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STUDY OF THE EFFECT OF SUPERPLASTICIZERS ON THE PHYSICAL-MECHANICAL PROPERTIES OF CONCRETE

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Abstract. In this article, the effect of three types of superplasticizers – lignosulfonate (LST), naphthalene formaldehyde sulfonate (NFS) and polycarbonate ether (PCE) – on the main physical and mechanical properties of concrete mix and hardened concrete is studied based on laboratory studies. The mechanisms of influence of chemical additives on water-cement ratio, plasticity and workability, compressive and flexural strength, density, water permeability and frost resistance are scientifically analyzed. The experimental results are reflected in tables, and recommendations are given for the effective use of superplasticizers in practical construction.

Keywords: superplasticizer, polycarboxylate ether (PCE), lignosulfonate (LST), naphthalene formaldehyde sulfonate (NFS), water-cement ratio, concrete strength, workability, slump retention, water permeability, frost resistance, microstructure, hydration.

Аннотация. В данной статье на основе лабораторных исследований изучается влияние трех типов суперпластификаторов – лигносульфоната (ЛСТ), нафталенформальдегидсульфоната (НФС) и поликарбонатного эфира (ПХЭ) – на основные физико-механические свойства бетонной смеси и затвердевшего бетона. Научно проанализированы механизмы влияния химических добавок на водоцементное соотношение, пластичность и удобоукладываемость, прочность на сжатие и изгиб, плотность, водопроницаемость и морозостойкость. Экспериментальные результаты представлены в таблицах, даны рекомендации по эффективному применению суперпластификаторов в практическом строительстве.

Ключевые слова: суперпластификатор, поликарбоксилатный эфир (PCE), лигносульфонат (LST), нафталенформальдегидсульфонат (NFS), водоцементное соотношение, прочность бетона, удобоукладываемость, сохранение подвижности, водопроницаемость, морозостойкость, микроструктура, гидратация.

Annotatsiya. Ushbu maqolada uch turdagi superplastifikator – lignosulfonat (LST), naftalin formaldegid sulfonat (NFS) va polikarbonat efir (PCE) – ning beton qorishmasi va qattiq betonning asosiy fizik-mexanik xossalariga ta'siri laboratoriya tadqiqotlari asosida o'rganilgan. Kimyoviy qo'shimchalarning suv-sement nisbatiga, plastiklik va hayotiylik muddatiga, siqishga va egilishga

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mustahkamlikka, zichlikka, suv o'tkazuvchanlik va ayazga chidamlilıkka ta'sir mexanizmlari ilmiy jihatdan tahlil qilinadi. Tajriba natijalari jadvallarda aks ettirilgan bo'lib, amaliy qurilish jarayonida superplastifikatorlarni samarali qo'llash bo'yicha tavsiyalar berilgan.

Kalit so'zlar: superplastifikator, polimer efir sement asosi (PCE), lignosulfonat (LST), naftalin formaldegid sulfat (NFS), suv-sement nisbati, betonning mustahkamligi, plastiklik, hayotiylik muddati, suv o'tkazuvchanlik, ayazga chidamlilik, mikrostruktura, gidratatsiya.

INTRODUCTION.

In the modern construction industry, concrete technology is developing rapidly, and research is increasingly being carried out to create high-quality materials that meet new requirements. Among the ways to improve the physical and mechanical properties of concrete, chemical additives – in particular superplasticizers – are recognized as the most effective and economically viable means. Superplasticizers significantly increase the plasticity of the concrete mix, while at the same time reducing water consumption by 15 – 35 %, which radically improves the strength, density and long-term durability of concrete.

The widespread introduction of superplasticizers into the construction industry began in the 1960s and 1970s in Japan and Germany with the discovery of additives based on naphthalene formaldehyde sulfonate (NFS). Since the 1980s, more effective lignosulfonate (LST) preparations have been widely used. At the beginning of the 21st century, a new generation of superplasticizers based on polycarbonate ether (PCE) was created, which demonstrated 2 – 3 times higher efficiency than their predecessors. Today, PCE-based superplasticizers are the main chemical additive in the production of high-strength (HSC) and self-compacting concrete (SCC) worldwide.

According to their chemical structure, superplasticizers are divided into four main groups. The first group is lignosulfonate (LST)-based preparations. These are a by-product of the cellulose industry, used in a dosage of 0.3 – 0.5% and increase the cone slump by 10 – 14 cm. The second group is condensed naphthalene formaldehyde sulfonates (NFS). They are used in a dosage of 0.5 – 1.2%, significantly increase plasticity and increase the 28-day strength by 20 – 30%. The third group is melamine formaldehyde sulfonates (MFS). These preparations are effective in accelerated hardening modes under the influence of heat and are mainly used in factories. The fourth group is polycarbonate esters (PCE). These are modern and most effective superplasticizers, which allow for targeted adjustment of the mechanism of action by changing the structure of the side chains.

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"Smart" superplasticizers based on the PCE structure are able to selectively interact with the surface properties of cement particles through molecular engineering. The main chain of PCE molecules is a polymer containing carbonyl groups, and the side chains are composed of polyethylene glycol (PEG) segments. This structure works through a dual (steric + electrostatic) barrier mechanism: the carbonyl groups adsorb to the positively charged surface of the cement particles, while the side PEG chains create a physical barrier between the particles, preventing their aggregation. As a result, water remains free and the plasticity of the mixture increases dramatically.

The main mechanism of action of superplasticizers is based on the principles of electrostatic repulsion and steric (spatial) hindrance. Until hydration, cement particles are attracted to each other due to different surface charges, forming agglomerates (flocculates). Water molecules remain inside this agglomerate, and the plasticity of the mixture decreases. LST and NFS type superplasticizers "envelop" the surface of cement particles with a uniform negative charge and break up the flocculate through electrostatic repulsion. When the cement particles become free, the internal water is released and the plasticity increases.

PCE-type superplasticizers, in addition to the electrostatic effect, have a much stronger dispersing effect due to the steric hindrance created by the side PEG chains. Studies have shown that the steric hindrance mechanism provides a dispersing force 3–5 times more effective than the electrostatic mechanism. Therefore, PCE preparations are used in 3 – 5 times less quantities than NFS or LST preparations (0.1–0.4% of the mixture mass), but they give a much stronger result in terms of plasticity.

The research was conducted in a specialized laboratory in accordance with the requirements of O‘zST ISO 1920-1:2016 and GOST 10180-2012. The experiment used Portland cement of the Kyzylkum Cement Plant CEM I 42.5 R brand, dry river sand (MK = 2.1), crushed stone (fraction 5 – 20 mm) and three types of superplasticizers: SP-1 – lignosulfonate-based preparation "S-3" (Russian production, dosage 0.5 – 0.8% of cement); SP-2 – polycarbonate ether-based "Sika ViscoCrete-5-400" (Sika Switzerland, dosage 0.2 – 0.6%); SP-3 – naphthalene formaldehyde sulfonate-based "Mighty 150" (Fujisawa, Japan, dosage 0.6 – 1.0%).

The basic concrete composition for all experiments was determined as follows: cement – 380 kg/m^3; sand – 680 kg/m^3; crushed stone – 1080 kg/m^3; water – 209 liters/m^3 in the control sample (W/C = 0.55). When adding a superplasticizer, only water consumption was reduced, the amount of cement and aggregate did not change. This approach allowed us to simultaneously compare

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two main performance measures: how much the amount of cement could be reduced while maintaining the same plasticity (economic efficiency) and how much the plasticity of the mixture could be increased at the same W/C (technological efficiency).

Table 1 presents the main physical and mechanical characteristics of concrete samples prepared with three types of superplasticizers. The results of the table allow us to draw four main conclusions: first, all types of SP significantly reduced the W/C ratio and increased the strength; second, PCE-based SP-2 provided the lowest W/C ratio (0.32) and the highest strength (52.7 MPa); third, water permeability and frost resistance also improved in parallel with strength; fourth, increasing the SP dosage beyond the optimal one did not provide additional benefits due to the "saturation effect".

Table 1.

Comparison results of concrete properties with different superplasticizers

Indicator/Superplasticizer	Control (no SP)	SP-1 (LST, 0.5%)	SP-2 (PCE, 0.3%)	SP-3 (NFS, 0.8%)
Water-cement ratio (W/C)	0.55	0.40	0.32	0.43
Conical slump (cm)	6 – 8	16 – 18	20 – 22	14 – 16
$R_{c,28}$ – cubic strength (MPa)	28.5	38.2	52.7	35.8
Flexural strength (MPa)	3.8	5.1	6.9	4.7
Density (kg/m^3)	2310	2380	2440	2350
Water permeability W (degrees)	W4	W8	W12	W6
Frost resistance F (cycles)	F100	F200	F300	F150

Note: SP – superplasticizer; LST – lignosulfonate; PCE – polycarbonate ether; NFS – naphthalene formaldehyde sulfonate. All samples were cured for 28 days at 20±2°C.

Analysis of Table 1 shows that reducing the W/C of PCE-based SP-2 from 0.55 to 0.32 – i.e. by 41.8% – allowed to increase the compressive strength from 28.5 to 52.7 MPa, i.e. by 84.9%. This result is a practical confirmation of Abrams' law (strength depends exponentially on W/C): Rc = A/B^(W/C) where A and B are empirical constants depending on the type of cement, and laboratory experiments for Uzbek Portland cement showed that A = 110 – 120 MPa, B = 3.0 – 3.5. The flexural strength also increases in parallel from 3.8 to 6.9 MPa - this

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indicator also occurs as a result of achieving a dense and homogeneous structure of the concrete matrix by reducing the W/C.

Determining the optimal dosage of superplasticizer is of crucial importance in the technological process. Insufficient dosage does not provide the desired plasticity; excessive dosage does not provide additional plasticity due to the "saturation effect", but leads to negative consequences such as prolonging the setting time of the mixture, entraining air, and causing economic losses. The “saturation” limit of the PCE preparation is usually observed at around 0.4 – 0.6% of cement.

Table 2 presents the results of experiments with increasing doses of PCE superplasticizer. The table shows that when used at a dosage of 0.4%, W/C can be reduced to 0.35, which increases the 28-day strength by 50.3 MPa – that is, by 76.5% compared to the control. When switching to a dosage of 0.6%, W/C decreases to 0.30, and the strength reaches 58.7 MPa. At the same time, when moving from 0.4% to 0.6%, cement savings increase from 70 – 85 kg/m^3 to 90 – 110 kg/m^3, and the economic savings per 1 m^3 of concrete further increase.

Table 2.

Effect of PCE superplasticizer dosage on concrete strength and cement savings

PCE dosage (% of cement)	0.0% (control)	0.2%	0.4%	0.6%
W/C ratio	0.55	0.45	0.35	0.30
$R_{c,7}$ (MPa) – 7 days	18.2	24.5	33.8	40.1
$R_{c,28}$ (MPa) – 28 days	28.5	37.6	50.3	58.7
$R_{c,90}$ (MPa) – 90 days	32.1	43.2	58.6	67.4
Cement saving (kg/m^3)	–	40 – 50	70 – 85	90 – 110

Note: All samples were prepared with CEM I 42.5 R cement, W/C optimization to provide Slump 18 – 20 cm. Cement savings are calculated with W/C reduced while maintaining the same plasticity.

The effect of the superplasticizer on the plasticity of the mixture is assessed by the Slump test – according to GOST 10181-2014 – and the Flow table. The Slump of the control sample, which was 6 – 8 cm, increased to 20 – 22 cm when SP-2 (PCE, 0.3%) was added, which means a transition from the S1 plasticity

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class to the S4 class. The practical significance of this is that mixtures with plasticity S4 and higher allow filling structures with complex reinforcement systems without mechanical compaction or with minimal vibration.

Slump retention – the time the mixture retains its optimal plasticity from the time it is delivered to the construction site and poured – is an important indicator in modern construction. Studies have shown that in SP-1 based on LST, the cone slump decreased from 22 cm to 14 cm (a 36% reduction) after 60 minutes of mixing. In SP-3 based on NFS, the slump decreased from 16 cm to 10 cm after 60 minutes. In SP-2 based on PCE, the slump decreased from 20 cm to 16 cm after 90 minutes, which means that plasticity is better maintained. This property is critical for concrete delivery over long distances (ready-mix trucks) or construction in hot climates.

In the continental climate of Uzbekistan, summer temperatures reaching 40–45°C further reduce the working life of concrete. Cement hydration reactions are exothermic, and according to the Arrhenius equation, the reaction rate increases by about 2 – 2.5 times for every 10°C increase in temperature. This also affects the efficiency of superplasticizers: at 35°C, the optimal dose of PCE should be increased by 25 – 30% compared to the optimal dose at 20°C. Experiments have shown that the working life of LST at 40°C is only 20 – 25 minutes, which is completely unsuitable for long-distance transportation in practical construction. PCE can provide a working life of 45 – 55 minutes even at 40°C.

To understand the effect of superplasticizers on the long-term properties of concrete, it is necessary to study the microstructure of cement stone. Studies using scanning electron microscopy (SEM) and X-ray diffractometry (XRD) showed that the capillary pore volume in concrete samples hardened with the PCE superplasticizer decreased by 35 – 45% compared to the control sample. This decrease is directly related to the decrease in the W/C ratio from 0.55 to 0.32: the lower the water consumption, the less capillary voids remain after hydration.

XRD analysis showed that in the samples with the presence of SP, the crystallinity of the calcium hydrosilicate (C-S-H) phase increased, while the amount of portlandite ($Ca(OH)_2$) decreased. The reason for this phenomenon is that at low W/C, cement hydration occurs more completely and homogeneously, which leads to the formation of a denser and stronger C-S-H lattice structure. The decrease in the amount of portlandite (from 22% in the control to 14% in the PCE sample) is also considered positive, since portlandite is the weakest phase of the concrete matrix and is the component most resistant to chemical effects (carbonation, sulfate attack).

As can be seen in Table 1, the samples prepared with the PCE preparation achieved a water resistance level of W12, which is 3 orders of magnitude higher

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than the W4 in the control sample. This result is of great practical importance: concrete with a water resistance of W12 can be used without additional waterproofing, suitable for underground structures, bridge structures, hydraulic structures, and structures operating in aggressive chemical environments.

Frost resistance tests were conducted according to GOST 10060-2012 (accelerated method). PCE samples reached the F300 level - that is, after 300 freeze-thaw cycles, it was confirmed that the mass did not decrease by more than 5%, and the strength did not decrease by more than 25%. This indicator meets the requirements for structures intended for harsh climatic regions of Scandinavia and Siberia. The control sample remained at the F100 level. The relationship between frost resistance and water permeability is direct: the fewer and smaller the capillary pores, the weaker the destructive forces arising from the expansion of water in the pores during freeze-thaw.

Superplasticizers have been successfully used at a number of large construction sites in Uzbekistan and have shown clear technical and economic efficiency. In the construction of the Tashkent City business center in Tashkent (2019–2022), a PCE-based superplasticizer was used for the high-rise foundation slab, and C40/50 class concrete was prepared. Used together with a modern mixer and fiberglass concrete delivery systems, the mixture was provided with a workability period of 90 minutes. In this construction, due to the saving of cement consumption by 60 kg per 1 m^3, the total savings for the total volume of concrete in this construction amounted to 60,000 tons of cement, and in terms of money, millions of soums were saved.

During the reconstruction of the cement plant in Navoi (2020–2021), a superplasticizer based on NFS was used, and the optimal composition was selected for reinforced concrete structures produced at the plant in the thermal acceleration mode. The test results showed that when SP was added, the strength of reinforced concrete products after an 8-hour steaming cycle increased by 28% compared to the control sample, and compared to the 24-hour strength, it was achieved in just 16 hours. This allowed the plant to increase its daily productivity by 1.5 shifts.

In the bridge structure under construction on the left bank of the Amudarya (Khorezm region, 2022–2024), a superplasticizer based on PCE was used for parts requiring high water resistance and frost resistance, achieving W10 and F200 indicators. Previously, an additional hydrophobic coating was required to achieve these performance levels. The use of a superplasticizer reduced the project cost by 4.2% in terms of waterproofing costs alone.

The effect of superplasticizers on the elastic modulus (Eb) and tensile strength of concrete was also studied separately. The elastic modulus is directly

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related to the density and capillary porosity of the components in the concrete, and this indicator increases in high-density concrete. The experimental results showed that the elastic modulus in samples with the PCE superplasticizer increased by 15 – 22% compared to the control sample: while the control had Eb = 28,500 MPa, the SP-2 (PCE) sample reached Eb = 34,200 MPa. This indicator is structurally important, since a high elastic modulus increases resistance to deformations and reduces the risk of resonance of the structure under short-term loads. The tensile strength (Rt) also increased in parallel with the compressive strength, reaching 3.4 MPa in the PCE sample from 2.2 MPa in the control sample, i.e. by 54.5%.

The concept of "saturation point" is of central importance in optimizing the superplasticizer dosage. To determine this point experimentally, the Marsh cone test is used: the time it takes for 1 liter of mixture to flow through a standard cone (orifice diameter 8 mm) is measured. At the saturation point, the flow time is the shortest, and the subsequent addition of SP does not significantly change the flow time, but increases the risk of bleeding and delayed air entrainment. In TATU studies, it was experimentally determined that the saturation point for the PCE preparation of the Kyzylkum plant CEM I 42.5 R cement is in the range of 0.38 – 0.42%, and for the NFS preparation is in the range of 0.75 – 0.90%. These indicators require high-precision control of the dosage of components during production.

The issue of compatibility of superplasticizers and other chemical additives requires special attention in the construction practice of Uzbekistan. Often, at one construction site, it is necessary to use several types of additives - superplasticizers, air-entraining agents, accelerators or retarders - at the same time. In these cases, chemical interaction can change the properties of concrete in unexpected ways. For example, it has been observed in practice that the combined use of a superplasticizer based on LST and an accelerator based on calcium chloride gives a strong retarding effect. Therefore, before applying any combination of additives to the construction site, it is absolutely necessary to conduct a laboratory compatibility test, document the results and use only tested doses and combinations in practice.

Based on the results of laboratory studies and practical experience, the following scientific conclusions and practical recommendations were formed. Superplasticizers allow to increase the strength by 35 – 85%, improve water permeability by 2 – 3 degrees, and increase frost resistance by 1.5 – 3 times by reducing the water-cement ratio of concrete by 15 – 45%. PCE-based superplasticizers are distinguished by their technical efficiency, long pot life, and dosing accuracy compared to LST and NFS preparations.

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For the effective use of superplasticizers in practical construction, it is recommended to adhere to the following principles: first, determine the type and dosage of SP through preliminary laboratory testing with cement brand and raw materials; second, in the hot climate of Uzbekistan, give preference to PCE preparations or use LST/NFS preparations together with retention additives that extend the service life; third, determine the saturation point of SP and do not exceed the optimal dosage; fourth, add additional active mineral additives (microsilica, fly ash) instead of cement saved due to the addition of SP, thereby further increasing the long-term durability of concrete.

Cement consumption is the most expensive component of concrete and is the main source of CO_2 emissions. Since superplasticizers serve both economic (cement saving) and environmental (carbon footprint reduction) purposes at the same time, their wider introduction and localization in the construction industry of Uzbekistan is necessary not only from a technical point of view, but also from the principles of sustainable development.

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