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Behaviour of silica-concrete based on quartz bond in sulphuric acid

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Abstract

The behaviour of silica-concrete (SC) under the constant or cyclical action of a sulphuric acid medium was considered. It was found that the compressive strength of SC depends on the coarse aggregate type and acid concentration. SC with quartzite aggregate achieved high-quality performance. It had high durability in weak to strong solutions (10–70%) of sulphuric acid for constant and cyclical tests. On the basis of its long-term immersion and cyclical tests in 30% H_2SO_4 the conclusion was reached that SC with quartzite coarse aggregate can be included in the same class as other traditional acid resistant materials, such as acid-resistant engineering brick. Acid permeability under capillary pressure conditions was also examined. It was established that the sulphuric acid can penetrate into SC on the depth of 20 mm. The direct determination of reinforcement corrosion in SC under conditions of capillary sulphuric acid suction showed that the protective layer of 40 mm reliably protected the reinforcement against corrosion: no traces of corrosion on the reinforcement were found for the duration of the experiment (3 years). © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Silica-concrete; Quartz bond; Monomineral aggregate; Polymineral aggregate; Compressive strength; Constant tests; Cyclical tests; Permeability; Sulphuric acid

1. Introduction

Chemical, petrochemical, cellulose and paper plants and thermal power stations face the acute problem of ensuring the durability of technological equipment, building and protective constructions against the action of acids and their vapours. In such cases, the equipment and construction elements are manufactured, as a rule, using metals and non-metallic materials such as ceramics, polymeric materials and concretes, in particular, polymerconcrete and concrete based on water glass. A promising chemically resistant non-metallic material is concrete based on the quartz bond, known as silica-concrete (SC).

The scientific principles of the quartz bond for such concrete were formulated in 1962 [1]. It was postulated that it could be obtained by the autoclave curing of a mixture containing fine vitreous silica, highly dispersed crystal silica and water. The basic principles of this process are as follows:

During hydrobarothermal treatment (autoclaving) under stable temperature, the vitreous silica is dissolved in the water–liquid phase of the raw mixture. The liquid phase is supersaturated by silica. The “superfluous” SiO_2 is then deposited from this solution and crystallized in the form of secondary quartz on particles of the initial highly dispersed crystal silica that serve as a seed. This results in the dissolution of a new portion of glass. The process is successively repeated until the vitreous silica is completely dissolved and crystallized as dense crystalline quartz matter – quartz bond. Successive investigations showed that it also includes 15–20% (by weight) colourless laminar crystals of sodium hydrosilicates and scales of anhydrous sodium silicates [2].

When autoclaving concrete-like material containing fine vitreous silica and highly dispersed crystal silica generating rims are formed in the contact zone of the quartz bond with grains of the fine and coarse aggregates. These rims and the quartz bond bind all the components of the concrete together.

The material obtained, silica-concrete (SC), has a conglomerate structure and is characterized by the presence of elongated, predominantly closed pores 0.01–1.5 mm in size.

The problems of production technology and peculiarities of SC have been given adequate consideration in researches carried out by Kirilishin, Freidin, Sedykh and Slonevsky et al. [1–4].

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Table 1
Silica-concrete (SC) properties (after autoclave treatment)

Properties	Unit	SC-G1	SC-Q
Compressive strength	MPa	64.1	69.2
Tensile strength	MPa	5.9	6.5
Flexural strength	MPa	–	11.3
Shear strength	MPa	–	12.3
Volume mass	kg/m^3	2250	2340
Porosity	%	14.4	12.0
Static modulus of elasticity in compression	MPa	36 000	35 700
Poisson's ratio in compression	–	0.17	0.12
Shrinkage	%	0.006	0.006
Temperature expansion coefficient at 20–80°C	$\times 10^{-6}$	–	10.06
Thermal conductivity	W/m K	–	1.57

Notes: SC-G1 – Silica-concrete with granite-1 coarse aggregate (see Table 2), SC-Q – those quartzite coarse aggregate (see Table 2).

The basic properties and indices of SC that contained (by parts) high silica glass with 90% SiO_2 (vitreous silica) – 1.0, fine ground quartz sand (highly dispersed crystal silica) – 0.9, natural quartz sand (fine aggregate) – 0.9, quartzite or granite crushed stone with grain size of 5–20 mm (coarse aggregate) – 4.3 and water – 0.44 are illustrated in Table 1 [4].

Taking into account the special composition and structure of the cementitious agent-quartz bond it can be expected that SC will give high resistance in acid media.

The present paper considers certain aspects of SC behaviour in sulphuric acid during long term permanent immersion and acid cyclical action.

2. Experimental

2.1. Materials

The SC mixtures were made using the following materials:

High silica glass: Glass contained approximately 90% SiO_2 and 10% Na_2O. It was crushed in a hammer crusher and screened on sieves. The 0.315–1.2 mm fraction was separated out and used as the vitreous silica component of SC to yield the quartz bond.

Fine ground quartz sand (*highly dispersed crystal silica*): Fine ground quartz sand was prepared by grinding of the natural quartz sand with an SiO_2 content of 98% in a ball mill. Its specific surface was of 430 m^2/kg (after Blaine) as defined in ASTM C204.

Aggregates: *The coarse aggregate* was prepared by crushing monomineral (quartzite) and polymineral (granite of two deposits, diabase and basalt) rocks. It had a nominal maximum size of 19 mm.

The fine aggregate was a natural quartz sand with an SiO_2 content of 98%.

The physical properties of both the coarse and fine aggregates as defined in ASTM C127-88, C127-93, C136-92 and C29/C29M-91a are shown in Table 2.

Water: Common tap water was used.

Brick RP3: Made in the former USSR (USSR Standard 9221-91 "Acid resistant ceramic products for chimney"), was used for comparison for the constant and cyclical tests of durability in the sulphuric acid.

Aggressive media: The sulphuric acid was chosen as a representative of an acid aggressive medium that is frequently used in practice. 10% (1.1 M), 30% (3.7 M) and 70% (11.5 M) H_2SO_4 were used in the experiments.

2.2. Silica-concrete composition

The above described SC composition was taken as a basis and adjusted with respect to the weight of consumed materials in accordance with their physical properties (Table 2).

2.3. Preparation of specimens

Test specimens were prepared according to the following scheme. Firstly, a concrete mixture was prepared. High silica glass, fine ground quartz sand and fine and coarse aggregates were premixed in a laboratory fixed-drum concrete mixer for 2 min. Water was then added to the mixture, and the mixing continued for another 2 min. Secondly, specimens of required sizes

Table 2
Properties of aggregates

Properties	Unit	Coarse aggregate, 4.75–19.0 mm					Fine aggregate
		Monomineral rock	Polymineral rock				Natural quartz sand
		Quartzite	Granite-1	Granite-2	Diabase	Basalt	
Density	kg/m^3	2.63	2.68	2.65	2.91	2.87	2.65
Bulk specific gravity	kg/m^3	1360	1400	1390	1410	1430	1640
Voids ratio	%	48.3	48.0	47.5	51.5	50.0	38.1
Absorption	%	0.29	0.20	0.40	0.75	0.34	1.1
Acid resistance in 30% H_2SO_4, AR	%	100.0	91.8	96.9	86.1	89.1	–
Fineness modulus	–	–	–	–	–	–	1.55

Note: Acid resistance (AR) of the aggregate rock was defined in the accelerate method that is described on p. 4.

(100- and 70-mm cubes) were shaped in steel molds vibrating on a standard vibratable for 1.5–2 min. The interval between the formation of a specimen and the start of its curing did not exceed 6 h.

The molds plus specimens were placed into a laboratory autoclave in which the required temperature and pressure were produced by saturated steam. Test samples were cured under conditions where steam pressure was raised to 1.2 MPa (temperature 187°C) for 3.5 h, isothermal exposure at 1.2 ± 0.05 MPa took 21 h and steam pressure was lowered to atmospheric pressure for 3.5 h.

The 100 × 100 × 100 mm specimens served to determine the behaviour of SC under constant and cyclical action of the sulphuric acid. Table 3 presents an inventory of these specimens.

The 70 × 70 × 70 mm specimens of SC based on monomineral quartzite crushed stone were used for examining its permeability under conditions of sulphuric acid capillary suction. At the molding stage, bronze electrodes 1.5 mm in diameter and 50 mm long with wire outlets were embedded into the specimens (Fig. 1). The electrodes were placed at the center of the specimen parallel to one of its surfaces at distances of 20, 30, 40 and 60 mm. After autoclave treatment, the specimens were dried to stable weight, and four side surfaces were hermetically coated by the acid resistant polymeric composition. Before the tests started the specimens were stored in a dessicator with calcium chloride.

2.4. Testing of specimens

Acid resistance. Acid resistance (AR) of the rocks used for preparing aggregates was determined by an accelerated method. This method was developed especially for the aggregates of acid resistant materials [5]. The dried rock sample with a mass of 1 g and grain size of 0.5–1.0 mm was boiled in 30% H_2SO_4 for 1 h, removed from the acid, cooled to 18–22°C, washed in water and dried to a constant weight at 105°C. The sample was then sieved on a No 35 sieve (square opening of 0.5 mm) and the sieved residue weighed. Acid resistance of a rock *R*, percentage, was calculated as follows:

$$\mathrm{AR} = 100 - [(M_\mathrm{i} - M_\mathrm{f})/M_\mathrm{i}] \times 100 = (M_\mathrm{f}/M_\mathrm{i}) \times 100\%,$$

where AR is the acid resistance, %; M_f the mass of the residue on sieve N°35, g; M_i the mass of the initial sample, g and $M_i - M_f$- mass loss of sample, g.

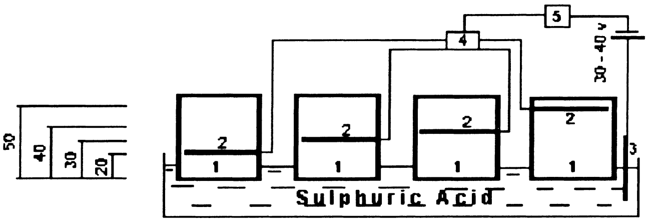

Fig. 1. Test set-up for determination of capillary suction permeability of SC: (1) 70 × 70 × 70 mm specimens with sidelong acid resistant sealing; (2, 3) bronze electrodes: Ø 1.5 mm, $L = 50$ mm; (4) switch and (5) AC resistance measurement.

Table 3
Inventory of specimens for constant and cyclical tests of SC in sulphuric acid

Designation of batch specimens	Rock	Medium
Monomineral aggregate		
IQ-10Cn	Quartzite	10% H_2SO_4
IQ-10Cy	Quartzite	10% H_2SO_4
IQ-30Cn	Quartzite	30% H_2SO_4
IQ-30Cy	Quartzite	30% H_2SO_4
IQ-70Cn	Quartzite	70% H_2SO_4
IQ-70Cy	Quartzite	70% H_2SO_4
Polymineral aggregate		
IIG1-10Cn	Granite-1	10% H_2SO_4
IIG1-30Cn	Granite-1	30% H_2SO_4
IIG1-70Cn	Granite-1	70% H_2SO_4
IIG2-30Cn	Granite-2	30% H_2SO_4
IID-30Cn	Diabase	30% H_2SO_4
IIB-30Cn	Basalt	30% H_2SO_4

Notes: Cn – designates the specimens tested after constant prolonged action of the sulphuric acid (constant tests), and Cy – those tested after cyclical action of the sulphuric acid and desiccation (cyclical tests).

In order to determine the stability of SC in the sulphuric acid, two separate tests were performed: long term immersion (constant) tests and cyclical tests.

Constant tests (*Long term immersion tests*). The batches of specimens IQ-10Cn, IQ-30Cn, IQ-70Cn, IIG1-10Cn, IIG1-30Cn, IIG1-70Cn, IIG-230Cn, IID-30Cn and IIB-30Cn were exposed in containers containing either 10, 30 or 70% H_2SO_4. After 30, 90, 180, 365 or 730 days they were taken out of the containers, inspected, weighed and tested for compressive strength.

Cyclical tests. Before tests were commenced, the batches of specimens IQ-10Cy, IQ-30Cy and IQ-70Cy were placed for 96 h in 10, 30 or 70% H_2SO_4. They were then removed from the acid and 6 specimens of each batch were tested to determine the initial compressive strength. The remained specimens were transferred into covered stainless steel containers with tubes in their lids for the removal of the vaporizing acid. One cycle of tests consisted of the following. The containers with specimens of a defined batch were put into individual drying ovens where they were heated for 4 h at the corresponding boiling temperature of the sulphuric acid (110°C for 10 and 30% H_2SO_4, 170°C for 70% H_2SO_4) and then cooled to the ambient temperature. After cooling, the specimens were taken out of the containers and placed for 4 h into 10, 30 or 70% H_2SO_4 solutions at 20 ± 2°C. After 10, 25, 50, 100 and 125 such cycles they were immersed in their respective H_2SO_4 solutions for 96 h, inspected, weighed and tested for compressive strength.

Capillary suction permeability. A dried specimen was immersed with its non-insulated side 10 mm deep into 10, 30 or 70% H_2SO_4. Periodically (3 times a day in the first week and once a day subsequently) measurements were taken of the electric resistance of the material layer between the electrode inside the specimen and the same electrode dipped into the acid at the time of measurement (Figure). With the increase in sulphuric acid capillary suction the resistance of the material layer falls drastically. Tests were finished at the moment when no changes in resistance of SC could be detected.

3. Results

3.1. Constant tests

Test results of SC with monomineral and polymineral coarse aggregates are presented in Tables 4 and 5.

SC with monomineral quartzite aggregate. Table 4 shows that the compressive strength of specimens IQ-10Cn was decreased only slightly (by 2.3%) after a 30-day exposure in 10% H_2SO_4. After being kept in 30% H_2SO_4 for the same period of exposure, the compressive strength of IQ-30Cn specimens remained unchanged. The compressive strength of specimens IQ-70Cn in 70% H_2SO_4 rose slightly (by 1%). During this time the acid penetrated into the specimens to a depth of 1–2 mm. The sharpest drop in strength of all specimens was noted from 90 to 180 days of exposure; by 13.7–25.0% in comparison with the initial compressive strength. The layer thickness of SC, which was impregnated by acid reached a depth of 8–12 mm.

After the 180-day period, the behaviour of SC in the sulphuric acid changed. By the end of the first year (365 days) of immersion in 10% H_2SO_4 the fall in specimens IQ-10Cn's strength slowed. Their compressive strength was 48.0 MPa, and acid permeated into the material to a depth of 20–25 mm. In contrast the compressive strength of IQ-30Cn and IQ-70Cn specimens in 30 and 70% acid was correspondingly increased by 1.8 and 3.1 MPa, respectively, in comparison with the strength of specimens after 180 days. By that time the penetration depth of the 30 and 70% H_2SO_4 in specimens was 10–20 mm.

When the immersion time of all specimens in the acid was increased from 365 to 730 days, their compressive strength was practically unchanged regardless of acid concentration. The acid penetration depth remained the same as after 365 days. The exterior of the specimens did not change in comparison with its initial state, and no traces of corrosion (cracks, corner chipping etc.) were discovered.

Table 4
Constant tests of SC with monomineral quartzite and polymineral granite-1 aggregates in sulphuric acid

Exposure, days	Compressive strength, MPa					
	Quartzite			Granite-1		
	IQ-10Cn	IQ-30Cn	IQ-70Cn	IIG1-10Cn	IIG1-30Cn	IIG1-70Cn
0	65.0	65.0	65.0	68.1	68.0	68.1
30	63.5	65.0	65.4	64.0	55.0	66.3
90	61.3	64.3	64.5	56.5	37.5	58.6
180	48.8	54.0	56.1	50.2	27.0	52.1
365	48.0	55.9	59.2	42.1	15.0 [a]	35.0
730	47.8	55.9	59.6	41.5	–	0

[a] The tests were stopped.

Table 5
Constant tests of SC in 30% H_2SO_4

Exposure, days	Compressive strength, MPa					
	Aggregate					Acid resistant brick
	Monomineral quartzite	Polymineral				
		Granite-1	Granite-2	Diabase	Basalt	
	IQ-30Cn	IIG1-30Cn	IIG2-30Cn	IID-30Cn	IIB-30Cn	
0	65.0	68.0	65.5	45.0	47.0	70.5
30	65.0	55.0	62.8	25.0	36.5	62.0
90	64.3	37.5	55.0	5.4[a]	24.1	61.5
180	54.0	27.0	51.1		18.0	59.4
365	55.9	15.0 [a]	49.8		3.3 [a]	59.4
730	55.9	–	49.8			59.4

[a] The tests were stopped.

SC with polymineral aggregates. Table 4 includes results of the compression tests for SC with the coarse granite-1 aggregate in sulphuric acid of various concentrations.

Test data indicate that after the early 30-day exposure of specimens in 10–70% H_2SO_4, its compressive strength was 2.7–19.1% lower than the initial value. The smallest decrease was found with specimens IIG1-70 kept in 70% H_2SO_4 while the largest decrease was found in specimens IIG1-30 that were exposed in 30% H_2SO_4. The intermediate decrease (6%) was found in specimens IIG1-10 stored in 10% H_2SO_4. The acid penetrated to a depth of 3–5 mm in the specimens.

Subsequently strength continued to decrease especially in 30% H_2SO_4. In the period from 30 to 180 days the compressive strength of specimens in 70 and 10% H_2SO_4 was reduced by the same deep while in 30% H_2SO_4 the decrease was almost three times quicker.

From 180 days the fall in compressive strength of specimens IIG1-10 in 10% H_2SO_4 slowed, particularly after 365 days. At the end of 730 days, these specimens still preserved their shapes, no visible cracks and chipping were registered and their compressive strength was of 41.5 MPa, i.e. 60% of the initial one.

By the end of 90 days of immersion in 30 and 70% H_2SO_4, cracks up to 1 mm wide appeared in specimens IIG1-30Cn and IIG1-70Cn. As time progressed, they widened and reached 3–4 mm across by 365 days. The acid penetrated into the material to a depth of 25–30 mm. Visual inspection showed that destruction spread through the aggregate. Specimens lost their geometry (corner chipping) and their strength fell to 23.1–51.5% of its initial value.

After 730 days of exposure to 30% and 70% H_2SO_4, the specimens were completely destroyed.

Results of tests of SC based on other polymineral coarse aggregates – granite-2, diabase and basalt (specimens IIG2-30Cn, IID-30Cn and IIB-30Cn) in 30% H_2SO_4 are presented in Table 5.

As can be seen from Table 5, after 30 days of exposure under acid the strength of specimens IID-30Cn fell by 44%. By the end of 90 days their strength was no more than 12% of its initial value. The specimens were cracked and testing was stopped.

After 30 days of storage under acid, specimens IIB-30Cn lost 22.7% of their original strength. This process was continued through test the time and by 365 days their strength had fallen to a mere 7% of the initial value. Corrosion had caused partial chipping and deep cracks in the specimens' corners. Testing of specimens was also stopped.

On the whole, under prolonged action of sulphuric acid, SC with monomineral quartzite coarse aggregate is more durable than SC with polymineral coarse aggregate.

The results of two-year comparison constant tests in the most aggressive 30% H_2SO_4, point to the fact that the final compressive strength of SC with quartzite aggregate and that of acid resistant brick RP3 were rather close, differing by 6% (Table 5).

3.2. Cyclical tests

Compressive strength of specimens IQ-10Cy, IQ-30Cy and IQ-70Cy changes during the cyclical tests in 10, 30 and 70% H_2SO_4.

In the first 25 cycles, the compressive strength of specimens decreased by 29.2–37.7% (the larger values being obtained for less concentrated acid). Afterwards the fall in strength was slowed con. E25, the compressive strength was reduced by 1–3% independent of the acid concentration. By the end of testing (125 cycles) SC compressive strength equalled 36.1–43.2 MPa. The sulphuric acid penetrated into specimens to a depth of 12–15 mm. Their corners and ribs were somewhat rounded, but no cracks or chipping were visible.

It should be noted that the compressive strength of SC with quartzite aggregate was the same level as that of acid resistant brick during the whole period of their comparative cyclical tests in 30% H_2SO_4.

3.3. Capillary suction permeability

Measurements of SC resistance showed that the sulphuric acid rose in the specimens to a height of not more than 20 mm. The speed of the rise depended on acid concentration. The 20-mm level was reached by 70% sulphuric acid in 94 days, by 30% acid in 79 days and by 10% acid in 58 days. Thus at a lower concentration of acid, a correspondingly higher speed of capillary suction was obtained.

The additional determination of the corrosion for the reinforcement in SC under conditions of capillary sulphuric acid suction showed that with a protective layer of 30 mm there were only traces of corrosion on the metal rods after 365 days. Increasing the SC layer to 40 mm reliably protected the reinforcement against corrosion during the whole test period (3 years).

4. Discussion

In order to account for SC behaviour under the action of sulphuric acid, it is necessary to consider a whole complex of physical, physico-chemical and chemical processes and their effect on the properties of the material.

Physical processes. These are in liquid penetration into the solid material and its "softening" with a corresponding decrease in strength.

Physico-chemical processes. These can take place due to chemical interaction between the sulphuric acid and the coarse aggregate. These processes as a rule are accompanied by an increase in volume, appearance of cracks and a decrease in strength of SC.

Chemical processes. Among the chemical processes it is necessary to point out the interaction of sulphuric acid with sodium silicates which exists in the quartz bond of SC. Silica gel that is formed as a product of this interaction gives additional density to SC and increases its strength.

Physical, physico-chemical and chemical processes mentioned above are closely connected with period of action of the sulphuric acid, its concentration and the type of the coarse aggregate of SC.

4.1. Constant tests

SC with monomineral quartzite aggregate. Under the action of sulphuric acid on SC only the physical and chemical processes take place.

In the first 30 days of SC exposure to 10% H_2SO_4 the physical process of liquid penetration into the material and its "softening" is prevalent, and a slight decrease in specimen strength was registered. In more concentrated sulphuric acid, chemical processes are dominant and SC strength in 30 and 70% H_2SO_4 is higher than that in 10% H_2SO_4. It remained at the initial level (in 30% H_2SO_4) or even exceeded this level (in 70% H_2SO_4). The higher strength of SC in 30 and 70% H_2SO_4 in comparison with that for 10% H_2SO_4 can be explained in that the chemical processes apparently proceed completely in the more concentrated acid. They are favourable for forming a greater quantity of silica gel and thus better compaction of SC structure. This compensates for SC "softening" to a greater extent than in the case of 10% H_2SO_4. The higher strength of SC in 70% H_2SO_4 than strength in 30% H_2SO_4 can be also accounted due to the same reasons.

With an increase in the duration of the tests from 30 up to 180 days, physical processes play the leading role under all acid concentrations and SC strength is decreased. As this take place the interrelation between the strength and acid concentration in this period was similar to that after 30 days of exposure, i.e. the higher the acid concentration, the higher the strength.

After 180 days in 10% H_2SO_4 physical processes continue to exert primary control over SC strength. However their effect is expressed in only a small decrease of strength since the material penetration with acid slows and by 365 days practically stops. The compressive strength of specimens additionally decreases by 1.5%. By the end of 2 years of immersion in 10% H_2SO_4, strength undergoes almost no changes. At the same time, in 30% and 70% H_2SO_4, chemical process becomes prevalent resulting in increased strength of SC, and the higher the acid concentration, the greater the material strength. The impregnation of specimens approximately finished by 365 days after which stabilization of their strength was observed until the end of testing at 730 days.

SC with polymineral aggregates. On immersion of SC with polymineral aggregates in the sulphuric acid physical, physico-chemical and chemical processes occur as the H_2SO_4 interacts with the material and its components. Their course can be described by the example of SC with the granite-1 aggregate.

During the first 180 days the physico-chemical processes of acid interplay with granite are the determining factors in strength changes of SC. This is apparent from Table 4: strength drop of specimens of SC with granite-1 aggregate for 10, 30 and 70% H_2SO_4 is greater than that on the monomineral quartzite aggregate. Since SC with monomineral quartzite aggregate is not subjected to the action of the physico-chemical processes, the lesser strength of SC with granite-1 aggregate can be assigned to these processes. As for the influence of the acid concentration on strength of SC, 30% H_2SO_4 was the most aggressive at all stages of tests up to 730 days. After 180 days the effects of the chemical processes usually lead to strengthening of SC and the influence of the acid concentration is manifested by the fact that the compressive strength of specimens IIG1-70 under the more concentrated acid (70% H_2SO_4) is higher than under the less concentrated acid (10% H_2SO_4). The analogous effect was marked and its explanation was given when analysing the results of constant tests of SC with monomineral quartzite aggregate.

After 180 days, the physico-chemical processes play a leading part as before. The interaction of 70% H_2SO_4 with the granite-1 aggregate and destruction of SC becomes so strong that by the 365th day its strength is lower than under 10% H_2SO_4. After 730 days destruction is extensive and the specimens lose any clear-cut shape. Under 10% H_2SO_4 by 180 days, acid action on the granite-1 has no such negative effect. Beginning from 365 to 730 days equilibrium is established between the negative physical and physico-chemical processes and the positive chemical processes so that SC strength remains almost unchanged.

The physico-chemical processes generating a disintegration of SC and a fall of its strength are directly linked with acid resistance of the aggregate rock. For instance, strength of IID-30Cn specimens made from SC with the less acid resistant diabase aggregate (AR = 86.1%) was lower than that of SC specimens IIB-30Cn with the more acid resistant basalt aggregate (AR = 89.1%). The compressive strength of IIB-30Cn and IID-30Cn specimens of SC with coarse aggregates from the less acid resistant basalt and diabase rocks was much less than that of IIG1-30Cn specimens of SC with coarse aggregate from the more acid resistant granite-1 rock with AR = 91.8%. In turn IIG1-30Cn specimens prepared with granite-1 demonstrated less compressive strength than IIG2-30Cn specimens of SC with the more acid resistant granite-2 aggregate (AR = 96.9%). Besides, to the certain date of tests the strength of specimens IIG2-30Cn fell more slowly than that of specimens IIG1-30Cn. To the end of testing (730 days), the specimens IIG2-30Cn had a satisfactory exterior without visible damage.

4.2. Cyclical tests

The changes occurring for SC with monomineral quartzite aggregate in constant tests as well as in cyclical tests are similar. The differences are as follows: When SC is kept under acid before the test start, the acid impregnates to a depth of 1–2 mm and simultaneously interacts with sodium silicates, creating silica gel in the empty pores of SC without any expansion. Heating specimens for 4 h at sulphuric acid boiling temperatures is accompanied by their incomplete desiccation. Besides vaporization of the sulphuric acid and the dehydration of the silica gel, compression of the system, with the emergence of internal stresses and resulting cracks, takes place in the layer of the drying material. Repeated desiccation and wetting under acid is accompanied by sign-changing deformations in the surface layer of the material and by additional internal stresses resulting from the silica gel dehydration as well as from microcracks being widened by the acid. After a certain number of cycles all this leads to a lowering in the mechanical strength of SC. The most strength lowering was observed in the first 25 cycles. By that time voids appear in the silica gel as revealed microscopically. Subsequently, (after more than 25 cycles) the silica gel accumulating in the SC makes it almost impermeable to the sulphuric acid, which is indicated by the insignificant decrease in strength after 25 test cycles.

4.3. Capillary suction permeability

Two conditions must be taken into account when dealing with capillary suction permeability of SC. Firstly, at contact of SC with the sulphuric acid, the chemical processes of forming silica gel immediately begin. Gel accumulates in the pores of the material, packs it and inhibits suction of acid. The lower the acid concentration the slower the gel creation and capillary suction continues with prolonged contact. Secondly, the lower the concentration of H_2SO_4 the lower its viscosity and thus the acid travels easier through capillaries.

As a result, the lower the acid concentration the higher the capillary suction rate and SC is more permeable to acid. These factors should be noted when designing for aggressive acid media.

5. Conclusions

The following conclusions can be drawn from the present study.

1. SC stableness to sulphuric acid under its constant prolonged and cyclical action depends on the concentration of acid and on the acid resistance of the coarse aggregate rock.
2. The greatest durability to the sulphuric acid is displayed by SC with the coarse aggregate from monomineral quartzite rock.
3. It is expected that SC will be resistant to other acid media especially with the correct choice of coarse aggregate.
4. Capillary suction permeability of SC depends on the sulphuric acid concentration. SC is the least permeable to the acid with the highest concentration (70% H_2SO_4). An SC layer of 40 mm reliably protects the reinforcement against corrosion under conditions of acid capillary suction.
5. SC behaviour under the action of sulphuric acid can be explained by consideration of physical, physicochemical and chemical processes and their connection with the period of acid action, its concentration and the type of coarse aggregate of SC.

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