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Creep of Cement Concretes.

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ABSTRACT

It is believed that cement concretes in the absence of external aggression preserve and improve their properties for indefinitely long time. In fact, concrete is not something “given to us to the end of time", which is evidenced by a large amount of empirical data indicating periodic occurrence of internal stresses in cement stone, which weaken the material and reduce its strength. The aim of this work is not so much to study creep as a specific rheological parameter; it is related to the need to attract the attention of professionals to the specific phenomena, accompanying this process, and their theoretical interpretation that must be taken into consideration, clarified and developed in the course of further research.

Keywords: concrete, structures, creep, elastoviscoplastic material, destructive phenomena.

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INTRODUCTION

Hardened "concrete is elastoviscoplastic material, the behavior of which in case of fast (instantaneous) loading largely obeys the generalized Hooke's law. In case of continuous load, it has the property of creep, i.e. shows the capacity for inelastic deformations, only partially reversible in the process of unloading" [1]. A clear notion of the physical essence of the mechanism of this phenomenon, the impact of different technological factors and environment on creep play an important role in the well-founded development and construction of concrete and reinforced concrete structures with low energy intensity, having the required strength and deformation properties, improved resistance and reliability. But there are certain gaps in the analysis of this issue. In particular, there is still no single point of view regarding the causes of the weakening of the structure of cement concretes and the manifestation of significant deformation properties in case of applying a compressive load which is much lower than the strength parameters of the composite.

In this regard, there are different opinions. The phenomenon of creep (inelastic strain of loaded material) is seen as a result of viscous (fluid-like) flow of concrete without disrupting its continuity (Reiner), formation and development of microcracks (O.Ya. Berg, Glyuklikh, Z.N. Tsilosani), squeezing adsorption-bound (colloidal) water out of cement stone and capillary shrinkage (G. Hansen, R. L'Hermite, E.P. Freyssinet). There are also assumptions of the possibility of the combined action of the above-mentioned phenomena, for example, by crystalline shift, viscous flow (similar to that of bitumen) and infiltration of adsorbed water from cement stone (R.E. Davis, G.E. Davis) or deformation of the gel component of cement stone, capillary factor and microfracturing (S.V. Aleksandrovskiy, K.S. Karapetyan, I.E. Prokopovich), or due to thermal fluctuations and mechanical stresses, leading to the destruction of weak coagulation contacts and gradual transfer of force to hard crystalhydrate frame (S.V. Zhurkov, B.N. Nurzulaev, A.E. Sheykin), or due to mutual sliding of the crystals of a cement aggregate on the basal planes, periodic breaking of intercrystalline bonds and emergence of new ones (A.A. Gvozdev, A.V. Yashin).

Without questioning the rightfulness and validity of the stated hypotheses, it is impossible not to note the following issues, which are difficult to explain and hardly yield to logical interpretation on their basis:

1) the presented destructive phenomena (formation and development of microcracks, destruction of structural bonds of stone, removal of bound water, etc.) would certainly have a most negative impact on the properties of concrete; "a sharp reduction of strength and elasticity modulus during unloading would take place. At low stress, creep doesn't cause such phenomena: strength and elasticity modulus remain practically unchanged" [2]. Moreover, strength not only remains the same, but in some cases significantly increases (which is convincingly shown in numerous and widely known works [3-5] on early loading of reinforced concrete structures);

2) hardened cement stone (concrete) is usually regarded as mechanical composition of crystalhydrate aggregate, gel (amorphous) component, not fully hydrated clinker grains, pores, cavities, capillaries, adsorption-bound water and other structural objects with specific and invariable (anyway, during testing) properties, which is hardly true. Like any organism, concrete, even the most mature one, is extremely sensitive to external factors (including force impact), immediately responds to the impact and instantly adapts its structure and properties in accordance with changing operating conditions [6];

3) creep deformation is regarded as a consequence of purely physical and mechanical processes taking place in cement stone under load (shift of structural elements, microfracturing, squeezing free and adsorption moisture, capillary compression of the system, etc.). At the same time, the researchers don't take into account the possibility of chemical transformations; "the impact of chemical processes is completely ignored" [7-9]. But these processes are inevitable in view of the deformation of structural elements, the possibility of the breaking of molecular (including hydrogen) bonds, formation of active, highly reactive energetically unsaturated zones.

METHODS

The experimental work conducted in cooperation with the student research group of the North-Caucasian Branch of the Belgorod State Technological University named after V.G. Shukhov (Drokov A.V., Aganova A.Yu., Esipova A.A., Ul'fanov G.V., Kozyrenko M.A) made it possible to provide some explanation of the issue under consideration. The most important stage of testing, which largely determines the end properties of a product, is the initial stage, during which the deformation of concrete is particularly intensive. Therefore, the methodical implementation of works slightly differed from the requirements of GOST 24544 (Methods of shrinkage and creep flow determination). Creep was determined using the samples having the size of 40x40x160 mm, the central loading of which with the force 280...285 kN (2800...2850 kg), amounting to of 0.3...0.5 of breaking load, was implemented using a hydraulic press and a reference compression dynamometer DOSM-3-5. The value of axial deformation was recorded using the dial gauge supplied with the dynamometer (with the conversion factor 0.7). During the first five days, the test was carried out under natural conditions (Figure 1, a), while during the following four days – with one-side heating (Figure 1, b). In the latter case, the surface temperature of the samples reached 100...120 °C.

Of course, in the process of the axial deformation of the samples (compression in case of loading or expansion in case of heating) a slight change in the value of their load was observed, due to the corresponding unloading or, on the contrary, compression of the dynamometer spring. However, it is unlikely that this aspect substantially affected the qualitative picture of the obtained results. Besides, the aim of this work is not so much to study creep as a specific rheological parameter; it is related to the need to attract the attention of professionals to the specific phenomena, accompanying this process, and their theoretical interpretation that must be taken into consideration, clarified and developed in the course of further research.

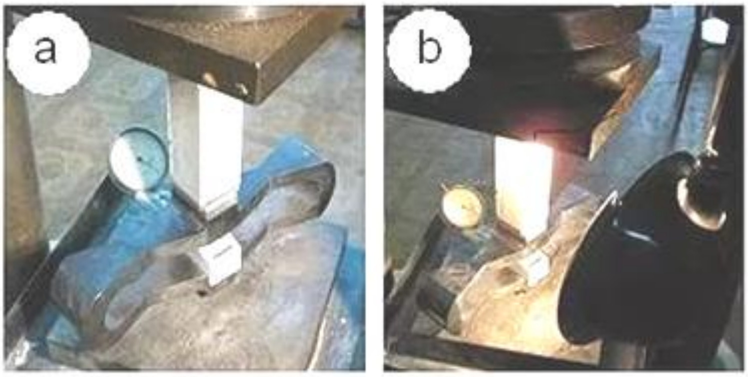

Figure 1. A plant for determining creep deformations of samples under natural conditions (a) and in case of one-side heating (b)

For the comparative analysis, the authors used the samples from stable natural (granite, marble), artificial (ceramics, silicate concrete) materials and 28-day-old cement mortars on the basis of Novorossiysk cement SSPTs500-D20, made of cement paste with standard consistency (w/c = 0.28), mortar mix with a composition cement:sand = 1:2 with w/c = 0.60; 0.50 (with the addition of superplasticizer based on polycarboxylate resins in the amount of 1.5% of the weight of cement) and 0.45 at the age of two years (with fivefold cyclic vibration during hardening). Until testing, the cement samples were held under conditions excluding the dehydration of the material. During the initial period of testing (in particular, during the initial stage of heating) measurements were carried out every 1...2 hours, during intermediate periods – once a day. For clarity and the ease of the analysis of the results, the initial state of the sample corresponded to the “zero” mark on the chart, while shrinkage and expansion phenomena (exceeding the “zero” value) were reflected in negative and positive areas of the deformation axis.

Despite the similarity of appearance of the obtained curves (Figure 2), what stands out is the following:

1) the creep deformation of the samples based on 28-day-old cement mortars (Figure 2, b) is more than an order of magnitude higher than the corresponding figures for stable structures (Figure 2, a);

2) the deformation of the latter (including silicate concrete) “fades out” till the second or third day, whereas for cement mortars (except for the 2-year-old vibration-activated sample) it is constantly increasing in the given time interval;

3) one-side heating understandably results in the initial thermal expansion of the samples with the preservation of the “deformation trend” for stable structures and “exploding” growth of the creep of cement mortars;

4) in the final stage of testing, the deformation of stable materials (marble, granite, etc.) stops, and a noticeable reduction of the intensity of the creep of cement samples is observed;

5) an increased water-cement factor plays an intensifying role in the creep, whereas the age of the concrete, on the contrary, significantly levels down the deformation phenomena, which is consistent with the generally known concepts [8];

6) the plasticized cement mortar with w/c = 0.5 has the highest creep; its deformation properties exceed those of plain cement mortar even with higher water content (w/c = 0.6).

Such significant differences of the creep dynamics of stable materials (granite, marble, silicate concrete and ceramics) from the deformation of cement mortars are related to exceptionally individual structural features of the latter, namely, to the existence of "not fully hydrated clinker grains." Hence, it is possible to draw a conclusion about an important (even decisive) role of these chemically not fully used objects in so clearly expressed deformation properties of loaded cement stone and concrete. In other words, one of the quite real mechanisms of the creep of loaded cement concrete is the chemistry of the process — the activation of the interaction of cement minerals with adsorption-bound water by force action in the later stages with the inevitable weakening of the structural bonds.

DISCUSSION AND RESULTS

A characteristic feature of a hydrated cement grain is the presence of locally dispersed dynamically balanced structures "residual unhydrated active centers – adsorbed clusters" on its surface, persisting under normal conditions for quite a long time. However, the balance of these compositions may be upset by various previously mentioned impacts, including force impact. Compressive load deforms the structural elements of cement stone, which results in mutual perturbation of the above-mentioned compositions (Figure 3), excitation, activation of adsorbed dipoles and hydration of active centers.

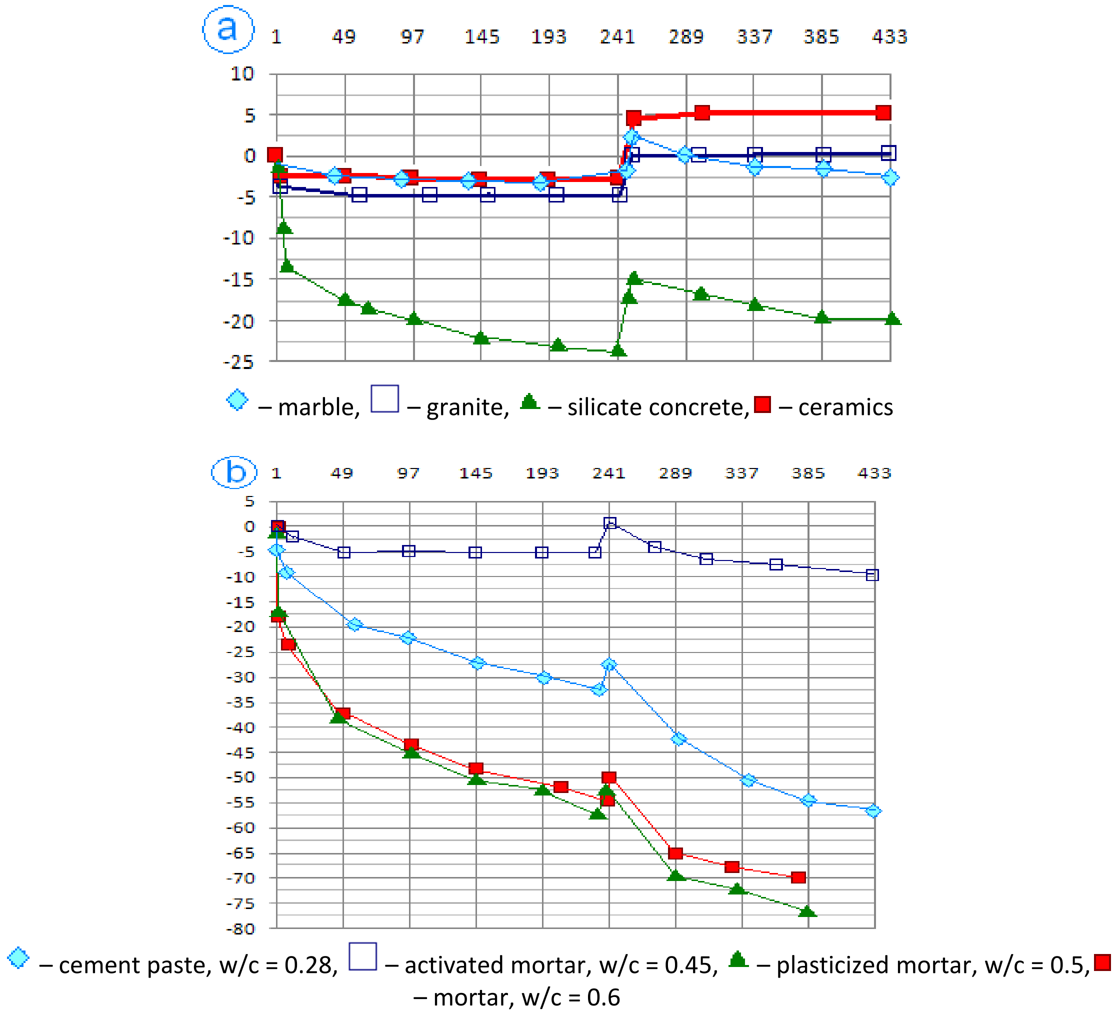

Figure 2. Creep deformation of stable structures (a) and cement compositions (b)

The combination of force and temperature factors to an even greater degree initiates chemical transformations and, respectively, the creep of cement concretes, which is confirmed by the experimental data. The hydrated product, which is formed in this case, is a source of internal stresses that weaken the contact zones of clinker particles and thereby determine intensive deformation phenomena.

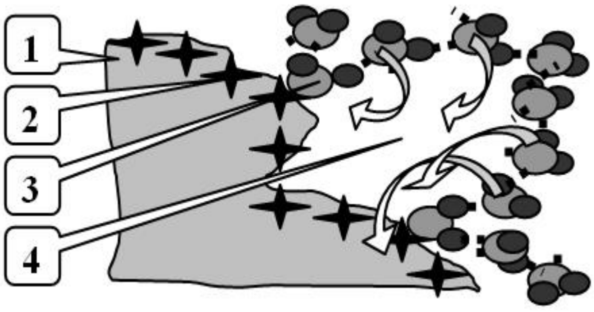

Figure 3. Schematic structure of cement stone:
1 – hydrated product; 2 – residual active centers; 3 – clinker grain; 4 – adsorption layer of dipoles

Compressive load activates adsorption-bound water, thereby contributing to the "deepening", increasing of the degree of the surface hydration of clinker particles, as compared to their reference (not loaded) state. Of course, one shouldn't expect a dramatic difference in the degree of hydration in the reference and deformed mortars, due to a slight increase in the number of hydration acts, initiated by force against the background of the previous month-long hardening. However, differential thermal and X-ray diffraction analyses of the cement stone (w/c = 0.28) clearly indicate an increase in the degree of the chemical use of Portland cement in the creep-tested mortar, as compared to the reference mortar.

The thermograms of samples (Figure 4) are characterized by three endothermic processes, related, respectively, to the removal of free and adsorption-bound water, partial dehydration of lime and decomposition of hydrosilicate products. At the same time, the latter endothermic effect is especially strongly pronounced in the deformed sample; besides, an additional effect is clearly seen, related, most probably, to the emergence of "modified hydrates" [10-12] developed under the conditions of the pressure of the cement composite, the thermal factor and limited water content.

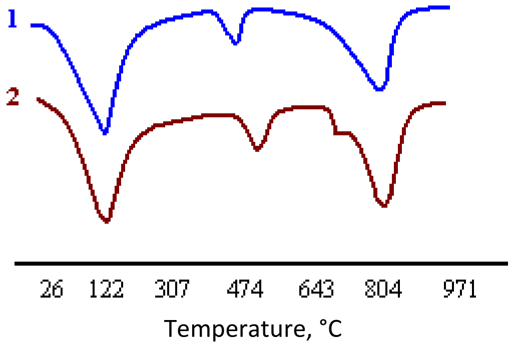

Figure 4. Differential thermal analysis of the reference (1) and creep-tested (2) cement stone

The radiographs of the considered mortars (Figure 5), at first glance, are little different from each other. However, one cannot fail to see a slightly higher content of calcium hydroxide in the creep-tested sample (diffraction maximum with d = 4.917...4.920). Further hydration of calcium silicates resulted in more complete hydrolytic processes and the release of the increased amount of calcium ions (lime) from the structure of minerals into the fluid medium, which was recorded during the experiment.

A dominant role in many "anomalies" of cement concretes at later stages ("self-testing", periodic drops of strength), including intensive creep, is played by "delay-action mines" – energy structures "residual active centers –adsorbed water layer", locally distributed on the surface of the hydrated cement particles [13].

To reduce the likelihood of triggering these "mines", as noted above, it is necessary to use a range of measures to ensure maximum possible completeness of surface hydration transformations of clinker grains.

In this regard, the conditions of the hardening of concretes are of great importance, which is confirmed by the following experiment. From the mortar mix with the composition 1:2 (Novorossiysk cement SSPTs500-D20, Kuban low-modulus quartz sand, w/c = 0.5), a series of bar samples was manufactured, which were hardened before testing under stripped-off (natural) conditions, in water environment, hermetically sealed by plastic film at a "normal" temperature and after eight-hour-long boiling (after a day of precuring), and at a low temperature (+2...+7 °C). At the age of one month, a test according to the above-described methodology was performed, after which the strength properties of unloaded and reference (not tested) samples were determined.

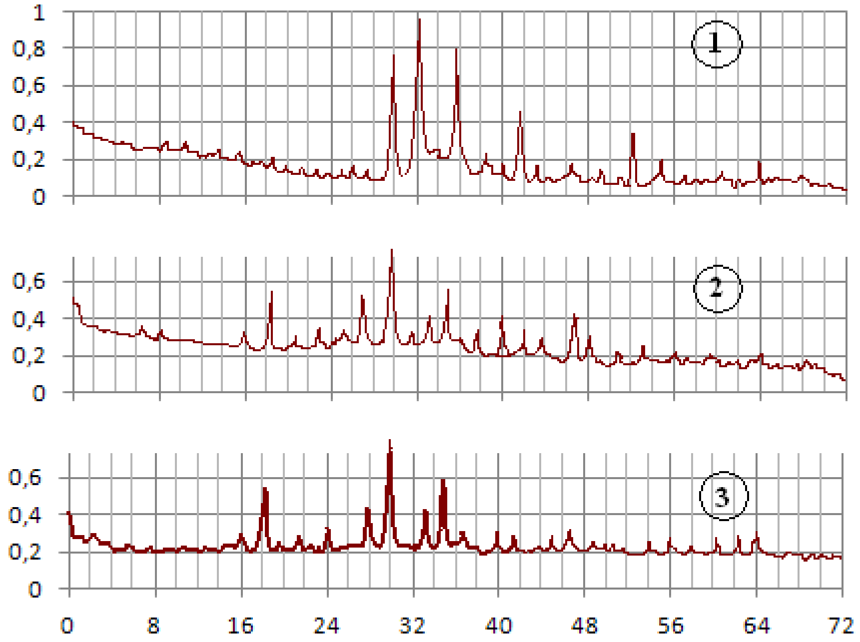

Figure 5. X-ray diffraction analysis of the initial cement (1), reference (2) and creep-tested (3) cement stone

The analysis of the deformation curves, presented in Figure 6, shows that the increased structural stability of micro-concrete is achieved in case of water, hermetically sealed hardening and in case of using heat treatment. The stable amount of water in intergranular cavities, reliable insulation of concrete, preventing dehydration, and thermal activation of water molecules provide a high degree of surface hydration processes, which is accompanied by rather close, relatively low deformation properties. At the same time, the samples, hardened under natural conditions, couldn't be tested for creep due to their destruction when loading (which explains the absence of the corresponding curve on the specified chart). Most probably, the dehydration of concrete during hardening resulted in incomplete hydration of clinker grains, formation of weak and defective structure of micro-concrete, including huge residual unhydrated areas, "triggered" by force impact and causing the destruction and weakening of the composite with the above-mentioned result. At low positive temperatures, water is characterized by highly associated, low-activity form with a low evaporation rate, which significantly slows down (but not stops) surface and hydration processes [14]. As a result, rather strong micro-concrete, able to sustain force impact, is formed; however, the presence of extensive residual energy compositions leads to the force activation of electrochemical interaction of reagents, the weakening of the structural bonds of the stone and increased creep deformation.

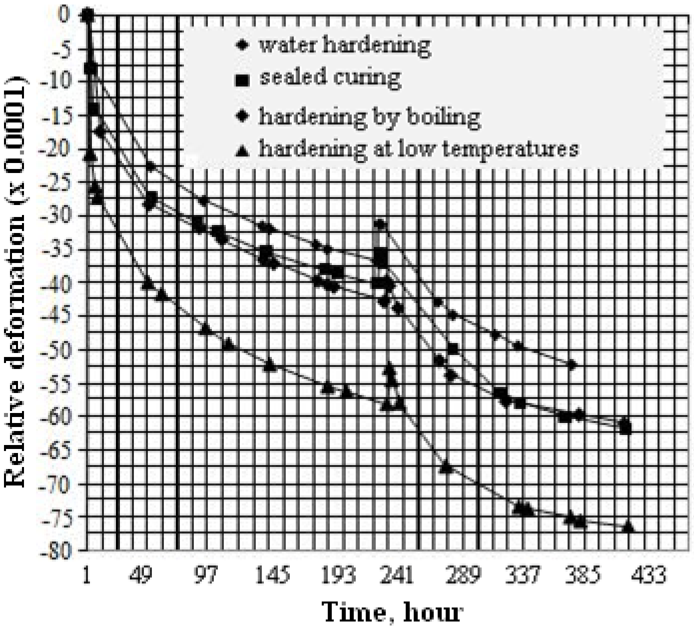

Figure 6. Creep deformations of the samples hardened under different temperature and humidity conditions

The structure of micro-concrete, as it has been noted, is extremely sensitive to the change in external temperature conditions, which is illustrated by the creep deformation curve of the sample (Figure 7, a) at a normal test temperature (Figure 1, a) for a period of five days, with one-side (Figure 1, b) and two-side heating during four and three days, respectively. At a normal temperature deformation "fades out" till the fourth or fifth day. In cases of one- and two-side heating, short-term extension, lasting 20-30 minutes, is followed by even more intense shrinkage phenomena.

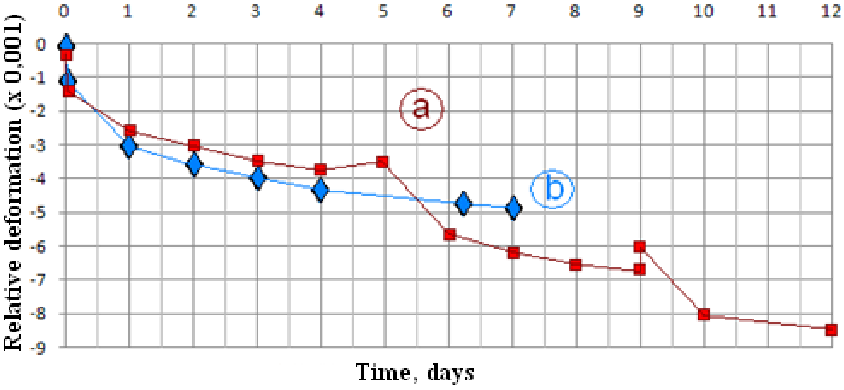

Figure 7. Kinetics of the deformation of the samples under different experimental conditions

Despite such significant creep parameters (Figures 6, 7), the appearance of samples after tests, in the vast majority of cases, didn't give cause for concern (clearly defined edges and faces, absence of fractures, cracks and other visible defects). It can be assumed that the test methodology (using open surface of samples) contributes to the participation in chemical process only of the part of adsorption-bound water, a significant share of which is removed from the concrete structure during heating as a result of mass exchange with the environment. The curing of the samples, insulated by plastic film, under load in molten paraffin at a temperature of 63...65 °C led to the situation shown in Figure 8. Despite the fact that the sample didn't lose its load-bearing capacity (at the load of 17.8 MPa its actual strength was about 21.9 MPa), it is not difficult to foresee its state on a short-term horizon. The sealing of the surface of the sample prevented the water loss of the concrete, contributed to the long preservation of water in its structure, its better binding by cement minerals with the corresponding destruction.

Figure 8. The appearance of the sample, creep-tested in a hermetically sealed state

The late hydration process, caused by force (thermal) impact, while leading to the destruction of cement stone and increased deformability of concretes, has also a positive aspect, namely, the capacity for "self-healing" of microdefects. Additional portions of hydrosilicate glue not only preserve the initial strength properties, but in some cases considerably improve them (Table 1). Thus, one has to agree with the opinion [15] that "in case of the long-term application of load the initial elasticity modulus of concrete is not reduced, and some studies even noted its slight increase. This is related to the fact that a long-term load of a certain level promotes the migration of free liquid, which ... forms new hydrated products." Moreover, this process (including the effect of "self-healing") is only characteristic for cement concretes which differ from stable materials (natural stone, ceramic, silicate materials, plastic concretes) in the presence of residual unhydrated areas on hydrated cement particles.

Attention should be paid to the 10% decrease in strength in case of the compression of the samples of the compositions "1" and "8" after the creep test. Most probably, in conducting such experiments account must be taken of the "time factor" of the determination of the strength properties of samples. The "self-healing" of the structure of deformed micro-concrete requires a definite and specific time interval; therefore, strength and other properties of concrete should be determined after the expiry of a structural "rehabilitation" (recovery) period. Premature tests (which probably took place in this case) are likely to distort the real picture and lead to incorrect results.

Table 1 Impact of creep deformation on the residual strength of the samples

No.	Type and composition of the mixture, conditions of sample hardening	Strength (MPa%) of the samples			
		Reference samples		After creep testing	
		at compressing	at bending	at compressing	at bending
1	Paste w/c = 0.28 "normal"	54.8/100	7.5/100	48.8/89.1	11.0/146.7
2	Mortar 1:2, w/c = 0.5 in a natural state	14.5/100	7.3/100	-	-
3	The same, in a hermetically sealed state	26.0/100	8.7/100	30.6/117.7	10.3/118.4
4	Mortar 1:2, w/c = 0.5 water	28.5/100	8.3/100	34.8/122.1	11.2/134.9
5	The same, cured in boiling water	21.1/100	7.9/100	32.8/155.5	14.7/186.1
6	The same, at low positive temperatures	22.8/100	-	32.4/142.1	9.5
7	The same, polycarboxylate – 1.5% "normal"	28.2/100	5.8/100	31.4/111.3	7.1/122.4
8	The same, w/c = 0.6, "normal"	29.0/100	8.0/100	26.0/89.7	9.0/112.5

CONCLUSION

The "self-healing" of the structure of deformed micro-concrete requires a definite and specific time interval; therefore, strength and other properties of concrete should be determined after the expiry of a structural "rehabilitation" (recovery) period. Premature tests (which probably took place in this case) are likely to distort the real picture and lead to incorrect results.

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