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HYDRATION AND STRUCTURE FORMATION OF MULTICOMPONENT MODIFIED BINDERS: MECHANISMS AND PROPERTIES

КӨП КОМПОНЕНТТІ МОДИФИКАЦИЯЛАНҒАН БАЙЛАНЫСТЫРУШЫ ЗАТТАРДЫҢ ГИДРАТТАНУЫ ЖӘНЕ ҚҰРЫЛЫМЫНЫҢ ҚАЛЫПТАСУЫ: МЕХАНИЗМДЕРІ МЕН ҚАСИЕТТЕРІ

ГИДРАТАЦИЯ И СТРУКТУРООБРАЗОВАНИЕ МНОГОКОМПОНЕНТНЫХ МОДИФИЦИРОВАННЫХ СВЯЗУЮЩИХ: МЕХАНИЗМЫ И СВОЙСТВА

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Keywords:
cement stone, multicomponent binder, hydration, structure formation, superplasticizer, metallurgical waste, portlandit

ABSTRACT
This paper presents the results of studies on hydration and hardening processes of multicomponent modified binders containing active mineral and chemical additives. The aim of the research was to establish the patterns of cement stone structure formation and identify the factors contributing to the improvement of its strength and durability. It is shown that the high strength of the modified binder is due to the formation of stable low-basic calcium hydrosilicates generated through the pozzolanic reaction between portlandite and active amorphous silica included in the complex additives. Mechanochemical activation of the components increases the number of active centers, accelerates hydration and intensifies hardening. X-ray diffraction and thermal analyses confirmed the presence of calcium hydrocarbonaluminates, whose formation enhances sulfate resistance. Electron microscopy revealed a denser microstructure of the cement stone and close intergrowth of portlandite and C–S–H phases, which contributes to the formation of a monolithic, low-porosity structure. The results demonstrate that adjusting the binder composition and curing conditions allows targeted regulation of hydrate morphology and optimization of the phase composition. This ensures the production of high-strength and chemically-resistant concretes under reduced-temperature curing, expanding the application potential of multicomponent binders in modern construction.

Түйінді сөздер:
цемент тас, көп компонентті тұтқыр, гидратация, құрылымның қалыптасуы, суперпластификатор, металлургия қалдықтары, портландит

ТҮЙІНДЕМЕ

Жұмыста "Сикамент–FF-N" суперпластификаторын және түсті металлургия қалдықтарын (мырыш қожы және полиметалл кендерін байыту өнімдері) қолдана отырып, портландцемент клинкеріне негізделген көп компонентті модификацияланған тұтқыр жүйелерді ылғалдандыру және құрылымдау процестерін зерттеу нәтижелері келтірілген. Химиялық модификатордың 0,5–1,0% - с бірге 15-30% мөлшерінде минералды қоспаларды енгізу кальций силикаттарының гидратациясының қарқындылығын, портландит құрамының азаюын және цемент тасының тығыз құрылымын қалыптастыруға ықпал ететін төмен негізді гидросиликаттардың түзілуін қамтамасыз ететіні көрсетілген. Рентгенографиялық және термиялық зерттеулер $CA(OH)_2$ мөлшерінің 23,6-дан 17,3 % дейін төмендегенін растады, бұл C_3S ылғалдану дәрежесінің 75-76 % дейін өсуімен және жылу-ылғалдылық өңдеуден кейін тастың беріктігінің 61-70 МПа-ға дейін жоғарылауымен бірге жүреді. Электронды-микроскопиялық бақылаулар ерте кезеңдерде ине тәрізді өсінділердің жедел түзілуін және құрылымның тығыздалуын анықтады. Ерімейтін кальций гидрокарбоалюминаттарының түзілуі сульфатқа төзімділікті 0,95-1,00 дейін арттырады. Көп компонентті жүйелердің механикалық-химиялық активтенуі белсенді орталықтардың өсуіне ықпал ететіні, поззоланикалық реакцияның жүруін жеделдететіні және біртекті супрамолекулалық құрылымның пайда болуын қамтамасыз ететіні анықталды. Әзірленген көп компонентті модификацияланған тұтқыр беріктікке, тығыздыққа және химиялық төзімділікке қойылатын кешенді талаптарды қанағаттандырады және әртүрлі функционалдық мақсаттағы жоғары сапалы бетондарды өндіру үшін пайдаланылуы мүмкін.

Ключевые слова:
цементный камень, многокомпонентное вяжущее, гидратация, структурообразование, суперпластификатор, отходы металлургии, портландит

АННОТАЦИЯ

В работе представлены результаты исследования процессов гидратации и структурообразования многокомпонентных модифицированных вяжущих систем на основе портландцементного клинкера с применением суперпластификатора «Сикамент–FF-N» и отходов цветной металлургии (цинкового шлака и продуктов обогащения полиметаллических руд). Показано, что введение минеральных добавок в количестве 15–30 % совместно с 0,5–1,0 % химического модификатора обеспечивает интенсификацию гидратации силикатов кальция, уменьшение содержания портландита и образование низкоосновных гидросиликатов, способствующих формированию плотной структуры цементного камня. Рентгенографические и термические исследования подтвердили снижение количества $Ca(OH)_2$ с 23,6 до 17,3 %, что сопровождается ростом степени гидратации C_3S до 75–76 % и увеличением прочности камня после тепловлажностной обработки до 61–70 МПа. Электронно-микроскопические наблюдения выявили ускоренное образование игольчатых новообразований в ранние сроки и более плотное уплотнение структуры. Образование труднорастворимых гидрокарбоалюминатов кальция повышает сульфатостойкость до 0,95–1,00. Установлено, что механохимическая активация многокомпонентных систем способствует росту активных центров, ускоряет протекание пуццоланической реакции и обеспечивает получение однородной надмолекулярной структуры. Разработанное многокомпонентное модифицированноевяжущее удовлетворяет комплексным требо-

ваниям к прочности, плотности и химической стойкости и может быть использовано для производства высококачественных бетонов различного функционального назначения.

INTRODUCTION

Modern high-performance binders are developed using complex multicomponent systems with active mineral and chemical additives. Their primary goal is to achieve improved strength and operational characteristics of concrete with reduced energy consumption. An important direction in this field is the utilization of industrial by-products, which can serve as active pozzolanic additives and contribute to the optimal structure formation of cement stone.

The modern development of construction materials science is characterized by a growing interest in multicomponent modified binders, driven by the need to improve the performance characteristics of construction materials, reduce the carbon footprint of cement production, and promote the efficient utilization of industrial by-products. In this context, particular importance is attached to studies aimed at gaining a deeper understanding of the hydration and structure formation processes that govern microstructure development and, consequently, the physical and mechanical properties of binder systems (Marchon & Flatt, 2016).

Hydration of binders is a complex multistage physicochemical process involving the dissolution of primary clinker minerals, nucleation and growth of hydration products, and the formation of a spatial structure of cement stone. When multicomponent systems incorporating mineral and chemical modifiers—such as slag, fly ash, reactive silica additives, micro- and nano-fillers, and superplasticizers—are used, these processes become significantly more complex. They are accompanied by changes in hydration kinetics, phase composition, and the morphology of hydration products (Izotov & Ibragimov, 2015).

As demonstrated by Zhakipbekov et al. (2021), the incorporation of complex mineral additives into low-clinker binders leads to an increased degree of hydration, the formation of low-basic calcium silicate hydrates, and a densification of the cement stone microstructure. Similar conclusions were drawn by Wilińska and Pacewska (2022), who reported that four-component binders with a high content of supplementary cementitious materials exhibit redistribution of hydration phases and a reduced portlandite content due to intensified pozzolanic reactions.

Considerable attention in contemporary research is devoted to micro- and nanoscale structure formation, as the characteristics of the C–S–H gel largely determine the durability and mechanical performance of binder systems. Studies by Masoero et al. (2018) showed that the density and nanostructure of the C–S–H gel have a decisive influence on self-desiccation processes, sorption properties, and shrinkage deformations. The application of infrared spectroscopy and electron microscopy enables detailed investigation of the evolution of hydration products and the interaction mechanisms between organomineral admixtures and the hydration phases (Zagorodnyuk & Sumskoy, 2019).

In recent years, increasing research efforts have focused on controlling hydration kinetics and rheological properties of binder systems. Li et al. (2024) demonstrated that targeted regulation of dissolution and crystallization processes of hydration phases using specialized additives allows the design of binders with tailored properties. Furthermore, Varshney et al. (2017) identified different structural aging mechanisms occurring during cement paste hydration, which significantly affect both early-age and long-term strength development.

Thus, the analysis of existing literature indicates that hydration and structure formation of multicomponent modified binders are governed by a combination of factors, including the mineralogical and chemical composition of the system, component fineness, type and dosage of modifying additives, and curing conditions. Despite the substantial body of experimental

research accumulated to date, the interrelationships between hydration mechanisms, microstructure evolution, and performance properties of binders remain insufficiently systematized, highlighting the relevance and scientific significance of the present study.

MATERIALS AND METHODS

The research object was a multicomponent binder containing up to 45% non-ferrous metallurgy waste. The mixture comprised Portland cement clinker (64–84.5%), carbonate-containing tailings (5–15%), quartz-containing tailings (10–20%), and a modifier (0.5–1%). Curing was carried out at 65 °C under a 2+4+1 h regime. Differential thermal analysis, X-ray diffraction, and electron microscopy were used to study structural development.

In this study, cement clinker from «Standard-Cement LLP», as well as synthetically produced clinker minerals C_3S, β-C_2S, C_3A, and C_4AF, Standard volsk sand, hydrated lime from the Sas-Tyube lime works, residues from the Kentau processing plant (20 wt%), zinc slag from the «Achpolymetall» combine (15 wt%), and the superplasticizer «Sikament-FF-N» in an amount of 0.5–1.0 wt% based on the mass of C_3S were used. The sand from the Nikolaevskoye deposit (Almaty region) had a bulk density of 1467 kg/m³, a net density of 2650 kg/m³, a pore volume of 43%, and a fineness modulus of 2.2–2.4. Its mineralogical composition (wt%) is shown in Table 1.

Table 1. Mineralogical composition of sand, % by weight

Sand	quartz	feldspar	mica	calcite	clay impuritie
	34.5-36.3	52.8-54.2	1-9 – 2.3	3.6 – 4.0	up to 4%
Note – compiled by the authors					

Table 2. Chemical composition of technogenic products, % by weight

Waste name	SiO_2	CaO	Fe_2O_3	Al_2O_3+ TiO_2	MgO	K_2O+ Na_2O	BaO	calcination losses
Tailings of the Kentau processing plant	11.7	24.24	1.7	1.53	13.8	2.0	10.20	30.35
zinc slag from the «Achpolymetall» combine	30.1	18.20	32.95	-	4.68	0.85	-	8.65
Note – compiled by the authors								

For the manufacture of heavy concrete, sulfate-resistant Portland cement CEM I 42.5H SS GOST 22266-2013 Standard Cement LLP was used as a binder, the properties of which are shown in Table 3.

Table 3. Characteristics of sulphate-resistant Portland cement LLP "Standard-Cement" CEM I 42,5N SS

Name of indicators, unit of measurement	The actual value
Fineness of grinding, %, (residue on the sieve) no more	0,3
Normal density of cement paste, %	28,7
W/C cone spread	0,38 114

end of table 3

Name of indicators, unit of measurement	The actual value
Setting time, h:min: – initial, not less than – final, not more than	 3-20 4-20
Compressive strength, MPa, at the age of: – 7 days – 28 days	 33,9 46,9
Soundness of cement	withstood
Specific surface area, cm^2/g	3250
SiO_2 content,%	22,93
Al_2O_3 content,%	4,22
Fe_2O_3 content,%	5,08
CaO content,%	64,47
MgO content,%	2,48
C_3A content,%	2,77
Note – compiled by the authors	

X-ray diffraction (XRD) analysis of the materials was performed using a URS-50I X-ray diffractometer. Diffraction patterns were recorded from flat powdered specimens rotating in the plane perpendicular to the goniometer axis at a rotational speed of 25 rpm. Data were collected over a 20 angular range of 20°–61°.

The measurements were carried out using ScKα radiation with a nickel filter of 14 μm thickness. The X-ray tube was operated at an anode current of 11.5 mA. The counter slit dimensions were 0.25 × 8 mm, while the primary beam was limited by a 1 × 5 mm slit. The recording constant was set to R°–IV, with an intensity recording range of D = 1000 impulses/s. The chart paper advance speed was 360 mm/h.

Differential thermal analysis was performed using a MOM-1000 derivatograph (Germany). The measurements were carried out in an air atmosphere over a temperature range of 25–1000 °C. The heating rate was maintained at 7.5 °C/min.

Thermal transformations were identified based on the thermogravimetric (TG), differential thermogravimetric (DTG), and differential thermal analysis (DTA) curves, which reflect mass loss, the rate of mass loss, and differential temperature changes, respectively.

Spectral analysis of the cement stone was performed using a two-channel Spekord spectrophotometer. The microstructural characteristics of the cement stone, including crystal morphology, size, spatial distribution, and crystal type, were investigated using REM-200 electron microscopes. In addition, three-dimensional images of the microstructure were obtained, and the chemical composition of selected local regions of the cement stone was

RESULTS AND DISCUSSION

Experimental results have shown that the complex additives contribute to the acceleration of hydration, an increase in the amount of chemically bound water, and the formation of stable hydrate phases. At the age of three days of curing, the formation of calcium hydrocarbonaluminates is observed, which ensures improved sulfate resistance. Microscopic studies revealed densification of the cement stone structure and intergrowth of portlandite blocks with the C–S–H phase.

The production of high-performance binders of a new generation is currently associated with the use of complex component systems aimed at obtaining high-strength concretes for

various functional applications with advanced structural and operational properties (Neville A.M., Brooks J.J., 2010).

The study demonstrated that the hydration of C_3S is accompanied by the intensive formation of portlandite and calcium hydrosilicates. The incorporation of complex additives altered the phase composition, reduced the $Ca(OH)_2$ content, and promoted the formation of additional calcium hydrosilicates and hydrocarbonaluminates.

After 28 days of curing, the degree of C_3S hydration in the reference sample was 71,5 %, whereas in compositions containing zinc slag and polymetallic ore beneficiation residues it reached 75–76 %. The amount of portlandite decreased from 23,6 % (control) to 17,3 % when 20 % of mineral additives were introduced.

The compressive strength of the cement stone based on the multicomponent binder after heat-moisture treatment reached 61–70 MPa, while the sulfate resistance coefficient was within 0,95–1,0.

Electron microscopy revealed accelerated formation of needle-like hydrates at early ages and the development of a denser structure due to the interaction between portlandite and the reactive silica contained in the additives.

The development of high-performance binders of a new generation currently relies on the use of complex component compositions aimed at producing high-quality concrete for various functional applications with improved physical and operational properties. The concept underlying the creation of such binders is the principle of targeted technological control at all stages– involving the selection of active components, optimization of mix compositions, application of chemical modifiers, and other technological measures.

Following this approach, a multicomponent binder was developed containing up to 45 % non-ferrous metallurgy waste (polymetallic ore beneficiation residues and zinc slag) and the superplasticizer «Sikament–FF-N» [1, 16].

The influence of «Sikament–FF-N» on the hydration and hardening of calcium silicates was investigated.

According to X-ray diffraction analysis Figure 1, the phase composition of C_3S without additives at the ages of 3 and 7 days mainly consists $Ca(OH)_2$ (d =0,493; 0,310; 2,262; 0,192; 0,179; 0,148 nm), the C_2S hydrate (d=0,304; 0,270; 0,247; 0,235; 0,189; 0,179; 0,165; 0,154 nm), tobermorite-like calcium hydrosilicate CSH_2 (d = 0,281; 0,183; 0,167 nm) and anhydrate C_3S (d =0,277; 0,267; 0,244; 0,198; 0,194; 0,177; 0,163; 0,149 nm).

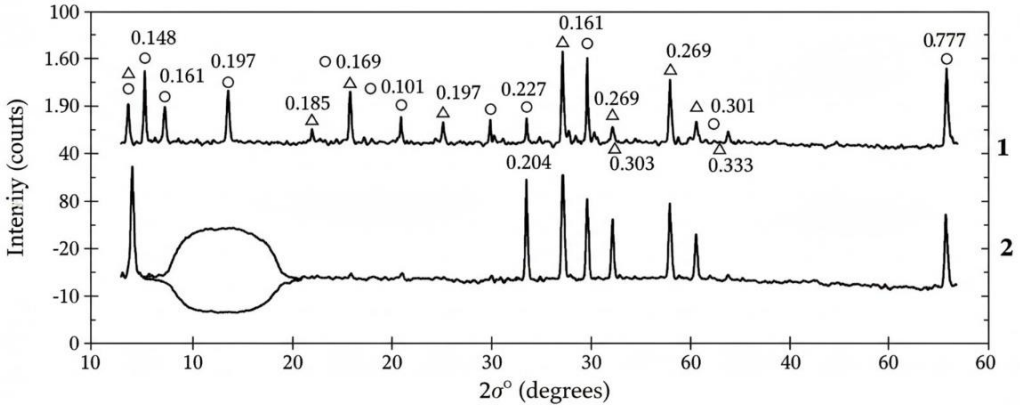


Figure 1. X-ray images of tailings from the Kentau concentrating plant (1), Zinc slag from the Achpolymetal plant (Kentau) (2)

Note – compiled by the authors

The presence of these hydration products was also confirmed by thermographic analysis. At around 200°C, the thermogram shows an endothermic peak typical of CSH_2. Endothermic effects at 540 and 760°C correspond to the decomposition of Ca $(OH)_2$ and α-hydrate of C_2S respectively.

By the age of 28 days, the amount of unhydrated clinker phases significantly decreased, which correlates with the increase in the degree of C_3S hydration–50%, 62,3% and 71,5% after 3,7 and 28 days, respectively Table 4.

It is known that in the X-ray diffraction pattern of pure calcium hydroxide, the intensity of the (0001) plane with d =0,490 nm is 70-80% of that of the (0011) plane with d =0,262 nm, due to the preferential formation of large $Ca(OH)_2$ crystals. However, in the diffraction pattern of C_3S, hydrated for 3 days, the intensity of the $Ca(OH)_2$ line at d = 0,490 nm exceeds that of the line at d = 0,262 nm.

Table 4. Effect of Active Mineral Additives on the Degree of Hydration of C3S stone (author's materials)

Additive, %	Degree of hydration, % after days:		
	7	27	28
Without additive	50	62,3	71,5
Zinc slag from the «Achpolimetal plant» (Kentau), 15*	54	65,7	75,8
Tailings of the Kentau processing plant, 30*	52,4	61,4	74,0
Note – compiled by the authors			

*containing 0,5% superplasticizer «Sikament-FF-N» by mass of C_3S.

During further hydration of C3S the intensity of the diffraction line with d =0.262 nm increases, and after 28 days of curing, the X-ray diffraction patterns show an equalization of the intensity of these lines. This indicates the formation of finer and predominantly oriented secondary crystals of portlandite.

The development of such binders is based on the principle of targeted control of technology at all stages, including the use of active components, optimization of compositions, application of chemical modifiers and other technological approaches (Le Chatelier H. and other, 2002)..

Following this principle, a multicomponent binder containing up to 45% non-ferrous metallurgy waste and chemical additives was developed. As shown in studies , the additives used do not increase the normal consistency of the paste and, unlike traditional systems, do not retard but rather accelerate the hydration rate of the binder. When combined with plasticizing additives and optimal curing regimes, such binders can be applied in the production of concrete and reinforced-concrete elements.

The binder composition includes the following mass percentages: Portland cement clinker 64–84.5%, carbonate-containing tailings 5–15%, quartz-containing tailings 10–20%, and a modifier 0.5–1.0%. The binder is produced by co-grinding the clinker and beneficiation tailings to a specific surface area of 300–330 m^2/kg.

Heat-moisture treatment of experimental samples was conducted under a 2 + 4 + 1 h regime at a maximum temperature of 65 °C. In this case, the maximum processing temperature was reduced by 20 °C compared to conventional treatment, and the duration of the isothermal holding stage was decreased by 3 hours.

Differential thermal analysis was carried out using Q-1000 and Q-1500 derivatographs (F. Paulik, I. Paulik, L. Erdey system), and X-ray diffraction was performed on a DRON-UM1 unit.

Electron microscopy (REM-200 and EVM-100 BR) was used to examine the morphology, size, spatial arrangement, and appearance of crystals, obtain three-dimensional images, and determine the composition of local areas of the cement stone. Quantitative evaluation of micrononuniformity distribution (2–100 nm) in the submicroscopic structure of cement stone was performed using small-angle scattering (SAS).

Table 5 presents the properties of the developed modified binder. The test results show that the compressive strength after heat treatment ranges from 61 to 70 MPa, while the sulfate resistance coefficient is 0.95–1.00.

Table 5. Properties of modified binders

Binder composition, mass %				Compressive strength after steaming, MPa	Sulfate resistance coefficient
Portland cement clinker	Carbonate-containing tailings	Quartz - containing tailings	Modifier		
84.5	5	10	0.5	61.5	0.95
74.2	10	15	0.8	63.0	0.98
64.0	15	20	1.0	70.0	1.0
Note – compiled by the authors based on their researches					

The advantage of the multicomponent modified binder lies in the fact that during hydration, calcium aluminates interact with calcium and magnesium carbonates contained in the carbonate-bearing tailings to form sparingly soluble hydrocarbonaluminates. The formation of these stable hydrates promotes the intensification of binder hardening and increases sulfate resistance.

In the X-ray diffraction pattern of the hydrated binder at the age of three days, diffraction lines with d-spacings of 0.380, 0.286, 0.249, and 0.166 nm appear, corresponding to calcium hydrocarbonaluminate $3CaO{\cdot}Al_2O_3{\cdot}CaCO_3{\cdot}11H_2O$ formed in the contact zone.

Differential thermal analysis confirms the XRD observations. The DTG curves and the results of moisture loss in the cement stone (Table 6) during heating demonstrate a strong correlation between the heating temperature and the ability of hydrate phases to retain water. The complex additives contribute to an increase in the amount of chemically bound water.

It can be assumed that these additives—beneficiation wastes—enhance the number of crystallization centers and promote the growth of intra- and intercrystalline voids formed during the development of a supramolecular layered structure. Such voids are capable of retaining water molecules in a highly oriented state, where their rotational degrees of freedom are inhibited and translational motion is partially restricted [10]. Within a monolayer, these water molecules possess significant mobility, creating favorable conditions for the easy sliding of the cement gel, which in turn facilitates the appearance of irreversible plastic deformations.

In the IR spectrum of the cement stone after one day, in the wavenumber range 700–1200 cm^{-1}, a broad absorption band appears, split into components characteristic of calcium silicates. Absorption maxima at 930, 885, and 840 cm^{-1} indicate the presence of unhydrated C_3S.

Table 6. Mass Loss of Cement Stone from Modified Binder (MMB) According to DTA Data

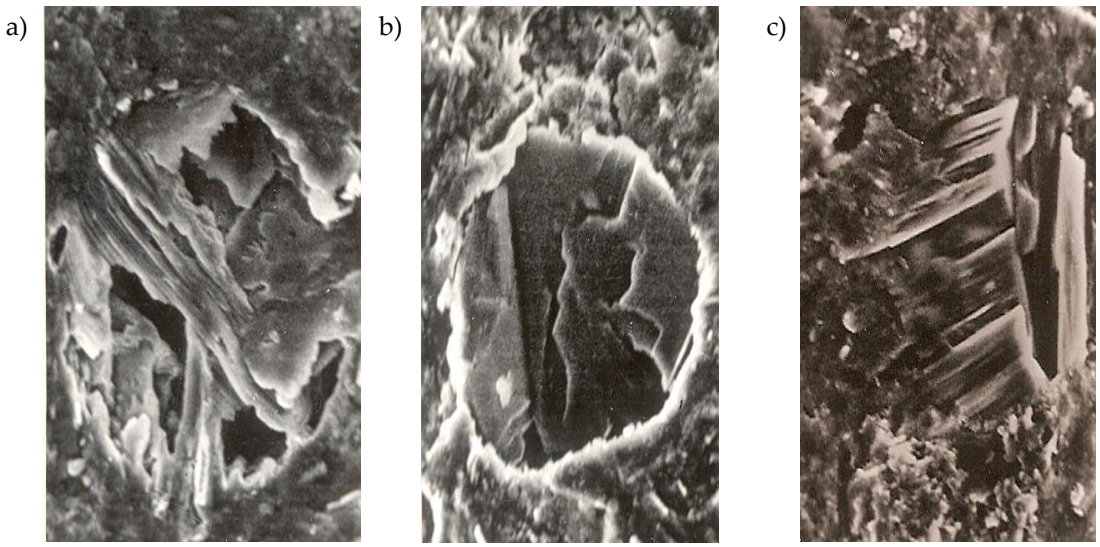
Type of binder	Mass loss in % in temperature ranges, ºC			Relative mass loss, %
	20-200	20-600	20-1000	
PC M400	4.9	13.5	23	36
MMB	5.2	12.3	22	41
Note – compiled by the authors based on their researches				

At the age of three days, the absorption band at 940 cm^{-1} observed in Portland cement clinker shifts toward higher wavenumbers and is detected at 970 cm^{-1} when complex additives are introduced. This shift indicates the polycondensation of [SiO_4] tetrahedra, which leads to a decrease in the basicity of the hydrosilicates in the modified binder.

Electron microscopy was used to examine the morphology, size, spatial arrangement, and appearance of crystals, obtain three-dimensional images, and determine the composition of local areas within the cement stone. The processes of growth and interpenetration of CH and C–S–H phases, as well as changes in hydrate morphology, were investigated. A quantitative assessment of micrononuniformity distribution (from 2 to 100 nm) in the submicroscopic structure of the cement stone was performed using the small-angle scattering method.

The complex additives significantly alter the rate of hydrate nucleation. As early as three minutes after mixing the binder with water, the first needle-like formations appear, indicating an intensified hydration process. At a magnification of 2000×, micropores measuring 2–3 μm are observed. At the age of three days of curing, hexagonal prismatic portlandite crystals are detected at the bottom of such pores, indicating a strong initial supersaturation of the liquid phase with Ca^{2+} ions. Further recrystallization and growth of hexagonal portlandite crystals follow the laws of collective growth and occur metasomatically.

During the hardening process, portlandite reacts with the active silica contained in the complex additive. As a result, the most typical form of C–S–H (Type I) is formed, represented by large but extremely thin sheets or foil whose thickness corresponds to that of the primary structural layer. Unlike the control sample, in the cement stone modified with complex additives, portlandite blocks tightly intergrow with the cement gel, forming a monolithic structure of gel and CH phases or zones of their mutual penetration (Figure 2).



a – formation of amorphous portlandite (at 90 days of curing);
b – micropores of the cement stone are densified with thin C–S–H (Type I) foil-like layers (at 180 days of curing);
c – intergrowth of portlandite blocks with gel-like C–S–H.

Figure 2. Microstructure of the modified binders, ×2000
Note – compiled by the authors based on their researches

Changes in the supramolecular structure are reflected in the logarithmic SAS curves of the cement stone under conditions of a dry hot climate. A slight increase in microporosity results from continued hydration during curing. Improvements in the submicroscopic structure

are observed with a minor increase in the effective micropore radius from 10.5 to 10.8 nm, which may be associated with the filling of larger pores (over 100 nm) with calcium hydrosilicates.

Analysis of the calculated maximum, minimum, and effective micropore radii as a function of curing time and conditions showed that the smallest variation in pore radii (Rmax → Rmin) occurs at 14 days of curing.

CONCLUSIONS

1. In the developed compositions of modified multicomponent binders, the fundamental principles of producing low-water-demand binders have been implemented. Mechanochemical activation leads to partial dispersion of binder grains along weak bonds and to mechanical destruction of structural elements, significantly increasing the number of active centers per unit volume.

2. The high strength of cement stone based on the modified multicomponent binder is determined by the composition and structure of the hydrate formations, which are predominantly represented by long-fibrous, low-basic calcium hydrosilicates formed on the surfaces of existing crystals (epitaxial effect), along with the absence of visible structural defects.

3. To ensure the formation of a cement stone structure characterized by minimal porosity and increased strength, it is necessary to stabilize the composition of hydrate formations, prevent their phase transitions, regulate the hydration process, and achieve an optimal ratio of crystalline and gel phases in the hydration products through the proper selection of mineral additives and curing conditions.

4. An additional source of low-basic calcium hydrosilicates is the pozzolanic reaction, during which portlandite released in the hydration of clinker minerals is absorbed by the amorphous silica of the complex additive, thereby preventing ettringite crystallization at later stages of hardening.

5. The results of the conducted research demonstrate the feasibility of controlled regulation of hydration processes and strength development of cement stone, which can be achieved by adjusting the mineralogical composition of cement and the types of mineral and chemical additives.

It was established that the use of non-ferrous metallurgy wastes (zinc slag and polymetallic ore beneficiation tailings) in multicomponent modified binder systems leads to an intensification of clinker silicate phase hydration. When 15–30 wt.% of mineral additives are introduced, the degree of C_3S hydration increases from 71.5% (control composition) to 75–76% after 28 days of curing.

2. X-ray diffraction and thermal analyses demonstrated that the incorporation of complex mineral additives is accompanied by a significant reduction in portlandite content. Its amount decreases from 23.6% in the control composition to 17.3% at the optimal additive dosage, indicating the active development of pozzolanic reactions and the formation of secondary hydrate phases.

3. Scanning electron microscopy revealed that the modified systems are characterized by a more homogeneous and denser microstructure compared to the control cement stone. The structure is dominated by fine-fibrous and needle-shaped low-basic calcium hydrosilicates (C–S–H), which uniformly fill the intergranular space and ensure effective densification of the cement stone.

4. Morphological analysis showed that zinc slag particles possess an irregular angular shape, a highly developed surface, and a microporous structure. These features promote an increase in the number of active crystallization centers and accelerate the nucleation of hydrate formations at the early stages of hardening.

5. It was established that the combined use of mineral additives and the superplasticizer Sikament–FF-N produces a synergistic effect, manifested in accelerated hydration of calcium silicates, suppression of coarse-crystalline portlandite formation, and the development of a more stable gel structure of the cement stone.

6. The developed multicomponent modified binders exhibit high physical and mechanical properties: the compressive strength of the cement stone after heat-and-moisture treatment reaches 61–70 MPa, while the sulfate resistance coefficient ranges from 0.95 to 1.00, confirming enhanced durability and service reliability of the material.

7. The obtained results confirm the possibility of targeted regulation of structure formation processes and hydration kinetics through optimization of the mineral composition and dosage of non-ferrous metallurgy wastes. This approach opens prospects for reducing clinker content in cement and improving the environmental efficiency of construction materials.

Overall, the study demonstrates that the use of zinc slag and polymetallic ore beneficiation tailings as components of multicomponent binders is scientifically substantiated and technologically feasible. Their application ensures the formation of a dense, stable, and durable cement stone structure and expands the potential for practical utilization of technogenic wastes in the construction industry.

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