

ТРАНСПОРТНЕ БУДІВНИЦТВО

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PROPERTIES OF MODIFIED CONCRETE FOR SPECIAL PURPOSE STRUCTURES

Purpose. The paper is aimed at developing the scientific fundamentals of new-generation monolithic concrete technology for special purpose structures by controlling the processes of structure formation of a modified cement system under natural hardening conditions. **Methodology.** The kinetics of interaction between the cement system and aggregates was evaluated by microcalorimetry. The measurements were carried out continuously for 24 hours after preparation of the mixture. The differential and integral characteristics of the heat release of the solidifying system were recorded. Investigation of the rheological properties of concrete mixtures was carried out on the mixtures with 10...15 cm consistency. The microhardness of contact layers was investigated on concrete cubes with dimensions from 20×20×20 to 50×50×50 mm. When determining the structural characteristics, x-ray phase and differential-thermal analyzes of the concrete cement matrix were used. Infrared spectroscopy was used to determine the effect of physicochemical modification on the cement system. Tensile creep was studied over a wide load range from $0.2R_t$ to $0.8R_t$. **Findings.** It is determined that the reason for changing the concrete properties of natural hardening is the change in its hygrometric and thermal state, as well as the harmonic fluctuations of these environmental factors. The hygrometry of concrete depends on the thermal moisture conditions of the environment, the type and composition of concrete, the massiveness of concrete elements. An analysis of these factors and experimental data made it possible to establish the exponential dependence of the change in the hygrometric state of monolithic natural hardening concrete. The change in the moisture state of concrete makes it possible to predict its volumetric deformations. **Originality.** For the first time, the features of the structure formation of a modified cement system are established, consisting in the fact that magnesium chloride hydrate crystals grow rapidly in the space between hydrated clinker minerals, and the resulting mechanical cohesion defines the development of initial strength and rigidity. Since the free growth of crystals is hampered by a lack of space, the crystals mutually intergrow, forming a dense structure, contributing to the growth of strength. The developed organo-mineral modifying complex provides disperse reinforcement of the cement matrix of concrete. **Practical value.** The obtained dependences of structural concrete stresses make it possible to analyze their effect on the structure of modified concrete: to determine the probability of formation around the filler particles of the plastic flow zone, the material microcrack formation zone, the crack initiation period, the microcrack onset conditions, and the change of elasticity modulus of the material caused by microcracks in its structure. Dispersive modification of cement matrix allows to obtain durable concrete of special purpose with design operational properties. The developed binder disperse modification technology, the established features of the structure formation mechanism for the modified cement system, as well as the use of the principle of congruence of a complex of technological influences to the physico-chemical processes of hydration of clinker minerals allowed developing the scientific fundamentals for the special purpose concrete technology. This helps to expand the use of modified concrete in various types of construction.

Keywords: modified concrete; disperse modification; structure formation; cement system; structural characteristics; durability

Introduction

The development of capital construction in a market economy is closely linked with the tasks of further increasing the efficiency of construction production, reducing the cost and complexity of technological processes, economical use of material and energy resources, the use of new progressive materials [7, 8, 10, 12, 18].

Obtaining concrete of special purpose with high operational properties is possible by using different additives of organic and mineral origin. However, along with the positive effect, organic additives have a number of significant drawbacks, the main of which is the violation of the initial processes of hydration of the cement system in concrete. The organic plasticizer molecules are adsorbed onto cement particles and inhibit the hydration of the cement matrix with all the resulting consequences.

One of the promising structural materials is dispersed reinforced concrete. Such concrete is one of the varieties of a large class of composite materials, which are now increasingly used in various industries. Disperse reinforcement is carried out by fibers of various nature, uniformly distributed in the volume of the cement matrix, and is one of the ways of modifying the concrete cement system [2, 3, 17].

The uniqueness of modern buildings and structures being erected determines a complex of high operational requirements for this material. First of all, they include the high strength, the stability of heavy concrete in different operating conditions and the highest possible durability of the selected material [1, 6, 11].

The current level of development of construction requires the further development of the concept of new generation concretes, which are necessary for the perception of increasing natural and man-made impacts, as well as for special conditions of exploitation.

The development of the binding system activation methods was promoted due to the studies by G. R. Wagner, V. M. Glushchenko, G. Gouda, I. G. Grankovsky, L. I. Dvorkin, P. Clark, M. M. Kruglytsky, V. A. Matvienko, M. I. Netesa, O. O. Pashchenko, O. M. Pshinko, D. M. Roy, N. M. Rudenko, M. A. Sainitskiy, V. I. Solomatov, M. B. Uriev, M. Sh. Finer, Yu. G. Hayutin,

O. O. Shishkin, Yu. Steierman, B. E. Yudovich and others.

Obtaining concrete of marginal strength is one of the main problems of modern concrete technology. Taking into account the considerable accumulated experience in this direction, it should be noted that the solution of this problem is possible with the purposeful management of the processes of hydration and structural formation of the cement matrix of concrete [9, 13–16].

The most vulnerable part of the concrete conglomerate is its cementing matrix. The study of foreign practice in the construction of unique objects has shown that the efforts of researchers and builders are aimed at increasing the physical and technical characteristics of the cement matrix. It is provided with the use of high-early cements of high grade or cement remilling, as well as various additives that provide the maximum possible reduction of water-cement ratio. In particular, the practice of using super- and hyperplasticizers is widely used. Improvement of other properties of concrete is also achieved by using various complex additives. Particular attention in obtaining concrete with high operational properties is paid to increasing the operational stability of the cementitious matrix. As a rule, this is achieved by a combination of the described technological measures with the use of highly dispersed microfiller with amorphous surface in the concrete composition.

Purpose

Development of scientific fundamentals of new-generation monolithic concrete technology for special purpose structures by controlling the processes of structure formation of a modified cement system under natural hardening conditions.

Methodology

The kinetics of interaction between the cement system and aggregates was evaluated by microcalorimetry. The measurements were carried out continuously for 24 hours after preparation of the mixture. The differential and integral characteristics of the heat release of the solidifying system were recorded. Investigation of the rheological properties of concrete mixtures was carried out on the mixtures with 10...15 cm consistency. The microhardness of contact layers was investigated on concrete

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cubes with dimensions from $20 \times 20 \times 20$ to $50 \times 50 \times 50$ mm. When determining the structural characteristics, x-ray phase and differential-thermal analyzes of the concrete cement matrix were used. Infrared spectroscopy was used to determine the effect of physicochemical modification on the cement system. Tensile creep was studied over a wide load range from $0.2R_t$ to $0.8R_t$.

Findings

The microstructure of a modified cement concrete matrix is formed in the form of well crystallized, spiral tubular filamentous crystals. The mechanical grip of these crystals is considered as the main source of strength formation along with the additional grip, which is achieved as a result of the mutual intergrowth of the crystals when they collide with each other. Slow solidification and rapid hardening of the modified cement concrete system allows the use of such concrete mixtures for concrete pumping transport and transport them over long distances when erecting buildings and structures.

The process of formation of the modified concrete coagulation structure in natural conditions is carried out due to the selective adsorption of ions and associates from the liquid phase, the change in the contact area in the spatial plastic structure, the directed growth of crystals. The coagulation-crystallization structure of the modified cement matrix derives the features of the mutual arrangement of aggregate structures, the porosity and dispersion type. Herewith, the mineral part of the modifier is a chemically active component – an additional source of hydrated phases, which contributes to the strengthening of the binding system. The physico-chemical modification of the cement system of concrete creates special conditions for the formation of a spatial structure that differs in structure from ordinary concrete.

From the moment of the preparation of the modified concrete mixture, the defect in the surface monolayer of the cement particle increases, thereby affecting the amplitude of the oscillations of the crystalline lattice nodal atoms. The combination of thermal, chemical and mechanical influences leads to a disturbance of the distant order of

the crystalline lattice of the cement particle surface layer, causing the atoms to oscillate near the equilibrium positions more intensively.

It is important that the complex modification of the concrete mixture creates special conditions for the formation of the contact area of the cement matrix and filler grains. Modification creates conditions for the formation of a pseudo-solid body, the deformation of which manifests itself in the form of an elastic aftereffect. This creates the conditions for marginal packing of grains of different granulometry and optimization of the thickness of the contact layers with the minimum possible porosity of the material. Modification of the cement system leads to the equalization of the water-cement ratio in all layers of the concrete mixture. The reason for this is the high level and constancy of the hydrostatic pressure of water. In this case, the formation of the contact layer cement matrix – filler occurs in special conditions.

The microhardness of the concrete contact layers was investigated. The microhardness value was characterized by the magnitude of the diamond cone imprint. The cement matrix microhardness parameters listed in Table 1 indicate that the strength of the intergranular area is substantially inferior to the strength of the contact area for ordinary concrete. The imprint diameters in the intergranular area are 15...17% bigger than the values in the contact area with the filler. For the cement matrix of modified concrete, these parameters are close by values. It is established that in modified concrete the strength of the contact and intergranular area of the cement matrix differs by 3...7%, which explains the increase in concrete strength during tension.

At low values of W/C close to $[W/C]$, the contact areas of the cement matrix are practically overlapping, which determines the high strength of such concrete during tension. Thus, it can be concluded that in the modified concrete a cement matrix is formed, practically isotropic from the surface of the filler to the centers of the intergranular layers. Such matrix is characterized by high adhesion to the filler surface, approximately equal to its cohesive properties. The established position is confirmed by the concrete structure analysis.

Table 1

Concrete cement matrix microhardness parameters

Type of concrete	W/C	Average diameter of the diamond cone imprint, 10^{-7} m	
		contact area	intergranular area
Modified	0.29	2.6	2.8
	0.31	3.0	3.1
	0.33	3.3	3.4
Ordinary	0.42	4.6	5.2
	0.44	5.1	5.7
	0.46	5.4	6.2

The kinetics of the interaction of the binder and fillers in the solidifying dispersion system was evaluated by methods of microcalorimetry. The measurements were carried out continuously for 24 hours after preparation of the mixture. The differential and integral characteristics of the heat generation of the solidifying mixture were recorded. In the process of measurements, the microcalorimeter maintained the temperature of 20°C. The heat generation of cement systems with W/C=0.30...0.42 differs significantly. The differentiated heat generation of cement systems, prone to modification, differs significantly. They are characterized by high-intensity heat generation in the period up to one day of hardening, whereas in traditional samples the heat generation rate change basically ends up to 7-day age.

After four hours of hardening of the modified concrete, we observe the heat generation process intensification, which indicates the recrystallization, as well as the stabilization of the cement matrix structure.

Comparison of the cement matrix microhardness data with the microcalorimetric study data shows that between the filler and the cement matrix there is a physical interaction, which leads to the formation of a contact area consisting of layers on the edge of the cement matrix and the filler and the surface of the partition between them. The value of the cement matrix adhesion to the filler surface is several orders of magnitude higher than that of the ordinary concrete. This explains the significant increase in the strength of concrete during tension compared with the ordinary concrete.

With almost constant ratio of volumes of hydrated phases and porous space, they undergo regular qualitative changes in time. In the solid phase, as far as the cementing agent is exponential-

ly accumulated, the volume of relic minerals exponentially decreases as well. Although the cementing agent at various stages of its formation is represented by a set of high-base forms of hydrated newgrowths, their structure depends on the technological conditions of structuring.

Change in quantitative characteristics of the modified concrete structure was observed when changing the modification parameters. The observed changes in the morphological structure of the cement matrix can not be random, as they are confirmed by repeated experiments with reproducibility from 82 to 96%. At the same time, such change in the newgrowth morphology is not observed in the ordinary concrete. The data obtained show a significant increase in the lamellar-prismatic component in the cement matrix of the modified concrete. With longer curing time, the number of formed crystalline newgrowths increases.

This can be explained by the system approach: the cement matrix structure morphology is the result of the interaction of the build and growth systems. In this case, the growth system (structure recrystallization and development in time) can effectively develop without a sufficiently complete development of the build system (accumulation of primary hydration products). The developed system of cement particle hydration build-up in favorable conditions of the hydraulic pressure of the surrounding water due to thixotropy will weaken the morphology of structural newgrowths. However, this phenomenon is not observed in ordinary concrete, where there is no structure modification. According to experimental data obtained by complex methods of studying the structure, development in volumes of similar morphological structures can reach 20%. Herewith, the hydration rate increases by 11...14%.

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The research of physical and mechanical properties of the concrete mixture and the concrete on the modified cement system was carried out. Research of rheological properties of the concrete mixtures was carried out on mixtures with 10...15 cm mobility. Physico-chemical modification of the cement system provides the obtaining of mobile concrete mixtures with the decreased cement cost per 1 m³ of concrete by 32...37%. The ease of laying these concrete mixtures is stable in the range of used compositions. This allows asserting that the cement system modification provides obtaining of non-disintegrating concrete mixtures. In contrast, the ordinary concrete mixtures were characterized by obvious signs of stratification. In this case, with the cone slump (CS) = 15 cm, the composition with a minimum cement consumption was subjected to the disintegration as well.

It is established that the use of modified cement systems contributes to increasing the water-retaining capacity of concrete mixtures. In view of transportation without the vibration effect, the water-retaining capacity of the modified cement system is $W/C = 1.3$ [W/C].

The technological properties of the concrete mixture are largely determined by its viability in a certain period of time. The viability of the mixtures is significantly affected by the environment. In the laboratory, the mixture mobility change in time was determined by the cone slump measurement. The intensity of CS change depended on the conditions of concrete and the type of experiments conducted. The results of experiments are presented in Table 2.

Table 2

Influence of concrete mixture curing time on its mobility (initial cone slump of 15 cm)								
Type of mixture	Curing conditions	Concrete mixture mobility, cm, in						
		15 min	30 min	45 min	60 min	75 min	90 min	105 min
Ordinary	Laboratory	12	10	7	6	4	3	3
	Climatic camera	12	8	5	4	3	2	2
On a modified binder	Laboratory	15	15	14	13	13	12	12
	Climatic camera	15	13	13	12	11	10	10

It was established that the modification of the cement system contributes to increased strength of the concrete during tension and bending. This ex-

plains the decrease in the values of the ratios R/R_t and R/R_b of the modified concrete, which solidified under natural conditions (Table 3).

Table 3

Concrete strength ratio at tension and compression				
Concrete strength limit, MPa			Ratio R/R_t	Ratio R/R_b
At compression (R)	At tension (R_t)	At bending (R_b)		
Ordinary concrete				
45.6	2.75	3.28	16.5	13.9
47.5	2.94	3.69	16.1	12.9
52.9	3.17	4.07	16.7	13.0
54.7	3.23	4.28	16.9	12.8
Modified concrete				
76.4	5.78	12.07	13.21	6.33
80.3	6.87	12.87	11.76	6.24
91.9	8.04	14.24	11.43	6.45

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It has been experimentally found that the modified concrete in specific conditions of operation is ensured with fairly high atmospheric resistance. The indicated is also confirmed by stable values of material strength in the research process. For ordinary concrete there is a decline in strength both during compression and bending. Standard samples began to collapse after 127 cycles of water saturation and drying, while samples of modified concrete were in a satisfactory condition to almost 200 cycles, after which the tests were discontinued.

Taking into account the operation of elements of concrete and reinforced concrete structures in conditions of variable water level, they are subjected to alternate freezing and thawing under conditions of capillary suction. Therefore, the concrete, intended for erection and restoration of special structures, must have high frost resistance. The theoretical prerequisite for increasing the frost resistance of concrete is the modification of its pore structure.

The estimation of the parameters of conditionally closed porosity of concrete was carried out by means of microscopic studies on concrete polished sections by the linear method. The chosen method of determining the specific surface of the concrete polished sections is the most widely used and is called the linear intercept method.

The X-ray diffraction and differential-thermal analyzes of concrete cement matrix have been carried out. As follows from diffractograms, the composition of newgrowths in a cement stone of the ordinary concrete is somewhat different from the same composition of the modified concrete. In the ordinary concrete, there is identified the three-sulfate form of hydrosulfoaluminate calcium ($d=9.73; 5.61; 3.85 \cdot 10^{-10}$ m), C_3AH_6 ($d=4.45; 2.30; 1.572 \cdot 10^{-10}$ m), $Ca(OH)_2$ ($d=4.91; 2.61; 1.79 \cdot 10^{-10}$ m), hydrosilicates of calcium of increased basicity ($d=3.03; 2.83; 2.026; 1.632$ m). The modified concrete newgrowths are characterized by formation of four-calcium hydroaluminate ($d = 7.8, 3.85, 2.43, 1.67 \cdot 10^{-10}$ m), as well as recrystallization into a monosulfate form of calcium hydrosulfoaluminate ($d = 8.92, 4.96; 3.99; 2.25 \cdot 10^{-10}$ m), which obviously contributes to the increased frost resistance of the modified concrete.

The data of the differential-thermal analysis confirm the results obtained during radiographic studies. The endoeffect with a maximum of 132°C on a thermogram of the ordinary concrete cement

stone subjected to the frost resistance test corresponds to the dehydration of the three-sulfate form of calcium hydrosulfoaluminate and calcium hydrosilicates. The temperatures $440\text{--}445^\circ\text{C}$ correspond to the decomposition of $Ca(OH)_2$, while for the modified cement matrix the effect is less noticeable. At low temperatures of $586, 698, 716^\circ\text{C}$, low-mass hydrosilicates of calcium type CSH (B) and C_2SH_2 are dehydrated. The endoeffects at temperatures of 690 and 710°C for the ordinary cement stone also correspond to the decomposition of $CaCO_3$, although calcium carbonate is exuded in a small amount.

The purpose of physico-chemical modification of the cement system is to create conditions for a highly efficient reaction of clinker minerals with water at sufficient rapidity. Herewith the solid products with very low solubility and microstructure should be formed, which provides the necessary mechanical strength, volume stability and other necessary properties. The formation of adsorption layers on the surface of cement grains is the most important stage of the modification process. While playing the same role as protective colloids, these layers regulate the growth of crystals at certain stages of the clinker minerals hydration process. The action of modifiers in a concrete mixture is reduced to multiplication of seeds and to their growth in the cement system. This is due to the fact that modifiers, being a surfactant and acting on the edge of the crystals formed from the solution, contribute to the increase of surface activity, and also affect their shape. Since under other equal conditions the growth rate of crystals is often proportional to the surface tension, even very small additions of substances that are capable of altering the surface tension significantly affect the degree of grain wetting, the crystallization nature and the newgrowth peculiarities.

The simulation of interconnections in the modified cement system was performed, as well as the differential equations for the potential were derived, which correspond to any distribution of physical boundaries and charges in the cement system. It was proved that it is necessary to divide the liquid phase into several areas, each of which the Laplace equation or the Poisson equation can be applied to. Then the solution of these equations depends on the conditions that obey the corresponding parameters within the boundaries of the areas where the equation data apply.

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When maintaining samples of concrete in a sulfate medium for 360 days, the decrease in the modified concrete strength is 3...6% (decrease in the ordinary concrete strength – 12...23%), the coefficient of sulfate resistance K_s is within 0.91...0.93.

Stabilization of the modified concrete strength in time indicates the predominance of constructive processes over destructive ones.

The mathematical model of the corrosion resistance processes was obtained. The experimental data resulted in the equation which binds the sulfate stability of the concrete with the parameters of the aggressive medium (content of sulfate ions) and the concrete characteristics (content of C_3A , cement, $CaCO_3$ in the fine filler, cement system modification degree) [5]. The test for adequacy has shown good convergence of model results. The deviation of the calculated K_s from the experimental one in the whole range of tests does not exceed $\delta_{K_s} = \pm 0.1$.

The deformation properties and the stress state of modified concrete for special purpose were investigated. It was established that the causes of volumetric changes of concrete are shrinkage and temperature deformation. Herewith, in the natural conditions of concrete hardening it is important to take into account both types. Moreover, the value of temperature deformations of concrete in natural conditions may be close to the amount of shrinkage.

Shrinkage deformations were investigated for conditions of linear drying, for which purpose the concrete was laid in glass tubes, open on one side. The 14-day age deformations vary depending on the sample length to five times. Despite some smoothing of this difference over time, it remains significant even at 60-day age.

The equations obtained from the test results allow us to solve the question of the minimum level of structural stresses in monolithic concrete with its certain saturation with large aggregate, and also to evaluate the influence of structural stresses on the concrete properties [4]. The ordinary concrete with a relatively thin cement sheath are characterized by high tangential and small radial stresses at temperature-shrinkage deformations. Under natural conditions, these stresses are higher as a result of increased values of $\Delta\epsilon(\tau)$, which is not observed in the modified concrete. In the modified concrete, only the tangential stresses present the greatest danger to the structure.

Change in shrinkage stresses in time is unambiguous. Total temperature-shrinkage deformations have a saw-tooth graph. For the modified concrete, the amplitude of fluctuations is 48...53% less.

The tensile creep was studied in a wide range of loads from $0.2R_t$ to $0.8R_t$ with the modified concrete strength during tension of 3.68 MPa and that of the ordinary concrete of 2.04 MPa. As the stresses σ/R_{tc} increase, the magnitude of the creep deformations of ordinary concrete increases significantly. However, the nature of the creep deformation of the modified concrete during tension differs from the generally known. The main difference between all the curves is a significant superiority of the creep deformation of the ordinary concrete samples. Up to 90-day age, for all values of σ/R_{tc} , the creep deformations are practically stabilized. Consequently, in this age it is convenient to compare the creep deformations of the samples with different values of σ/R_{tc} .

Originality and practical value

For the first time, the features of the structure formation of a modified cement system are established, consisting in the fact that magnesium chloride hydrate crystals grow rapidly in the space between hydrated clinker minerals, and the resulting mechanical cohesion defines the development of initial strength and rigidity. Since the free growth of crystals is hampered by a lack of space, the crystals mutually intergrow, forming a dense structure, contributing to the growth of strength. The developed organo-mineral modifying complex provides disperse reinforcement of the cement matrix of concrete.

The obtained dependences of structural concrete stresses make it possible to analyze their effect on the structure of modified concrete: to determine the probability of formation around the filler particles of the plastic flow zone, the material microcrack formation zone, the crack initiation period, the microcrack onset conditions, and the change of elasticity modulus of the material caused by microcracks in its structure. Dispersive modification of cement matrix allows to obtain durable concrete of special purpose with design operational properties. The developed binder disperse modification technology, the established features of the structure formation mechanism for the modified cement system, as well as the use of the principle of

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congruence of a complex of technological influences to the physico-chemical processes of hydration of clinker minerals allowed developing the scientific fundamentals for the special purpose concrete technology. This helps to expand the use of modified concrete in various types of construction.

Conclusions

It is determined that the reason for changing the concrete properties of natural hardening is the change in its hygrometric and thermal state, as well as the harmonic fluctuations of these environmental factors. The hygrometry of concrete depends on the thermal moisture conditions of the environment, the type and composition of concrete,

the massiveness of concrete elements. An analysis of these factors and experimental data made it possible to establish the exponential dependence of the change in the hygrometric state of monolithic natural hardening concrete.

According to the hygrometric data of the concrete, a dependence is obtained to determine its temperature-shrinkage deformation. This confirms the physical principles of changed hygrometry and shrinkage of concrete in time. The obtained dependences also take into account the concrete composition (relative content of the filler), as well as allow to determine volumetric deformations of concrete elements of different composition and massiveness.

LIST OF REFERENCE LINKS

1. Большаков, В. И. Контактная прочность механоактивированных мелкозернистых бетонов из доменных гранулированных шлаков / В. И. Большаков, М. А. Елисеева, С. А. Щербак // Наука та прогрес транспорту. – 2014. – № 5 (53). – С. 138–149. doi: 10.15802/stp2014/29975
2. Пшінько, О. М. Вибір матеріалів для ремонту та відновлення бетонних та залізобетонних конструкцій транспортних споруд з урахуванням критерію сумісності : монографія / О. М. Пшінько, А. В. Краснюк, О. В. Громова. – Дніпропетровськ : Дніпропетр. нац. ун-т заліз. трансп. ім. акад. В. Лазаряна, 2015. – 195 с.
3. Рабинович, Ф. Н. Композиты на основе дисперсноармированных бетонов. Вопросы теории и проектирования, технология, конструкции : монография / Ф. Н. Рабинович. – Москва : АСВ, 2004. – 560 с.
4. Руденко, Д. В. Бетон на основі дисперсно модифікованої цементної системи / Д. В. Руденко // Наука та прогрес транспорту. – 2016. – № 4 (64). – С. 169–175. doi: 10.15802/stp2016/78008
5. Руденко, Д. В. Дослідження напруженого стану модифікованого монолітного бетону / Д. В. Руденко // Наука та прогрес транспорту. – 2016. – № 6 (66). – С. 166–174. doi: 10.15802/stp2016/90515
6. Руденко, Д. В. Фізико-хімічна модифікація цементної системи монолітного бетону / Д. В. Руденко // Наука та прогрес транспорту. – 2015. – № 6 (60). – С. 174–182. doi: 10.15802/stp2015/57103
7. Шишкін, О. О. Наномодифікований реакційно-порошковий бетон / О. О. Шишкін // Ресурсоекономні матеріали, конструкції, будівлі та споруди : зб. наук. пр. – Рівне, 2015. – Вип. 31. – С. 106–111.
8. Шумаков, И. В. Оптимизационные тенденции в прогнозировании продолжительности строительства / И. В. Шумаков, Р. И. Микаутадзе, И. И. Ляхов // Наук. вісн. буд-ва : зб. наук. пр. – Харків, 2018. – Т. 91, № 1. – С. 115–121. doi: 10.29295/2311-7257-2018-91-1-115-121
9. Шумаков, І. В. Перспективність техногенних територій для міського цивільного будівництва / І. В. Шумаков, О. А. Гринчук, Ю. В. Фурсов // Наук. вісн. буд-ва : зб. наук. пр. – Харків, 2016. – № 3 (85). – С. 73–77.
10. Aitcin, P. C. The Art and Science of Durable High-Performance Concrete / P. C. Aitcin // Nelu Spiratos Symposium on Superplasticizers : proc. of a symposium honouring Dr. N. Spiratos (Bucharest, Romania, June 2003). – Bucharest, 2003. – P. 69–88.
11. Collepardi, M. The New Concrete / M. Collepardi, N. B. Singh. – Milan : Grafishe Tintoretto, 2006. – 421 p.
12. Holland, T. C. High-Performance Concrete: As High as It Gets / T. C. Holland // The Concrete Producer. – 1998. – Vol. 16, No. 7. – P. 501–505.
13. Lee, M. G. A preliminary study of reactive powder concrete as a new repair material / Ming-Gin Lee, Yung-Chih Wang, Chui-Te Chiu // Construction and Building Materials. – 2007. – Vol. 21. – Iss. 1. – P. 182–189. doi: 10.1016/j.conbuildmat.2005.06.024
14. Lee, C. Y. Strength and microstructural characteristics of chemically activated fly ash-cement systems / C. Y. Lee, H. K. Lee, K. M. Lee // Cement and Concrete Research. – 2003. – Vol. 33. – Iss. 3. – P. 425–431. doi: 10.1016/S0008-8846(02)00973-0

ТРАНСПОРТНЕ БУДІВНИЦТВО

15. Middendorf, B. Nanoscience and Nanotechnology in Cementations Materials / B. Middendorf // Cement International. – 2006. – No. 4. – P. 80–86.
16. Rudenko, D. Properties of the phase components of the modified cement system / D. Rudenko // Teka. Commission of Motorization and Energetics in Agriculture. – 2013. – Vol. 13, No. 4. – P. 218–224.
17. Rudenko, N. The Development of Conception of New Generation Concretes / N. Rudenko // Teka. Commission of Motorization and Energetics in Agriculture. – 2010. – Vol. XB. – P. 128–133.
18. Sanytsky, M. Chemical processes causing dissolution of calcium cement minerals / M. Sanytsky // Будівельні матеріали і вироби. – 2016. – № 4. – С. 34–37.
19. Sanytsky, M. Department of building production: educational activity and scientific research / M. Sanytsky // Internationalizing higher education and research in civil engineering and architecture : Proceedings of the Exploratory Visit Grant of «Internationalising Higher Education» program supported by British Council Ukraine. – Rivne, 2016. – P. 70–73.
20. Shishkin, A. Effect of the iron-containing filler on the strength of concrete / A. Shishkin, N. Netesa, V. Scherba // Eastern-European Journal of Enterprise Technologies. – Vol. 5. – Iss. 6 (89). – 2017. – P. 11–16. doi: 10.15587/1729-4061.2017.109977

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ОСОБЛИВОСТІ ФОРМУВАННЯ ЕКСПЛУАТАЦІЙНИХ ВЛАСТИВОСТЕЙ МОДИФІКОВАНОГО БЕТОНУ ДЛЯ СПОРУД СПЕЦІАЛЬНОГО ПРИЗНАЧЕННЯ

Мета. У роботі потрібно розробити наукові основи технології монолітного бетону нового покоління для споруд спеціального призначення за рахунок керування процесами структуроутворення модифікованої цементної системи в природних умовах тверднення. **Методика.** Кінетику взаємодії цементної системи й заповнювачів оцінювали за методами мікрокалориметрії. Вимірювання проводили безперервно протягом 24 годин після приготування суміші. Реєстрували диференційну та інтегральну характеристики тепловиділення твердіючої системи. Дослідження реологічних властивостей бетонних сумішей здійснювали на сумішах рухливості 10...15 см. Мікротвердість контактних шарів досліджували на бетонних кубиках розмірами від 20×20×20 до 50×50×50 мм. Під час визначення структурних характеристик застосовували рентгенофазовий і диференційно-термічний аналізи цементної матриці бетону. Інфрачервона спектроскопія проведена з метою визначення впливу фізико-хімічного модифікування на цементну систему. Повзучість при розтягу досліджувалася в широкому діапазоні навантаження від 0,2 до 0,8 R_p . **Результати.** Встановлено, що причиною зміни властивостей бетону природного тверднення є зміна його гігromетричного й термічного стану, а також гармонічні коливання цих факторів навколишнього середовища. Гігromетрія бетону залежить від термовологісних умов середовища, виду й складу бетону, масивності бетонних елементів. Аналіз цих факторів та експериментальні дані дозволили встановити експонентну залежність зміни гігromетричного стану монолітного бетону природного тверднення. Зміна вологісного стану бетону дозволяє прогнозувати його об'ємні деформації. **Наукова новизна.** Уперше встановлені особливості структуроутворення модифікованої цементної системи. Вони полягають у тому, що кристали гідрату хлориду магнію швидко ростуть у просторі між гідратними новоутвореннями клінкерних мінералів. Механічне зчеплення, що виникає в результаті цього, обумовлює розвиток початкової міцності й жорсткості. Оскільки вільному росту кристалів перешкоджає брак простору, кристали взаємно проростають, утворюючи щільну структуру, яка обумовлює зростання міцності. Розроблений органо-мінеральний модифікуючий комплекс забезпечує дисперсне армування цементної матриці бетону. **Практична значимість.** Отримані залежності структурних напружень дозволяють аналізувати їх вплив на структуру модифікованого бетону, а саме: встановити ймовірність утворення навколо частинок заповнювача зони пластичної течії, зони мікротріщиноутворення матеріалу, період початку тріщиноутворення, умови виникнення мікротріщин, зміну модуля пружності матеріалу від виникнення в його структурі мікротріщин. Дисперсне модифікування цементної матриці дозволяє одержати довговічні бетони спеціального призначення з проектними експлуатаційними властивостями. Запропонована технологія дисперсного модифікування в'язучої речовини

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ни, встановлені особливості механізму структуроутворення модифікованої цементної системи, а також використання принципу конгруентності комплексу технологічних впливів фізико-хімічним процесам гідратації клінкерних мінералів дозволили розробити наукові основи технології бетонів спеціального призначення. Це сприяє розширенню напрямків використання модифікованих бетонів у різних видах будівельного виробництва.

Ключові слова: модифікований бетон; дисперсне модифікування; структуроутворення; цементна система; структурні характеристики; довговічність

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ОСОБЕННОСТИ ФОРМИРОВАНИЯ ЭКСПЛУАТАЦИОННЫХ СВОЙСТВ МОДИФИЦИРОВАННЫХ БЕТОНОВ ДЛЯ СООРУЖЕНИЙ СПЕЦИАЛЬНОГО НАЗНАЧЕНИЯ

Цель. В работе нужно разработать научные основы технологии монолитного бетона нового поколения для сооружений специального назначения за счет управления процессами структурообразования модифицированной цементной системы в естественных условиях твердения. **Методика.** Кинетика взаимодействия цементной системы и заполнителей оценивалась методами микрокалориметрии. Измерения проводились непрерывно в течение 24 часов после приготовления смеси. Регистрировались дифференциальная и интегральная характеристики тепловыделения твердеющей системы. Исследование реологических свойств бетонных смесей осуществлялось на смесях подвижностью 10...15 см. Микротвердость контактных слоев исследовалась на бетонных кубиках размерами от 20×20×20 до 50×50×50 мм. При определении структурных характеристик применялись рентгенофазовый и дифференциально-термический анализы цементной матрицы бетона. Инфракрасная спектроскопия применялась с целью определения влияния физико-химического модифицирования на цементную систему. Ползучесть при растяжении исследовалась в широком диапазоне нагрузки от 0,2 до 0,8 R_p . **Результаты.** Установлено, что причиной изменения свойств бетона естественного твердения является изменение его гигрометрического и термического состояния, а также гармонические колебания этих факторов окружающей среды. Гигрометрия бетона зависит от термовлажностных условий среды, вида и состава бетона, массивности бетонных элементов. Анализ этих факторов и экспериментальные данные позволили установить экспоненциальную зависимость изменения гигрометрического состояния монолитного бетона естественного твердения. Изменение влажностного состояния бетона позволяет прогнозировать его объемные деформации. **Научная новизна.** Впервые установлены особенности структурообразования модифицированной цементной системы. Они заключаются в том, что кристаллы гидрата хлороксида магния быстро растут в пространстве между гидратными новообразованиями клинкерных минералов. Механическое сцепление, возникающее в результате этого, обуславливает развитие начальной прочности и жесткости. Так как свободному росту кристаллов препятствует недостаток пространства, кристаллы взаимно прорастают, образуя плотную структуру, способствуя росту прочности. Разработанный органо-минеральный модифицирующий комплекс обеспечивает дисперсное армирование цементной матрицы бетона. **Практическое значение.** Полученные зависимости структурных напряжений позволяют анализировать их влияние на структуру модифицированного бетона, а именно: установить вероятность образования вокруг частиц заполнителя зоны пластического течения, зоны микротрещинообразования материала, период начала трещинообразования, условия возникновения микротрещин, изменение модуля упругости материала от возникновения в его структуре микротрещин. Дисперсное модифицирование цементной матрицы позволяет получить долговечные бетоны специального назначения с проектными эксплуатационными свойствами. Предложенная технология дисперсного модифицирования вяжущего вещества, установленные особенности механизма структурообразования модифицированной цементной системы, а также использование принципа конгруэнтности комплекса технологических воздействий физико-химическим процессам гидратации клинкерных минералов позволили разработать научные основы технологии бетонов специального назначения. Это способствует расширению направлений использования модифицированных бетонов в различных видах строительного производства.

Ключевые слова: модифицированный бетон; дисперсное модифицирование; структурообразование; цементная система; структурные характеристики; долговечность

REFERENCES

1. Bolshakov, V. I., Yelisieieva, M. O., & Shcherbak, S. A. (2014). Contact strength of mechanoactivated fine concretes from granulated blast-furnace slags. *Science and Transport Progress*, 5(53), 138-149. doi: 10.15802/stp2014/29975 (in Russian)
2. Pshinko, O. M., Krasniuk, A. V., Hromova, O. V. (2015). *Vybir materialiv dlia remontu ta vidnovlennia betonnykh ta zalizobetonnykh konstrukttsii transportnykh sporud z urakhuvanniam kryteriiu sumisnosti: Monohrafiia*. Dnipropetrovsk: Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan. (in Ukrainian)
3. Rabinovich, F. N. (2004). *Kompozity na osnove dispersnoarmirovannykh betonov. Voprosy teorii i projektirovaniya, tekhnologiya, konstrukttsii: monografiya*. Moscow: ASV. (in Russian)
4. Rudenko, D. V. (2016). Concrete based on modified disperse cement system. *Science and Transport Progress*, 4(64), 169-175. doi: 10.15802/stp2016/78008 (in Ukrainian)
5. Rudenko, D. V. (2016). Research of the stress state of a modified in-situ concrete. *Science and Transport Progress*, 6(66), 166-174. doi: 10.15802/stp2016/90515 (in Ukrainian)
6. Rudenko, D. V. (2015). Physico-chemical modification of monolithic concrete cement system. *Science and Transport Progress*, 6(60), 174-182. doi: 10.15802/stp2015/57103 (in Ukrainian)
7. Shyshkin, O. O. (2015). Nanomodyfikovanyi reaktsiino-poroshkovyi beton. *Resursoekonomni materialy, konstrukttsii, budivli ta sporudy*, 31, 106-111. (in Ukrainian)
8. Shumakov, I. V., Mikautadze, R. I., & Lyakhov, I. I. (2018). Optimization Trends in Forecasting the Duration of Construction. *Scientific Bulletin of Civil Engineering*, 91(1), 115-121. doi: 10.29295/2311-7257-2018-91-1-115-121 (in Russian)
9. Shumakov, I. V. (2016). Perspektyvnistj tekhnoghennykh terytorij dlja misjkogho cyvilnogho budivnyctva. *Naukovyj visnyk budivnyctva*, 3(85), 73-77. (in Ukrainian)
10. Aitcin, P. C. (2003). The Art and Science of Durable High-Performance Concrete. *Nelu Spiratos Symposium on Superplasticizers: Proceedings of a Symposium Honouring Dr. N. Spiratos (Bucharest, Romania, June 2003)* (pp. 69-88). Bucharest. (in English)
11. Collepardi, M. & Singh, N. B. (2006). The New Concrete. Milan: Grafishe Tintoretto. (in English)
12. Holland, T. C. (1998). High-Performance Concrete: As High as It Gets. *The Concrete Producer*, 16(7), 501-505. (in English)
13. Lee, M.-G., Wang, Y.-C., & Chiu, C.-T. (2007). A preliminary study of reactive powder concrete as a new repair material. *Construction and Building Materials*, 21(1), 182-189. doi: 10.1016/j.conbuildmat.2005.06.024 (in English)
14. Lee, C. Y., Lee, H. K., & Lee, K. M. (2003). Strength and microstructural characteristics of chemically activated fly ash-cement systems. *Cement and Concrete Research*, 33(3), 425-431. doi: 10.1016/s0008-8846(02)00973-0 (in English)
15. Middendorf, B. (2006). Nanoscience and Nanotechnology in Cementations Materials. *Cement International*, 4, 80-86. (in English)
16. Rudenko, D. (2013). Properties of the phase components of the modified cement system. *Teka. Commission of Motorization and Energetics in Agriculture*, 13(4), 218-224. (in English)
17. Rudenko, N. (2010). The Development of Conception of New Generation Concretes. *Teka. Commission of Motorization and Energetics in Agriculture*. XB, 128-133. (in English)
18. Sanytsky, M. (2016). Chemical processes causing dissolution of calcium cement minerals. *Будівельні матеріали і виробу*, 4, 34-37. (in English)
19. Sanytsky, M. (2016). Department of building production: educational activity and scientific research. *Internationalizing higher education and research in civil engineering and architecture. Proceedings of the Exploratory Visit Grant of «Internationalizing Higher Education» program supported by British Council Ukraine*. (pp. 70-73). Rivne. (in English)
20. Shishkin, A., Netesa, M., & Scherba, V. (2017). Effect of the iron-containing filler on the strength of concrete. *Eastern-European Journal of Enterprise Technologies*, 5/6(89), 11-16. doi: 10.15587/1729-4061.2017.109977 (in English)

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