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УМНЫЕ КОМПОЗИТЫ В СТРОИТЕЛЬСТВЕ
SMART COMPOSITE IN CONSTRUCTION

SCIENTIFIC ARTICLE

Assessment of biological aggressive environment effects on the strength properties and structural-phase composition of concrete

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The article points out the lack of radically effective worldwide methods of anti-biocorrosion protection. The author considers the role of microorganisms on concrete corrosion, describes the mechanisms of biological effect and biofilm formation on concrete surface. The article focuses on the determination of causes and peculiarities of cement concrete biocorrosion in conditions of high humidity. According to the author, biocorrosive impact reduces strength characteristics of concrete and causes its fast destruction. The author has revealed changes in structural-phase composition of concrete during surface biofouling. Although there are available methods to increase the bio-resistance of cement-based concretes, it is problematic to guarantee their preservation because bio-destructors have the ability to adapt to the work environment. The paper attempts to assess and predict the resistance of a building material in a biologically aggressive environment properly.

Keywords: concrete, biofilm, biodegradation, corrosion, durability

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НАУЧНАЯ СТАТЬЯ

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Оценка влияния биологически агрессивной среды на прочностные характеристики и структурно-фазовый состав бетона

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Отмечается недостаток кардинально действующих в мире способов антибиокоррозионной защиты. Рассмотрена роль микроорганизмов при коррозии бетона, описаны механизмы биологического воздействия и образования биопленок на поверхности бетона. Акцентируется внимание на установлении причин и особенностей биокоррозии цементных бетонов, эксплуатируемых в условиях повышенной влажности. Установлено, что воздействие биодеструкторов снижает прочностные характеристики бетона, приводит к быстрому его разрушению. Выявлены изменения структурно-фазового состава бетона при биообрастании поверхности. Несмотря на известные способы повышения биосопротивления цементных бетонов, проблематично гарантировать их сохранность, поскольку биодеструкторы обладают способностью приспособиться к эксплуатационной среде. Предпринята попытка адекватной оценки и прогнозирования сопротивления строительного материала в биологически агрессивной среде.

Ключевые слова: бетон, биопленка, биодеградация, коррозия, прочность

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INTRODUCTION

The area of biological corrosion of concrete still remains understudied. The issue of protecting structures against biofouling affects all sectors of the economy. Biodegradation negatively affects on the underground and aboveground structures, oil and gas industry equipment, pipeline systems, etc. The development of a systematic approach to predicting the corrosion of concrete in biologically aggressive environments is of increasing relevance due to the growth of the species diversity of microorganisms damaging the human health.

Concrete is a composite material. It has the capillary-porous structure providing the penetration of biological agents and chemical compounds from the external environment into it. Researchers differentiate several types of biocorrosion in concrete – bacterial, fungal, and algal [1]. The most dangerous for concrete are bacterial and fungal ones. Biocorrosion of concrete is most often localised and characterised by the appearance of a biofilm on its surface. *Penicillium* and *Aspergillus* fungi pose the greatest danger to humans (Fig. 1) [2].

Meanwhile, researchers have studied biofilms in many systems. Probably, since Van Leeuwenhoek examined plaque on his own teeth in the 17th century [2]. However, a theory describing the process of biofilm formation appeared only in 1978 [2, 3]. According to this theory, the majority of bacteria grow in biofilms enclosed in a matrix attaching to surfaces in aquatic ecosystems with sufficient nutrients. Decades of studies confirmed the similar formation of bacterial biofilms in any ecosystem [4].

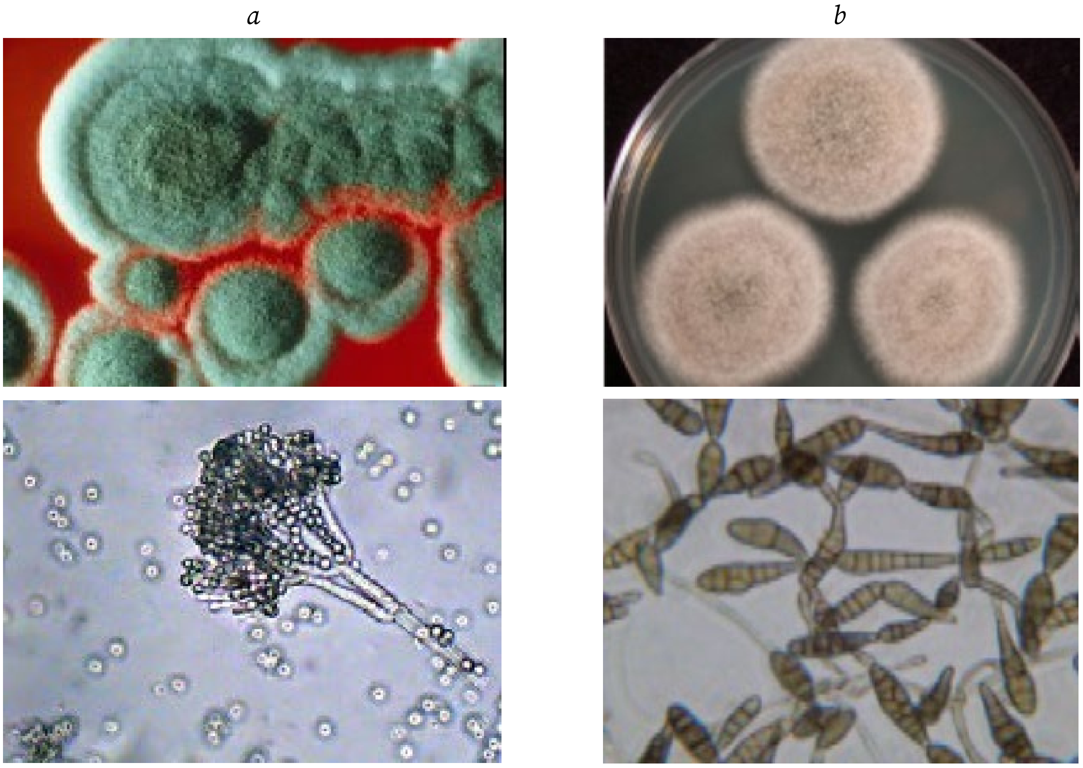

Fig. 1. Fungi of the genus *Penicillium* (*a*) and *Aspergillus* (*b*)

Some micro-organisms exist in a free state. But most often micro-organisms form biocenoses on a substrate. The process of biofilm formation involves several stages:

– Stage I (reversible process): Adhesion of microorganisms to the substrate, biofilm formation due to the interaction of physical and chemical forces between the cell wall elements of the microorganisms and the substrate;

– Stage II (irreversible process): firm attachment of the microorganisms to the substrate, characterised by loss of intercellular interaction and bacterial cell motility;

– Stage III: microbial synthesis of extracellular polymeric matter, which makes up about 85% of the mature biofilm [5];

– Stage IV: formation and growth of a mature biofilm, including attaching new micro-organisms to an existing biofilm.

As a rule, formation of tightly bound microbial colonies takes several hours [6]. In addition, biofilms can quickly regain their integrity after any mechanical impact. The roughness of the surface has no effect on the settlement of microorganisms.

Indeed, the rate of biofilm formation significantly increases in high shear conditions. Note, it is characteristic for aqueous media. Microorganisms can adhere to surfaces and initiate biofilm formation in the presence of shear forces that exceed Reynolds number. Turbulent flow enhances microbial adhesion and biofilm formation. When biofilms occur in media with low shear force, they tend to have a low tensile strength and therefore collapse easily [5-7].

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Many years the RAACS academician, Professor V.T. Erofeev and his colleagues have been working on biocorrosion processes of various construction materials as well as development of anticorrosion protection methods [8-10]. However, the mechanism of microbial action on concrete remains uncertain [11].

The assessment of the micro-organisms impact on the concrete general degradation is quite formidable for the development of corrosion protection measures.

The purpose of the study is to assess the strength and structural-phase changes observed in concrete as a result of bio-damage.

EXPERIMENTAL PART

We conducted a biodegradation resistance test on cubic samples made of Portland cement CEM I 42.5.

The bioaffection of the test samples was of localised nature, with 3/4 of their surface covered by a biofilm. We tested the samples under conditions of high humidity.

We applied compression and differential thermal analysis methods to study the structural changes in the solid phase of concrete.

Furthermore, we determined the strength characteristics of the samples by destructive testing on the press, in compliance with the requirements of GOST 10180-2012.

Procedure for the compression test: the samples are placed alternately on the cleaned base plate of the press, centered precisely in accordance with the marks on the base plate. The capacity of the testing machine is selected to ensure the expected breaking loads are in the range of 20-80% of the force-measuring scale. The samples are loaded continuously at a constant rate of (60±20) $kPa \cdot s^{-1}$. The value of destructive load is taken as equal to the maximum force achieved during the test. The average cross-sectional area of the sample is determined as the arithmetic average of the areas of its opposite faces in contact with the press plates.

The resistance of concrete to compression is calculated as follows:

$$R_c = \alpha \frac{F}{A} \ ,$$

where F is the maximum load, N; A is the working cross-sectional area of the sample, mm^2; α is the scaling factor to convert the strength of the cement stone to that of samples of basic size and shape.

We conducted differential thermal analysis on a Q-1500D derivatograph (Fig. 2). The order of the test is as follows: a sample of crushed material is placed in a box, poured into 100% ethanol and incubated for 10 hours. The alcohol is separated from the material by filtration. The dehydrated material is ground in a mortar to a powder passing through a No. 008 sieve. A 0.5 g sample is then placed in the crucible of a derivatograph, after which a temperature and mass loss curve of the material is recorded. We analysed at a heating rate of 10 °C·min^{-1} in the temperature range 20-1000 °C.

The differential thermal analysis of concrete samples indicates the course of characteristic endothermic reactions caused by dehydration of hydrate new formations and destruction of their crystalline structure, as well as exothermic reactions caused by the formation of new compounds at high temperatures.

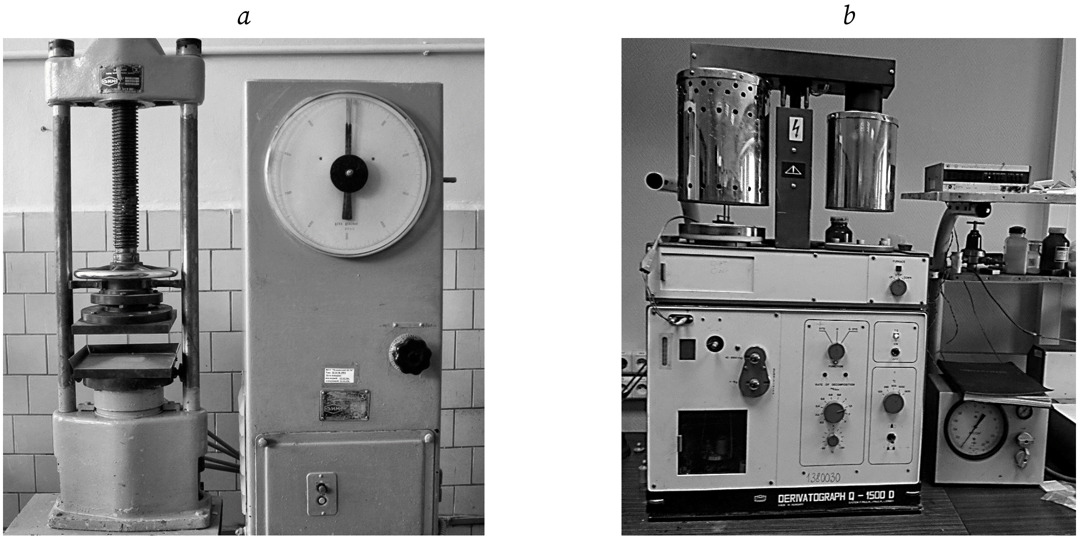

Fig. 2. Test equipment: *a* – press, *b* – Q-1500D derivatograph

With the help of the mentioned method there is a principal possibility to determine in the system calcium hydroxide, hydrosilicates and hydroaluminates, calcite, various complex compounds, types and modifications of gypsum, and other new formations in the cement stone.

RESULTS AND DISCUSSION

The average compressive strength of samples unexposed to microorganisms for 90 days was 36.2 MPa. On the other hand, the average compressive strength of samples exposed for 90 days in a bioaggressive environment was estimated to be 19.6 MPa. The results obtained confirm the negative effect of microorganisms on the physico-mechanical properties of concrete.

The results of the differential thermal analysis of the bioimpacted samples are shown in Fig. 3 and Table 1.

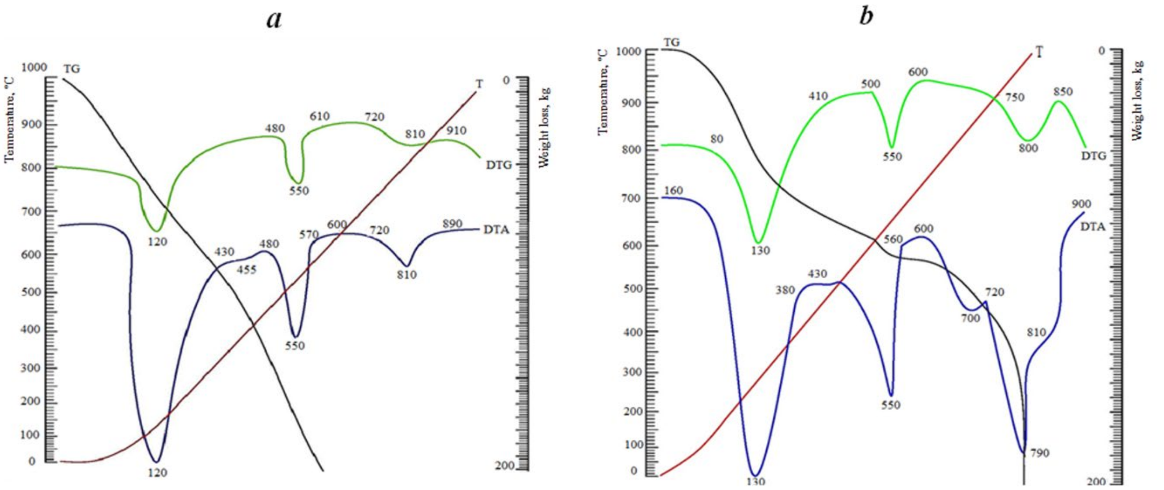

Fig. 3. Results of differential thermal analysis of control sample (*a*) and biodegradable samples (*b*)

Table 1. Results of biodegradation test on a derivatograph

t, °C	Effect	Weight change before external influences, %	Weight change after external influences, %
Bio-damaged samples			
100-130	Removing physically bound water	6.2	11.7
430-480	Dehydration of calcium hydroxide $Ca\ (OH)_2 \rightarrow CaO + H_2O$	1.8	0.8
550-650	Polymorphic transformations of quartz $\alpha\text{-Si0}_2 \rightarrow \beta\text{-Si0}_2$	7.9	1.1
650-815 (2 peaks)	Decarbonisation $CaCO_3 \rightarrow CaO + CO_2$	4.4	6.8
Total weight change		20.3	20.4

We identified four main endothermic effects from the differential thermal analysis of the concrete samples: (-) 130 °C, (-) 450 °C, (-) 550 °C, (-) 700 °C, (-) 790 °C, which are responsible for the dehydration of the respective hydrate compounds.

We determined the mineralogical composition of the samples by comparing the thermograms with the reference samples. The amount of bound water in the bio-damaged samples is 40% higher than in the control samples. Additionally, we fixed the change of $Ca(OH)_2$ content by endo-effect at 430-480 °C in the samples. We fixed a decrease in the area by the effect characterizing dehydration of $Ca(OH)_2$ to a greater extent in biologically damaged samples. At the same time they were characterized by a decrease in the temperature of final hydrate dehydration (down to 790-800 °C), indicating the presence of a small amount of calcium carbonates in the cement stone. The bio-damaged samples showed a peak at 700 °C, further indicating decarbonisation of $CaCO_3$. The decarbonisation of $CaCO_3$ begins at 600 °C, but proceeds slowly. Complete decomposition of the sample occurs at 790 °C.

CONCLUSIONS

A reduction in the mechanical strength of concrete is directly related to the enzymatic activity of microorganisms. Changes in the physical and mechanical properties of materials are one of the criteria for the bioproofness assessment.

On the basis of the differential-thermal analysis of concrete samples it has been revealed a phase composition of a cement stone at biocorrosion changes aside reduction of $Ca(OH)_2$ and increase of other calcium compounds in a solid phase of system.

Results of research provide a basis for the further development of anticorrosive protection methods of concrete structures maintained in biologically aggressive environments.

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