

## IMPROVING THE PROPERTIES OF CEMENT COMPOSITES BY CURING THEM USING AGGRESSIVE INFLUENCES

*Anatoly P. Fedortsov*<sup>1</sup>, *Vladimir T. Erofeev*<sup>2</sup>

<sup>1</sup> Research Institute of Building Physics of the Russian Academy of Architecture and Construction Sciences, Moscow, RUSSIA

<sup>2</sup> National Research Moscow State University of Civil Engineering, Moscow, RUSSIA

**Abstract:** It is noted that the curing of cement composites is impossible without effects and is a reaction to them. In this case, the forces of the resulting resistance, according to the laws of thermodynamics, are aimed at weakening the impact. Experimental prerequisites and arguments are given that by choosing the time, intensity and duration of aggressive action on cement composites during their curing, it is possible to obtain more impact-resistant or ordered and durable structures of the material. The creation of conditions for the hardening of cement composites using liquid aggressive media leads to the formation of a dense inert layer on their surface, more adapted to the effects of this type. Using temperature and humidity influences, freezing and thawing, and loads, more durable composites were obtained. Thus, the curing of cement composites using time- and intensity-determined harsh temperature and humidity conditions, freezing and thawing, aggressive liquids, and loads makes it possible to obtain more durable or resistant structures of the material to specific destructive factors.

**Keywords:** cement composites, curing, aggressive effects, strength, loads, freezing and thawing, structure, material

## УЛУЧШЕНИЕ СВОЙСТВ ЦЕМЕНТНЫХ КОМПОЗИТОВ ПУТЕМ ИХ ОТВЕРЖДЕНИЯ С ПРИМЕНЕНИЕМ АГРЕССИВНЫХ ВОЗДЕЙСТВИЙ

*А.П. Федорцов*<sup>1</sup>, *В.Т. Ерофеев*<sup>2</sup>

<sup>1</sup> Научно-исследовательский институт строительной физики РААСН, г. Москва, РОССИЯ

<sup>2</sup> Национальный исследовательский Московский государственный строительный университет, г. Москва, РОССИЯ

**Аннотация:** Отмечается, что отверждение цементных композитов невозможно без воздействий и является реакцией на них. При этом силы возникающего сопротивления, согласно законам термодинамики, направлены на ослабление воздействия. Приводятся экспериментальные предпосылки и доводы, что подбирая время, интенсивность и длительность агрессивного воздействия на цементные композиты в период их отвердевания можно получать более приспособленные к воздействиям или упорядоченные и прочные структуры материала. Создание условий отвердевания цементных композитов с применением жидких агрессивных сред приводит к формированию на их поверхности плотного инертного слоя, более приспособленного к воздействиям такого вида. С применением температурно-влажностных воздействий, замораживания и оттаивания, нагрузок были получены более прочные композиты. Таким образом, отверждение цементных композитов с применением, установленных по времени и интенсивности, жестких температурно-влажностных воздействий, замораживания и оттаивания, агрессивных жидкостей, нагрузок позволяет получать более прочные или стойкие к конкретным разрушающим факторам структуры материала.

**Ключевые слова:** цементные композиты, отверждение, агрессивные воздействия, прочность, нагрузки, замораживание и оттаивание, структура, материал

### INTRODUCTION

In the 1970s, Professor V.I. Solomatov proposed the idea that the interaction of liquid

aggressive media with concrete components can lead not only to deterioration but also contribute to compaction, structural strengthening, etc., i.e., improve their properties. We have termed

processes of this kind "positive corrosion of concrete" [1], and its consequences such as compaction and strengthening are the "positive effect of corrosion" [2].

These experimentally confirmed propositions were further developed in the study [3]. This was based on the fact that if liquid aggressive media can cause effects such as compaction, hardening, and increased physicochemical resistance, then under the action of other destructive environmental factors (loads, freezing and thawing, etc.), corresponding positive changes are also feasible.

The scientific literature contains some instances where the action of an aggressive factor was thought to have improved or contributed to the improvement of a material's properties. For example, according to L. A. Malinina [4], reducing the relative humidity of the environment during the initial hardening period can regulate the evaporation of moisture from concrete and result in a finer-pored structure. According to our research [5], there is always such an initial curing time for cement concrete in air ( $t = 20 \pm 2^\circ\text{C}$ ,  $W = 65\text{--}75\%$ ), at which its compressive strength during subsequent hardening in water is greater than that of a material that initially hardened for 24 hours under normal conditions.

Concrete curing also occurs through loading [6, 7, 8], freezing [9, 10, 11], and exposure to aggressive liquids [12]. According to research by A. V. Satalkin [6], concrete at an early age under compressive stresses up to no more than 0.6 Rpr experiences an increase in its compressive strength. It is evident that in this case, the material is strengthened due to resistance forces that contributed to the formation of a structure better adapted to this particular load.

Investigations by I. A. Kireenko, S. A. Mironova, and I. N. Akhverdov show that freezing cement concrete at specific stages of its hardening can improve its structure and, consequently, increase its strength [9]. However, this should not occur before the induction period has completed. According to the data in [13],

cement concrete subjected to a single freeze-thaw cycle after two weeks of storage in water increased its strength by 17%. Studies by A. G. Olginsky and V.L. Chernyavsky [14, 15] indicate that cement composites can adapt to the effects of a low-intensity aggressive environment even in their mature state. There are cases where loading concrete, both in the early and mature stages, with compressive or tensile forces led to a corresponding increase in strength of up to 20% [16].

Based on the above studies, the issue of applying aggressive treatments to cement composites to improve their properties has not been fully investigated. It is necessary to determine the optimal age at which cement concrete should be subjected to such treatments. Furthermore, what is needed is not merely data, but specific methodologies (protocols) for applying aggressive treatments to composites to improve their properties. In this regard, the proposed study is relevant, as it aims to address these objectives.

## METHODOLOGY

This study presents the results of investigations conducted to demonstrate that a cement composite can more effectively resist a specific destructive factor if, during a certain stage of its evolution (hardening), it is exposed to that same factor at a predetermined intensity and for a predetermined duration. Thus, the following objectives were stated:

- theoretical justification of the possibility of improving the properties of cement composites by applying aggressive environmental factors during the hardening process;
- experimental studies to determine the effect on cement composites of an initial "harsher" air curing environment, as well as the effects of freezing and thawing and exposure to aggressive liquid media during a specified period of hardening;
- analysis of the correlation between experimental data and theoretical justification.

Portland cement M500 D0 from the Alekseevsky Cement Plant in Mordovia was used to produce cement stone and fine-grained concrete. The compressive strength of the cement stone was determined by testing specimens of  $20 \times 20 \times 20$  mm, while that of the fine-grained concrete was determined by testing halves of specimens measuring  $40 \times 40 \times 160$  mm in accordance with GOST 310.4-81.

The composition ratios of the cement stone and fine-grained concrete are presented throughout the paper. The following curing conditions were adopted, including exposure to aggressive environments:

Cement stone with  $W/C = 0.33$

- Curing under normal conditions ( $t = 20 \pm 2^\circ\text{C}$ ,  $W = 95\text{--}100\%$ );
- 1 day under normal conditions, then 27 days in water ( $t = 20 \pm 2^\circ\text{C}$ );
- 1 day under normal conditions, then 13 days in  $0.5\%$   $\text{H}_2\text{SO}_4$ , then 14 days in water;
- 1 day under normal conditions, then 27 days in  $2\%$   $(\text{NH}_4)_2\text{SO}_4$  solution;
- 1 day under normal conditions, then 27 days in  $2\%$   $\text{Al}_2(\text{SO}_4)_3$  solution.

Fine-grained concrete with mix proportion 1:3 and  $W/C = 0.45$

- 1 day under normal conditions, then 27 days in water ( $t = 20 \pm 2^\circ\text{C}$ );
- 1 day under normal conditions, then 27 days in  $0.5\%$   $\text{H}_2\text{SO}_4$ ;
- 1 day under normal conditions, then 1 day in water, then 26 days in  $0.5\%$   $\text{H}_2\text{SO}_4$ ;
- 1 day under normal conditions, then 3 days in water, then 24 days in  $0.5\%$   $\text{H}_2\text{SO}_4$ .

Other exposure conditions: The duration and parameters of exposure to a "harsh" air environment, as well as the number of freeze-thaw cycles, are shown in the figures of the text. Frost resistance was determined according to GOST 10060-2012 (Method 1).

## RESULTS AND DISCUSSION

A hardening cementitious composite is a dynamic system which, according to [17], contains more microstates than it would if it

were in a mature state. This means there are more competing structures, from which the ones best adapted to the external environment can be "strictly" selected.

Consider the possibilities of open systems from the perspective of thermodynamics. The tendency of physicochemical systems toward irreversible motion toward equilibrium is expressed by entropy (S). It is also a measure of the system's degree of order, i.e., a measure of structure formation. The rate of change of entropy for open systems can be determined by the expression [18]:

$$\frac{dS}{dt} = \frac{d_e S}{dt} + \frac{d_i S}{dt} \quad (1)$$

where  $\frac{d_e S}{dt}$  is the rate of change in entropy due to external influences,  $\frac{d_i S}{dt}$  is the same due to internal processes.

For isolated systems

$$\frac{d_e S}{dt} = 0 \quad (2)$$

Then

$$\frac{dS}{dt} = \frac{d_i S}{dt} \quad (3)$$

The second law of thermodynamics states that entropy is always produced by internal processes, i.e.

$$\frac{d_i S}{dt} \geq 0 \quad (4)$$

As a result, for an isolated system, we have

$$\frac{dS}{dt} \geq 0 \quad (5)$$

This means that the entropy of an isolated system increases if the processes within it are out of equilibrium. The disorder of the system (material) increases, with the resulting negative consequences. While the value  $\frac{d_i S}{dt}$  is never negative,  $\frac{d_e S}{dt}$  has no definite sign. This allows us

to view evolution as a process in which the system can reach a state of lower entropy through the exchange of matter and energy with the external environment. It is evident that by adjusting mass and heat fluxes, one can influence the entropy increase, i.e., achieve the creation of an ordered or more adapted material structure, which is then fixed as a result of curing.

Thus, there are arguments that suggest that the application of aggressive influences to improve the properties of cement composites is most effective during the hardening phase. Furthermore, it is recommended that the material be adapted to aggressive environmental factors—not only liquid ones—in advance, during the hardening stages, to avoid disrupting the equilibrium of its structure during service [5]. Based on the above, it is possible to determine the timing, intensity, and duration of exposure to a high-temperature air environment during the curing of composites, when structural formation processes will prevail over degradation, and to consolidate the formed structures through curing. Thus, by pre-curing the molded fine-grained concrete with an open surface at a temperature of  $40 \pm 3^\circ\text{C}$  and a humidity of 70–80%, followed by curing for up to 28 days in water, an increase in compressive strength in water of more than 20% was achieved (Fig. 1).

For comparison, a material was used that initially cured for 24 hours under normal conditions and then for up to 28 days in water. In Fig. 1, the strength value of such concrete was taken as the initial reference point.

Figure 2 shows the results of studies in which fine-grained cement concrete, after two weeks of storage in water, was subjected to three cycles of alternating freezing and thawing, followed by a 28-day immersion in water, and gained approximately 18% in strength. The increase in material strength is attributed to more complete cement hydration resulting from increased water penetration into the concrete structure due to the rise in water pressure during freezing and its activity during thawing.

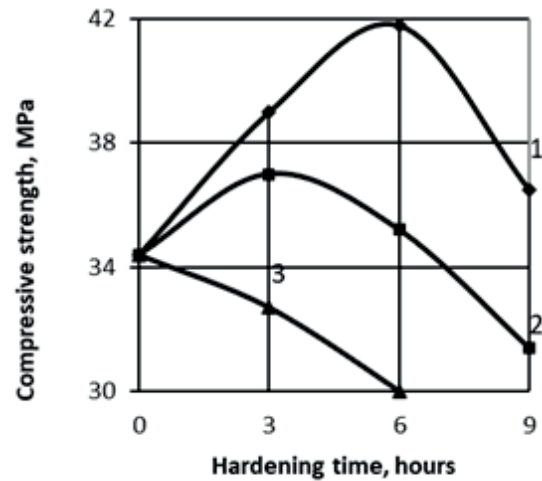


Figure 1. The relationship between the strength of concrete with a 1:3 mix ratio ( $W/C = 0.45$ ) and the duration of initial air-setting at elevated temperatures and relative humidity (RH) of 70–80%: 1 – hardening at  $40 \pm 3^\circ\text{C}$ ; 2 – same at  $50 \pm 3^\circ\text{C}$ ; 3 – same at  $60 \pm 3^\circ\text{C}$

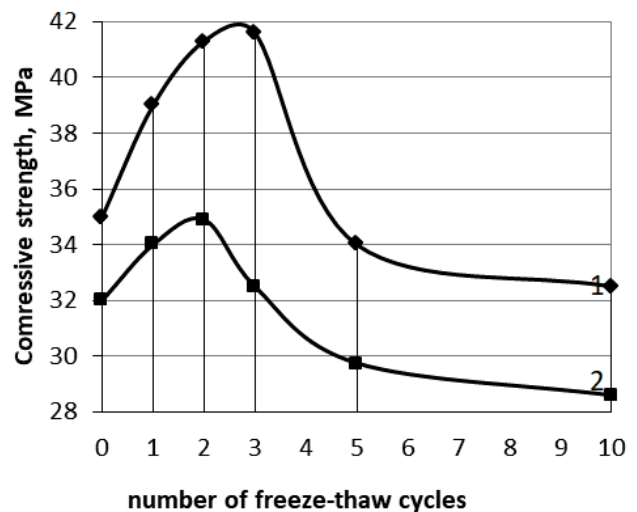
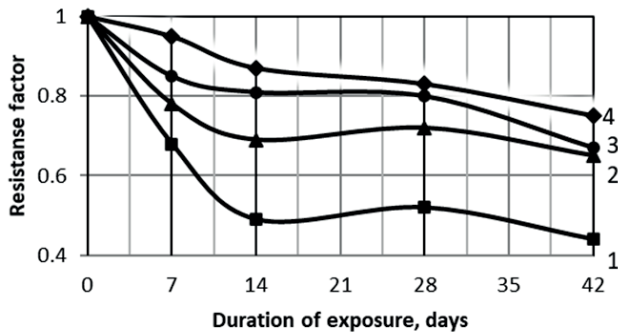


Figure 2. The effect of alternate freezing and thawing of fine-grained concrete during its hardening in water (after 14 days) on compressive strength: 1 – composition 1:3 with  $W/C = 0.45$ ; 2 – the same with  $W/C = 0.5$

According to [9], this is a result of the increased density of the crystalline hydrate structure and the reduced porosity of the cement paste. It is evident that freezing leads to the emergence of structural features in concrete that, according to established theory, contribute to increased

resistance to this same type of stress. And the curing of cement paste (W/C = 0.33) using a 0.5% sulfuric acid solution led to an increase in its resistance in a 2% solution of the same acid (Fig. 3).



*Figure 3. Effect of curing conditions on the stone's resistance in a 2% H<sub>2</sub>SO<sub>4</sub> solution: 1 – cured for 1 day under standard conditions, 27 days in water; 2 – 1 day under standard conditions, 13 days in a 0.5% H<sub>2</sub>SO<sub>4</sub> solution, 14 days in water; 3 – 1 day under normal conditions, 27 days in a 2% solution of (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>; 4 – 1 day under normal conditions, 27 days in a 2% solution of Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub>*

The physical and chemical resistance of concrete also increases when the components of the curing medium are merely individual constituents of that medium. Thus, the curing of cement paste (W/C = 0.33) using 2% acidic salts—ammonium sulfate and aluminum sulfate—contributed to a significant increase in its resistance to a 2% H<sub>2</sub>SO<sub>4</sub> solution. It should be noted, however, that the use of curing media containing aggressive components in all cases led to a partial loss of initial strength. The initial strength values, according to Fig. 1, were: 1 – 68 MPa, 2 – 56 MPa, 3 – 54 MPa, 4 – 47 MPa. At the same time, cement stone cured under such conditions always exhibited higher strength (by 18–22%) after aging in an aggressive environment than that aged in water. The table presents the results of a test on the resistance of fine-grained concrete with a 1:3 mix ratio and a water-cement ratio (W/C) of 0.45 to a 1% H<sub>2</sub>SO<sub>4</sub> solution; which, during the hardening period, was exposed at specified intervals to the same medium but at a lower concentration (0.5%) and under different conditions than those applied to the cement paste.

*Table 1. The Effect of the Curing Environment on the Resistance of Fine-Grained Concrete to 1% H<sub>2</sub>SO<sub>4</sub>*

Curing Environment	$\sigma_0$ , MPa	Duration of exposure, days	$\sigma_T$ , MPa	K <sub>CT</sub>
1 days under standard conditions, 27 days in water	21.9	20	13.1	0.6
1 days under standard conditions, 1 days in water, 26 days under 0.5% solution of H <sub>2</sub> SO <sub>4</sub>	21.7	20	16.9	0.78
1 days under standard conditions, 3 days in water, 24 days under 0.5% solution of H <sub>2</sub> SO <sub>4</sub>	19.8	20	16.6	0.84

The table shows that concrete specimens exposed to an aggressive agent of a specified intensity and duration during the hardening period are more resistant, once matured, to the same type of environment but at a higher concentration. Their compressive strength after exposure to the environment is 27% and 29% higher than that of concrete that hardened in water.

Cement paste and fine-grained concrete, which were partially adapted to a weak sulfuric acid solution, had a dense protective layer on their surface, the main components of which were: silicic acid gel, sulfates, and cement paste minerals modified by them.

The condition for the formation of a composite more resistant to a specific aggressive influence during its hardening with the formation of adapted bonds can be expressed as follows:

$$V_o(t) \geq V_n(t), \quad (6)$$

where  $V_o(t)$  is the rate at which defects are eliminated and adapted bonds are formed as a result of positive interactions over a period of time  $\Delta t$ ,  $V_n(t)$  is the the rate of decay of initial bonds over a time interval  $\Delta t$ .

Previous studies [5] also confirm the positive effect of early loading on the performance properties of concrete. At the same time, the application of a bending load to the concrete during the curing period—amounting to approximately 5% of the ultimate load at the moments of its application, which is significantly less than in known studies—did not lead to an increase in the average flexural strength but contributed to a 5.2-fold reduction in the coefficient of variation of the flexural test results. At the same time, the flexural strength guaranteed with 95% confidence increased by 13%, while deflections and their deviations from the mean value decreased by more than 12% and 30%, respectively.

Studies have also shown that the duration of load application during the concrete hardening period depends on the magnitude of the load. The failure factor should not lead to material failure.

## CONCLUSION

1. The hardening of cementitious composites through the application of temperature and humidity stresses, freezing and thawing cycles, and aggressive liquids—with precisely controlled duration and intensity—enables the creation of material structures that are stronger or more resistant to specific destructive factors.
2. To produce a composite that would more effectively resist a specific destructive factor, it is necessary for the composite to be exposed to that same factor during a specific period of its development, but at a predetermined intensity and duration. In this case, the aggressive factor must not lead to the destruction of the composite.

3. Since exposure to liquid corrosive media of a certain intensity and duration during the specified curing periods of cement composites can lead to their partial or complete adaptation to the exposure, it can be concluded that during the adaptation of the composite (system), a selection of processes occurs that contribute to increasing its resistance to a specific impact.

## FUNDING

The research was funded by the National Research Moscow State University of Civil Engineering.

## REFERENCES

1. **Solomatov V.I., Fedortsov A.P. Positive Corrosion of Concretes / V.I. Solomatov, A.P. Fedortsov // Performance of Composite Building Materials under Various Operational Factors.** – Kazan : Publishing House of KCTI named after S. M. Kirov, 1982. – P. 10 – 13.
2. **Solomatov V.I., Fedortsov A.P. Positive Effect of Corrosion of Polymer Concretes / V. I. Solomatov, A. P. Fedortsov // Concrete and Reinforced Concrete.** – 1981. - No. 2. – P. 20 – 21.
3. **Fedortsov A.P. Positive Corrosion of Concretes as a Prerequisite for Improving Their Properties by Aggressive Influences / A. P. Fedortsov // Bull. of Mordov. Univ.** – 2002. - No. 1 – 2. – P. 152 – 156.
4. **Malinina L.A. Heat and Moisture Treatment of Heavy Concrete / L. A. Malinina.** – M. : Stroyizdat, 1977. – 159 p.
5. **Fedortsov A.P. Physicochemical Resistance of Building Composites and Ways to Increase It : monograph / A.P. Fedortsov.** – Saransk : Publishing House of Mordov. Univ., 2015. – 464 p.
6. **Satalkin A.V., Senchenko B.A. Early Loading of Concrete and Reinforced Concrete in Bridge Construction / A.V.**

- Satalkin, B.A. Senchenko. – M. : Avtotransizdat, 1956. – 214 p.
7. **Baiburin A.Kh.** Investigation of Strength and Deformability of Heavy Concrete under Early Loading / A.Kh. Baiburin // Engineering Bulletin of the Don. – 2022. - No. 6. URL: [ivdon.ru/ru/magazine/archive/n6y2022/7603](http://ivdon.ru/ru/magazine/archive/n6y2022/7603)
  8. **Obayes O., Gad E., Pokharel T., Lee J. et al.** Evaluation of Concrete Material Properties at Early Age // Civil Engineering. – 2020 – Vol. 1 – Pp. 326 – 350.
  9. **Akhverdov I.N.** Fundamentals of Concrete Physics / I. N. Akhverdov. – M. : Stroyizdat, 1981. – 464 p.
  10. **Trinker A.B.** Winter Concreting and Work in Permafrost Conditions / A. B. Trinker // Concrete Technologies. – 2013. – No. 2. – P. 42 – 44.
  11. **Batyanovsky E.I., Gurienko N.S., Korsun A.M.** Increasing the Frost Resistance of Cement Concrete / E. I. Batyanovsky, N. S. Gurienko, A. M. Korsun // Mechanics and Technology Scientific Journal. – 2022. - No. 2(7). – P. 148 – 159.
  12. **Fedortsov A.P., Erofeev V.T.** Increasing the Physicochemical Resistance of Cement Composites by Using Aggressive Media during Their Curing / A. P. Fedortsov, V. T. Erofeev // Bull. of the Volga Region Branch of the RAASN [N. Novgorod]. – 2002. – Iss. 5. – P. 98 – 101.
  13. **Fedortsov A.P.** Improving the Properties of Concretes by Aggressive Influences / A. P. Fedortsov // Bull. of Mordov. Univ. – 2003. - No. 1 – 2. – P. 135 – 138.
  14. **Olginsky A.G., Chernyavsky V.L.** Influence of the Environment on the Adaptation of the Aggregate-Cement Stone Contact Zone in Concrete / A.G. Olginsky, V.L. Chernyavsky // Concrete and Reinforced Concrete. – 2000. - No. 4. – P. 5 – 8.
  15. **Chernyavsky V.L.** The Role of Adaptation in the Formation of Concrete Corrosion Resistance / V.L. Chernyavsky // Proceedings of Universities. Construction Series [Novosibirsk]. – 1995. - No. 4. – P. 34 – 39.
  16. **Makarenko L.P.** Change in Physicomechanical Properties of Concretes under Compression and Tension under Repeated Loading / L. P. Makarenko // Concrete and Reinforced Concrete. – 1989. - No. 2. – P. 38 – 40.
  17. **Haken H.** Synergetics : trans. from English / H. Haken. – M. : Mir, 1980. – 404 p.
  18. **Nicolis G., Prigogine I.** Self-Organization in Nonequilibrium Systems : trans. from English / G. Nicolis, I. Prigogine. – M. : Mir, 1979. – 512 p.

## СПИСОК ЛИТЕРАТУРЫ

1. **Соломатов В.И., Федорцов А.П.** Положительная коррозия бетонов / В.И. Соломатов, А.П. Федорцов // Эксплуатационные характеристики композитных строительных материалов при различных эксплуатационных факторах. – Казань: Издательство КЦТИ им. С. М. Кирова, 1982. – С. 10–13.
2. **Соломатов В.И., Федорцов А.П.** Положительное влияние коррозии полимерных бетонов / В. И. Соломатов, А. П. Федорцов // Бетон и железобетон. – 1981. – № 2. – С. 20–21.
3. **Федорцов А.П.** Положительная коррозия бетонов как предпосылка для улучшения их свойств агрессивными воздействиями / А. П. Федорцов // Вестник Мордовского университета. – 2002. – № 1 – 2. – С. 152 – 156.
4. **Малинина Л.А.** Тепловая и влагозащитная обработка тяжелого бетона / Л. А. Малинина. – М.: Стройиздат, 1977. – 159 с.
5. **Федорцов А.П.** Физико-химическая стойкость строительных композитов и способы ее повышения: монография / А. П. Федорцов. – Саранск: Издательство Мордовского университета, 2015. – 464 с.

6. **Саталкин А.В., Сенченко Б.А.** Ранняя нагрузка бетона и железобетона при строительстве мостов / А. В. Саталкин, Б. А. Сенченко. – М.: Автотрансиздат, 1956. – 214 с.
7. **Байбурин А.Х.** Исследование прочности и деформируемости тяжелого бетона при ранней нагрузке / А.Х. Байбурин // Инженерный вестник Дона. – 2022. – № 6. URL: [ivdon.ru/ru/magazine/archive/nby2022/7603](http://ivdon.ru/ru/magazine/archive/nby2022/7603).
8. **Обайес О., Гад Е., Покхарел Т., Ли Дж. и др.** Оценка свойств бетонных материалов в раннем возрасте // Гражданское строительство. – 2020 – Т. 1 – С. 326 – 350.
9. **Ахвердов И.Н.** Основы физики бетона / И. Н. Ахвердов. – М.: Стройиздат, 1981. – 464 с.
10. **Тринкер А.Б.** Зимнее бетонирование и работы в условиях вечной мерзлоты / А. Б. Тринкер // Технологии бетона. – 2013. – № 2. – С. 42–44.
11. **Батяновский Е.И., Гуриенко Н.С., Корсун А.М.** Повышение морозостойкости цементного бетона / Е.И. Батяновский, Н.С. Гуриенко, А.М. Корсун // Научно-технический журнал «Механика и техника». – 2022. – № 2(7). – С. 148–159.
12. **Федорцов А.П., Ерофеев В.Т.** Повышение физико-химической стойкости цементных композитов с использованием агрессивных сред в процессе их твердения / А. П. Федорцов, В. Т. Ерофеев // Вестник Поволжского отделения РААКС [Н. Новгород]. – 2002. – Вып. 5. – С. 98 – 101.
13. **Федорцов А.П.** Улучшение свойств бетона агрессивными воздействиями / А. П. Федорцов // Вестник Мордовского университета – 2003. – № 1 – 2. – С. 135 – 138.
14. **Ольгинский А.Г., Чернявский В.Л.** Влияние окружающей среды на адаптацию зоны контакта заполнителя и цементного камня в бетоне / А. Г. Ольгинский, В. Л. Чернявский // Бетон и железобетон. – 2000. – № 4. – С. 5 – 8.
15. **Чернявский В.Л.** Роль адаптации в формировании коррозионной стойкости бетона / В. Л. Чернявский // Труды университетов. Строительная серия [Новосибирск]. – 1995. – № 4. – С. 34–39.
16. **Макаренко Л.П.** Изменение физико-механических свойств бетона при сжатии и растяжении при многократной нагрузке / Л.П. Макаренко // Бетон и железобетон. – 1989. – № 2. – С. 38–40.
17. **Хакен Г.** Синергетика: перевод с английского / Г. Хакен. – М.: Мир, 1980. – 404 с.
18. **Николис Г., Пригожин И.** Самоорганизация в неравновесных системах: перевод с английского / Г. Николис, И. Пригожин. – М.: Мир, 1979. – 512 с.

---

*Anatoly Petrovich Fedortsov*, PhD, Docent, Research Institute of Building Physics of the Russian Academy of Architecture and Construction Sciences (NIISF RAASN), 127238, Russia, Moscow, Lokomotivny proezd, 21b3. e-mail: [antoliy.fedortsov@mail.ru](mailto:antoliy.fedortsov@mail.ru)

*Vladimir Trofimovich Erofeev*, Dr. Sc., Professor, Academician of the Russian Academy of Architecture and Construction Sciences (RAASN), Professor of the Department of Construction Materials of the National Research Moscow State University of Civil Engineering (NRU MGSU), 129337, Russia, Moscow, Yaroslavl'skoe Shosse, 26, e-mail: [ErofeevaV@gic.mgsu.ru](mailto:ErofeevaV@gic.mgsu.ru)

*Анатолий Петрович Федорцов*, кандидат технических наук, доцент, главный научный сотрудник Научно-исследовательского института строительной физики (НИИСФ РААСН), 127238 г. Москва, Локомотивный проезд, 21с3. e-mail: [antoliy.fedortsov@mail.ru](mailto:antoliy.fedortsov@mail.ru)

*Владимир Трофимович Ерофеев*, доктор технических наук, профессор, академик РААСН, профессор кафедры «Строительных материалов» Национального исследовательского Московского государственного строительного университета (НИУ МГСУ) 129337, г. Москва, Ярославское шоссе, д. 26. e-mail: [erofeevvt@bk.ru](mailto:erofeevvt@bk.ru)