International Journal for Computational Civil and Structural Engineering, 18(4) 49–61 (2022)

DOI:10.22337/2587-9618-2022-18-4-49-61

POWDER-ACTIVATED CONCRETE WITH A GRANULAR SURFACE TEXTURE

Vladimir T. Erofeev [1]***, Nikolai I. Vatin*** [2]***, Irina. N. Maksimova*** [3]***,***
Oleg V. Tarakanov [3]***, Yana A. Sanyagina*** [1]***, Irina V. Erofeeva*** [4]***, Oleg V. Suzdaltsev*** [5]

[1] N.P. Ogarev National Mordovian State University (Ogarev Moscow State University), Saransk, RUSSIA
[2] St. Petersburg Polytechnic University named after Peter the Great, St. Petersburg, RUSSIA
[3] Penzensky State University of Architecture and Construction, Penza, RUSSIA
[4] National Research Moscow State University of Civil Engineering, Moscow, RUSSIA
[5] Asia Cement LLC, Penza, RUSSIA

Abstracts. In recent years, self-compacting concrete mixtures have been widely used. Such mixtures are characterized by high workability without the use of vibration exposure. The application of innovative technologies allows manufactoring of various materials and products for architectural and construction purposes with improved decorative properties. The paper provides the results of a study on the selection of compositions for decorative-finishing powder-activated concrete with a granular surface texture according to rheological properties, strength and frost resistance had been adopted.

The following components were adopted for the research. Egyptian white cement was used as a binder, microquartz as a microfiller, screenings of crushing granite and cooper slag of 0–0.63 mm fraction was used as a finely dispersed component, granite cuts 0.63–5.0 mm and cooper slag of 0.63–2.5 mm fraction as an aggregate sand. A new generation superplasticizer of domestic and foreign productionplasticized the mixtures. Structural and rheotechnological parameters of powder-activated concretes were calculated.

From the obtained values of the conditional rheological criteria of powder-activated concretes, it follows that all of them are much greater than unity and characterize a significant excess of the volumes of rheological matriиces over the volumes of fine-grained, coarse-grained components that fit into them with large separation of particles and grains.

Strength as a complex mechanical characteristic, including a combination of strength, reliability and durability criteria, is the most important quality parameter of the concrete structure as an active and the most massive building material for structural purposes. A significant number of facilities made of concrete and reinforced concrete are being built in the southern and northern regions, characterized by extreme climatic conditions. Buildings and structures are exposed to cyclic loadings of various types and climatic influences, characterized by cyclic manifestations of negative and alternating temperatures. The research revealed high indicators of strength and frost resistance of decorative powder-activated concretes with a granular surface texture.

Keywords: decorative concrete, powder activation, composition selection, structural and rheotechnological indicators, strength, frost resistance

ПОРОШКОВО-АКТИВИРОВАНННЫЕ БЕТОНЫ С ЗЕРНИСТОЙ ФАКТУРОЙ ПОВЕРХНОСТИ

В.Т. Ерофеев [1]***, Н.И. Ватин*** [2]***, И.Н. Максимова*** [3]***, О.В. Тараканов*** [3]***, Я.А. Санягина*** [1]***,***
И.В. Ерофеева [4]***, О.В. Суздальцев*** [5]

[1] Национальный мордовский государственный университет им. Н. П. Огарева (МГУ им. Н. П. Огарева), г. Саранск, РОССИЯ
[2] Санкт-Петербургский политехнический университет им. Петра Великого, г. Санкт-Петербург, РОССИЯ
[3] Пензенский государственный университет архитектуры и строительства, г. Пенза, РОССИЯ
[4] Национальный исследовательский Московский государственный строительный университет, г. Москва, РОССИЯ
[5] ООО «Азия Цемент», г. Пенза, РОССИЯ

Аннотация. Показано, что в последние годы в отечественной и мировой практике широкое применение нашли самоуплотняющиеся бетонные смеси отличающиеся высокой удобоукладываемостью без применения вибрационного воздействия. С применением инновационных технологий могут быть изготовлены разнообразные материалы и изделия архитектурно-строительного назначения с улучшенными декоративными свойствами. Приведены результаты исследования по подбору составов декоративно-отделочных порошково-активированных бетонов зернистой фактурой поверхности по реологическим свойствам, показателям прочности и морозостойкости.

При проведении исследований в качестве вяжущего использовался египетский белый цемент, микронаполнителя – микрокварц, тонкодисперсного компонента – отсевы дробления гранита и купершлака фр. 0–0,63 мм, песка-заполнителя – гранитные высевки фр. 0,63–5 мм и купершлак фр. 0,63–2,5 мм. Смеси пластифицировались суперпластификаторами нового поколения отечественного и зарубежного производства. Рассчитаны структурные и реотехнологические показатели порошково-активированных бетонов.

Из полученных значений условных реологических критериев порошково-активированных бетонов следует, что все они значительно больше единицы и характеризуют существенное превышение объемов реологических матриц над объемами тонкозернистых, грубозернистых компонентов, которые вмещаются в них с большими раздвижками частиц и зерен.

Прочность как комплексная механическая характеристика, включающая сочетание критериев прочности, надежности и долговечности, является важнейшим параметром качества структуры бетона как активного и самого массового строительного материала конструкционного назначения. Здания и сооружения в условиях эксплуатации подвергаются циклическим механическим нагрузкам различного вида и климатическим воздействиям, характеризующимся циклическими проявлениями отрицательных и знакопеременных температур. В результате выполнения исследований выявлены высокие показатели прочности и морозостойкости декоративных порошково-активированных бетонов с зернистой фактурой поверхности.

Ключевые слова: декоративные бетоны, порошковая активация, подбор составов, структурные и реотехнологические показатели, прочность, морозостойкость

INTRODUCTION

In recent years, self-compacting concrete mixtures have been widely used. Such mixtures are characterized by high workability and do not require the use of vibration exposure [1, 2]. Modern construction is already impossible to imagine without it. Due to the unique rheological properties, such as good flowability, high resistance to delamination and effective air removal, self-compacting concrete is actively used primarily in those areas of construction where the use of vibration compacting is difficult. For example, it is relevant for work in residential areas where the requirements for sound insulation are stringent, as well as when forming products with high reinforcement density or complex geometry [3]. The production of self-compacting concrete mixtures is less expensive.

To date, it is relevant the studies aimed to obtaining construction materials and products with new properties, for example, ensuring environmental safety, expanding the use of additives that give surfaces special properties, etc. Among them, chemically resistant, biostable, self-cleaning decorative and other products and coatings are known [2]. One of the effective technologies for implementation in construction is also 3D printing, which is carried out by layer-by-layer extrusion in accordance with a given three-dimensional digital model [4].

The usage of innovative technologies allowsmanufacturing of various materials and products with improved decorative properties for architectural and construction purposes. Decorative concrete with a granular surface texture can be obtained using waste screenings from stone crushing quarries, which have accumulated more than 6 billion tons in the Russian Federation. These all allow obtaining fine aggregates and aggregate sand.

A large number of works [5] are devoted to the selection of concrete compositions with a rational binder consumption. In concretes of optimal structure, the cement paste not only covers the surface of the aggregate grains, but also fills the remaining voids between them. For this purpose, the principle of successive filling of voids is used. According to this principle, the grains of finer fractions fall into voids between coarse aggregate grains without causing its expansion. It is known that a decrease in the voidness between the grains of fine aggregate (sand) causes descending of the consumption of the binder, and the strength of the solution increases [6].

One of the most effective ways to control the rheological properties and aggregate stability of cement composites, including decorative ones, is the use of substances that have surface activity at the solid-solution interface. In the industry of construction materials, these additives are called as plasticizers and superplasticizers (SP). The introduction of plasticizing additives helps to increase the strength of cement stone by reducing the water-cement ratio [7].

As it follows from the basics of physical chemistry, a concrete mixture must contain a sufficient amount of a highly concentrated water-dispersed mixture (matrix), which can be converted from aggregation-unstable to aggregation-stable using a plasticizer. In this case, it is necessary to meet the basic rule: an increase in the volume of the dispersed phase should be provided without increasing the consumption of cement, but by adding powder filler in an amount of 40–70%, and in low-cement concrete - up to 90–100%. [8]. Such a high content of dispersed powder, for example, ground quartz sand, leads to increase the volume of the water-cement-mineral mixture and achievement of a high thinning effect of the superplasticizers. In this case, it is also necessary to take into account the limiting values of the volume concentration of the solid phase C_V :

$$C_V = \frac{V_{\mathrm{SP}}}{V_{\mathrm{SP}} + V_{\mathrm{W}}}, \qquad (1)$$

where V_{SP} – is thevolume of the solid phase (cement, ground sand, fine sand, aggregate sand, crushed stone); V_{W} – is the water volume.

Kalashnikov V.I. noted that an important task of choosing mineral additives as microfillers of cement concretes is to determine not only their rheotechnological activity in comparison with cement systems, but also their reactive activity in relation to cement systems in terms of binding hydrolytic lime released during cement hydration, and the possibility of formation of intergrowth contacts on defect-free surfaces of microcrystals formed on the surface of hydrated particles of cement and microfiller.

Structural strength as a complex mechanical characteristic is the most important parameter of the quality of the concrete structure as an active and most widespread construction material for structural purposes [9]. It includes a combination of strength, reliability and durability criteria.

Modern construction shows more pronounced the tendency to use high-strength materials, in particular concrete. Over the past decades, the strength of used ready-mixed concrete has increased 1.5 times in some countries. And there is a task to increase it up 2–3 times (to the level of 100–150 MPa) in the coming decades [9].

A significant number of construction projects are being built in the southern and northern regions, which have extreme natural and climatic conditions. Buildings and structures under operating conditions are subjected to cyclic mechanical loadings and climatic influences. For this conditions, special operational requirements are imposed on construction materials and products. For example, the durability of pavement and similar elements of transport communications and landscaping is mainly estimated by indicators of frost resistance and strength.

In the construction industry, decorative concretes are used in the manufacture of various building products [10, 11]. Based on this, complex studies on the formation of a dense and time-stable structure of decorative concretes under cyclic physical and mechanical impacts have a particular interest. As well know, it is also necessary to ensure the required workability of concrete mixtures in addition to the requirements of strength and frost resistance of hardened concrete. The workability is more consistent with powder-activated concrete.

Decorative powder-activated concrete is one of the most promising materials for use in the construction of buildings and structures of increased architectural expressiveness since it allows choosing a rational recipe composition.

The reason for the high strength of new generation concrete is not only the presence of a powder component. To enhance the action of the superplasticizer (SP) in new generation concretes (NGC), there should be fine-grained sand of 0.16–0.63 mm fraction, capable of being liquefied by plasticizers in an aqueous extract of cement paste.

One of the main quality criteria in assessing durability and service life without loss of strength and aesthetic characteristics of architectural and decorative concretes operating under atmospheric conditions is the frost resistance. A large number of studies in this field are devoted to the investigation of the resistance of concrete to the effects of frost in a water-saturated state and to increase their frost resistance [12]. Most researchers note that the fundamental reason for the frost destruction of cement concrete is the phase transition of water into ice, accompanied by an increase in its volume and the appearance of stresses in a rigid frame. The water to cement ratio significantly affects the porosity and frost resistance of concrete. At the same time, it was also found that finely ground additives introduced in an amount of up to 25–30% by weight of cement contribute to an increase the frost resistance of concrete due to better filling of voids between fine aggregate grains. In addition, a decrease in the specific consumption of cement per unit volume of concrete reduces the relative volume of cement stone and reduces internal stresses from unmanifested capillary shrinkage. Thereby, it increases the crack resistance of the concrete matrix and its frost resistance.

As a rule, the frost resistance grade of the old generation concretes does not exceed F 300–400, which is quite sufficient for the predicted high durability of concretes [13]. However, the period of operation before the disappearance of the decorative expressiveness of surfaces significantly reduced for architectural and decorative concretes in this case.

For hard operating conditions, the developed concretes must perceive more than 1000 cycles of alternating freeze-thaw. At the initial stage of selecting the composition of concrete, it is necessary to evaluate the rheotechnological properties of the components for their liquefaction using various superplasticizers, not only individual cement and mineral suspensions, but also their compositions.

In this regard, studies aimed to creation of construction materials with increased strength, density and high frost resistance are urgent. The task of the composition selectingwas not only to obtain high-strength concrete with a low water absorption value, but also to significantly increase frost resistance without the use of special air-entraining additives that increase the cost of concrete.

AIMS AND SCOPE OF THE RESEARCH

The present research aims to the selection of compositions of decorative and finishing powder-activated concretes with a granular surface texture according to rheological properties, strength and frost resistance indicators.

The tasks of the Research:

1. Analysis of the state of art in researches on concretes of a new generation with the allocation of structural and rheotechnological properties of powder-activated concretes.
2. Selection of the components for the formation of powder-activated concrete, considering cost minimization, providing the required view of the granular texture of the concrete surface, and ensuring high rheology of concrete mixtures based on the selected components.
3. Calculation of the structural and rheotechnological indicators of decorative and finishing powder-activated concrete and selection of the optimal compositions for technological properties.
4. Experimental studies of powder-activated concrete, depending on the type of superplasticizer and various fillers.
5. Determination of the volumes of various matrices, volumetric content of water-dispersed, water-dispersed-fine-grained and mortar components, relative excesses of volumes of conditional rheological matrices in decorative powder-activated concretes.

6. Experimental studies of powder-activated concrete strength and frost resistance, depending on the type of superplasticizer (SP) and fillers used.

MATERIALS AND METHODS

In these studies, the rheotechnological properties of cement composites of several types and several types of dispersed fillers in suspensions plasticized with plasticizers of various types were investigated at the first stage. And at the second stage, the strength and frost resistance of cement composites plasticized by superplasticizer such as Melflux-1641 were studied. The selection of components was carried out in regard with the combination of the following parameters: the cost of the components, providing the required view of the granular texture of the concrete surface, ensuring high rheology of concrete mixtures based on the selected components.

Fillers including those of the above type, were used as a finely dispersed component that increases the volume of the rheological matrix of the first row, which was microquartz from the Lebedinsky Mining and Processing Plant. And as filling components, that provide a granular surface texture, screenings of crushed granite of 0–5.0 mm fracture and cooper slag of 0–2.5 mm were adopted. The binder was Egyptian white cement (CEM 52.5). Materials of both domestic and foreign production were used as SP and GP, including Melflux 1641 and Khidetal γ-9.

We used a standard cone (GOST 10181–2014) to determine the rheotechnological parameters of the concrete mixture. The relevant regulatory documents (GOST 18105-2018; GOST 10060-2012) were used to determine the strength indicators and frost resistance of concrete.

Based on experiments, four most optimal compositions were proposed with optimized rheological matrices in terms of the content of cement, microquartz (ground sand), fine sand of 0.16–0.63 fracture and aggregate sand.

The studied compositions that differ in the type of superplasticizer and the quantitative content of filling components are given in [14]. In addition to mass contents, the volume content of the components, as well as the sediments of a standard cone, are indicated there.

The volumes of various matrices, the volume content of water-dispersed, water-dispersed fine-grained and mortar components in new generation concretes were calculated. These results are also in [15].The technology for calculating indicators is given below.

Frost resistance was determined according to GOST 10060-2012 “Concretes. Methods for determination of frost-resistance" according to the 3rd accelerated method, for which the samples are saturated with a 5% aqueous solution of sodium chloride. The tests were carried out in an independent laboratory of the production enterprise Penza Construction Department LLC in a freezer of the KTX-14 type at a temperature of minus 50 °C. The test mode was as follows: 8 hours of freezing, 16 hours of thawing.

CALCULATION OF STRUCTURAL AND RHEOTECHNOLOGICAL INDICATORS OF DECORATIVE AND FINISHING POWDER-ACTIVATED CONCRETE

The calculation of structural and rheotechnological indicators of decorative and finishing powder-activated concretes of a new generation, as well as relative excess volumes of conditional rheological matrices, was carried out using methods developed by V.I. Kalashnikov.

The volumes of various matrices, depending on their type, are calculated using the following formulas:

$$\text{I kind: } V_{\mathrm{I}} = V_{\mathrm{C}} + V_{\mathrm{P_M}} + V_{\mathrm{W}}; \quad (2)$$

$$\text{II kind: } V_{\mathrm{II}} = V_{\mathrm{I}} + V_{\mathrm{P_T}}; \quad (3)$$

$$\text{III kind: } V_{\mathrm{III}} = V_{\mathrm{II}} + V_{\mathrm{P_Z}}, \quad (4)$$

where V_{C} – isthe volume of cement per 1000 liters of concrete mix; $V_{\mathrm{P_M}}$ – is thevolume of microquartz (ground sand) per 1000 liters; V_{W} – is the water volume per 1000 liters; V_{P_T} – isthe volume of fine sand based on stone crushing screenings of granite stone and cooper slag of 0–0.63 mm fraction per 1000 liters; V_{P_Z} – isthe volume of aggregate sand based on a fraction of 0.63–2.5 mm per 1000 liters.

For comparison, the volumes of matrices in concrete of the old generation with the above composition can be calculated as follows:

$$\text{Ikind: } V_I = V_C + V_W ; \quad (5)$$

$$\text{III kind: } V_{III} = V_I + V_{P_T} . \quad (6)$$

Taking into account the established volumes, the volume content of water-dispersed, water-dispersed-fine-grained mortar suspension components in plasticized powder-activated concrete of a new generation is calculated. The calculation of the volume content of water-dispersed (C^V_{WD}), water-dispersed fine-grained ($C^V_{WDP_T}$) and solution ($C^V_{sol.}$) suspension components in plasticized powder-activated crushed stone concrete of a new generation is carried out according to the formulas:

$$C^V_{WD} = \frac{V_C + V_{P_M} + V_W}{V_{conc.mix}} \cdot 100\% ; \quad (7)$$

$$C^V_{WDP_T} = \frac{V_C + V_{P_M} + V_W + V_{P_T}}{V_{conc.mix}} \cdot 100\% ; \quad (8)$$

$$C^V_{sol.} == \frac{V_C + V_{P_M} + V_W + V_{P_T} + V_{P_Z}}{V_{conc.mix}} \cdot 100\% . \quad (9)$$

The limits of volume concentrations of the studied concrete mixes are: C^V_{WD} varies from 39.91 to 43.94%, $C^V_{WDP_T}$ varies from 63.85 to 66.19% and for $C^V_{sol.}$ from 99.61 to 99.76%.

Only one composition in self-compacting mixtures has the volume concentration of a water-dispersed suspension less than 40%. Moreover, even in those mixtures, the rigid consistency of which is associated with a change in the content of the filler, the volume concentration of the water-dispersed suspension is more than 60%. Concrete mixtures of optimal composition have an equal volume concentration of the mortar component (over 60%). This is the fundamental difference between the developed concretes and traditional ones, in which the volumetric concentrations C^V_{WD} and $C^V_{sol.}$ are in the range of 24–26% and 54–57%, respectively.

For the topological analysis of all types of new concretes, developed and traditional concretes of the old generation, it is effective to use dimensionless rheological criteria. For powder concrete, the first criterion is the relative excess of the volume of the conditional rheological matrix of the I kind $I^{WD}_{P_T}$, i.e., relative excess of the volume of the water-dispersed system V_{WD} over the absolute volume of fine sand V_{P_T} . It is calculated by the following formula:

$$I^{WD}_{P_T} = V_{WD} / V_{P_T} = \left(V_C + V_{P_M} + V_W\right) / V_{P_T} , \quad (10)$$

where V_C , V_{P_M} , V_W , V_{P_T} – areabsolute volumes of cement, ground sand, water, fine sand, respectively.

There are two rheological matrices in powder-activated sandy concretes of the new generation: a water-dispersed matrix of the I kind and a water-dispersed fine-grained matrix of the II kind, including cement, microquartz (ground sand), fine sand and water. Fine sand in this matrix participates in the rheological process, providing the displacement of aggregate sand grains in the matrix of the I kind. The latter one is located discretely in a matrix of the II kind, ensuring the fluidity of the system without steric obstacles. The relative excess of the volume of the rheological matrix of the II kind over the absolute volume of aggregate sand is calculated by the formula:

$$I^{WDP_T}_{P_Z} = V_{WDP_T} / V_{P_Z} = \left(V_C + V_{P_M} + V_W + V_{P_T}\right) / V_{P_Z} , \quad (11)$$

where V_{C}, $V_{\mathrm{P_M}}$, V_{W}, $V_{\mathrm{P_T}}$, $V_{\mathrm{P_Z}}$ – are absolute volumes of cement, ground sand, water, fine sand, aggregate sand, respectively.

The excess rheological matrix of the II kind also provides the necessary distances between the aggregate sand grains. For narrow granulometry of sand, the theoretical calculation of distances can be close to the real one. For a wider granulometry, a distribution curve of the granulometric composition should be constructed, and then the distances between grains in narrow fractions can be calculated. Topological patterns of particle placement in narrow fractions are then combined into a single topological pattern with the free space maximization algorithm. This approach belongs to the problems of computer materials science, which can be useful for studying the topology of new generation concretes and optimizing the granulometric composition of components.

For concretes of the old generation, these criteria may not be excess volumes of rheological matrices over the volumes of sand and crushed stone, but shortcomings. They are calculated according to the formulas:

$$I_{\mathrm{P_Z}}^{\mathrm{CD}} = V_{\mathrm{CD}} / V_{\mathrm{P_Z}} = \left(V_{\mathrm{C}} + V_{\mathrm{W}}\right) / V_{\mathrm{P_Z}}, \qquad (12)$$

$$I_{\mathrm{SH}}^{\mathrm{CDP}} = V_{\mathrm{CDP}} / V_{\mathrm{SH}} = \left(V_{\mathrm{C}} + V_{\mathrm{W}} + V_{\mathrm{P_Z}}\right) / V_{\mathrm{SH}}. \qquad (13)$$

ANALYSIS OF EXPERIMENTAL RESULTS

From the point of view of rheotechnological indicators, all compositions showed a fairly high quality as follows from the results of the study. According to the calculated values of conditional rheological matrices of the I and II kind, compositions 2 and 1 seem to be the most qualitative, compositions 4 and 3 are slightly less qualitative. Compositions 2 and 1 are self-compacting concretes with a cone draft of 27.4 and 28.5 cm, which corresponds to the American SF2 standard. There is a regularity in achieving close values of conditional rheological matrices ($I_{\mathrm{P_T}}^{\mathrm{WD}}$, $I_{\mathrm{P_Z}}^{\mathrm{WDP_T}}$), equal to 1.67–1.97 and 1.78–1.98, respectively. Thus, the volume content of the water-dispersed-fine-grained suspension component ($C_{\mathrm{WDP_T}}^{V}$) for self-compacting powder-activated sand concrete should be in the range of 60–70%. The self-flowing can be ensured only at a high content of water-dispersed-fine-grained suspension.

The difference between compositions 2 and 1 is that the composition 1contains the increased volume of the conditional rheological matrix of the I kind due to a larger amount of microquartz (300 kg/m^3) relative to composition 2 (200 kg/m^3). While maintaining the sum of the masses of all components in composition 2, a part of microquartz is replaced by screening of stone crushing for greater saturation with granular components of the concrete mix and providing the most complete visual picture of the surface. As a result of this, rheotechnological, physical and technical indicators fall very slightly (see tables 1, 2). At the same time, in such self-compacting concrete mixtures, it is important to ensure aggregative stability and prevent sedimentation of particles.

As can be seen from the values of the conditional rheological criteria of powder-activated concretes, all of these values are much greater than unity and characterize a significant excess of the volumes of rheological matrices over the volumes of fine-grained, coarse-grained components that fit into them with large separation of particles and grains.

The physical and technical properties of powder-activated concretes of four compositions were studied. Indicators of compressive and bending strength and complex indicators for evaluating the effectiveness of materials of 4 compositions were obtained from testing of standard samples.

To assess the economic indicators of individual compositions, we determine the specific consumption of cement per unit of compressive and flexural strength as follows:

$$C_{\mathrm{R_c}}^{\mathrm{S}} = \frac{C}{R_{\mathrm{c}}}, \ kg/MPa, \qquad (14)$$

$$C_{R_{\mathrm{b}}}^{\mathrm{S}} = \frac{C}{R_{\mathrm{b}}}, \ kg/MPa. \qquad (15)$$

The specific strength per unit of cement consumption was determined by the formulas:

$$R^{\mathrm{S}}_{CR_{\mathrm{c}}}=\frac{R_{\mathrm{c}}}{C},\ MPa/kg;\quad R^{\mathrm{S}}_{CR_{\mathrm{b}}}=\frac{R_{\mathrm{b}}}{C},\ MPa/kg. \quad (16)$$

The ratio of strength indicators in compression and bending was also determined as follows:

$$K=R_{\mathrm{c}}/R_{\mathrm{b}}. \quad (17)$$

According to the data from [15] it follows that composition No. 3 [15] has improved performance. The table 1 presents the results of comprehensive studies of the properties of concrete, taking into account the data from table 3 in [15].

Table 1. Properties of decorative powder-activated sand concretes

Components	Disperse-fractional composition	Per 1 m^3, *kg*	Volum eper 1 m^3, l	*W*/*C*, *W*/*T*	*P*, *kg*/*m*^{3}	$\frac{P_{\mathrm{M}}}{C}$	$\frac{P_{\mathrm{T}}}{C}$	$\frac{P_{\mathrm{Z}}}{C}$	Strength *MPa*, at days	
									1	28
1	2	3	4	5	6	7	8	9	10	11
Cement 600 DO Egyptian	3800 cm^2/g	500	161	0,4	P_w1 days 2415	0,4	1,4	2,1 1	R_{c}=37 R_{b}= 6,1	R_{c}=90 R_{b}= 11
Melflux 1641 0,9 % ofC	—	4,5	3			$\frac{\Sigma P}{C}=3,916$			$C^{\mathrm{s}}_{R_{\mathrm{c}}}=5,55$	
Microquartz	3400 cm^2/g	200	75,5	0,081	P_{theor} 2434	$I^{\mathrm{WD}}_{\mathrm{P_T}}=1,67$			$R^{\mathrm{s}}_{CR_{\mathrm{c}}}=0,18$	
Screening stone crushing granite	0-0,63 mm	450	165			$I^{\mathrm{WDT}}_{\mathrm{P_Z}}=1,78$			$C^{\mathrm{s}}_{R_{\mathrm{b}}}=45,4$	
	0,63-5,0 mm	930	344		K_{seal} 0,992	$V_{\mathrm{WD}}=436,5$ $V_{\mathrm{WDP_T}}=698,4$ $V_{\mathrm{sol.}}=1090,8$			$R_{\mathrm{c}}/R_{\mathrm{b}}=8,18$	
Cooperslag	0-0,63 mm	252	96,9	CS_{sm}=11*cm*		$C^V_{\mathrm{WD}}=39,91\ \%$ $C^V_{\mathrm{WDP_T}}=63,85\ \%$ $C^V_{\mathrm{sol.}}=99,73\ \%$				
	0,63-2,5 mm	126	48,4							
$\sum M_{\mathrm{dry}}$ $\sum V_{\mathrm{dry}}$ Water	—	2464 — 200	— 894,4 200							
$M_{\mathrm{conc.mix}}$		2664	—							
$V_{\mathrm{conc.mix}}$		—	1094							

We calculated the dimensionless parameters of raw components' ratios and criteria of conditional rheological matrices, which have the following values: $\mathrm{P}/\mathrm{C} = 3,55$; $R_{\mathrm{C}}^{\mathrm{s}} = 0,418$ MPa/kg; $I_{\mathrm{P_T}}^{\mathrm{WD}} = 1,67$; $I_{\mathrm{P_Z}}^{\mathrm{CDP}} = 1,78$.

It should be noted that a change in these criteria in the direction of a slight decrease or increase leads to a decrease in strength indicators by 10–20%. It is important that an extremely low specific consumption of cement per unit of concrete strength in compression ($C_{R_c}^{s}$ = 5.55 *kg / MPa*) and tension in bending ($C_{R_b}^{s}$ = 45.4 *kg / M*Pa) has been achieved. Strength ratio of indicators is $R_b/R_c = 0.112$.

The supposed correctness of the forecast of high frost resistance depending on the kinetics of water absorption was accounted. It was less than 1.5% by weight after four days of exposure. After two weeks of testing, this value was 1.98% and exceeded the 4-day water absorption by approximately 25–28%. That is, such a kinetics of water absorption for a sufficiently long time causes a large number of free pores which remain after water saturation of concrete for four days before testing for frost resistance. It is known that the volume of water increases by 9.6% at freezing. Thus, it can be safely predicted that an almost threefold excess of the volume of free pores over the increment in the volume of water when it passes into ice contributes to extremely high frost resistance.

The results of the experiment showed that after 1000 cycles of alternating freezing and thawing the weight of the samples decreased by an average of 0.7%. At the same time, there were no obvious signs of external destruction such as chipping of the corners of the samples, peeling of the surface, which shows the presence just of minimal destructive processes in the concrete structure and a slight change in strength. Besides, this result guarantees the preservation of the visual architectural appeal of the concrete surface over a long period of operation under the influence of harsh environmental factors.

After 1000 cycles of alternating freeze-thaw, the samples were tested for strength. The standard compressive strength of the test concrete after 28 days of hardening in normal humidity conditions was 85 MPa. By the end of the test, the samples stored in saline had a strength of 92 MPa. In this case, the samples that were tested had a strength of 90 MPa (after 1000 freeze-thaw cycles). That is, the loss of strength was slightly more than 2%, which is within the experimental error and meets the requirements of GOST.

Thus, the composition of architectural and decorative concrete proposed for implementation corresponds to the required properties in terms of strength and frost resistance. The results provide a basis for setting the limit levels of loads on concrete of various coatings, as well as for establishing requirements for the properties of concrete when designing it for operating conditions.

CONCLUSIONS

1. In recent years, self-compacting concrete mixtures have been widely used. Such mixtures are characterized by high workability without the usage of vibration compacting. Using innovative technologies, various materials and products for architectural and construction purposes with improved decorative properties can be manufactured.
2. According to physical chemistry, it follows necessity for the concrete mixture to have a sufficient amount of highly concentrated water-dispersed mixture (matrix), which can be converted from aggregation-unstable to aggregation-stable with the help of a plasticizer. In this case, it is required to stay the basic rule: an increase in the volume of the dispersed phase is provided without increasing the consumption of cement, but by adding powder filler in an amount of 40–70%, and in low-cement concrete - up to 90–100%.
3. The studies have been performed to select the compositions of decorative and finishing concretes with a granular surface texture according to rheological properties. Egyptian white cement served as a binder, micro-quartz as a microfiller, and screenings of crushed granite and cooper-slag of 0–0.63 mm fraction and the same components as filler sand of 0.63–5.0 mm and 0.63–2.5 mm fractions. The new generation su-

perplasticizers plasticized the mixture. At the initial stage of selecting the concrete composition, it is necessary to evaluate the rheotechnological properties of the components for their liquefaction using various superplasticizers, not only individual cement and mineral suspensions, but also their compositions.

4. The paper provides determined in the study structural and rheotechnological indicators of powder-activated concretes such as volumes of various matrices, volumetric contents of water-dispersed, water-dispersed-fine-grained and mortar components, relative excesses of volumes of conditional rheological matrices in decorative powder-activated concretes.

5. The research results shows that all compositions showed a fairly high quality in terms of rheotechnological indicators. According to the calculated values of conditional rheological matrices of the I and II kind, compositions 2 and 1 seem to be the most qualitative, compositions 4 and 3 are slightly less qualitative. Compositions 2 and 1 are self-compacting concretes with a cone draft of 27.4 and 28.5 cm, which corresponds to the American SF2 standard. There is a regularity in achieving close values of conditional rheological matrices ($I_{\mathrm{P_T}}^{\mathrm{WD}}$, $I_{\mathrm{P_Z}}^{\mathrm{WDP_T}}$), equal to 1.67–1.97 and 1.78–1.98, respectively. Thus, the volume content of the water-dispersed-fine-grained suspension component ($C_{\mathrm{WDP_T}}^{V}$) for self-compacting powder-activated sand concrete should be in the range of 60–70%. Only a high content of water-dispersed-fine-grained suspension ensure absolute self-flowing.

6. The difference between compositions 2 and 1 is that in composition 1, the volume of the conditional rheological matrix of the I kind increases due to a larger amount of microquartz (300 kg/m^3) relative to composition 2 (200 kg/m^3). While maintaining the sum of the masses of all components in composition 2, part of the microquartz is replaced by screening of stone crushing for greater saturation with the granular components of the concrete mixture and ensuring the most complete visual picture of the surface (while the sum of the masses of all components is preserved). This leads to a slight decrease in rheotechnological and physical and technical indicators. It is essential to ensure aggregative stability and prevent particle sedimentation in such self-compacting concrete mixtures.

7. All values of the conditional rheological criteria of powder-activated concretes are significantly greater than one and characterize a significant excess of the volumes of rheological matrices over the volumes of fine-grained, coarse-grained components that fit into them with large separation of particles and grains.

8. The second stage included studies of the strength and frost resistance of concrete. As a result of testing for strength and frost resistance, high rates of these properties were revealed for decorative concretes.

9. The reason for the high strength of new generation concrete is not only the presence of a powder component. New generation concrete should contain fine-grained sand of a fraction of 0.16–0.63 mm capable of being liquefied by plasticizers in an aqueous extract of cement paste to enhance the action of the SP.

10. The results of the experiment showed that the weight of the samples decreased by an average of 0.7% after 1000 cycles of alternate freezing and thawing. At the same time, there were no obvious signs of external destruction, which allows us to assume the presence of minimal destructive processes in the concrete structure and a slight change in strength. Besides, this result guarantees the preservation of the visual architectural appeal of the concrete surface over a long period of operation under the influence of harsh environmental factors.

11. The samples were tested for strength after 1000 cycles of alternate freezing-thawing. The characteristic compressive strength of the test concrete after 28 days of hardening under normal humidity conditions was 85 MPa. The samples stored in saline had a strength of 92 MPa. In this case, the samples that were tested had a strength of 90 MPa (after 1000 freeze-thaw cycles). That is, the loss of strength was slightly more than 2%, which is within the experimental error and meets the requirements of GOST.

12. Thus, the composition of architectural and decorative concrete developed and proposed for

implementation corresponds to the properties in terms of strength and frost resistance. The obtained results allow setting the limit levels of loads on concrete of various coatings, as well as establishing the requirements and properties of concrete for designing with regard to operating conditions.

REFERENCIES

1. Intelligent dynamic concrete / B. Barragan, X. Roncero, R. Magarotto [et al.] // CP1 Int. Concrete production. 2011. № 2. P. 58–67.
2. **Kalashnikov V.I., Erofeev V.T., Tarakanov O.V.** Suspenzionno-napolnennye betonnye smesi dlya poroshkovo-aktivirovannyh betonov novogo pokoleniya [Technical and economic efficiency of the implementation of architectural and decorative powder-activated carbonate sand concrete] // Izvestija vuzov. Stroitel'stvo. 2016. No. 6 (690). pp. 39–46 (In Russian).
3. **Volpi E., Foiadelli C., Trasatti S.** Development of Smart Corrosion Inhibitors for Reinforced Concrete Structures Exposed to a Microbial Environment // Industrial and Engineering Chemistry Research. Volume 56, Issue 20, 24 May 2017, pp. 5778-5794. DOI: 10.1021/acs.iecr.7b00127.
4. **Mukhametrakhimov R.** Influence of the technological properties of cement-sand mortar on the quality of 3D printed products / R. Mukhametrakhimov, L. Lukmanova // IOP Conference Series: Materials Science and Engineering. 2020. Vol. 890. P. 012082.
5. **Jonkers H.M. and Schlangen E.** Development of a bacteria-based self-healing concrete // Tailor Made Concrete Structures – New Solution for Society. 2008. pp. 425–30.
6. **Zhang G.D., Zhang X.Z., Zhou Z.H., Cheng X.** Preparation and properties of concrete containing iron tailings manufactured sand as fine aggregate // Advanced Materials Research. 2014. Vol. 838-841 P. 152–155. DOI: 10.4028/www.scientific.net/AMR.838-841.152.
7. Study of effects of redispersable latex powders on hardening kinetics of cement-sand composites / A.A. Bobrishev, L.N. Shafigullin, V.T. Erofeev, (...), M.I. Sotnikov, Vyacheslav A. // Research Journal of Pharmaceutical, Biological and Chemical Sciences, 2016.7(4). pp. 795–802.
8. **Senhadji Y., Escadeillas G., Mouli M., Khelafi H.** Benosman Influence of natural pozzolan, silica fume and limestone on strength, acid resistance and microstructure of mortar // Powder Technology. 2014. Vol. 254. pp. 314–323. DOI: 10.1016/j.powtec.2014.01.046.
9. **Kalashnikov V.I.** Selecting the type of control setting composite cement-ash binder / V.I. Kalashnikov, E.A. Belyakova, R.N. Moskvin // Procedia Engineering. 2016. Vol. 150. P. 1631–1635. Doi:10.1016/j.proeng.2016.07.143.
10. **Resner O.** New opportunities in the field of design of architectural facades / O. Resner// Intern. Concreteproduction. 2013. No. 6. pp. 152–155.
11. Visualization of photos and graphics on a concrete surface / Reckli Gmbh, 44268, Herne, Germany // Intern. concrete.pr-in. 2014. No. 3. P. 173.
12. **Jiang G., Keller J., Bond P.L.** Determining the long-term effects of H_2S concentration, relative humidity and air temperature on concrete sewer corrosion // Water Research. 2014. Vol. 65. P. 157–169. DOI: 10.1016/j.watres.2014.07.026.
13. Density of structure and extent of saturation by water of composites as a factor of change of their durability when freezing and thawing / Y.V. Trofimovich, F.A. Petrovich, N.P. Ignatyevich, (...), L.V. Stanislavovich, R.V. Ivanovich // International Journal of Applied Engineering Research, 2015, 10(10), pp. 25711–25720.
14. **Erofeev V. T., Sanyagina Ya. A., Erofeeva I. V., Maksimova I. N.** Podbor sostavov dekorativno-otdelochnyh poroshkovo-aktivirovannyh betonov s zernistoj fakturoj poverhnosti po reologicheskim

svojstvam [The selection of compositions of the decorative and finishing powder-activated concrete with a granular surface texture according to the rheological properties]. // Regional'naya arhitektura i stroitel'stvo. – 2022. – № 3 (52).– pp. 16–31 (In Russian).

15. **Erofeev V.T., Sanyagina Ya. A., Erofeeva I.V., Maksimova I.N.** Prochnost' i morozostojkost' dekorativno-otdelochnyh poroshkovo-aktivirovannyh betonov s zernistoj fakturoj poverhnosti [The durability and frost resistance of the decorative and finishing powder-activated concrete with a granular surface texture]. // Regional'naya arhitektura i stroitel'stvo. – 2022. – № 3 (52). – pp. 32–45 (In Russian).

СПИСОК ЛИТЕРАТУРЫ

1. Intelligent dynamic concrete / B. Barragan, X. Roncero, R. Magarotto [et al.] // CP1 Int. Concrete production. 2011. № 2. P. 58–67.
2. **Калашников В. И.** Суспензионно-наполненные бетонные смеси для порошково-активированных бетонов нового поколения / В. И. Калашников, В. Т. Ерофеев, О. В. Тараканов // Изв. вузов. Стр-во. – 2016. – № 4. – С. 38–37.
3. **Volpi E., Foiadelli C., Trasatti S.** Development of Smart Corrosion Inhibitors for Reinforced Concrete Structures Exposed to a Microbial Environment // Industrial and Engineering Chemistry Research. Volume 56, Issue 20, 24 May 2017, pp. 5778-5794. DOI: 10.1021/acs.iecr.7b00127.
4. **Mukhametrakhimov R.** Influence of the technological properties of cement-sand mortar on the quality of 3D printed products / R. Mukhametrakhimov, L. Lukmanova // IOP Conference Series: Materials Science and Engineering. 2020. Vol. 890. P. 012082.
5. **Jonkers H.M. and Schlangen E.** Development of a bacteria-based self-healing concrete // Tailor Made Concrete Structures – New Solution for Society. 2008. P. 425–30.
6. **Zhang G.D., Zhang X.Z., Zhou Z.H., Cheng X.** Preparation and properties of concrete containing iron tailings manufactured sand as fine aggregate // Advanced Materials Research. 2014. Vol. 838-841 pp. 152–155. DOI: 10.4028/www.scientific.net/AMR.838-841.152.
7. Study of effects of redispersable latex powders on hardening kinetics of cement-sand composites / A.A. Bobrishev, L.N. Shafigullin, V.T. Erofeev, (...), M.I. Sotnikov, Vyacheslav A. // Research Journal of Pharmaceutical, Biological and Chemical Sciences, 2016.7(4). pp. 795–802.
8. **Senhadji Y., Escadeillas G., Mouli M., Khelafi H.** Benosman Influence of natural pozzolan, silica fume and limestone on strength, acid resistance and microstructure of mortar // Powder Technology. 2014. Vol. 254. pp. 314–323. DOI: 10.1016/j.powtec.2014.01.046.
9. **Kalashnikov V.I.** Selecting the type of control setting composite cement-ash binder / V.I. Kalashnikov, E.A. Belyakova, R.N. Moskvin // Procedia Engineering. 2016. Vol. 150. pp. 1631–1635. Doi:10.1016/j.proeng.2016.07.143.
10. **Resner O.** New opportunities in the field of design of architectural facades / O. Resner// Intern. Concreteproduction. 2013. No. 6. pp. 152–155.
11. Visualization of photos and graphics on a concrete surface / Reckli Gmbh, 44268, Herne, Germany // Intern. concrete.pr-in. 2014. No. 3. P. 173.
12. **Jiang G., Keller J., Bond P.L.** Determining the long-term effects of H_2S concentration, relative humidity and air temperature on concrete sewer corrosion // Water Research. 2014. Vol. 65. P. 157–169. DOI: 10.1016/j.watres.2014.07.026.
13. Density of structure and extent of saturation by water of composites as a factor of change of their durability when freezing and thawing / Y.V. Trofimovich, F.A. Pe-

trovich, N.P. Ignatyevich, (...), L.V. Stanislavovich, R.V. Ivanovich // International Journal of Applied Engineering Research, 2015, 10(10), P. 25711–25720.

14. **Ерофеев В. Т., Санягина Я. А., Ерофеева И. В., Максимова И. Н.** Подбор составов декоративно-отделочных порошково-активированных бетонов с зернистой фактурой поверхности по реологическим свойствам // Региональная архитектура и строительство. 2022. № 3 (52). С. 16–31.
15. **Ерофеев В. Т., Санягина Я. А., Ерофеева И. В., Максимова И. Н.** Прочность и морозостойкость декоративно-отделочных порошково-активированных бетонов с зернистой фактурой поверхности // Региональная архитектура и строительство. 2022. № 3 (52). С. 32–45.

Vladimir T. Erofeev, Academician of the RAACS, Professor, Doctor of Technical Sciences, Director of the Institute of Architecture and Construction, National Research Mordovian State University name N.P. Ogaryov; 430005, Republic of Mordovia, Saransk, st. Bolshevik, d. 68; tel. +7(8342) 48-25-64; E-mail: erofeevvt@bk.ru.

Nikolai I. Vatin, Professor, Doctor of Technical Sciences, Chief Researcher, St. Petersburg Polytechnic University name Peter the Great; 109992, Moscow, st. Solyanka, 14; E-mail: vatin_ni@spbstu.ru

Irina N. Maksimova, Associate Professor, Candidate of Technical Sciences, Associate Professor of the Department of Quality Management and Technology of Construction Production, Penza State University of Architecture and Construction; tel. +7(903) 324-95-02; E-mail: maksimovain@mail.ru.

Oleg V. Tarakanov, Professor, Doctor of Technical Sciences, Dean of the Faculty of Territory Management, Penza State University of Architecture and Construction; tel. +7 (927) 384-72-64; E-mail: tarov60@mail.ru.

Yana A. Sanyagina, Competitor of the Department of Building Materials and Technologies, National Research Mordovian State University name N.P. Ogaryov; 430005, Republic of Mordovia, Saransk, st. Bolshevik, d. 68; E-mail: sanyagina@mail.ru.

Irina V. Erofeeva, Candidate of Technical Sciences, Senior Lecturer of the Department "Fundamentals of Architecture and Artistic Communications", National Research Moscow State University of Civil Engineering; 129337, Moscow, Yaroslavl highway, 26; E-mail: ira.erofeeva.90@mail.ru.

Oleg V. Suzdaltsev, Candidate of Technical Sciences, Head of the Concrete Technology Department, Asia Cement LLC; 440000, Penza, st. Bakunin/Plekhanova d.20"B"/34; E-mail: spartak88ru@mail.ru.

Ерофеев Владимир Трофимович, академик РААСН, профессор, доктор технических наук, директор Института архитектуры и строительства, Национальный исследовательский Мордовский государственный университет им. Н.П. Огарёва; 430005, Республика Мордовия, г. Саранск, ул. Большевистская, д. 68; тел. +7(8342) 48-25-64; E-mail: erofeevvt@bk.ru.

Ватин Николай Иванович, профессор, доктор технических наук, главный научный сотрудник, Санкт-Петербургский политехнический университет им. Петра Великого; 109992, г. Москва, ул. Солянка, д. 14; E-mail: vatin_ni@spbstu.ru.

Максимова Ирина Николаевна, доцент, кандидат технических наук, доцент кафедры «Управление качеством и технология строительного производства», Пензенский государственный университет архитектуры и строительства; тел. +7(903) 324-95-02; E-mail: maksimovain@mail.ru.

Тараканов Олег Вячеславович, профессор, доктор технических наук, декан факультета Управления территориями, Пензенский государственный университет архитектуры и строительства; тел. +7 (927) 384-72-64; E-mail: tarov60@mail.ru.

Санягина Яна Андреевна, соискатель кафедры «Строительные материалы и технологии», Национальный исследовательский Мордовский государственный университет им. Н.П. Огарёва; 430005, Республика Мордовия, г. Саранск, ул. Большевистская, д. 68; E-mail: sanyagina@mail.ru.

Ерофеева Ирина Владимировна, кандидат технических наук, старший преподаватель кафедры «Основы архитектуры и художественных коммуникаций», Национальный исследовательский Московский государственный строительный университет; 129337, г. Москва, Ярославское шоссе, д. 26; E-mail: ira.erofeeva.90@mail.ru.

Суздальцев Олег Владимирович, кандидат технических наук, начальник отдела технологии бетонов, ООО «Азия Цемент»; 440000, г. Пенза, ул. Бакунина/Плеханова д.20«Б»/34; E-mail: spartak88ru@mail.ru