High-performance concrete in road pavement construction

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ABSTRACT This paper describes that concrete physical and mechanical properties such as density, crack resistance, durability and reliability can be improved with introducing a high-performance chemical additive based on polycarboxylate polymers modified with electrolytes based on group I metal cations of the main subgroup in D.I. Mendeleev's table. These high mobility polymers facilitate their diffusion ability. It is recommended to use silicon hydroxide nanoparticle dispersion as an additional component as they have such unique properties as increased reactivity.

The superplasticity and reactivity of the complex chemical additive under study proved to increase cement hydration process and enhance the formation of new hydrate phases, which contributed to a greater bending tensile strength and chemical resistance of concrete. The use of this complex chemical additive increased the compressive strength by more than 41 % and the bending tensile strength by 56 %, which contributed to concrete crack resistance.

Concrete water resistance was proved to increase by 75 % and corresponded to W14 class while concrete frost resistance increased by 70 % to the value of F2500, and chemical resistance increased by 16 % to the value Kx.s. l 0.93. According to GOST 58895-2020, this advanced concrete corresponds to the concrete with increased chemical resistance.

According to the test results of physical and mechanical properties, concrete with this complex chemical additive is recommended to use in federal highway pavement construction.

KEYWORDS: concrete; strength; crack resistance; corrosion resistance; water absorption; frost resistance; durability; chemical additives; polycarboxylates; nanoparticle dispersion; silicon dioxide


Научная статья

Высокоэффективный бетон для дорожных покрытий

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АННОТАЦИЯ Показано, что уровень основных физико-механических свойств бетона — плотность, устойчивость к трещинообразованию, долговечность и надежность можно улучшить использованием высокоэффективной комплексной химической добавки на основе поликарбоксилатных полимеров, модифицированных электролитами на основе катионов металлов I группы главной подгруппы таблицы Д.И. Менделеева, обладающих повышенной подвижностью и, как следствие, диффузионной способностью, а также эффективно использовать в качестве дополнительного компонента добавки нанодисперсии гидроксида кремния, которые отличаются уникальными свойствами, а именно повышенной реакционной активностью.

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INTRODUCTION

High-performance concretes (with increased crack resistance, density, water resistance, frost resistance and corrosion resistance) are highly demanded in modern construction, both domestic and foreign, for a wide range of products and structures.

In road construction, especially in the construction of federal highways with a high traffic flow, concrete is preferable as it is more durable than asphalt [1–3].

The traffic density including multi-tonnage traffic is constantly increasing, which leads to increased requirements for the road pavement quality.

Road surfaces are not protected from various negative effects such as increased mechanical stresses, temperature changes from negative to positive in different seasons, precipitations and aggressive salt solutions used in anti-icing mixtures, which require highly reliable and ecologically friendly materials not to have a negative impact on the environment [4–6].

Cement-based concrete can meet these requirements to the greatest extent as its properties can be modified and advanced. In world practice, concrete is being used increasingly for road pavements providing better reliability and durability due to the formation of such properties as:

- enhanced compressive and bending tensile strengths so as to increase crack resistance;
- enhanced hardness so as the riding quality is not affected and the pavement is not deformed under the wheels of multi-tonnage vehicles;
- enhanced density to prevent the penetration of excess moisture and aggressive salt solutions inside, thus improving the concrete water and frost resistance and durability [7–10].

Studies on concrete hardening process have shown that these specified properties can be generated by activating certain chemical processes occurring during concrete mixture hardening.

The number and composition of the generated complex hydrate compounds as well as bonding concrete mix components with the formation of hydrate phases due to generating new chemical bonds have an important impact on the formation of these properties.

In a traditional concrete mixture, cement is a reactive component forming certain complex hydrate compounds as a result of thermal or chemical processes. Stress-strain properties and the structure of the hardened concrete largely depend on these hydrate formations.

MATERIALS AND METHODS

This scientific research describes the concrete with improved properties. During the scientific experiment, B30-class concrete was used. It consisted of PC 500-D0 Portland cement produced at JSC “Pikalevsky cement” according to GOST 10178-85:

- grade (MPa) — 50.0;
- cement average activity in steaming (MPa) — 40.8;
- standard density of cement paste (%) — 25.75;
- soundness (expansion) is standard;
- GOST 8736-2014 construction sand with particle modulus size Mk = 2.6, medium-size, dust and clay particles content is 0.8–1.0 %, bulk density is 1550 kg/m³;
- GOST 8267-93 crushed granite fractions of 5–20 mm. The following amount of basic materials per 1 m³ of concrete mix were used:
  - 500-D0 PC Portland cement 410 kg/m³;
  - sand of Mk = 2.6 770 kg/m³;
  - crushed stone fractions (5–20) mm 1000 kg/m³.
All the investigated mixtures had the same fluidity corresponding to P2 fluidity grade (cone slump was 5–9 cm) according to GOST 7473-2010 “Concrete mixtures. Technical conditions”.

The control concrete mixture and the tested concrete mixture with a complex chemical additive were subjected to the following stress-strain tests.

- Tests for compressive and bending tensile strengths were carried out in accordance with GOST 10180-2012. Four 100 × 100 × 100-mm sample cubes and three 100 × 100 × 400-mm sample prisms were made for the experiment. The samples were hardened under standard conditions in accordance with GOST 10180-2020, paragraph 4.3 (with the temperature of 20 ± 2 °C and relative humidity of 95 ± 5 %).
- Water permeability was tested according to GOST 12730.5-2018 “Concrete. Water Resistance Test Methods”. For testing, six 150-mm-diameter and 150-mm-height sample cylinders were made and placed in the standard curing conditions for 28 days. For the water penetration test, the samples were placed under the highest water pressure for a period of 16 hours. At least four of the six concrete samples showed resistance against penetration of water.
- Concrete frost resistance was tested by the third accelerated method according to GOST 10090-2012. The samples were pre-saturated and thawed in a 5 % NaCl solution and frozen at the temperature of −50 °C. For the frost resistance test, twelve 100 × 100 × 100-mm cubes were prepared and placed under standard curing conditions for 28 days.
- Concrete abrasion resistance test was carried out according to GOST 13087-2018 “Test Methods for Abrasion”. For testing, two cubes with 70-mm ribs were made. Pre-hardening of the samples to the design age (28 days) was carried out under standard conditions.
- Concrete chemical resistance was tested in accordance with GOST R 58896-2020 “Chemically resistant concretes. Test methods”.
- For testing, three 40 × 40 × 160-mm sample beams were made for each test period of a comparative strength assessment.

As an aggressive medium, a 5 % MgCl₂ solution was used and the tests were carried out every 30 days for 360 days.

In order to ensure good workability, various lyophilic additives were used in a concrete mixture. In our opinion, the most effective ones were polycarboxylate-based surfactants (SAA) which had a better plasticizing effect contributing to a greater workability of the concrete mixture and the density of the hardened concrete. A water-soluble polycarboxylate copolymer of methacrylic acid with a density of ρ = 1.027 g/cm³ and a pH value of 6.0 was used.

The above-mentioned surfactant performance was enhanced with an electrolyte, a 6 % aqueous solution of potassium nitrite (KNO₂). Theoretically, the potassium cation has an increased radius according to the position in D.I. Mendeleev’s Periodic Table, hence an increased mobility. The potassium-cation-based electrolyte provided a deeper penetration into Portland cement mineral conglomerates and involved a greater number of Portland cement mineral molecules in the hydration processes. Therefore, the use of a cation-based electrolyte increased the hydration of the mixture forming a stronger concrete paste [11–13].

In order to improve the concrete quality, namely, to increase its crack and corrosion resistance, the unique properties of 1–100-nm nanoparticles were studied. Silicon hydro-dioxide nanoparticles SiO₂ ‧ nH₂O with a particle size of ≈ 60 nm determined by a laser analyzer were investigated. They were included in a colloidal aqueous solution with a density of ρ = 1.021 g/cm³ and a pH value of 4.0 and were supposed to enhance the hydration processes in the main mineral of Portland cement, for example, tricalcium silicate, following the reaction:

\[3\text{CaO} \cdot \text{SiO}_2 + (n + 1)\text{H}_2\text{O} = 2\text{CaO} \cdot \text{SiO}_2 \cdot n\text{H}_2\text{O} + \text{Ca(OH)}_2,\]

enhancing the bicalcium hydrosilicate 2CaO ‧ SiO₂ ‧ nH₂O and calcium hydroxide Ca(OH)₂ formation.

In addition, the silicon hydro-dioxide nanoparticles with an improved activity were likely to couple with dicalcium hydro-silicate forming low-base calcium hydrosilicate with a fibrous or needle-like structure reinforcing the bending tensile strength of the concrete structure [14–16].

At the same time, the interaction of silicon hydroxide SiO₂ ‧ nH₂O with the newly formed hydrolysis lime Ca(OH)₂ was supposed to take place according to the following scheme:

\[2\text{Ca(OH)}_2 + \text{SiO}_2 \cdot n\text{H}_2\text{O} = 2\text{CaO} \cdot \text{SiO}_2 (n + 2)\text{H}_2\text{O}.\]

As a result, Ca(OH)₂-based low-soluble calcium hydro-silicates would be formed improving the concrete corrosion resistance [17].

The above-mentioned chemical additive components were evaluated from the point of view of the water-cement ratio changes required to ensure the homogeneous fluidity of the concrete mixture, of variations in the compressive and bending tensile strengths, and of changes in the concrete density according to the water absorption parameter.

Concrete water absorption was tested according to GOST 12730.3-78 “Concrete. Water absorption test methods”.

**Results analysis No. 1**

The experimental results presented in Table 1 confirm the theoretical assumption that with the use...
of an aqueous solution of a methacrylic acid polycarboxylate copolymer with a density of \( \rho = 1.027 \text{ g/cm}^3 \) and a pH value of 6.0 as an additive, a concrete mix acquires more plasticity. As a result, the water content in a concrete mixture of the same fluidity as that of the control mixture decreases by more than 15 %, and the concrete density increases due to a 13 % decrease in water absorption. Meanwhile, the compressive and bending tensile strengths increase by around 14–18 %.

A higher concrete structure density results in a higher strength changing the concrete mixture activity only slightly without new hydrate formations.

When a 6 % solution of KNO\(_2\) (potassium nitrite) electrolyte was added to the methacrylic acid polycarboxylate copolymer, the plasticity was not enhanced as the W/C ratio decreased slightly, within 0.02 units, but the concrete water absorption was reduced by 10 % up to \( W_m = 3.7 \% \) increasing the concrete structure density.

Due to an enhanced hydration activity in the concrete structure, the concrete pores were filled with new hydrate compounds formed in an increased amount.

Compressive and bending tensile strength increased by 26–28 % more or less equally, which may be due to increased hydration, the formation of more hydrate complex compounds and a greater number of strong bonds between the concrete mix components without forming new hydrate phases affecting each type of strength.

An additional portion of SiO\(_2\) • nH\(_2\)O silicon hydroxide nanoparticles in the additive increased the concrete mix reactivity as well as enhanced the formation of new phases. This was due to a greater bending tensile strength in comparison with the compressive strength; thus, new hydrate phases were formed. Low-base hydrous silicates with a higher SiO\(_2\) content having a fibrous or needle structure in the hydrate phase may serve as an example of new hydrate phases.

The results obtained showed that according to the basic laws of chemistry it is possible to change the hydration processes in the concrete mixture using certain materials as additive components ensuring the production of hardened concrete with specified properties.

Having calculated the efficient amount of each additive component, a new high performance complex chemical additive has been established, wt. %:

- aqueous solution of methacrylic acid polycarboxylate copolymer with density \( \rho = 1.027 \text{ g/cm}^3 \) and pH = 6 — 62.5 %
- 6 % aqueous potassium nitrite solution, KNO\(_2\) — 31.25 %
- colloidal aqueous solution of silicon hydroxide nanodispersions — 6.25 %
- SiO\(_2\) • nH\(_2\)O, with density \( \rho = 1.021 \text{ g/cm}^3 \) and pH = 4.0.

The aqueous solution of the new nanopolymer modified (NPM) additive had density \( \rho = 1.031 \text{ g/cm}^3 \) and pH = 5.5.

Results analysis No. 2

Further experimental results presented in Table 2 have shown that the new NPM complex chemical addi-

<table>
<thead>
<tr>
<th>No.</th>
<th>Design class of concrete, B (required strength, ( R_{eq}, \text{MPa} ))</th>
<th>Design class of concrete Bb (required strength, ( R_{eq}, \text{MPa} ))</th>
<th>Portland cement, PCS 00-00</th>
<th>aqueous solution of polycarboxylate copolymer</th>
<th>6 % aqueous solution of KNO(_2)</th>
<th>SiO(_2) • nH(_2)O colloidal solution</th>
<th>water</th>
<th>W/C</th>
<th>Fluidity grade, ( P )</th>
<th>Compressive strength, MPa/%</th>
<th>Tensile strength in bending, MPa/%</th>
<th>Water absorption, ( W_m ) %</th>
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The experimental additive proved to have an enhanced reactivity increasing the compressive strength by up to 40 % and the bending tensile strength even more, thus improving the concrete class by four grades.

Another advantage of the tested additive was its ability to increase concrete crack resistance. It was confirmed by the crack resistance coefficient increase $K_{cr} = R_{ben}/R_{comp}$ from 0.117 in the control mixture to 0.13 in the modified mixture. According to GOST 10180-2012 “Concretes. Strength Test Methods by Control Samples”, the $R_{ben}/R_{comp}$ ratio must be no less than 0.12.

**Results analysis No. 3**

The theoretical assumptions about the chemical processes in a concrete hardening mixture, the formation of new phases and concrete higher density and strength were tested experimentally and revealed that the concrete quality parameters were improved with the use of a newly developed complex additive.

Additional experimental data on concrete durability parameters are presented in Table 3.

### CONCLUSION

The experimental research carried out have shown that:

- basic physical and mechanical properties of concrete such as density, crack resistance, durability, and reliability can be improved with a polycarboxylate polymers chemical additive in combination with potassium cations-based electrolytes and nanostructured silicon hydroxide;
- the new complex chemical additive has proved to enhance the concrete mixture super-plasticity and reactivity increasing the degree of hydration of its components;
- the experiments have revealed that the use of the tested complex chemical additive increases concrete compressive strength by 41 %, bending tensile strength by 56 %, crack resistance by more than 10 %, water resistance and frost resistance are 1.5 times higher and a chemical resistance coefficient increases by 16 %; thus, the modified concrete durability has proved to be enhanced.
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