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WHITE CEMENT-BASED BINDER FOR SELF-CLEANING FINE-GRAINED CONCRETE

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Abstract

Introduction. The production of concrete products with complex shapes that are thin-walled, durable, and resistant to environmental influences — while retaining their decorative appearance during service and maximizing the use of industrial (secondary) mineral raw materials — poses a significant challenge. This challenge is particularly pronounced when producing white-colored products, as the range of suitable raw materials becomes severely limited. Additionally, reducing the Portland cement content in such concretes is essential. Therefore, a pressing task is the development of modern binders and concretes with reduced Portland cement content based on white-colored mineral components. **Materials and methods.** White Portland cement without mineral additives (PCB 1-500-D0 Cemix ProWhite, Cemix LLC, Republic of Bashkortostan) was used as the binder; expanded perlite sand (pozzolanic additive), microcalcite (carbonate additive), and anatase (photocatalytic additive), as well as their mixtures, were considered as additives; and polycarboxylate-based plasticizer Melflux 1641 F was employed to improve workability. The main physical and mechanical properties of the binder and the resulting cement stone — including normal consistency, mini-cone spread, and compressive strength — were evaluated according to standard procedures. Workability of the mixtures was assessed using rheological measurements, and the rate of heat release during cement stone hydration was determined calorimetrically. The study also examined the microstructural features of the resulting cement stone. **Results.** Replacing 40 % of cement with a complex of mineral additives in combination with a plasticizer mitigates the negative impact of fine components on the water demand of the mixture. This modification promotes intensified hydration, enhanced uniformity and density of the cement stone, and a reduction in the specific surface area and total nanopore volume of the cement stone by 39 % and 36 %, respectively. The presence of mineral additives enables the production of a binder achieving a compressive strength of 65.2 MPa after 28 days of standard curing.

Keywords: white Portland cement, perlite sand, complex additive, microstructure, hydration, concrete.

Introduction

In recent years, the production of modern high-performance construction materials has demonstrated new trends. Both manufacturers and consumers are increasingly focusing on the rational use of natural resources, with particular attention given to the recycling of industrial waste and the search for ways to reduce the energy intensity of production. Consequently, in the development, design, and implementation of composites, economic considerations are now taken into account alongside environmental ones. At the same time, modern construction materials are required to meet a wide range of performance criteria reflecting the high level of technological advancement, including workability, enhanced strength, frost resistance, corrosion resistance, self-cleaning capabilities, etc. Achieving an optimal balance of these properties is made possible through the development of multicomponent systems, in which the processes of phase and structure formation are controlled through the rational selection of raw materials, including modern additives, as well as by-products and industrial waste (Abouelnour et al., 2024; Cherkasov et al., 2015; Ledyaykina and Ledyaykin, 2024; Luo et al., 2024; Pogorelov, 2010; Tarasov et al., 2018).

In the modern construction industry, the production and use of binder systems with reduced Portland cement clinker content, in which a portion of clinker is replaced with mineral additives of various origins, are expanding. Such binders demonstrate enhanced environmental performance and efficiency by utilizing either industrial waste or locally available materials. At the same time, they maintain their operational properties while offering reduced energy consumption and cost, achieved through the rational design of the composition and the use of chemical admixtures.

The application of these advanced binders is particularly relevant for producing non-standard decorative and architectural concretes, which can be used in the manufacture of thin-walled elements as well as other non-standard products with complex geometries, coloring, surface texturing, etc. (Bazhenova and Bazhenova, 2016; Kalashnikov, 2011; Kalashnikov et al., 2023; Loganina and

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Fokin, 2019; Moroz et al., 2016; Mousavinejad and Pourjamali, 2024; Stenechkina, 2023; Tolstoy et al., 2018).

The analysis of the challenges associated with producing thin-walled products from fine-grained white-cement-based concrete (Fig. 1) has identified rational approaches that can improve production efficiency and the durability of the resulting products, thereby contributing to the enhancement of the architectural appearance of the urban environment.

The solution to the specific challenges associated with concretes intended for thin-walled products — such as ensuring high resistance to environmental effects and achieving complex product geometries, which require good workability of the mix and high matrix strength — lies in the development and use of a binder based on white Portland cement and white-colored mineral additives. This approach reduces cement content while maintaining the rheological properties of the binder composition as well as the physical and mechanical characteristics of the hardened system. To impart self-cleaning ability and preserve the decorative appearance over extended periods under aggressive environmental conditions, the use of a photocatalytic additive, pre-immobilized on one of the binder components, is advisable. This strategy minimizes leaching (weathering) of the photocatalyst from the surface, ensures uniform distribution of the photocatalyst in the surface layer of the product, and enhances its self-cleaning performance.

The proposed set of measures, forming a comprehensive technological solution, enables the production of white fine-grained concrete with high physical and mechanical performance and resistance to environmental, man-induced, and biological impacts. This is achieved through reduced porosity of the cement matrix as well as physical and chemical immobilization of the photocatalyst within the cement-sand matrix.

The specific characteristics of white Portland cement, particularly its high degree of whiteness, significantly limit the range of mineral additives, including pozzolanic ones, that can be used in the binder composition, since changes in the concrete color would reduce the aesthetic appeal of the products. The use of mineral additives, fillers, and aggregates with colors substantially different from white together with white cement is economically impractical, as the cost of the latter is higher than that of ordinary Portland cement due to stricter raw material requirements and higher clinker sintering temperatures. Considering these primary criteria (color and inherent reactivity), expanded perlite sand was selected as one of the additives to partially replace cement (Ayubov et al., 2024; Grzeszczyk and Janus, 2021; Natsievsky, 2006; Shirina and Zagorodnyuk, 2007).

Expanded perlite used in cementitious materials is commonly addressed as a lightweight filler and aggregate (Berov et al., 2006; Kharitonov et al., 2023; Kotwica et al., 2017; Miryuk and Zagorodnyuk, 2022; Sidorova, 2024). However, its application as a pozzolanic additive and a carrier for a photocatalyst has received limited attention in the literature. Therefore, the objective of this stage

DEVELOPMENT OF FINE-GRAINED CONCRETE FOR THIN-WALLED PRODUCTS		
CHALLENGES	**SOLUTIONS**	**RESULTS**
High cost of white Portland cement and the carbon footprint of the global cement industry	Partial replacement of white Portland cement with mineral additives, including industrial by-products	Reduced production costs. Lower carbon footprint. Expanded raw material base for fine-grained concrete production.
Demand for white and light-colored concrete products and structures to create a favorable architectural environment	Use of binders, mineral additives, fillers, and aggregates of white color	Products exhibit high decorative qualities. Ability to produce products in a wide range of colors.
Increased water demand of the binder when using finely dispersed mineral additives	Control of rheological parameters of the binder through rational use of mineral and plasticizing additives	Improved workability of the mixture without increasing water content, enabling production of thin-walled products with complex shapes.
Loss of decorative appearance during long-term operation due to man-induced and biological impacts	Use of a photocatalyst immobilized on a mineral additive	Products gain properties of photocatalytic self-cleaning against organic contaminants, remaining resistant to environmental effects (weathering).
Difficulty achieving high performance and durability in thin-walled products with complex shapes	Control of the particle size distribution of components at the nano-, micro-, and macro-levels of fine-grained concrete to create a high-density structure	Products exhibit high strength and frost resistance, reduced water absorption, and resistance to environmental impacts and biological aggressions.

Fig. 1. Challenges and approaches to improving the efficiency of fine-grained concretes for thin-walled products

of the study was to evaluate the potential use of expanded perlite sand as an active (pozzolanic) additive to white Portland cement by examining its properties, the dependence of these properties on surface preparation (activation), and the influence of its composition and typomorphic features on the properties of the cement system.

Accordingly, the research aims to establish the properties — workability, strength, and durability — of fine-grained concrete for light-colored thin-walled products with reduced white Portland cement content. This reduction is achieved through the combined action of siliceous (expanded perlite) and carbonate (microcalcite) components at an optimal granulometric composition and content within the binder. Additionally, the leaching of nanosized photocatalyst during the service life of the products is prevented by pre-immobilizing it on the particles of the siliceous component of the binder.

Methods

A binder mixture consisting of white Portland cement without mineral additives PCB 1-500-D0 Cemix ProWhite produced by Cemix LLC, Republic of Bashkortostan (used as the control composition), and a binder mixture with the partial replacement of cement with mineral additives, were the object of the study. Ground expanded perlite sand (GEPS) produced by Oskolsnab JSC, Stary Oskol, was used as a pozzolanic additive; microcalcite (MC) produced by MramorPro LLC, Yekaterinburg, served as a carbonate additive; and nanosized titanium dioxide in the anatase modification (An) produced by Hangzhou Wanjing New Material Co., Ltd., China, was used as a photocatalytic additive. Additionally, a multifunctional composite material (MCM) of the "expanded perlite sand – nanosized anatase" (EPS–An) system was employed. It was produced by co-grinding expanded perlite sand pre-treated in a 2.0 % aqueous solution of oxalic acid with anatase in a 1:1 ratio.

To study the features of phase and structure formation in the binder, the influence of the additives on the normal consistency of the cement paste was evaluated according to GOST 30744-2001 using a Vicat apparatus.

A plasticizing admixture was selected with account for the requirement to maintain the white color of the mixture and the presence of highly dispersed components. Due to its well-documented effectiveness in such systems, polycarboxylate-based plasticizer Melflux 1641 F (BASF Construction Additives, Germany) was chosen. The dosage range of the admixture was determined based on the manufacturer's recommendations. The admixture was introduced in equal increments of 0.05 % until no further increase in mini-cone spread was observed.

The influence of the nature of mineral additives on the rheological characteristics (viscosity and shear stress) of the binder systems was assessed using a Rheotest RN4.1 rotational viscometer with a cylindrical measuring system under shear deformation at a gradient of 0–150 s^{-1}.

To evaluate the effect of mineral additives on the early hydration of cement, isothermal calorimetry was performed using a ToniCAL 7339 differential calorimeter. The water-to-binder ratio for all mixtures was 0.5. Differential and integral heat release curves of the binder systems were recalculated per 1 g of white Portland cement.

The study of phase formation in the binder with various additives was carried out by determining the mineral composition of the resulting cement stone using X-ray diffraction patterns obtained with an ARL X'TRA diffractometer in the 4–56° range.

The effect of mineral additives on the strength properties (flexural and compressive strength) of the cement stone was evaluated according to GOST 30744-2001 after 3, 7, and 28 days of curing of 40×40×160 mm test beams.

The structural features of the cement stone based on binders with different additives were investigated through micrographs obtained using a TESCAN MIRA scanning electron microscope after preliminary chromium coating of the specimen surfaces.

The specific surface area and nanopore distribution in the cement stone based on binders with different additives were determined using BET (Brunauer–Emmett–Teller) and BJH (Barrett–Joyner–Halenda) methods based on low-temperature nitrogen adsorption on the specimen surface.

Results and Discussion

The results of normal consistency measurements of the cement paste show that replacing 20 % of white Portland cement with EPS–An increases the water demand of the binder by 21 %, while replacement with microcalcite reduces it by 9 %. A 40 % replacement of cement with a mixture of the above additives is accompanied by a 15 % increase in water demand compared to pure Portland cement (Table 1). The increase in normal consistency observed in all compositions is attributed to the physical sorption of water by highly dispersed and porous particles and their aggregates.

Accordingly, the next stage in the development of the binder was the rational selection of a plasticizing admixture. Traditionally, a plasticizer is introduced at the stage of concrete mix preparation, often regardless of the type of cement used. However, due to the multicomponent composition of the proposed binder and the high fineness of its components, conventional concrete mix designs may not ensure the required workability and may lead to excessive consumption of plasticizer or mixing water.

The obtained mini-cone spread results (Fig. 2) generally demonstrate an increase in the water

Table 1. **Normal consistency of binders depending on composition**

No.	Component content, %				Normal consistency, %
	Mixture composition	**White Portland cement (WPC), %**	**EPS–An**	**Microcalcite (MC)**	
1.	WPC	100	–	–	33
2.	WPC + EPS–An	80	20	–	40
3.	WPC + MC	80	–	20	30
4.	WPC + EPS–An + MC	60	20	20	38

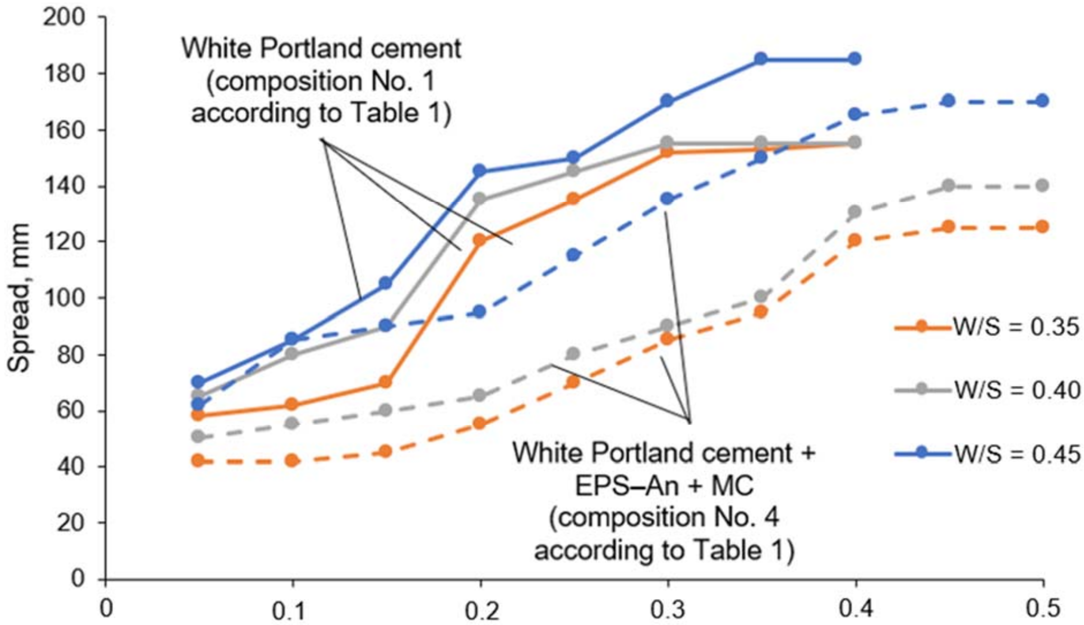

Fig. 2. Dependence of mini-cone spread of binders on the water-solid ratio and plasticizer dosage

demand of the binder when 40 % of Portland cement is replaced with finely dispersed additives, which is attributed to the excessive absorption of water from the mixture. Increasing the water-solid ratio from 0.35 to 0.45 allowed for greater mini-cone spreads in both binders: the maximum spread for white Portland cement was 185 mm, while that of the investigated composition reached 170 mm. The optimal dosage of the polycarboxylate-based plasticizer was determined, enabling a mini-cone spread diameter close to that of white Portland cement paste without mineral additives: at a water-solid ratio of 0.45, the dosage was 0.4 %.

The influence of each binder component on its rheological characteristics was determined for several mixture compositions (Table 2). The additives were introduced at their established optimal dosages.

For the systems containing only one type of additive with Portland cement (Table 2, Nos. 2–4), the influence of nanosized anatase was observed. Its presence leads to a significant increase in viscosity and shear stress of the system compared with unmodified Portland cement (Figs. 3, 4). This effect is attributed to the high specific surface area of anatase particles, the presence of numerous aggregates and agglomerates, and the difficulty of wetting the particles with water, all of which collectively hinder the flow of the mixture.

An increase in viscosity was also observed when ground expanded perlite sand was used. Its particles have irregular shapes and a highly developed surface morphology, leading to uneven water distribution in the system and hindering mixture flow.

In contrast, the use of microcalcite reduces the viscosity of the suspension, which is explained by the well-known enhancement of the dispersing effect of polycarboxylate superplasticizers in the presence of positively charged carbonate particles (Balykov et al., 2018; Martins et al., 2024; Xu et al., 2025).

The study of a suspension containing a mixture of all the components mentioned above (WPC + GEPS + + An + MC) still showed very high viscosity and shear stress values, primarily due to the presence of nanosized anatase, but these effects were slightly mitigated by the presence of microcalcite.

The negative influence of nanosized anatase on the rheological characteristics of the cement paste

Table 2. **Compositions of binder mixtures**

No.	Mixture composition	Component content, %					Content relative to binder mixture components, %	
		White Portland cement (WPC)	Ground expanded perlite sand (GEPS)	Nanosized anatase (An)	Microcalcite (MC)	EPS–An	Superplasticizer Melflux 1641 F	Water
1.	WPC	100	–	–	–	–	0.4	45
2.	WPC + GEPS	90	10	–	–	–		
3.	WPC + An	90	–	10	–	–		
4.	WPC + MC	80	–	–	20	–		
5.	WPC + GEPS + An + MC	60	10	10	20	–		
6.	WPC + EPS–An	80	–	–	–	20		
7.	WPC + EPS–An + MC	60	–	–	20	20		

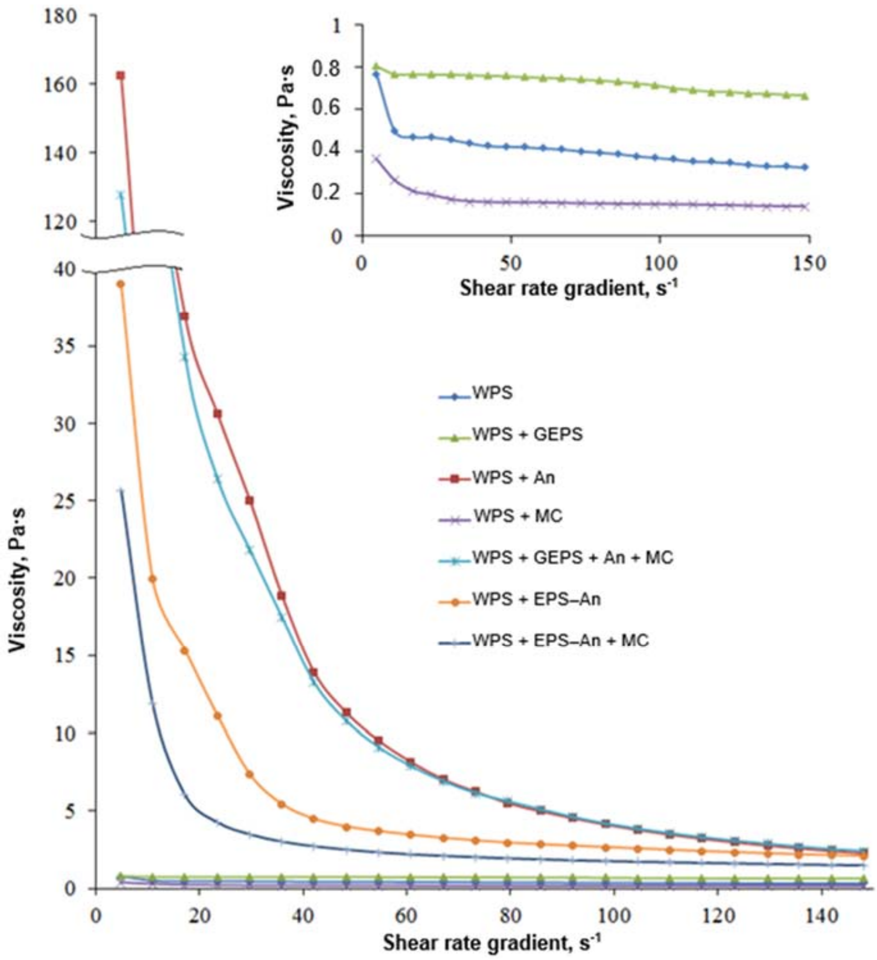

Fig. 3. Dependence of binder mixture viscosity (compositions according to Table 2) on shear rate gradient

was effectively reduced by using a product obtained through co-grinding expanded perlite sand and anatase (EPS–An). The co-grinding process allowed the breakdown of aggregates and agglomerates of the initial products, uniform distribution of individual particles, partial reduction of particle surface activity by deposition onto perlite particles, and smoothing of the perlite particle shape. This facilitated the flow of the suspension, reducing both its viscosity and shear stress.

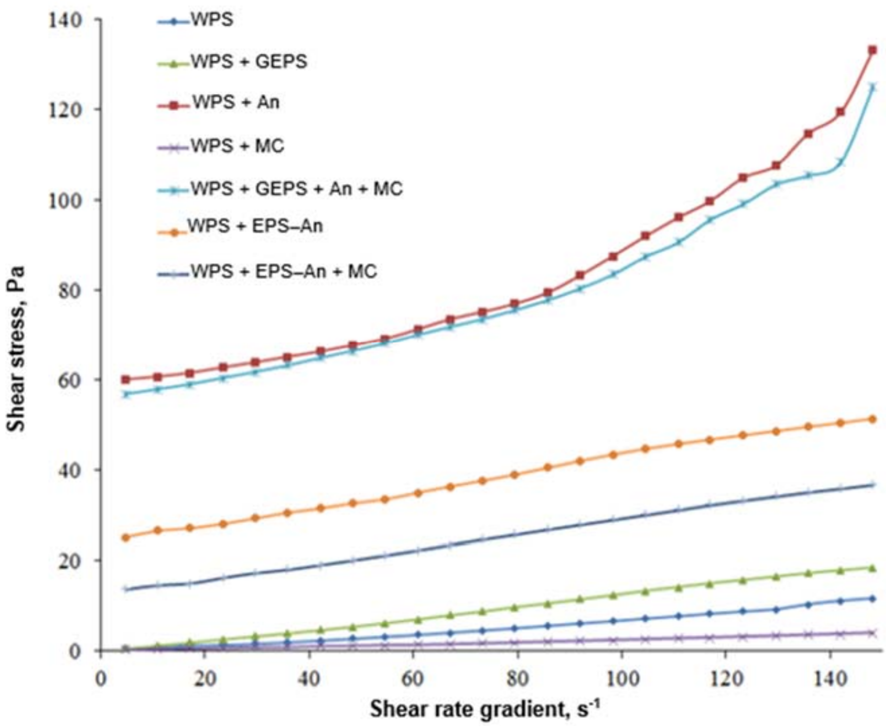

Fig. 4. Dependence of shear stress of binder mixtures on shear rate gradient (compositions according to Table 2)

In combination with microcalcite (WPC + EPS–An + MC), the viscosity and shear stress of the suspension are further reduced, which is attributed to the enhanced efficiency of the polycarboxylate plasticizer in the presence of carbonate particles. This allowed a reduction in water demand to achieve the required workability of the concrete mixture and resulted in a denser composite matrix.

Comparative analysis of differential heat release curves shows that the use of ground expanded perlite sand slightly slows down cement hydration, as evidenced by a shift of the main peak, corresponding to calcium silicate hydration, by 1 h 40 min relative to white Portland cement (Table 3). However, in the perlite-containing mixture, this peak is more intense, reaching 21 J/g cement·h compared to 18 J/g cement·h for cement without additives. Additionally, the perlite system exhibits a distinct shoulder and secondary peak following the main peak, which may be associated with ettringite formation (Taylor, 1996) or indicate a more gradual hydration process, including related to the pozzolanic reaction — a secondary hydration process (Voronov and Glagolev, 2020). The initial retardation of hydration is caused by limited water access to cement particles due to the developed morphology and high specific surface area of ground expanded perlite sand particles. The subsequent intensification and smoothing of the hydration process are related to the provision of additional surface area for new phase growth (the “crystallization seeding” effect) and gradual water release at later stages of hydration and the pozzolanic reaction.

The use of the EPS–An additive, obtained by co-grinding expanded perlite sand with nanosized anatase, led to several effects. First, a slight acceleration of the onset of the main hydration stage was observed, reflected in a leftward shift of the rising edge of the peak by several minutes (Fig. 5a). Second, the intensity of the main peak is higher compared with cement without additives, indicating an enhancement of silicate hydration. Third, the main heat release peak is more extended in time, which, as in the case of expanded perlite, may indicate the contribution of the pozzolanic reaction to the exothermic effect. The acceleration and intensification of the main hydration stage with the EPS–An additive are attributed to a reduction in the activation energy of the hydration process and an increase in the number of crystallization centers, which accelerates the formation and growth of hydration products — a well-known effect of using mineral additives (Beregovoy et al., 2023; Kuznetsova et al., 2015; Li et al., 2024; Stoyanov et al., 2024). Meanwhile, the effect of temporary water retention and hydration retardation observed when using pure expanded perlite sand is mitigated due to the partial coverage of perlite surfaces by anatase particles.

The application of the additive complex (EPS–An + MC) results in a 27-minute shift of the main heat release peak during hydration and a 21 % increase in heat release intensity compared with the

Table 3. **Heat release characteristics during hydration depending on binder mixture composition**

Mixture composition	Main hydration peak			Heat release over 72 h, J/g
	Time, h:min	dQ/dt (J/g cement·h)	Q(t) (J/g cement)	
WPC — 100 %	8:35	18.1	104.8	350.1
WPC — 90 % GEPS — 10 %	10:06	21.0	94.5	377.5
WPC — 80 % EPS–An — 20 %	8:35	20.5	118.4	395.6
WPC — 60 % EPS–An — 20 % MC — 20 %	8:08	21.9	125.0	417.6

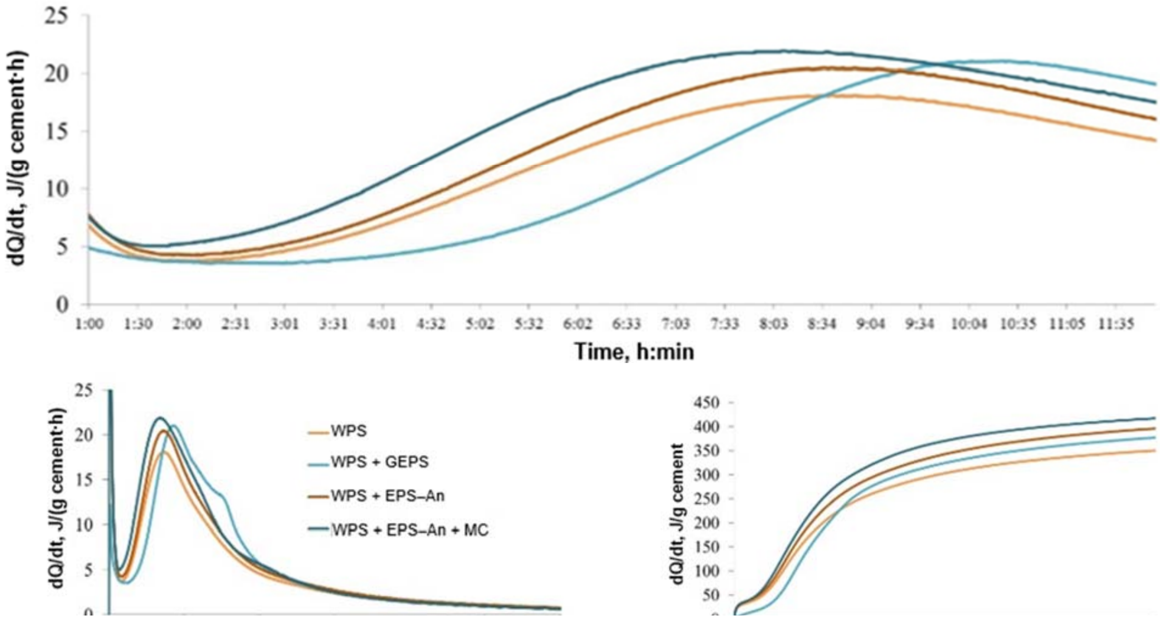

Fig. 5. Differential (*a, b*) and integral (*c*) heat release curves during hydration depending on binder mixture composition (calculated per 1 g of white Portland cement)

composition without additives (Figs. 5a, 5b). This is attributed to the nucleation effect provided by the highly dispersed particles and the progression of the pozzolanic reaction. Microcalcite may additionally participate in cement hydration reactions, forming calcium aluminum hydrocarbonates and calcium hydrocarbonates (Kulikova et al., 2019; Kopanitsa et al., 2023; Zhao et al., 2023).

Thus, all the aforementioned effects for the additives used contribute to an increase in the total heat release over 72 hours of binder hydration (Fig. 5b, Table 3). Based on the increase in heat release, the additives can be ranked as follows:

GEPS → EPS–An → EPS–An + MC.

A comparison of strength measurements for various binder mixture compositions (Table 4) also shows that the use of GEPS and EPS–An is less effective than EPS–An combined with microcalcite.

Replacing 10 % of white Portland cement with ground expanded perlite sand leads to a slowdown in strength development, manifested as a reduction in compressive strength by 12.5 % and 13.2 % at 3 and 7 days, respectively, compared with cement without additives. By 28 days, this difference decreases to 4.7 %. After steam curing, the strength of the GEPS-containing composition exceeds that of the control one by 4.2 %. These trends are attributed: first, to a slight retardation of hydration during the first few days in the presence of EPS, as observed in the heat release study; second, to the reduced Portland cement content; and third, to the enhanced pozzolanic reaction at elevated temperature.

For the composition with EPS–An, despite an even lower Portland cement content, the strength at 3 and 7 days remains almost equal to that of the GEPS-containing composition. This is due to the contribution of nanosized anatase particles, which accelerate hydration and early hardening. At 28 days, compressive strength decreases by 5.9 % compared with cement without additives, which is attributed

Table 4. **Strength of the binder depending on mixture composition**

No.	Mixture composition	Compressive/flexural strength, MPa at testing age			Specific compressive strength at 28 days	Compressive/flexural strength after steam curing, MPa
		3 days	7 days	28 days		
1.	WPC — 100 %	43.1/6.0	49.2/6.8	67.3/7.7	0.115	47.2/6.7
2.	WPC — 90 % GEPS — 10 %	37.7/5.3	42.7/5.9	64.1/7.3	0.122	49.3/6.9
3.	WPC — 80 % EPS–An — 20 %	37.4/5.2	43.1/6.1	63.3/7.1	0.135	47.0/6.6
4.	WPC — 60 % EPS–An — 20 % MC — 20 %	39.3/5.5	47.1/6.7	65.2/7.5	0.185	48.2/6.8

both to the reduced Portland cement content and possibly to a slight decrease in pozzolanic reaction intensity due to partial shielding of the perlite particle surfaces. After steam curing, the strength of EPS–An specimens is practically equal to that of the control ones, reflecting the progression of the pozzolanic reaction.

The determination of strength characteristics for the composition with EPS–An and microcalcite showed that, in this case, with a significant replacement of white Portland cement by the additive complex (Table 4, No. 4), there is no substantial loss of compressive or flexural strength at any of the tested curing ages (at 28 days, a decrease of 3 % in compressive strength and 2.5 % in flexural strength), while after steam curing, compressive strength exceeds that of the control specimen by 2 % and flexural strength — by 1.5 %.

Analysis of the specific strength of the specimens, i.e., the strength per 1 kg of cement relative to the total mass of solid components, revealed that despite the reduced white cement content, its contribution to overall strength increases. The achievement of high strength when using the additive combination may be attributed to the formation of a more monolithic and dense structure of hydration products on fine mineral particles, including those produced by the pozzolanic reaction, as well as the filling of micro- and nanopores with inert components.

Thus, based on the results of studying heat release during hydration and strength development kinetics, it can be concluded that the use of EPS–An together with microcalcite leads to a faster onset of the main cement hydration reactions, their more complete progression accompanied by the pozzolanic reaction, resulting in more intensive heat release, increased early strength, and the retention of 28-day strength even with a 40 % replacement of Portland cement by additives.

These findings are consistent with the results of mineralogical analysis of the hardened cement stone at 28 days (Fig. 6). In the cement stone from white Portland cement, both unreacted clinker minerals — alite and belite — and hydration products — C–S–H, portlandite, and ettringite — can be observed.

The use of ground expanded perlite sand (WPC + GEPS) led to hydration retardation, as evidenced by more pronounced peaks corresponding to alite, belite, and ettringite. The slightly reduced portlandite content may also be attributed to hydration retardation or to the pozzolanic reaction.

The use of ground expanded perlite sand with anatase (WPC + EPS–An) accelerated hydration, which reflected in a reduction of peaks associated with clinker minerals. No significant changes in portlandite content were observed. Peaks corresponding to anatase can also be noted.

When ground expanded perlite sand with anatase was combined with microcalcite (WPC + EPS–An + MC), low contents of alite, belite, and ettringite were observed, which can be attributed to the substantial reduction in Portland cement content, but may also reflect intensified hydration. The presence of mineral additives is confirmed by reflections of anatase and calcite. Peaks of the hydrosilicate phase — tobermorite — are also detected. The reduced portlandite content may result both from the lower Portland cement fraction and the ongoing pozzolanic reaction.

Investigation of the microstructural features of cement stone with different compositions revealed a decrease in microporosity and matrix densification upon the use of mineral additives (Fig. 7). In general, all specimens exhibit similar newly formed structures of varying size and morphology, including needle-like, columnar, layered, and dendritic forms. On GEPS particles, growths with a well-developed surface are observed, indicating reactions with cement hydration products and the formation of a developed but less compact interfacial zone.

A denser microstructure is observed when using EPS–An (Fig. 7). In the fracture, pores on the surface of EPS–An particles show active growth of newly formed structures with various morphologies. The addition of microcalcite to the system, despite an even greater reduction in the cement fraction, did not significantly alter the nature of the microstructure: it

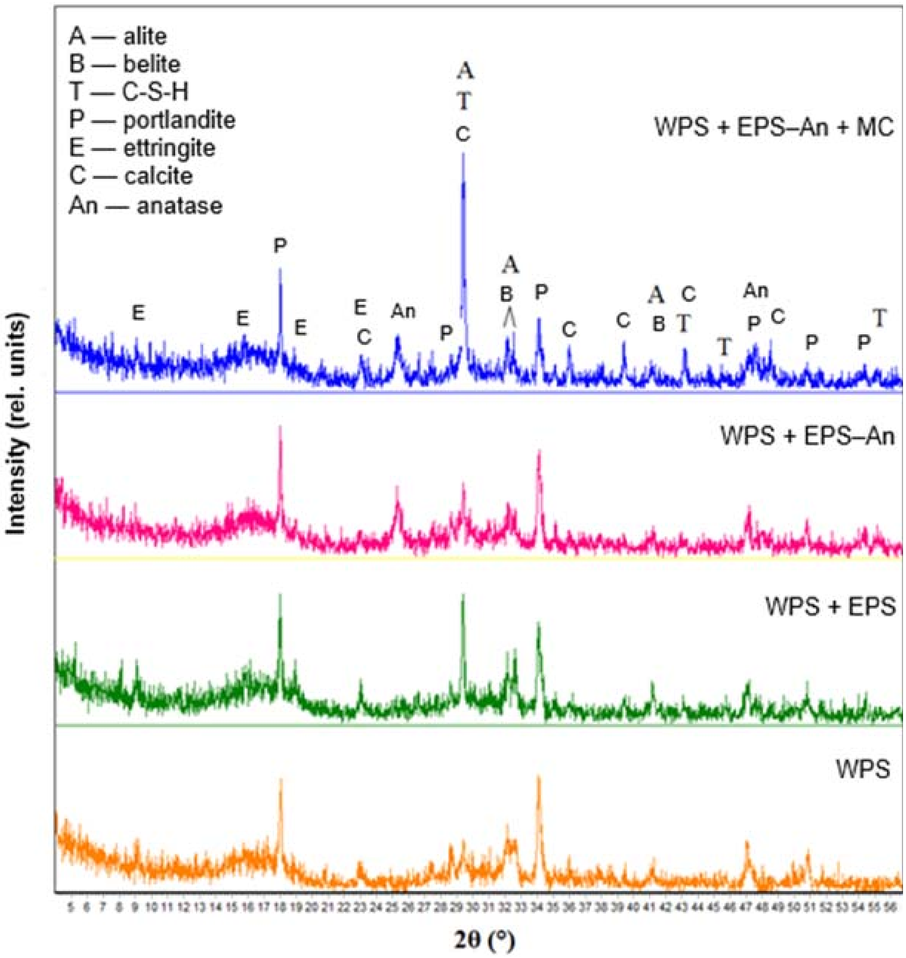

Fig. 6. X-ray diffraction patterns of cement stone at 28 days depending on binder mixture composition

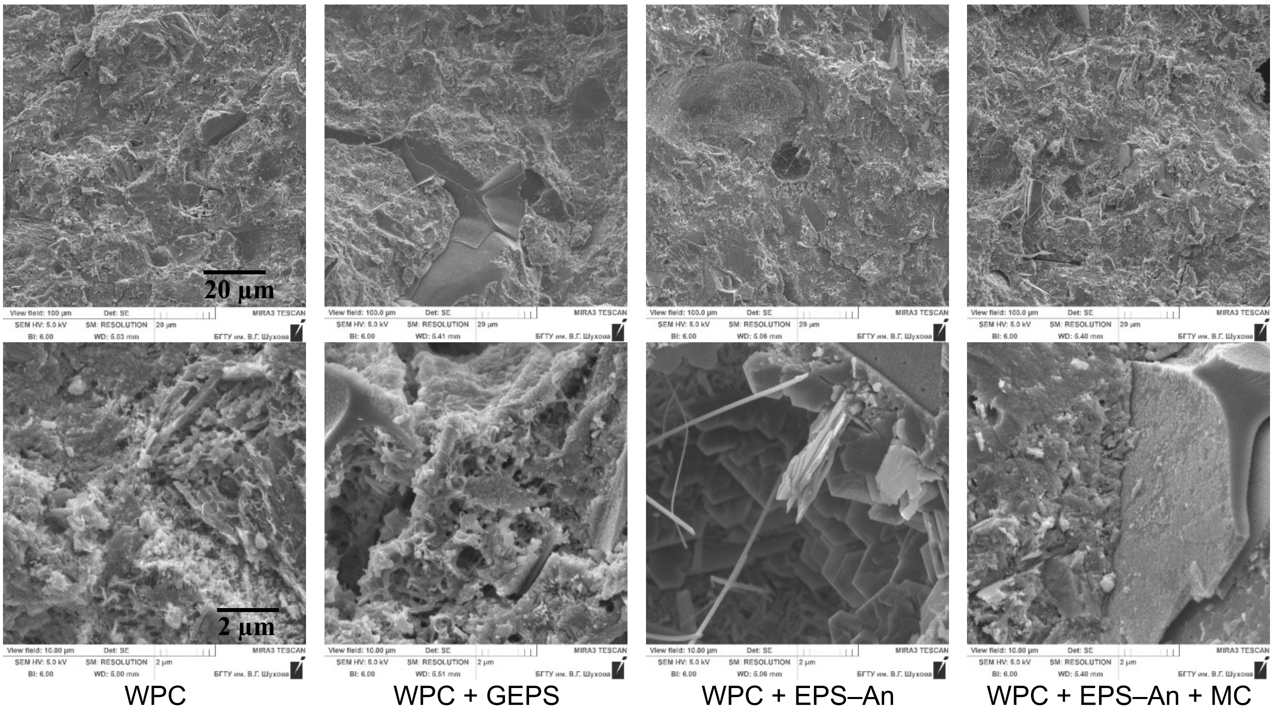

Fig. 7. Microstructure of cement stone at 28 days depending on binder mixture composition

remains dense, well-developed, with clearly defined boundaries of irregularly shaped perlite particles, partially interacting with cement components.

At higher magnification, the interfacial zone of the cement stone with EPS–An and MC (Fig. 8) shows a well-developed rough surface of the acid-pretreated expanded perlite sand, as well as accumulations of spherical particles smaller than 100 nm, corresponding to anatase.

Chemical element mapping of the WPC + EPS–An + MC specimen indicates a uniform distribution of titanium throughout the matrix, with accumulation near the surface of the perlite particles (Fig. 9).

The determination of specific surface area and nanopore distribution using BET and BJH methods (Table 5, Fig. 10) showed a higher specific surface area and greater nanopore volume for the specimen without additives. The lowest values were observed for the GEPS-containing specimen. The low specific surface area in this case may indicate incomplete hydration of Portland cement, consistent with results obtained by other methods for the GEPS specimen. The presence

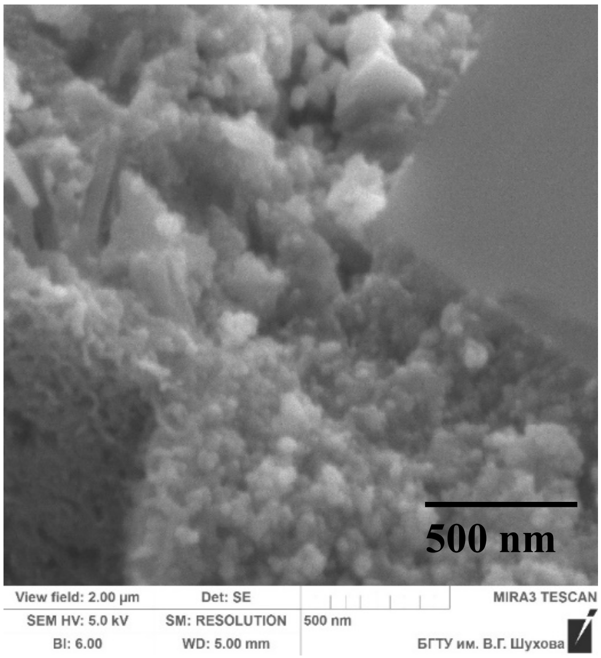

Fig. 8. Interfacial zone of cement stone with EPS–An and MC

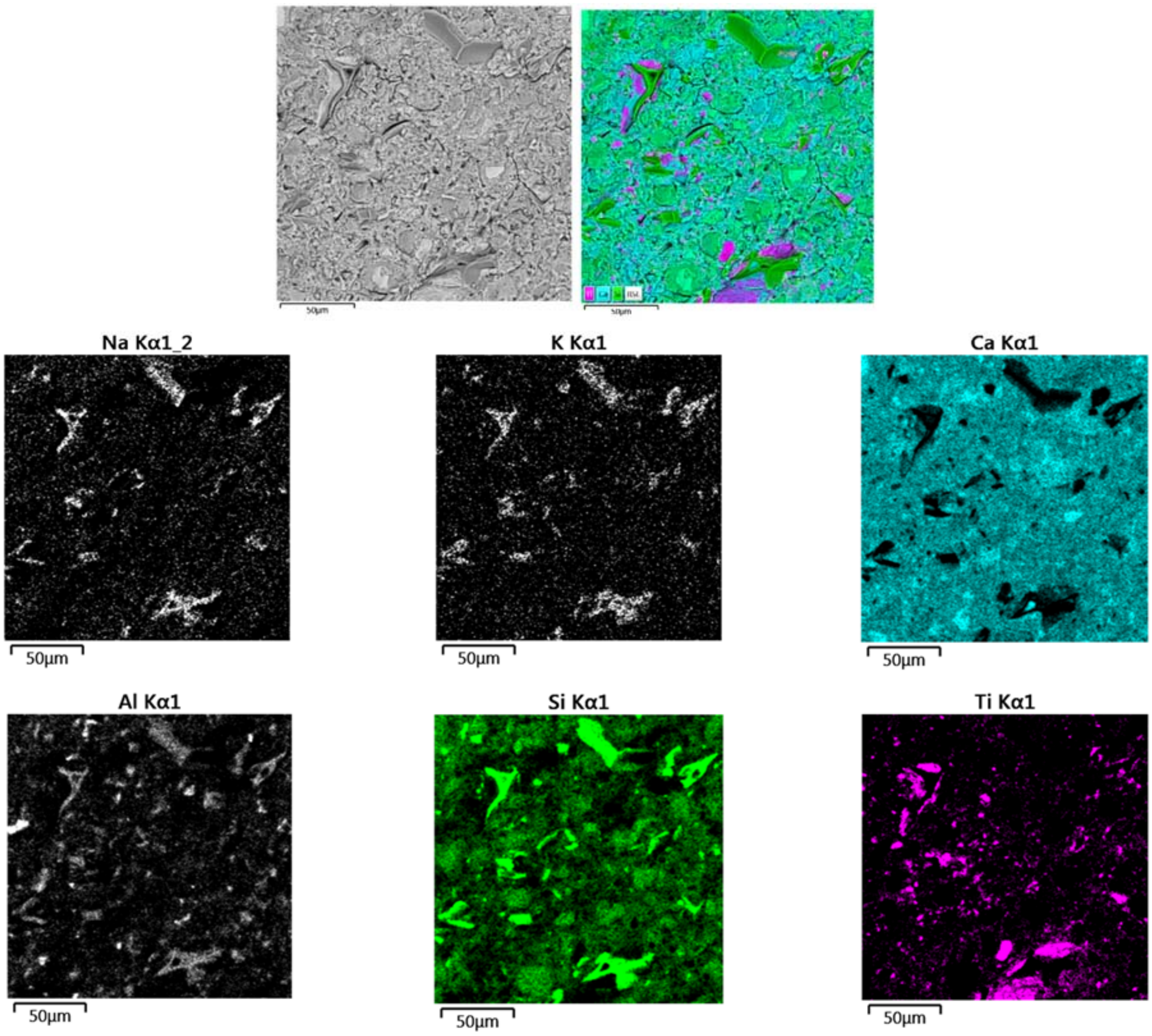

Fig. 9. Chemical element mapping of cement stone for the WPC + EPS–An + MC composition at 28 days

Table 5. **Dependence of specific surface area (BET) and nanoporous structure of cement stone at 28 days on binder mixture composition**

No.	Mixture composition	Specific surface area of the material, m^2/g	Total pore volume, cm^3/g	Average pore diameter, nm
1.	WPC — 100 %	62.06	0.078	5.02
2.	WPC — 90 % GEPS — 10 %	22.93	0.030	5.21
3.	WPC — 80 % EPS–An — 20 %	41.12	0.053	5.20
4.	WPC — 60 % EPS–An — 20 % MC — 20 %	37.84	0.050	5.25

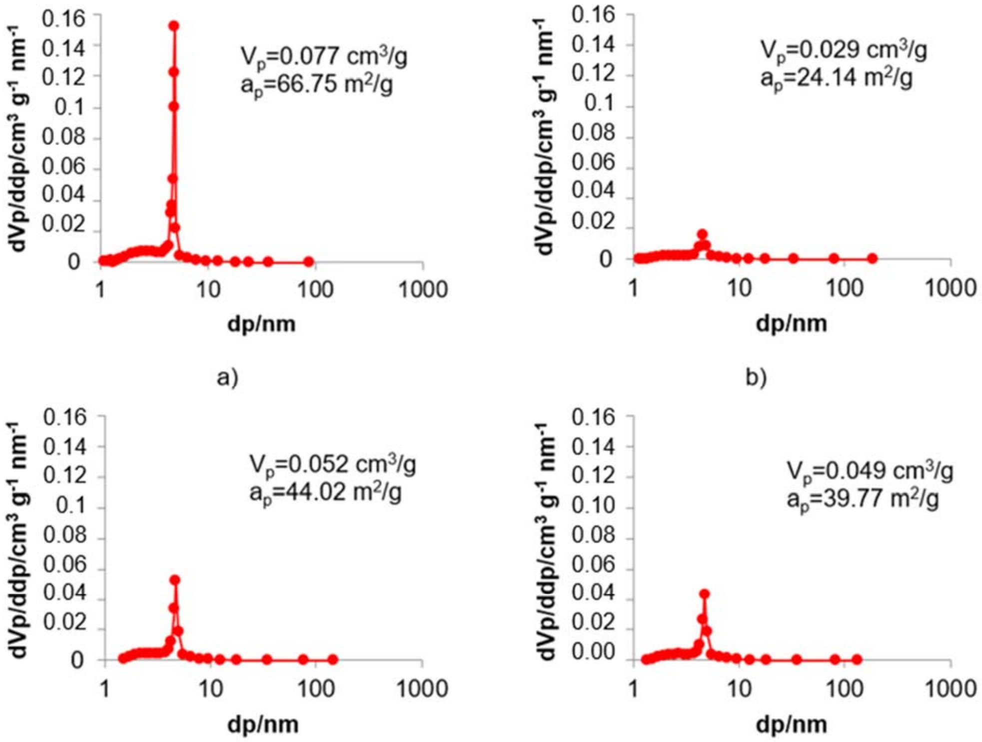

Fig. 10. Specific surface area values and pore size distribution (Barrett–Joyner–Halenda method) in cement stone at 28 days depending on binder mixture composition: a) WPC, b) WPC + GEPS, c) WPC + EPS–An, d) WPC + EPS–An + MC

of anatase on the surface of GEPS particles (Table 5, No. 3) mitigated hydration retardation, reflected in intermediate values of specific surface area and total pore volume between the specimen without additives and the GEPS-containing specimen. Slightly lower and similar values were observed for the EPS–An + + MC specimen. The decrease in specific surface area (by 39 %) and total nanopore volume (by 36 %) compared with the composition without additives indicates the clogging of pore space by both newly formed structures and additive components acting as microfillers.

Conclusion

It has been found that the combined use of a multifunctional composite material EPS–An, produced by co-grinding acid-pretreated expanded perlite sand with anatase, poly-dispersed microcalcite, and a plasticizer in a white Portland cement-based binder allows mitigating the negative impact of fine mineral additives on the water demand of the mixture. This effect is attributed to the improved particle size distribution of the multicomponent binder as well as to the enhanced efficiency of the polycarboxylate plasticizer in the presence of carbonate particles.

Analysis of the phase composition and microstructural features demonstrated that the application of the EPS–An + MC additive complex promotes accelerated hydration, reduces microporosity, and increases the homogeneity and density of cement stone. Low-temperature nitrogen adsorption showed a decrease in specific surface area and total nanopore volume of cement stone by 39 % and 36 %, respectively, compared with the composition without additives, indicating a higher degree of cement hydration and pore space clogging by reaction products in the presence of reactive components.

It has been established that replacing 40 % of white Portland cement with the fine mineral additive complex EPS–An + MC (1:1 ratio) allows obtaining a binder with a compressive strength of 65.2 MPa at 28 days of standard curing. The presence of mineral additives shifts the main hydration peak by 27 minutes and increases the heat release intensity by 21 % compared with the additive-free composition due to the nucleation effect on the surface of highly dispersed particles and the pozzolanic reaction. After steam curing, the compressive and flexural strength of the binder exceeds that of the control specimen by 2 % and 1.5 %, respectively.

The study has established patterns of influence of the mineral additive complex on the rheological properties, heat release kinetics, phase composition, and microstructure of cement stone. Optimal dosages and particle size distribution of the mineral additive complex have been proposed, ensuring: production of highly workable cement pastes with reduced water demand, acceleration of the main hydration period onset, intensification of phase and structure formation processes, formation of dense homogeneous cement stone, and high photocatalytic activity.

It has been established that the combined use of the proposed mineral additive complex, with reduced cement content, provides high physical and mechanical performance of the cement system and can be applied to produce white decorative fine-grained concretes suitable for thin-walled products.

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ВЯЖУЩЕЕ НА ОСНОВЕ БЕЛОГО ЦЕМЕНТА ДЛЯ САМООЧИЩАЮЩЕГОСЯ МЕЛКОЗЕРНИСТОГО БЕТОНА

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Аннотация
Введение. Проблема получения бетонных изделий сложных форм, тонкостенных, прочных и устойчивых к атмосферным воздействиям, способных сохранять декоративный вид в процессе эксплуатации, при максимальном вовлечении в их производство техногенного (вторичного) минерального сырья, заключается в том, что при необходимости получения изделий белого цвета диапазон возможного сырья резко сокращается. Также необходимым является снижение содержания портландцемента в бетонах. В связи с этим, актуальной задачей является разработка современных вяжущих и бетонов с пониженным содержанием портландцемента на основе минеральных компонентов белого цвета. **Материалы и методы.** В качестве вяжущего вещества использован белый портландцемент без минеральных добавок ПЦБ 1-500-Д0 Cemix ProWhite производства ООО «Цемикс», респ. Башкортостан; в качестве добавок рассмотрены: вспученный перлитовый песок (пуццолановая добавка), микрокальцит (карбонатная добавка) и анатаз (фотокаталитическая добавка), а также их смеси; в качестве пластифицирующей добавки использован пластификатор на поликарбоксилатной основе Melflux 1641 F. Оценка основных физико-механических свойств вяжущего и цементного камня на его основе (нормальная густота, расплыв мини-конуса, предел прочности) проведена по стандартным методикам, удобоукладываемость смесей анализирована по результатам реотехнологических показателей, показатели интенсивности тепловыделения при гидратации цементного камня получены методом калориметрии. Также в работе отражены особенности микроструктуры получаемого цементного камня. **Результаты.** Выявлено, что замена 40 % цемента на комплекс минеральных добавок при использовании пластификатора позволяет нивелировать негативное влияние тонкодисперсных компонентов на водопотребность смеси. Отмечается интенсификация процессов гидратации, повышение однородности и плотности цементного камня, а также снижение удельной поверхности и суммарного объема нанопор цементного камня на 39 % и 36 % соответственно. Присутствие минеральных добавок позволяет получить вяжущее с прочностью на сжатие 65,2 МПа в возрасте 28 суток нормального твердения.

Ключевые слова: белый портландцемент, перлитовый песок, комплексная добавка, микроструктура, гидратация, бетон.