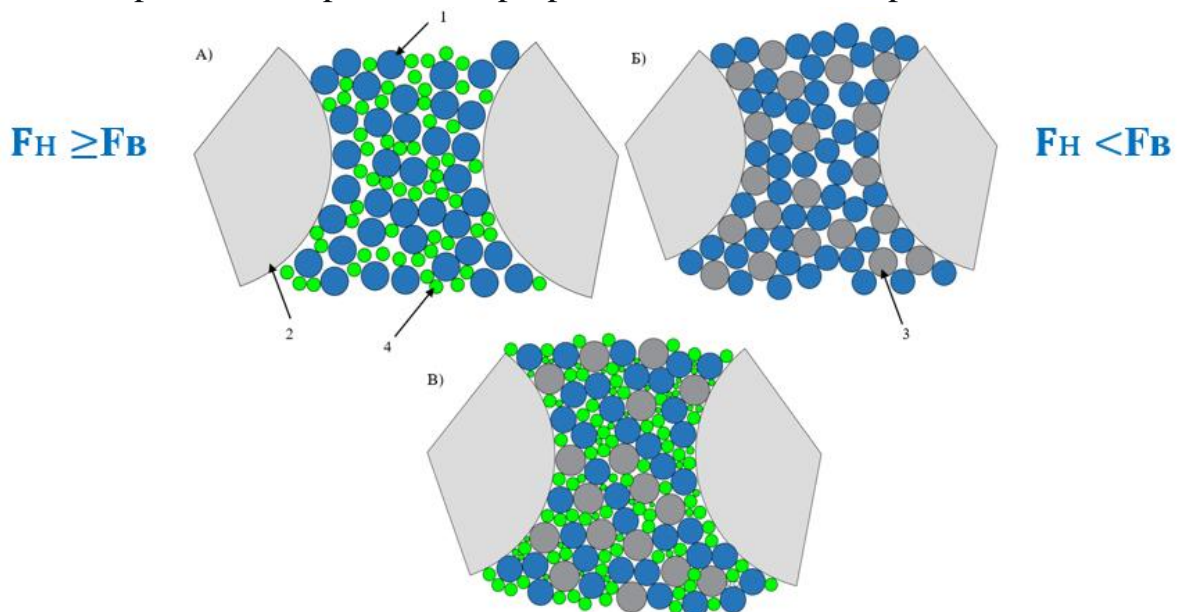


Figure 1. Spatial-structural topology of a binder

A - Dispersity of mineral filler higher than cement dispersity; B - The dispersity of the mineral filler is significantly lower than the dispersity of cement; B - The dispersity of binary mineral filler is greater and less than the dispersity of cement (optimal packaging).

Optimizing the granulometric composition represents one of the basic principles of materials science and serves as the basis for the rational design of cement composites. Its essence lies in ensuring the maximum compact packing of particles of different fractions, which leads to a reduction in pore space and an increase in strength, density, and durability of the material.

In traditional concrete mixtures, each aggregate fraction has a significant void: in gravel and sand, it can reach 45%. However, when used together, fine sand particles fill the gaps between large grains, reducing the total porosity to 25%. Adding finely

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dispersed fraction - cement and mineral fillers - allows for further compaction of the structure and reduction of voidiness to 10% or less, forming a dense and strong contact frame.

The principle of dense packing of particles underlies the design of binary and multicomponent cement systems. Fillers of various nature and dispersity create a multi-mode structure in which particles of different sizes effectively fill the intergranular spaces. This ensures:

- reduction of emptiness and, consequently, increase in strength and durability;
- increase in density and decrease in cement stone permeability;
- improvement of rheological properties due to the "micropodshipper" effect of fine particles.

Thus, the use of binary and multicomponent mineral fillers allows for the formation of a dense, homogeneous, and stable microstructure of cement stone, which ensures an increase in the physical and mechanical properties, energy efficiency, and durability of new generation cement composites.

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