ISSN: 2582-4686 SJIF 2021-3.261,SJIF 2022-2.889,
2024-6.875 ResearchBib IF: 9.948 / 2024

THE MULTIDISCIPLINARY JOURNAL OF SCIENCE AND TECHNOLOGY

VOLUME-5, ISSUE-10

UDC 666.972.16

ANALYSIS OF THE USE OF FINELY DISPERSED MINERAL FILLERS IN CEMENT SYSTEMS: ASPECTS OF EFFICIENCY, ACTION MECHANISM, AND TECHNOLOGICAL FEATURES

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Abstract: This article provides an analytical overview of the application of finely dispersed mineral fillers in cement systems. Current challenges in the cement industry, including high energy costs, carbon footprint, and the need to recycle industrial waste, were discussed. The mechanisms of influence of fillers on the structure formation of cement stone, including physical, nucleation, and pozzolan effects, were analyzed in detail. Classification of fillers by origin, chemical composition, and reactivity is provided. Key research results on the effectiveness of various additives, such as microsilica, fly ash, metakaolin, and limestone flour, have been summarized. Special attention is paid to the synergistic effect of binary systems and the potential negative aspects of their application. As a scientific hypothesis, the necessity of a comprehensive approach to designing multicomponent systems, taking into account the surface activity of fillers, to achieve optimal properties, has been put forward.

Keywords: cement systems, finely dispersed fillers, pozzolan reaction, microstructure, durability, carbon footprint, synergistic effect.

Introduction. The modern cement industry faces a complex of interconnected challenges driven by both economic and environmental factors. The need to intensify the production of construction materials while simultaneously tightening environmental protection standards necessitates the development and implementation of new resource- and energy-saving technologies.

One of the most effective and scientifically based approaches to solving these problems is the targeted modification of cement systems by introducing finely dispersed mineral fillers, also known as micropilling agents. The use of these materials allows not only to improve the physical and mechanical properties of concrete and mortars, but also to significantly reduce the consumption of cement clinker, the production of which is one of the main sources of carbon dioxide emissions.

The introduction of finely dispersed aggregates allows for targeted management of the hydration and structure formation processes of cement stone, leading to the formation of a denser, stronger, and more durable matrix. This approach opens up broad prospects for creating composite materials with predetermined operational characteristics, optimized for specific application conditions.

This review is dedicated to systematizing modern scientific concepts about the role, classification, and application aspects of finely dispersed fillers, as well as promising directions and new ways of using additives, which is a key step towards creating a new generation of highly efficient and environmentally friendly cement materials.

1. Current issues in the cement industry: ecology, economy, and resource conservation.

The cement industry is traditionally one of the most resource-intensive and environmentally demanding industries, which necessitates addressing a number of pressing issues. The key challenges facing industry are related to high energy intensity and significant carbon footprint. The production of Portland cement clinker requires significant expenditure of thermal and electrical energy (around 4-5 GJ/t) and is accompanied by large-scale emissions of greenhouse gases, particularly carbon dioxide (CO_2). About 50% of CO_2 emissions are due to the decarbonization of raw limestone ($CaCO_3 \rightarrow CaO + CO_2$), and the remaining part (40%) is due to the combustion of fuel for firing. On average, the production of one ton of cement leads to the emission of 0.8-0.9 tons of CO_2, making the cement industry responsible for approximately 8% of global anthropogenic CO_2 emissions. Thus, the problem of decarbonization of the industry is acquiring strategic importance [1-5].

In addition to environmental problems, cement production is associated with the depletion of natural resources, as it requires large volumes of primary mineral raw materials such as limestone, clay, and gypsum. Intensive extraction of these materials leads to the depletion of deposits and the destruction of natural landscapes. In parallel, many related industries - metallurgy, energy, chemistry, and mining - generate enormous volumes of finely dispersed waste (ash, slag, sludge), which requires the organization of large landfills for burial. These landfills occupy fertile lands and serve as sources of dust and chemical pollution of the environment.

The solution to these problems lies in the concept of sustainable development, based on the principles of "green" chemistry and technology. The most effective strategy is the partial replacement of expensive and "dirty" clinker production with affordable, often technogenic materials. These materials can have pozzolan and/or hydraulic activity, or act as inert fine-disperse fillers. This approach allows for achieving several interconnected goals simultaneously: reducing clinker consumption, ensuring the utilization of industrial waste, and improving several key operational characteristics of cement stone and concrete, which contributes to the creation of more efficient and environmentally friendly construction materials [6].

2. The role of finely dispersed aggregates in cement systems.

The introduction of finely dispersed mineral fillers into the composition of cement composites is a key tool for their targeted modification, ensuring a multifaceted role that goes beyond simply diluting cement. The main functions of microfillers can be conditionally divided into three groups: technical-economic, ecological, and physicochemical.

Technical-economic and ecological functions. From a technical and economic point of view, the use of fillers provides significant savings in expensive cement due to its partial replacement with cheaper mineral components. This leads to a significant reduction in the cost of construction materials and, no less importantly, a reduction in carbon footprint, as the need for energy-intensive cement clinker production decreases [7].

The ecological function of fillers is to use technogenic waste such as ash, slag, and microsilica as secondary raw material resources. This solves the problem of utilizing industrial and agricultural waste, prevents their disposal at landfills, which contributes to the preservation of fertile lands and a reduction in environmental pollution.

Physicochemical function. The physicochemical role of finely dispersed aggregates is most complex and lies in their influence on the structure formation processes and properties of cement stone.

- Filling Effect (Microfiller Effect): Fine particles of the filler, evenly distributed in the intergranular space, optimize the granulometric composition of the mixture. This leads to the compaction of the structure, a decrease in porosity, and an increase in the packing density of particles, which, in turn, contributes to an increase in strength and a decrease in water permeability.
- Crystallization center effect: Filler particles act as additional nucleation centers for neoplasms - cement hydration products (calcium hydrosilicates and hydroaluminates). This intensifies the processes of structure formation, contributing to the formation of a more homogeneous and fine-crystalline structure of cement stone.
- Puzzolan and hydraulic activity: A number of fillers, including ash, microsilica, and metakaolin, possess puzzolan activity. In the presence of water, they chemically interact with calcium hydroxide (Ca (OH) 2), which is formed during the hydration of clinker minerals, creating an additional amount of secondary calcium hydrosilicates and hydroaluminates. These compounds are stronger and more stable than Ca $(OH)_2$, which increases the density and durability of the cement matrix, especially in the later stages of hardening. Some materials, such as granulated blast furnace slag, exhibit hydraulic activity, meaning they can solidify independently in the presence of water and activators (often $Ca(OH)_2$ and sulfates contained in cement).

3. The mechanism of action of aggregates in the cement system

The mechanism of influence of microfillers on the structure formation processes and properties of cement composites is complex and includes several interconnected stages that act synergistically.

Physical and nucleation effects. First and foremost, finely dispersed fillers exert physical compaction, known as the filling effect. Filler particles effectively fill the intergranular space. This leads to the displacement of excess water into larger pores, which, in turn, reduces the water demand of the mixture while maintaining its rheological mobility. As a result, you can either reduce the amount of water, which increases the strength, or use more filler without losing its workability, making the structure denser and more homogeneous.

Simultaneously, the filler particles exert a nucleation effect. Their surface serves as additional centers for the heterogeneous crystallization of hydrate neoplasms, such as calcium hydrosilicates. This process accelerates hydration kinetics in the early stages, contributes to the formation of a more homogeneous and fine-crystalline structure that is less susceptible to defects and has higher strength [8].

Pozzolan reaction. For active fillers such as microsilica or metakaolin, the key is the putzzolan reaction, which occurs at later stages of hardening (usually from 7 days and beyond). This reaction includes three main stages:

1. Dissolution: On the surface of the filler particles, in the alkaline environment of the porous solution (pH>13), the dissolution of amorphous silica (SiO_2 (amorph.)) occurs.
2. Diffusion and interaction: The resulting SiO_4^{4-} ions diffuse to the calcium hydroxide (Ca $(OH)_2$) particles formed during cement hydration and enter into chemical interactions with them.
3. Gel phase formation: As a result of the reaction, nanocrystalline low-basic calcium hydrosilicates (C-S-H phases) are formed on the surface of the filler particles and in the adjacent space. These secondary hydrate phases adhere firmly to the initial matrix.

This process is characterized by "self-sampling," as the volume of solid reaction products exceeds the volume of the initial reactants. This leads to a further reduction in capillary porosity and an increase in the strength and durability of the material.

The combined effect of all these mechanisms - physical compaction, nucleation, and pozzolan reaction - leads to the formation of cement stone with optimized microstructure: reduced total porosity, smaller pore sizes, increased content of highly stable gel-like C-S-H phases, and reduced content of large-crystal and less stable Portlandite ($Ca\ (OH)_2$).

4. Classification of microfillers.

Microfillers used to modify cement systems are a diverse group of materials that can be classified according to several key characteristics reflecting their origin, chemical-mineralogical composition, and reactivity.

Classification by origin. By origin, microfillers are divided into natural and technogenic. Natural fillers are formed as a result of natural geological processes and include volcanic or sedimentary rocks such as opoka, diatomite, and trepel. Technogenic (secondary) fillers, on the contrary, are by-products or industrial waste. These include materials generated by the energy, metallurgical, chemical industries, and mining and processing plants. The use of technogenic fillers solves not only economic but also important environmental problems related to the disposal of industrial waste.

Classification by composition and reactivity. According to their chemical-mineralogical composition and reactivity, microfillers are divided into several categories.

- Siliceous fillers consist mainly of silicon dioxide (SiO_2). This group includes materials such as quartz sand, diatomite, tripoli, and microsilica.
- Alumina fillers are characterized by high aluminum oxide (Al_2O_3), examples of which are bauxites and alumina slags.
- Mixed (silicate-aluminate) composition fillers are complex compounds and include fly ash, metakaolin, granulated blast furnace slag, and natural pozzolans.

By phase composition and reactivity, fillers can be inert (inactive) or active. Inert fillers, such as finely ground quartz sand, do not chemically interact with cement hydration products under standard conditions. Their effectiveness is based solely on the filling effect, which contributes to the physical compaction of the cement matrix.

Unlike them, active fillers are divided into several types:

- Pozzolan fillers contain amorphous or glassy silica, capable of reacting with calcium hydroxide ($Ca\ (OH)_2$) formed during cement hydration. As a result of this reaction, secondary calcium hydrosilicates (C-S-H phases) are formed, which increase the density, strength, and durability of cement stone. Classic examples include microsilica, fly ash, and natural pozzolans.
- Latent-hydraulic fillers, which include granulated blast furnace slag, are capable of solidifying independently in the presence of water after being activated by alkalis or sulfates.
- Carbonate fillers such as finely ground limestone and dolomite exhibit both physical effects and participate in chemical reactions, contributing to the formation of carboaluminate phases that modify the composition of the hydrate matrix.

5. Types of fillers used.

In the modern practice of cement and concrete production, a wide range of microfillers is used, which can be conditionally classified according to their origin and functional properties. This section presents the most frequently used concrete additives.

Technogenic fillers are by-products of industrial activity and play a key role in the concept of "green" chemistry.

Fly ash is the most common microcomponent, a byproduct of coal combustion at thermal power plants. It is divided into class F (low and medium calcium) and class C (high calcium). F-class ash has pronounced pozzolan activity, while C-class ash has pozzolan and hydraulic activity.

Granulated blast furnace slag (GGBFS). The product of rapid cooling of the molten slag formed in the blast furnaces during the smelting of cast iron. Slag has latent-hydraulic properties, which means its ability to solidify in the presence of water only after being activated by alkalis or sulfates contained in cement.

Microsilica (Microsilica). Ultrafine material captured in the production of silicon and ferroalloys. Its particles are spherical and consist of amorphous silicon dioxide. With a specific surface area from 9000 to 25000 cm^2/g, it possesses exceptionally high pozzolan activity, which allows for a sharp compaction of the structure, a significant increase in strength (especially in early stages), and durability.

Metakaolin (Metakaolin). Artificial highly active pozzolan material obtained by controlled firing of kaolinite clay. Metakaolin effectively improves the properties of concrete, and also has a unique ability to suppress the alkaline-silicate reaction, which is crucial for concrete durability in aggressive environments.

Natural fillers have been used since ancient times, but their application is also relevant in modern technology. These include natural pozzolans of volcanic (volcanic ash, tuffs) and sedimentary (diatomites, tripoli) origin, containing active silica, as well as limestone fillers, which are finely ground limestones or dolomites. Although limestones are mostly inert, they effectively compact the matrix and can participate in the formation of carboaluminates that stabilize the structure.

Other fillers include rice husk ash (RHA) - a highly active pozzolan material containing up to 95% amorphous silica, as well as crushed sand and various finely dispersed waste from ore beneficiation, which can be used to confirm their safety and effectiveness.

6. Some research on the effectiveness of finely dispersed mineral fillers in cement systems.

Numerous studies conducted by such scientists have proven that the introduction of metakaolin into cement compositions leads to a significant increase in the compressive and bending strength of concrete. This effect is due to two main mechanisms. Firstly, this is a pozzolan reaction, in which highly active metakaolin reacts with calcium hydroxide ($Ca(OH)_2$) formed during cement hydration. As a result, additional hydrated calcium silicates and aluminates (C-S-H and C-A-H gels) are formed, which compact the structure of the cement stone. Secondly, the effect of the microfiller is that highly dispersed metakaolin particles (size 1-3 μm) fill the smallest pores and voids between cement particles, contributing to the additional compaction of the matrix. Regarding deformability, studies [9] show that metakaolin reduces the creep of concrete, making it more stable under long-term loads, although its effect on shrinkage may be ambiguous and requires further study. One of the most significant advantages of using metakaolin is its effect on the porous structure and, consequently, on the durability of concrete. The work clearly demonstrated that metakaolin significantly reduces the overall porosity and permeability of concrete. This is achieved by reducing the size and cohesion of capillary pores, making the material less susceptible to aggressive substances. In addition, metakaolin increases the chemical resistance of concrete. It has been shown that the addition of metakaolin improves the resistance to sulfate corrosion, as it binds calcium hydroxide, which is a vulnerable component. Additionally, metakaolin is one of the most effective materials for suppressing the alkaline-silica reaction, as it binds alkalis, preventing their destructive interaction with the filler.

The research of Pierre-Claude Aitchine (P.-C. Aïtcin) and his school (University of Sherbrook, Canada) [10] was on the introduction of MC into the practice of high-strength concrete. The scientist experimentally established that the introduction of 5-10% MC of the cement mass increases the compressive strength at 28 days by 20-40% or more. This effect is explained by the synergy of MC and superplasticizers, which allows for a significant reduction in W/C (up to 0.25 and below) and the creation of an overly dense matrix.

Work [11] using scanning electron microscopy (SEM) has clearly demonstrated that ultradisperse MK particles effectively fill the intergranular space between cement particles, acting as a micropilling agent. This leads to the compaction of the structure already in the early stages of hardening, which is confirmed by the increase in strength at 1-3 days. e MC on deformation characteristics is ambiguous and requires a differentiated approach.

Research by V.I. Solomatov [12] showed that, despite a significant increase in compressive strength, the bending strength increases to a lesser extent. This is due to the increased brittleness of the matrix due to the formation of a fine-pored structure and the decrease in the proportion of macropores that could play the role of dampers during crack propagation. The modulus of elasticity of high-strength concretes with MC, as a rule, increases proportionally to the strength, however, its relative increase (10-15%) may lag behind the increase in strength. This indicates a slight increase in the material's brittleness, which must be taken into account when calculating structures.

The works [13] were devoted to a detailed study of the kinetics of the putzzolan reaction and its influence on porosity. It has been established that MC not only fills macropores and capillaries but also significantly reduces the pore volume with a diameter of >100 nm, which are the most dangerous in terms of permeability and frost resistance. The total porosity can decrease by 15-20%. Using the method of mercury porometry, it was proven that MK contributes to the shift of the pore space to the nanopores region (<10 nm), which, according to Powers' theory, are filled with bound water and do not significantly affect permeability and strength.

Studies by the group [14] (EPFL, Switzerland) using quantitative X-ray diffractometry (QXRD) and high-resolution electron microscopy (FE-SEM) showed that MC effectively binds free Portlandite ($Ca(OH)_2$) - the most vulnerable component of cement stone. Its content can decrease by 2-3 times, which sharply increases its resistance to sulfate corrosion and acidic effects.

The works [15] proved the high effectiveness of MC in suppressing the alkaline-silica reaction. The mechanism is based on the binding of alkali metal ions (Na^+, K^+) in the additional C-S-H phase and a decrease in permeability, which prevents the access of water necessary for large-scale reactions.

The use of fly ash (FAS) in cement systems has a comprehensive impact on their properties, which is confirmed by numerous studies. The effectiveness of FA is determined by its chemical composition and dispersity, which necessitates a multifaceted influence on the strength, deformation, microstructure, and durability characteristics of concrete.

Studies [16] within the concept of high-volume ash concretes (HVFA), where the FA content reaches 50-60% of the binder's mass, have shown that, despite the slow strength gain at early stages (7-28 days), in the long term (90-360 days), the strength of such concretes not only reaches but can exceed the strength of the control sample. This phenomenon is explained by the slow but prolonged pozzolan reaction, which contributes to the strength in later stages. In the early stages of hardening, FA acts as a microfiller, diluting cement and slightly slowing down hydration, while the main increase in strength after 28 days occurs due to the formation of secondary calcium hydrosilicates (C-S-H phases) as a result of the interaction of amorphous silica ash with Portlandite. Research by Robert E. Foller and his colleagues also established that the activity of the rectum is directly proportional to its specific surface area. Thinner fractions (<10-20 µm) make the main contribution to the putzolan reaction and subsequent strength increase.

It has been established that the deformation characteristics of concretes with microfillers based on fly ash are characterized by a reduced elastic modulus at early stages, which correlates with their lower strength. However, at 90-180 days, the elastic modulus values are compared with the control values. Moreover, due to the increase in the density of the "filler-matrix" contact zone and the decrease in stress concentration, such concretes exhibit better load redistribution capability. Numerous experiments also confirm that replacing part of the cement with ash removal leads to a decrease in the creep and shrinkage of the finished product. This is due to the reduction in the volume of the most mobile capillary moisture and the overall heat release, which minimizes thermal deformations in massive structures [17].

The influence of fly ash on the formation of composite porosity is key to explaining the mechanism for increasing concrete durability. Karen Skriviner's (EPFL, Switzerland) work, using quantitative X-ray diffractometry and electron microscopy, proved that the putzzolan reaction involving ash removal leads to a transformation of the pore structure: a decrease in the volume of capillary pores (>50 nm) and an increase in the proportion of gel pores (<10 nm) occur.

Research by M.D.A. Thomas (University of New Brunswick, Canada) [18]. has demonstrated the high effectiveness of using abrasive ash in increasing the chemical resistance of concrete. Numerous examples of using fly ash in solving specific issues related to the physical and mechanical performance indicators of concrete can be cited.

As is known, limestone was used in the cement industry as an inert component, primarily designed to save clinker. However, the works of such scholars as H. Uchida, S. Tsukimak, and V. Bonen in the 1990s radically changed this view. Using advanced methods such as X-ray phase analysis (XRD) and scanning electron microscopy (SEM), they experimentally proved that finely dispersed calcium carbonate (CaCO3) particles are not inert but actively participate in the chemical and physical processes of clinker phase hydration [19].

The key discovery made by P.K. Mehta and elaborated by K.L. Skriviner was that limestone reacts with the aluminate phases of cement (C_3A) to form stable carboaluminate hydrates. The main products of this interaction are the hexagonal calcium hydrocarboaluminate ($Ca_4Al_2(CO_3)(OH)_{12}5H_2O$) and calcium monocarboaluminate ($Ca_4Al_2(CO_3)(OH)_{12}\cdot 6H_2O$). The formation of these stable phases, unlike metastable hydrosulfoaluminates (ettringite), contributes to the stabilization of the system and the formation of a denser microstructure. Furthermore, L. Robert and J.-J. Shen established that finely dispersed particles of $CaCO_3$ serve as nucleation centers for the hydration of silicate phases (C_3S, C_2S), accelerating the early stages of solidification [20,21].

Numerous studies, including the works of V.I. Kalashnikov and I.V. Klyushnikov, demonstrate that the introduction of 5-10% limestone flour leads to an increase in compressive strength. This is due to the acceleration of C_3S hydration due to the nucleation effect and the formation of strong carboaluminate phases. With the content of limestone flour up to 10-15%, the late strength does not decrease and can be comparable to the strength of pure cement. However, at higher doses (more than 20%), a decrease in strength is observed due to the dilution of the clinker phases and the inertness of excess $CaCO_3$ [22].

Yu.S. Volkov and (A. Neville) established that the introduction of limestone meal in optimal quantities (5-10%) does not negatively affect the deformation characteristics of concrete. Shrinkage and creep remain at the level of the control samples or are slightly reduced due to a denser and more uniform microstructure [23].

Studies by M.I. Brusser and G.Y. Isliker, conducted using mercury porometry, confirm that the optimal amount of limestone flour (up to 15%) contributes to a decrease in overall porosity and the redistribution of pores towards smaller ones. This effect is achieved due to the filling effect, in which the smallest particles of $CaCO_3$ fill the intergranular space, as well as due to the formation of additional hydration products (carboaluminates) that compact the structure of the cement stone. As a result, the permeability coefficient of concrete decreases, which increases its durability [24].

The effect of limestone flour on sulfate resistance is ambiguous and depends on the cement composition. On the one hand, the formation of stable monocarboaluminate instead of ettringite reduces the risk of expansion associated with sulfate corrosion. On the other hand, excess limestone can react with sulfates to form gypsum and taumasite, leading to destruction. In this regard, P. Bramaot recommends using limestone cements under sulfate aggression conditions with caution and in combination with other additives (e.g., slag or ash). The compacted structure formed when limestone flour is introduced contributes to increasing the frost resistance of concretes with a moderate content of this aggregate.

Based on a brief overview of the most widely used micro-fillers in construction materials science, a comparative table is presented showing the influence of various types of finely dispersed additives on the properties of cement paste [25].

Table 1

Comparative table of cement stone properties

Indicator	**MS**	**FA**	**MKL**	**GFS**	**LM**
Early strength	→	↓↓	→	↓	↑↑
Latent strength	↑↑	↑↑	↑↑↑	↑↑↑	→
Water demand	↑↑↑	↑↑↑	↑↑	↑	↓↓
Sulfate resistance	↑	↑	↑	↑	↑↑
Heat release	→	↓↓↓	→	↓↓	→
Reinforcement corrosion	↑↑	↑↑	↑↑	↑↑	→

Note: MS-microsilica; FA- ash-discharge; MKL-metakaolin; GFS-granulated furnace slag; LM-Limestone Filler

The use of finely dispersed mineral additives, despite its numerous advantages, has a number of potential negative aspects that require careful scientific analysis and consideration when designing concrete compositions [26].

One of the most serious risks associated with the use of silica additives (such as microsilica and ash) is their ability to reduce the alkalinity of the porous cement matrix solution. During the putzzolan reaction, active amorphous silica (SiO_2) interacts with free calcium hydroxide ($Ca(OH)_2$), which ensures a high pH (around 12.5-13.5). As a result of this interaction, secondary calcium hydrosilicates are formed, and the concentration of $Ca(OH)_2$ decreases. This leads to a decrease in the alkalinity of the porous solution, which can disrupt the passivating layer on the surface of the steel reinforcement, consisting of iron oxides. When the pH decreases below the critical level (usually <10), the passivating film breaks down, making the reinforcement vulnerable to corrosion, especially in the presence of chloride ions. Thus, despite the overall compaction of the structure, the decrease in alkalinity is a significant risk factor for the durability of reinforced concrete structures.

When the alkaline environment of cement decreases, the introduction of additives can intensify the formation of "dormant" phases - ettringite and taumasite, which are products of sulfate corrosion.

Carbonate rocks, although they improve early strength and compact the structure, also have their drawbacks. The use of limestone in large doses (more than 15%) leads to a significant dilution of the clinker phases. This reduces the total amount of calcium hydrosilicates, which negatively affects the final strength of the concrete [27].

The modern technology of cement systems has undergone significant evolution, going beyond the traditional component system. Currently, the design of cement composite compositions is a complex scientific and technical process aimed at creating multi-component systems that include two or more functional additives[28]. This transition is due to the need to improve the operational characteristics of concrete, as well as the solution of environmental and economic problems.

A promising scientific direction is the integrated use of finely dispersed mineral fillers in cement systems. Composition design technologies have transitioned from mono- to binary, as well as triple and more multi-component systems, which allows achieving a synergistic effect exceeding the sum of individual contributions of each component.

Combining two or more fillers with different operating mechanisms allows you to eliminate the shortcomings of each of them and strengthen the positive aspects [29].

The combined use of finely ground carbonate and other types of active additives can contribute to the creation of the most favorable conditions for the formation of the necessary complex of properties. For example, the use of limestone ensures early strength gain due to the filling effect and acceleration of the hydration of the aluminate phases, which is especially important in the first 24 hours. At the same time, the active additive in the form of microsilica enters into an intensive putzzolan reaction with the formation of secondary C-S-H phases. As a result, high strength and durability are ensured in the late hardening periods [30].

Based on the presented theoretical provisions, the following statement can be put forward as a scientific hypothesis (Figure 1):

The development of highly effective cement composites should be based on the principles of targeted microstructure management, implemented through the combination of finely dispersed mineral fillers with varying surface activity and nature.

We assume that the synergistic effect is achieved when using binary or multicomponent systems, where fillers play two complementary roles, according to the postulates of V.I. Salomatov's theory [12]:

1. Creating crystallization centers and accelerating hydration: To accelerate structure formation processes in the early stages of hardening, it is necessary to use fillers whose surface activity is equal to or higher than the binding activity ($Fn \geq Fv$). Particles of such fillers (e.g., microsilica, metacaolin) act as active nucleation centers, intensifying hydration and forming a strong matrix.
2. Structure ordering and deformation reduction: To optimize mechanical characteristics and increase durability in later stages, it is necessary to introduce fillers with surface activity lower than

that of the binder (Fn<Fv). These particles (e.g., finely ground limestone, crushed sand) contribute to the reduction of inter-particle deformations at the interface, resulting in a more ordered, dense, and stable structure, minimizing the risk of microcracture formation.

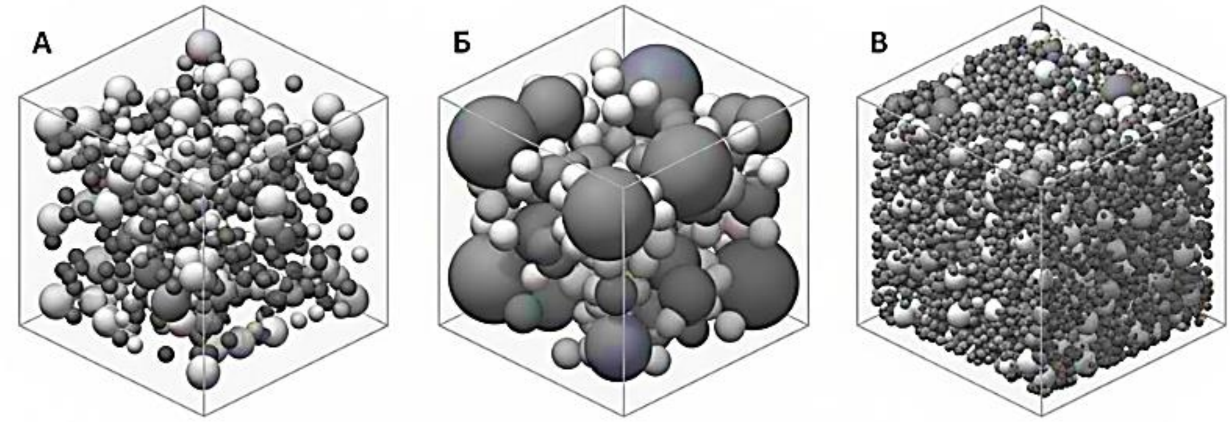

Figure 1. Spatial-structural topology of a binder
A - Dispersity of mineral filler higher than cement dispersity; B - The dispersity of the mineral filler is significantly lower than the dispersity of cement; B - The dispersity of binary mineral filler is greater and less than the dispersity of cement (optimal packaging).

This phenomenon, known as granulometric composition optimization, can be explained using the principles of dense packing of particles. If we consider the components of concrete, the void content of the separately taken coarse aggregate (gravel) and fine aggregate (sand) can exceed 45%. However, when they are combined, smaller sand particles fill the voids between the larger gravel fractions, resulting in a significant decrease in total porosity to 25%. Additional introduction of finely dispersed fraction in the form of cement and, in particular, finely dispersed mineral fillers allows for filling the remaining pores, bringing the voidiness to 10% or less [31].

The principle of tight packing underlies the use of binary and multicomponent fillers in cement systems. The use of fillers of different nature and dispersity allows for the creation of a multi-mode system where particles of different sizes effectively fill the intergranular space of each other. This leads to:

- Reducing emptiness. Closer packaging of solid phases reduces pore volume, which is a key factor in increasing strength and durability.
- Increasing density. The reduction of voidiness increases the density of cement stone.
- Improvement of rheological properties. Fine-dispersed filler particles can act as "ball bearings," improving the workability of the fresh mixture and reducing water requirements.

Thus, the use of binary fillers allows for the creation of a dense, homogeneous structure of cement stone, which ultimately improves the physical-mechanical and operational properties of the cement composite.

Conclusion. The analysis confirmed that the introduction of finely dispersed mineral fillers is a key direction in the evolution of cement system technology. Deviation from the traditional system to polykomponent mineral filler compositions, including binary and triple additives, allows not only to solve acute environmental and economic problems but also to ensure the production of materials with improved operational characteristics.

Hypothesis and prospects

The proposed hypothesis about the purposeful control of the structure through the combination of fillers with different surface activity and nature appears to be scientifically based and promising. Further research in this area will allow for a shift from empirical composition selection to precise engineering design of materials with specified properties, taking into account hydration kinetics, mixture rheology, and the durability of the final product. This opens the way to creating a new generation of cement composites capable of meeting the strictest requirements of modern construction and sustainable development.

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