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EXPERIMENTAL STUDY OF THE EFFECT OF SURFACTANTS AND WATER-CEMENT RATIO ON ABRASION RESISTANCE OF HYDRAULIC CONCRETES

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ABSTRACT

The effect of surfactants and water-cement ratio on the abrasion resistance of hydraulic concrete are presented. A series of laboratory tests and field surveys of hydraulic structures were carried out to determine the effect of various factors on the wear resistance of hydraulic concrete to abrasive effects. The basic studies of abrasion of mortar and concretes were carried out at the Portland cement of the Shymkent plant without active mineral and filler additives with activity in 28 days 462 kg/cm^2, a specific surface area of 2740 cm^2/g. In addition, Portland cement from the Karaganda plant was used, with an activity of 28 days 431 kg/cm^2, and a specific surface area of 3450 cm^2/g. The presence of dependencies of the abrasion of concrete on several factors was established: water-cement ratio and strength, the type of filler, the fineness of cement grinding, the age of the samples, the use of surfactant additives, and the method of laying.

Keywords: Surfactants, Hydraulic Concrete, Cement Mortar, Abrasiveness, Abrasion.
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INTRODUCTION

Many cases of destruction of concrete by bottom sediments are known in the practice maintenance of hydraulic structures.[1] In hydraulic structures located on mountain-foothill sections of rivers, concrete can be destroyed as a result of abrasion or wear (i.e., the combined action of abrasion and impact) by sediments of different sizes.[2-4] Frost resistance, chemical resistance, and other properties of concrete have been studied widely. However, the wear resistance of concrete is currently at the stage of the study, which explains the fact that GOST for hydraulic concrete does not contain requirements for concrete in terms of its resistance to wear.[5,6] The aim of this research is to investigate the impact of surfactants and water-cement ratio on the abrasion resistance of hydraulic concretes. To date, the increase in the wear resistance of concrete is limited by recommendations for improving its grade. However, as the study shows, these recommendations are not justified in any way.[7] It was found that Portland cement of the same strength as pozzolan cement has abrasion resistance much higher than the latter.[8-12] Obviously, the concretes on the pozzolan Portland cement will be less resistant to abrasion than the concretes on the Portland cement.[9,13-15] Thus, the design of hard-to-wear concrete is not similar to the design of concrete of a given grade in strength. To obtain concrete with increased abrasion resistance, special studies are required.[9-11,16-18] The study of the properties of cement by researchers is based on the premise of dependency of the physical and mechanical properties of cement on its mineralogical composition.[19-22] From this perspective, they consider the ability of cement of a particular mineralogical composition to resist abrasion. Alite cement have been found to be the most resistant to abrasion, whereas belite cement shows the least resistance. As for C_3A and C_4AF, there is no

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significant influence of their quantity on cement abradability.[23-25] Other conclusions were reached by, those who believe that C_3A has a negative effect on the abrasiveness of cement, C_4AF positive, C_3S, and C_2S do not have a decisive effect on the abradability indicators.[24,26-29] There is also disagreement on the extent to which the resistance of concrete to abrasion changes as cement consumption increases by 1 m^3 of concrete. Many researchers agree that as the water-cement ratio increases, the resistance to concrete abrasion decreases. However, there is no relationship between the abradability of concrete and the water-cement ratio.[30] This article presents the results of studies of the abrasion resistance of cement concretes and mortars carried out by authors over three years.

EXPERIMENTAL

Materials Used in the Studies

The main studies of abrasion of mortars and concretes were carried out at the Portland cement of the Shymkent plant without active mineral additives and filler additives, activity in 28 days 462 kg/cm^2, with a specific surface area of 2740 cm^2/g. In addition, Portland cement from the Karaganda plant was used, with an activity of 28 days 431 kg/cm^2, with a specific surface area of 3450 cm^2/g. Sand and gravel, screened out of a natural mixture of sand and gravel deposits of the Syrdaria River were used for mortar and concrete. Sand is used as fine-grained aggregate; crushed stone is obtained by crushing Saryagash gravel.

Mechanism of Abrasive Abrasion of Concretes and Mortars

In the first few days of hardening, the cement stone is an isotropic undifferentiated mass with numerous interspersed grains of undeveloped clinker. Neoplasms are colloidal. The hardening process is accompanied by gel compaction and crystallization of calcium hydro aluminate and calcium hydroxide. By the monthly hardening time in the colloidal mass a large number of submicroscopic and very small crystals scattered in it, as well as undecomposed clinker grains, are observed. However, the predominant gel content in the cement stone persists for a very long time. Thus, the cement stone in the concrete is mainly an amorphous mass of calcium hydro silicate, into which fragments of unreacted cement grains are immersed. The whole mass is permeated with thin needle crystals of calcium hydro aluminate and crystals of $Ca(OH)_2$. During long-term hardening cement stone mainly consists of calcium hydro silicate gel (about 60%) and calcium oxide hydrate crystals (at least 15%).[31] It has been found that the hardness of crystalline calcium oxide hydrate is low. On the Mohs hardness scale, it is ranked 3-4. The gel-like mass of calcium hydro silicate has an even lower hardness.[32] The abrasive sand particles represented mainly by quartz and feldspar have hardness in the range of 6-7. The protrusions of the abrasive sand grains, as harder, when moving on the surface of the cement stone, "gouge" the soft gel of calcium hydro silicate and break the crystals of $Ca(OH)_2$ and the needles of calcium hydro aluminate, themselves receiving minor damage. The mechanical abrasion process is accompanied by the dissolution of exposed $Ca(OH)_2$ crystals in water. In parallel with the described processes in the deeper "pre-fracture zones," obviously, the cement stone is weakened by the "proppant action of water films" in the "microcracks" of the material. In pozzolan Portland cement, the interaction between the hydraulic additive and lime hydrate at ordinary temperatures is rather slow. In the first weeks of hardening, the hydraulic additive from the saturated solution absorbs lime hydrate, which is in a colloidal dispersed state. In this case, it turns into a swelling mass having a colloidal character. In parallel with this, and then more vigorously, lime is bound by active silica to a new chemical compound of the crystalline state, which in general can be represented by the expression $mCaO*SiO_2*nH_2O$. This process has been going on for months.[33] Some researchers believe that within a year, the hydraulic additive binds no more than 20% of $Ca(OH)_2$. Thus, for a rather long time of hardening of pozzolan Portland cement in its composition, compared with conventional Portland cement, there will be an increased content of colloidal masses, which will negatively affect its abrasion resistance. This explains the results of studies, according to which the abrasion rate of cement mortar on cement with additives of 25% flask in all periods from 28 days to 1 year turned out to be 1.7-2.0 times more than on Portland cement without additives.[34-38]

Fabrication of Samples from Cement Mortars and Concretes

The samples from cement mortars and concretes for abrasion testing were prepared as hollow cylinders of outer diameter 314 mm, inner diameter 228 mm, thickness 44 mm, and height 214 or 143 mm. Compressive cubes associated with abrasion samples were prepared with dimensions of 10×10×10 cm. Mortar and concrete samples were prepared manually, after which they were subjected to vibration on a vibrating platform. The samples in the molds were then placed in a wet environment and disbanded after 48 hours. Samples from the solution were prepared with a plastic consistency with a small cone settlement of 2.5 cm, the mobility of the concrete mixture corresponded to a standard cone settlement of 2.5-3.5 cm. 2 days before the test the samples were placed in water for saturation. The bayonet concrete mixture was laid in layers, in molds for samples with a height of 214 mm in 3 layers, and a height of 143 mm in 2 layers with stitching of each layer 100 times. Compression cubes were prepared according to the standard method.

Sample Testing

A number of questions had to be resolved in the development of the sample test procedure, namely:
1) quantitative assessment of abrasion;
2) selection and dosage of abrasive;
3) period of abrasion and number of periods;
4) a number of twin samples.

Abradability is characterized by the destruction and removal of material in the surface layer, resulting in a decrease in body weight.

In the test, abrasion resistance was determined by loss in the weight of the sample assigned to the area unit per time unit:

$$U = [(P_1-P_2)/(F\text{-}t)] \text{ kg/m}^2\text{*hr} \quad (1)$$

Where: P_1 and P_2 - sample weight before and after the test in kg, F - sample area in m^2, t-test time per hour. Sand sifted from the bottom sediments of the Syrdaria River was used as an abrasive. To determine the sand size and its dosage, a series of experiments were carried out, during which the fractional composition of sand and its amount, as well as the test time for one period, were established. Sand with a grain size of 2.5 to 0.75 mm in an amount of about 14% of the weight of water poured into the device was adopted as an abrasive. The duration of tests for one period is set at 5 hours. The test cycle, that is, the total test time, for samples from the mortar is accepted in one period, for concrete - two; after the first period, the concrete sample is weighed, the abrasive is replaced, and the test begins again. The number of twin samples was two.

RESULTS AND DISCUSSION

Abradability of Cement Concretes

The studies established the presence of dependencies of the abrasion of concrete on several factors: water-cement ratio and strength, the type of filler, the fineness of cement grinding, the age of the samples, the use of surfactant additives, and the method of laying.

Abradability of Cement Grout

The results of experiments to determine the dependence of the abradability of samples from the solution on W/C, strength, and age are given in Table-1.

Table-1: Dependence of Abrasion of Cement Slurry Samples on Water-Cement Ratio, Strength, and Age

W/C	Compressive strength, kg/cm^2			Tensile strength, kg/cm^2	Abradability, kg/cm^2*hr		
	28 days	90 days	198 days		28 days	90 days	198 days
0.50	290	-	-	34	1.00	-	-
0.65	235	339	422	31	1.70	0.66	0.24
0.80	157	-	-	21	4.00	-	-

As can be seen from Table-1 that the abradability decreases with the decrease in W/C. In this case, the increase in strength occurs less intensively than the decrease in abrasion. The found relationship between the abradability and the cement-water ratio of the cement slurry suggests that abradability will also be dependent on strength. This assumption is supported by experimental data (Table-1 and Fig.-1).

The results of parallel abrasion and tensile tests of samples from the mortar show that increasing the tensile strength, as well as compression, by reducing the W/C dramatically increases the abrasion resistance of the mortar (Table-1 and Fig.-2). The decrease in porosity in the solution has a positive effect on the abrasion resistance of the mortar (Table-2).

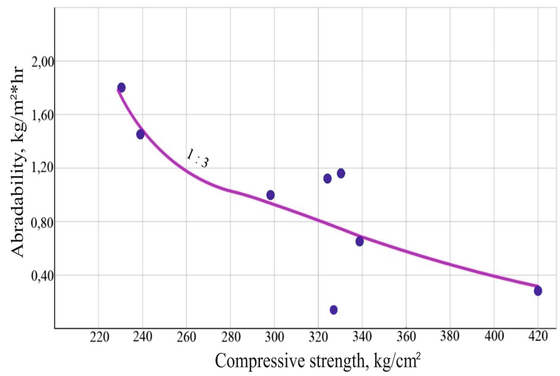

Fig.-1: Dependence of Abradability of Samples from Mortar on Compression Strength

Table-2: The Ratio of Porosity and Abrasion of Samples

Porosity (%)	Abradability (kg/m^2*hr)
17	0.30
26	1.00
28	2.20

As a result of tests of cement stone prepared from 6 different types of cement on the "Abrasion circle", the presence of a relationship between abradability and porosity of cement stone was established.

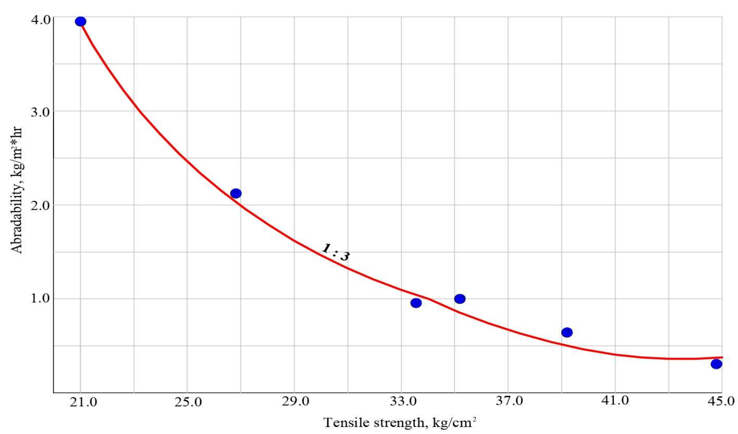

Fig.-2: Dependence of Abradability of Samples from Mortar on Tensile Strength

It can be seen from Table-1 that with an increase in the age of the mortar samples, stored under normal conditions a continuous increase in abrasion resistance occurred. Even at more than three months of age, the strength build-up slows down greatly, whereas abrasion resistance grows quite intensely.

Water-Cement Ratio and Strength

Table-3 shows the results of tests of abrasion resistance of vibrated concretes of different types and compositions and for comparison solution (composition 1:3, at the age of 28 days). From Table-3 and Fig.-3, it can be seen that the strength of all types of concrete decreased due to the increase in W/C, which leads to the increase in the abrasion of concrete samples.

Thus, an increase in W/C, a decrease in the strength of the cement stone, and a decrease in the adhesion forces holding the filler grains are the main reasons for the decrease in the abrasion resistance of the mortars and concretes. It follows from Table-3 that concrete on fine sand showed lower abrasion resistance than concrete of the same strength on sand of normal size. At the same time, the solutions of the same strength as the concrete have a much lower abrasion resistance than the latter.

Table-3: Results of Concrete and Mortar Abradability Tests

No.	Type of concrete and mortar	W/C	Cement consumption per 1 m^2 of concrete (mortar)	The ratio of cement dough volume (area) to aggregate volume (area)	Compressive strength, kg/cm^2	Abradability, kg/cm^2*hr
1	Concrete on the cement of the Shymkent plant, sand, and gravel from Syrdaria river	0.55 0.65 0.75	324 269 227	0.41 0.37 0.33	307 245 170	0.29 0.45 0.72
2	Concrete on the cement of the Shymkent plant, gravel, and fine-grained sand from the Syrdaria River	0.55 0.65 0.75	366 302 256	0.48 0.43 0.39	298 193 114	0.44 0.65 0.97
3	Concrete on the cement of the Shymkent plant, sand and gravel from the river Syrdaria and rubble	0.55 0.65 0.75	407 312 272	0.56 0.44 0.41	340 278 189	0.11 0.14 0.29
4	Concrete on the cement of the Shymkent plant, sand, and gravel from Syrdaria river	0.55 0.65 0.75	324 269 227	0.41 0.37 0.33	319 213 178	0.13 0.19 0.46
5	Solution of 1:3 composition on the cement of Shymkent plant and sand from Syrdaria river	0.55 0.65 0.75	488 465 445	0.78 0.87 0.96	280 235 177	0.95 1.70 2.80

Note: for all types and compositions of concrete, the ductility of the mixture was kept constant. The plasticity of the solution increased with the V/C increase.

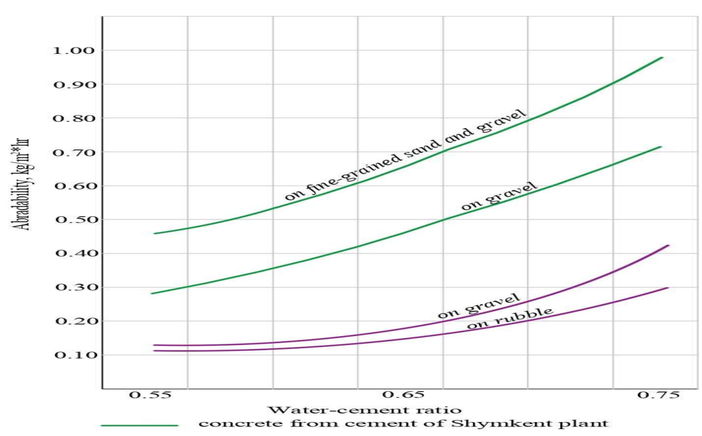

Fig.-3: Dependence of Concrete Abrasion on Water-Cement Ratio

The volume of cement dough in 1 m^3 of concrete (mortar) is determined by the formula:

$$V = [(C+B)/ \tau_C] \quad (2)$$

Where: C - cement consumption per 1 m^3 of concrete (mortar) in kg, B - water consumption per 1 m^3 of concrete (mortar) in kg, τ_C - volume weight of cement dough obtained experimentally in kg/l. The volume of sand and gravel in 1 m^3 of concrete is defined as a quotient of the weight of the aggregate divided by the volume weight of its grains. These calculations were carried out for all varieties of concrete, as well as mortar at W/C = 0.55; 0.65, and 0.75. The data on the ratios of cement slurry volumes (areas) to aggregate volumes (areas) for them are summarized in Table-3. Analysis of the tabular data and the graph in Fig.-4 shows that at the same water-cement ratios in the mortar compared to the concretes, the cross-sectional area of the sample occupied by the cement stone is much larger.

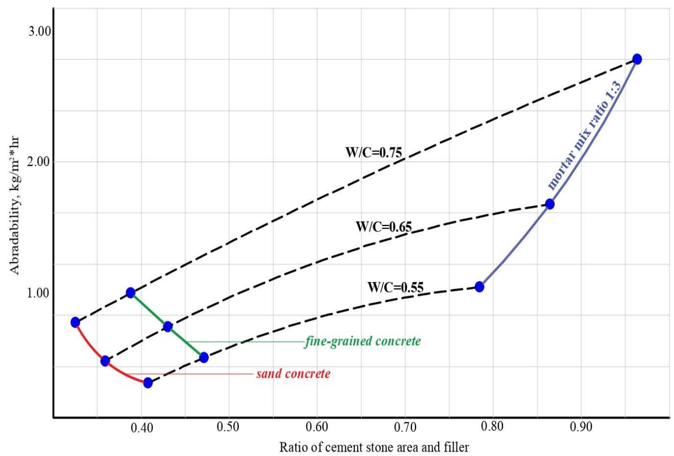

Fig.-4: Abradability of Mortars and Concretes Depending on the Ratio of Cement Stone Areas and Aggregates

When the W/C is reduced due to a reduction in water consumption per unit volume of the mixture, which is accompanied by a decrease in its plasticity, then, along with an increase in the abrasion resistance of cement stone an increase in the proportion of aggregates in the total volume of concrete (mortar) is also occurred. Both circumstances lead to a sharp increase in the resistance to abrasion of the concrete (mortar) itself. This assumption was confirmed by experiments with mortars (Table-3 and Fig.-4).

Age of Samples

Experiments carried out on samples from the mortar showed that as the age of the samples increases, their abrasion resistance increases. When inspecting hydraulic structures exposed to sediment flow the young concrete has a very low wear resistance (Fig.-5).

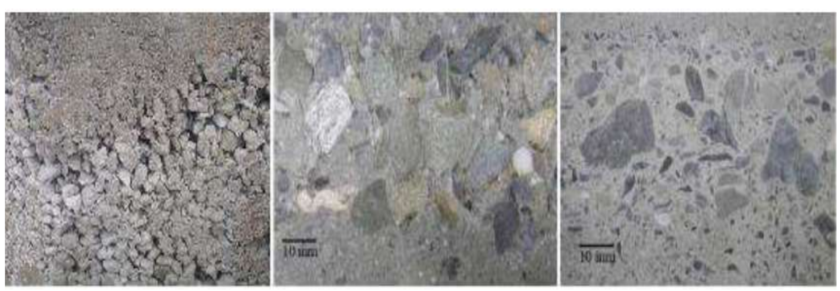

Fig.-5: Abrasion Process and Abrasive Damage to the Surface of Hydraulic Concrete

In laboratory conditions, concrete samples made on Portland cement of the Shymkent plant and aggregates from the Syrdaria River were tested at W/C = 0.65, which at different ages had the following abradability indicators. (Table-4)

Table-4: Abradability Parameters of Samples

Age of concrete (days)	Compressive strength, kg/cm^2	Abrasion, kg/cm^2*hr
7	47	11.6
28	245	0.45
105	330	0.26
180	395	0.22

Method of Concrete Mix Laying

Laboratory tests showed that the vibrated concrete had an abrasiveness of 0.45 kg/m^2*h and a compressive strength of 215 kg/cm^2, while the abrasiveness of the bayonet concrete of the same composition was 0.25

kg/m^2*h and a compressive strength of 220 kg/cm^2. These experiments, however, do not indicate that in parts of structures subject to abrasion with sediment, it is necessary to avoid laying the concrete mixture with vibrators. Vibration weakens only the top layer, not the entire mass of concrete. The deeper layers, on the contrary, as a result of vibration, obtain increased density, which means better abrasion resistance. So as to avoid rapid damage to the surface layer of vibrated concrete as a result of its abrasion of it with sediments, it is necessary to subject the vibrated surface of the concrete to special "hardening" (evacuation, use of absorbent formwork, etc.).

Fineness of Cement Grinding

From the data in Table-3, it can be seen that concretes on the cement of the Karaganda plant, having similar indicators of compressive strength with concrete on the cement of the Shymkent plant, have a significantly higher abrasion resistance. Both of these cement, having a similar mineralogical composition and activity, differ in the fineness of grinding. The specific cement surface of the Shymkent plant is 2740 cm^2/g, and the Karaganda plant is 3450 cm^2/g. In the increased fineness of grinding, obviously, lies the main reason that the abrasion of concrete on the cement of the Karaganda plant is much lower than the abrasion of concrete on the Shymkent cement.

Addition of Surfactant Additives

A series of experiments carried out on concretes with surfactant additives made it possible to establish the presence of this influence. As a hydrophilic surface-active additive in experiments, sulfite-alcohol bard (SAB) was used, as a hydrophobic soap (Table-5).

Table-5: Effect of Surfactant Additives on Concrete Abrasion Resistance

No.	Type of additives	Cement consumption per 1 m^3 of concrete	Compressive strength, kg/cm^2	Abrasion, kg/cm^2*hr
	W/C=0,55			
1	Without additives	324	-	0.29
2	SAB	281	-	0.22
3	Naphthenate soap	303	-	0.23
	W/C=0,65			
4	Without additives	324	245	0.45
5	SAB	281	181	0.27
6	Naphthenate soap	303	168	0.28
	W/C=0,75			
7	Without additives	227	-	0.72
8	SAB	223	-	0.38
9	Naphthenate soap	218	-	0.51

The results of the experiments (Table-5) show that the introduction of SAB and naphthenate soap additives at constant W/C and plasticity of the mixture leads to cement savings and an increase in the resistance of concretes to abrasion. The microstructure of the concrete samples was examined using a JEOL JSM7500 scanning electron microscope with an X-ray spectral analysis attachment (Fig.-6). The results obtained are correlated with the above experimental data.

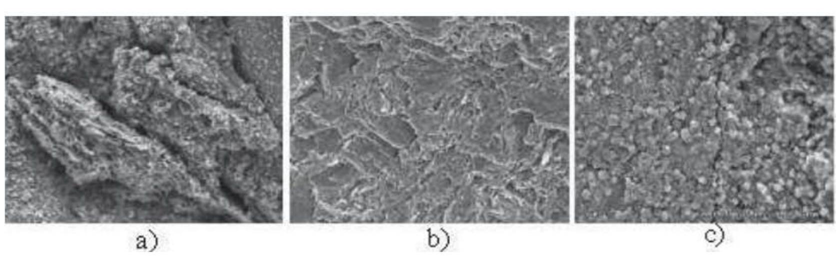

Fig.-6: Microstructure of Concrete Samples: a - Without Additive; b - with the Addition of SBA; c - with the Addition of Naphthenate Soap, Scale: 60 μm

Effect of Abrasive Speed and Size on Abrasion Intensity of Samples

As the number of revolutions of the rotor of the device increases, and with it the speed of flow with abrasive, the centrifugal force in the flow grows, under the action of which sand grains are pressed with even greater force against the concrete sample, which is equivalent to an increase in the mass of particles without changing their size. During laboratory testing, concrete samples completely identical in all respects were tested. In one case, the rotor speed was 960 rpm, which corresponds to the movement of the corner blades at a speed of 10.6 m/s, in the second case, the rotor speed was 1070 rpm, which is accordingly 11.1 m/s for the farthest points of the blade. Thus, the speed of movement of the abrasive increased by 1.1 times. Considering that the speed of movement of the abrasive will change with known approximation in proportion to the change in the speed of movement of the rotor blades contacting it, we obtain an increase in the degree of abrasion of samples from 0.45 kg/m^2*hr in the first case to 0.51 kg/m^2*hr in the second. Consequently, the degree of abrasion of the samples increased 1.2-fold (Fig.-7).

Fig.-7: Samples of Concretes Used in the Abrasion Test (Laboratory Abrasion Circle LKI-3)

It follows from Table-6 that the use of smaller abrasives leads to a decrease in the abrasion of the samples. This is because fine sand particles have a smaller mass compared to coarse sand, which causes a weakening of the destructive capacity of the flow of water with sand.

Table-6: Effect of Abrasive Grain Size and Shape on Abrasiveness of Samples from Solution

Characteristics of sand-abrasive	Sand size (mm)	Abrasion of samples, kg/m^2*hr
The sand of the Saryagash quarry	2.50-0.75	1.77
Zhetysai quarry sand	1.20-0.60	1.25
Flaky sand obtained from crushing gravel of the Zhetysai quarry	1.20-0.60	0.66

The results of the work show that the abrasion of concretes and solutions is not some specific property of them, regardless of other properties, as individual researchers suggest. Abrasion resistance is closely related to other characteristics of concrete (mortar) and, above all, its density and strength. Experimental studies carried out in laboratory conditions and confirmed by full-scale surveys of hydraulic structures have established that in the process of abrasion of cement mortars and concretes with solid abrasive in the presence of water, the cement stone that binds aggregate grains into one whole is primarily subjected to destruction. Since cement stone mainly consists of calcium hydro silicate gel and calcium oxide hydrate crystals, the hardness of which is small, abrasive grains, when moving, "gouge" the soft gel and cut off $Ca(OH)_2$ crystals. Mechanical attrition processes are accompanied by chemical processes of dissolution in water $Ca(OH)_2$. As the destruction products are washed away by water, new layers of cement stone are exposed and abrasion goes further. Dense grains of filler as a result of the abrasion of cement stone are gradually freed from bonding and fall out on the masses of concrete.

CONCLUSION

1. Since the weakest, from the point of view of abrasion resistance, the component of concrete (mortar) is cement stone, then it should be as small as possible in concrete (mortar).
2. To reduce the consumption of cement dough, the mixture of aggregates in concrete (mortar) should be selected with a minimum void, and when compiling it, it is necessary to use fractions of the maximum permissible size.

3. In accordance with the recommendations for concretes (mortars), high-elite cement without active mineral and microfilter additives should be used.
4. In concretes (solutions), it is advisable to use cement of increased grinding fineness.
5. Sand and crushed stone from dense and strong rocks should be used as fillers. Gravel is not recommended.
6. Decreasing the W/C in the concrete (mortar) with constant mobility of the mixture leads to an increase in the strength of the cement stone, and, therefore, its resistance to abrasion. In addition, it reduces the number of voids under the filler grains, which increases the total adhesion of the cement stone to the aggregate and makes it difficult to separate its grains from the mass of concrete (mortar) during abrasion. To reduce W/C, it is advisable to use surfactants and plasticizers in concretes.
7. Resistance of concrete (mortar) to abrasion in time increases more intensively than strength. At the same time, concrete of an early age (7-10 days) is completely unstable to abrasion. Therefore, in all cases, when possible, it is necessary to lay concrete in parts of the structures subject to abrasion in the first place.
8. Laying of the concrete mixture by vibration contributes to the production of dense concrete. However, the surface layers of such concrete are weak because of the vibration of water and air. To obtain vibrated concretes with a surface of increased abrasion resistance, they must be evacuated or absorbent panels used.

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CONFLICT OF INTERESTS

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS

All the authors contributed significantly to this manuscript, participated in reviewing/editing, and approved the final draft for publication. The research profile of the authors can be verified from their ORCID ids, given below:

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