

# The influence of cyclic temperature and humidity effects on the compressive strength of heavy concrete

Igor Garanzha<sup>1\*</sup>, Anton Tanasoglo<sup>1</sup>, Milena Pisareva<sup>1</sup>, Yevgeniy Gorokhov<sup>2</sup>, and Natalia Smirnova<sup>2</sup>

<sup>1</sup>Moscow State University of Civil Engineering (National Research University), 129337, Moscow, Russia

<sup>2</sup>Donbas National Academy of Civil Engineering and Architecture, 86123, Makeevka, Russia

**Abstract.** The paper presents the results of experimental studies of the effect of cyclic exposure to elevated temperatures up to 90°C and 150°C and moistening to full water saturation on the strength of heavy concrete. Quantitative data on the change of concrete strength properties depending on the influence factors are obtained. Proposals are formulated to take into account in calculations the influence of heating and moistening modes on the strength of concrete in axial compression. Under cyclic exposure to elevated temperatures and subsequent moistening at normal temperature, there are significant changes in the compressive strength of concrete at different stages of each cycle. At the short-term heating stage, the reduction in the prismatic strength of the concrete amounted to 15 - 22% of the concrete strength before heating. Prolonged isothermal heating results in a 13 - 25% increase in concrete strength. At the stage of subsequent moistening of concrete after heating, there is a decrease in strength by 25 - 27%, while the relative magnitude of strength reduction does not significantly depend on the number of previous cycles. In the investigated interval of up to twenty-five cycles of exposure to elevated temperatures and moistening, the greatest reduction in concrete strength was observed in the first and last cycles. For cycles with heating temperature up to 90°C at short-term heating at the beginning of the second cycle the concrete strength drop was 45.5%, and the concrete strength drop at short-term heating for the 25th cycle was 9.7%. For cycles with heating temperature of 150°C the strength drop was 45.9% and 52.5%, respectively. The accepted experimental mode according to the formula of cycle  $(6+1) + (6+1)$  is the most unfavorable for the strength of concrete under cyclic effects of elevated temperatures and subsequent moistening.

## 1 Introduction

Cyclic effects of elevated temperatures and subsequent moistening during cooling down are typical for structures of chimneys and gas ducts, power facilities, metallurgical and

---

\* Corresponding author: [garigo@mail.ru](mailto:garigo@mail.ru)

chemical industries. Such impacts lead to changes in physical and mechanical properties of concrete and stress-strain state of reinforced concrete structures [1-2].

**Research relevance:** improvement of design solutions of reinforced concrete structures, development of calculation methods of their stress-strain state, design principles and protection from temperature and humidity effects.

**Research object:** compressed reinforced concrete and bending elements of heavy concrete structures.

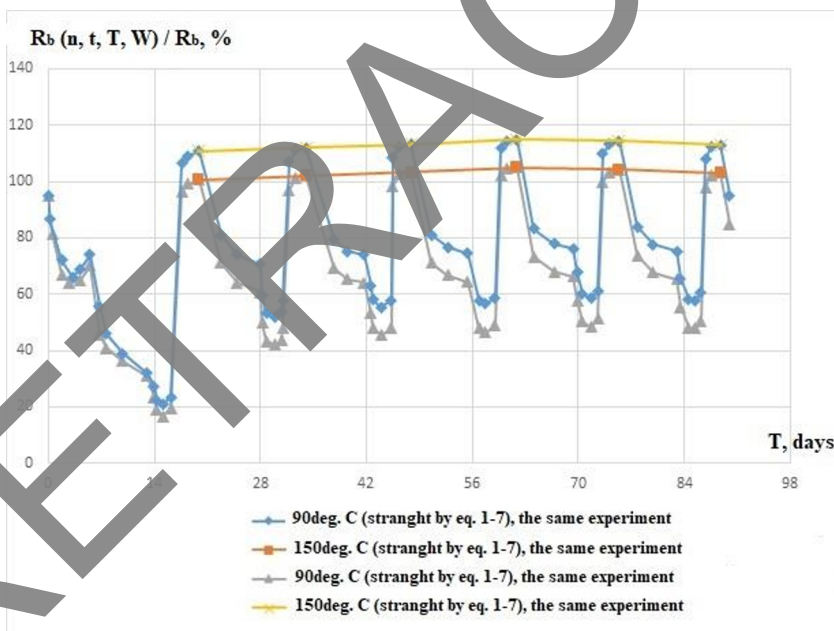
**Research subject:** stress-strain state and compressive strength of reinforced concrete elements and heavy concrete structures under cyclic temperature-humidity impacts.

**Research goals and objectives:**

- to study the peculiarities of cyclic temperature-humidity impacts of climatic and anthropogenic character on temperature and humidity deformations in heavy concretes;
- to deduce analytical dependences of physical and mechanical properties of heavy concretes operating in conditions of increased temperatures and humidity of cyclic character.

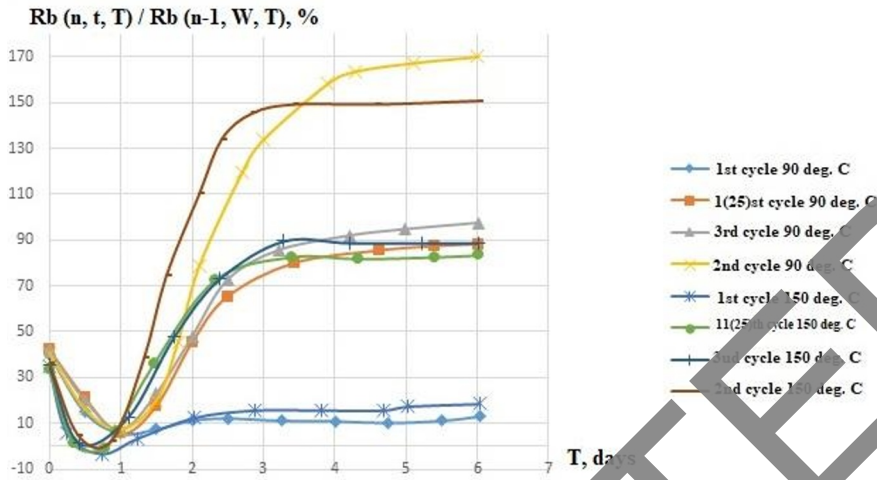
## 2 Materials and methods

Significant changes in concrete strength occur at each cycle when affecting with elevated temperatures and moistening (fig.1) [3-5].



**Fig 1.** Change in the prismatic strength of concrete under cyclic temperature and humidity influences with the maximum temperature of the cycle

At the beginning of each cycle at the stage of short-term heating there is a decrease in the strength of concrete. The strength reduction at short-term heating of dry concrete at the first cycle was 17 - 22% and when heating moistened concrete at subsequent cycles it made up 15 - 20% of the strength of concrete before heating (fig.2) [2, 6-8].



**Fig 2.** Change in the prismatic strength of concrete during the heating stage under cyclic temperature and humidity influences

There is a significant increase in the strength of concrete at each cycle of further six days isothermal heating which stays unchanged at the following cooling. The strength gain during prolonged heating depends not only on the heating temperature, but also on the number of previous cycles of temperature-moisture influences. Under the influence of elevated temperatures on moistened concrete at the second and third cycles there is a more significant increase in strength (by 20 - 25%) than at a greater number of cycles of temperature-humidity influences [4, 9-11].

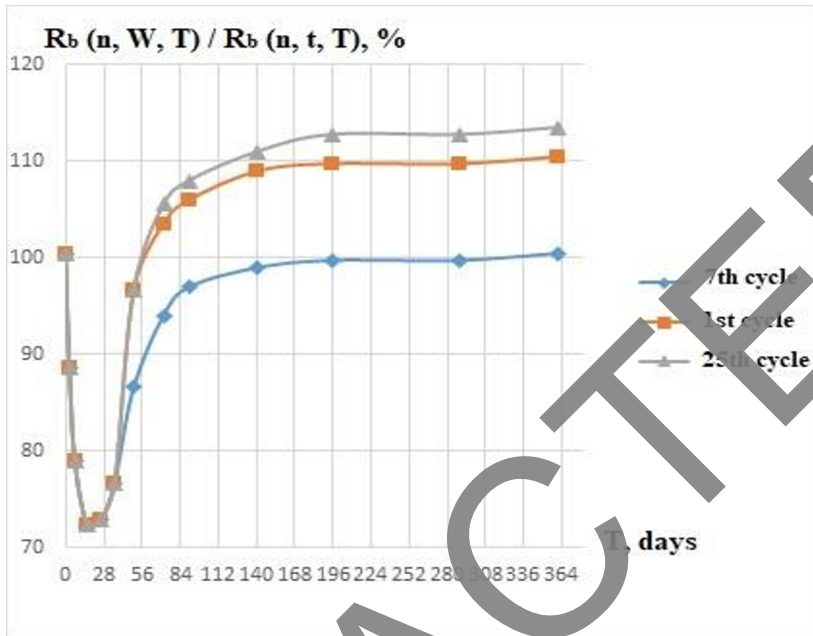
### 3 Results and discussion

The described change of strength while heating can be explained by the change of concrete moistness and structural and destructive processes occurring in it. They are caused by the occurrence of self-equilibrated structural stresses, a decrease in water viscosity and an increase in its wedging action, adsorption reduction of strength and a number of other factors that lead to the occurrence and development of microcracks and, as a consequence, to a decrease in strength. In addition, the heating of moistened concrete results in intensive water absorption by some crystalline hydrates, which leads to their softening. There is also a decrease in the hardening pressure of liquid menisci in micropores and capillaries [12, 13]. Another factor reducing the strength of concrete is, on the one hand, the difference in the coefficients of linear thermal expansion of the aggregate and cement stone and the water clogged in confined pores and capillaries on the other hand, which causes the appearance of additional tensile stresses in the contact zone of a cement stone. Vapor pressure in microcracks and micropores at phase transition of water into vapor state while heating leads to the appearance of tensile stresses in the defects of the structure and to the development of additional damage [14, 15].

During prolonged heating a number of processes leading to an increase in concrete strength occur, including relaxation of self-equilibrated structural stresses, removal of a part of free moisture, additional hydration of cement stone, crystallization of its helium component [1-3].

At the stage of subsequent moistening at normal temperature, the strength decreases significantly again. When both normal and dried concrete are moistened, a 25-27%

decrease in concrete strength is observed compared to the strength of concrete before moistening (fig.3)[ 1, 3, 7].



**Fig. 3.** Change in the prismatic strength of concrete at the moistening stage under cyclic temperature and humidity influences by equations(6)-(7).

The strength reduction is mainly caused by the wedging action of water in the defects of the concrete structure. The strength reduction occurs during the first 5 - 7 days of wetting. The strength of concrete (both normal and dried on the first cycle) during long-term (up to 365 days) moistening exceeds the strength of concrete before moistening by 15 - 25%. There are processes of smoothing the effect of water wedging, densification of concrete structure, removal of microstresses from unequal distribution of moisture over the cross-section of the sample and hydration of clinker relics. It should be noted that cement hydration is mainly completed after the first two to three cycles, so the concrete strength gain after prolonged humidification will be somewhat less than during the first cycles of temperature and humidity effects. After the fifth to seventh cycles of temperature and humidity effects during long-term moistening, the initial (before this moistening) strength of concrete is restored.

Structural processes prevail at the initial cycles of impact, which leads to the growth of concrete strength at a small number of cycles of impact. In addition to the above-mentioned destructive processes, we should also include the processes of microcracks in the cement stone and aggregate contact zone under the influence of repeated alternating stresses and physical and chemical changes in the structure, such as leaching of cement stone components, formation of corrosion products and recrystallization processes of the hydrosilicate phase.

Therefore, the following three characteristic points at each heating and moistening cycle can be defined: short-term heating strength - minimal strength at each cycle, long-term heating strength - maximal strength at each cycle, and concrete strength at subsequent moistening - minimal strength at each cycle at normal temperature.

The maximal strength (long-term heating) at a cycle temperature of 90°C varies as follows: after heating the concrete at the first cycle there is a sharp decrease in its value, at

the second cycle after heating the moistened concrete there is a recovery of strength so that the prismatic strength of concrete exceeds the strength of unheated concrete by 6.8%. On subsequent cycling, there is some further strength gain until the fifth to sixth cycles, the strength increases by 10.4% over the initial strength. Then there is a gradual slight drop in concrete strength by 0.5 - 1.1% of the maximal concrete strength at each cycle.

The minimal strength at normal temperature (moistening) at the cycle temperature of 90°C changes as follows: when moistening the concrete cooled down after heating at the first cycle there is a sharp decrease in its value to 60 - 62% of the strength of normal reference concrete, at the second cycle after moistening the strength of concrete exceeds the strength of concrete at moistening at the first cycle by 7-9%. In subsequent cycling, there is some further increase in strength until the fifth to sixth cycles, the strength increases by 11.2% compared to the strength of concrete after wetting at the first cycle. Then there is a gradual slight drop in concrete strength by 0.3 - 0.9% of the maximum concrete strength at each cycle.

The minimal strength (short-term heating) at a cycle temperature of 90°C varies as follows: during short-term heating of normal concrete at the first cycle there is a sharp drop in the strength of concrete, at the second cycle during heating of moistened concrete there is a further drop in the strength of concrete by 8-9%, so that the strength of concrete after short-term heating at the second cycle is 54-55% of the strength of normal concrete. At short-term heating on the third cycle of moistened concrete, there is a drop in strength by 8 - 10%, but the strength is higher than that of short-term heating on the second cycle by 9 - 12%. Under further cyclic action, there is some further increase in strength up to the fifth to sixth cycles, the strength increases by 15.8% compared to the strength of concrete under short-term heating at the first cycle. Afterwards, there is a gradual slight drop in concrete strength by 0.3 - 0.8% of the maximal concrete strength at each cycle.

Under cyclic exposure to elevated temperatures and moistening with a heating temperature of 150°C, the tendencies of concrete compressive strength changes are the same as in cycles with a heating temperature of 90°C.

The maximal strength in this case is observed in the third to fifth cycles, when the strength of concrete at prolonged heating exceeds by 2.6% the strength of the reference unheated concrete.

In the investigated interval from one to twenty-five cycles of exposure to elevated temperatures and moistening, the greatest reduction in concrete strength was observed at the initial and final cycles. For cycles with heating temperature up to 90°C at short-term heating at the beginning of the second cycle, the reduction in concrete strength was 45.5%, and the assumed reduction in concrete strength at short-term heating for the 26th cycle was 49.7%. For cycles with heating temperature of 150°C, the strength drop was 45.9% and 52.5%, respectively.

Extrapolation of the experimental data allows us to consider that the concrete strength will continue to decrease with the number of exposure cycles over 25. It is expected that the long-term heating strength will reach 50% of the reference strength after 90-100 cycles of temperature and moisture exposure with a cycle temperature of 90°C, and after 85-90 with a cycle temperature of 150°C.

The prism strength of concrete exposed to cyclic influence of elevated temperatures and moistening is calculated as an algebraic sum of components describing the action of destructive and constructive factors:

$$R_b(n, t, T, W) = R_b - \sum_{i=1}^n \sigma_c(i, t, T) + \sum \Delta R_b(i, t, T) - \sum_{i=1}^n \sigma_c(i, t, T) + \sum_{i=1}^n \Delta R_b(i, w, T) \quad (1),$$

where  $\Delta R_b(n, t, T)$  and  $\sigma_c(n, t, T)$  are calculated at each cycle in the case of elevated temperatures, and  $\Delta R_b(n, W, T)$  and  $\sigma_c(n, W, T)$  – in the case of moistening. The reduction

of concrete strength during short-term heating is accounted for by the function  $\sigma_e(n, t, T)$  determined by the formula:

$$\sigma_e(n, t, T) = \frac{E(n, t, T)}{K(t, T)} \times \varepsilon_e(t) \times \left(1 - \frac{\varepsilon_e(t)}{2K(t, T) \times (\varepsilon_{on} + \Delta\varepsilon_{on})}\right) \quad (2),$$

where  $K(t, T)$  accounts the consequent change in ultimate strains,

$$\varepsilon_{on} = \frac{2R_b(n-1, w, T)}{E(n-1, w, T)} \quad (3);$$

$$\Delta\varepsilon = \frac{2R_b(n, w, T)}{E(n, w, T)} \quad (4).$$

The strength gain of concrete under prolonged isothermal heating is described by a function:

$$\Delta R(n, t, T) = R_b(0.58 - 0.001t + \left(\frac{3.6 + 0.01t}{\sum_{i=1}^n T_i}\right) \times (1 - \exp(-0.01T_n \times F(t)^{0.1}))) \quad (5).$$

The reduction of concrete strength during wetting is accounted by the function  $\sigma_e(n, w, T)$ , determined by the formula:

$$\sigma_e(n, t, T) = R_b(n, t, T) \times 0.28(1 - \exp(-T_n)) \quad (6).$$

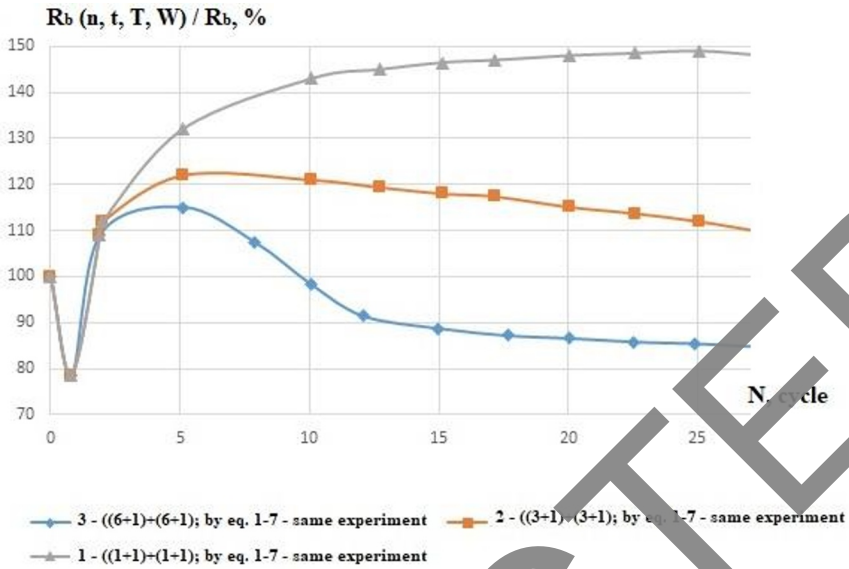
Concrete strength gain during long-term concrete moistening is accounted for by the formula:

$$\Delta R_b(n, t, T) = R_b(n, t, T) \times \left(0.3 + 0.4 \frac{t}{\sum_{i=1}^n T_i}\right) \times (1 - \exp(-0.1T_n)) \quad (7).$$

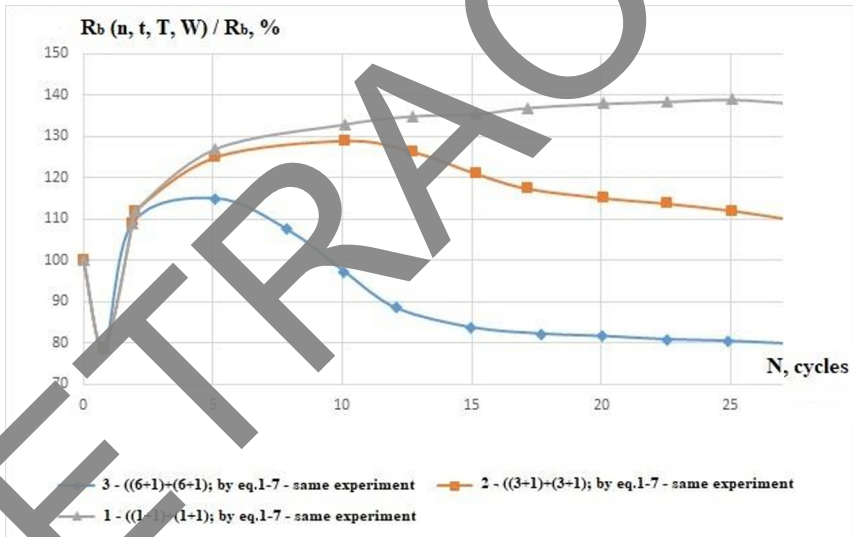
Comparing the results of the experiment and concrete strength calculations according to the proposed method (see fig.1) indicates their sufficient similarity. The largest discrepancy is 2.5%.

The duration of the cycle of elevated temperatures and moistening has a noticeable effect on the strength of concrete. Fig. 4, 5 shows the results of compression tests of prisms under the cyclic modes of elevated temperatures and humidity (3+1) + (3+1) and (1+1) + (1+1).

At the heating temperature of 90°C and the cycle formula (3+1) + (3+1) the maximal strength is reached by 10-15 cycles of temperature and moistening influences and its value is 120.3% of the strength of unheated concrete. At a cycle temperature of 150°C, the maximal strength is reached by 5-6 cycles and its value is 106.4% of the initial strength. When the heating temperature is 90°C and the cycle formula is (1+1) + (1+1) the maximal strength is reached by the 25th cycle and its value is 146.5% of the initial strength. At a heating temperature of 150°C and the same cycle, the maximal strength is reached by 10 - 15 cycles and its value is 116.1% of the initial one. Therefore, with a shorter cycle duration a greater increase in concrete strength is achieved and the maximal strength is achieved with a greater number of cycles.



**Fig.4.** Change in the prismatic strength of concrete at a cycle temperature of 90°C and cycle modes



**Fig. 5.** Change in the prismatic strength of concrete at a cycle temperature of 150°C and cycle modes

The strength of concrete that has been subjected to a constant longitudinal compressive force during cyclic heating and moistening is higher than that of unstressed concrete. The greater the number of cycles, the more the strength of the stressed concrete differs from that of the unstressed concrete.

After seven cycles of temperature and moisture influences, the strength of the compressed concrete exceeded the strength of the uncompressed concrete by 0.3 - 6.2%, and after twenty-five cycles, by 15.3 - 20.2%. At a concrete compression level of 0.2 R, the strength of concrete is slightly higher (by 7 - 4.0%) than at a compression level of 0.4 R. Concrete compression also has a positive effect on the strength of concrete under short-term moistening. When wetting the uncompressed concrete at the 25th cycle of exposure, its

strength decreased by 25.8 - 26%, and for the concrete compressed by longitudinal compressive force, the strength drop during wetting was 23.7 - 24%, respectively.

Therefore, the results of the experiments show that the cycle formula (6+1) + (6+1) leads to the greatest damage in the structure of concrete and the greatest decrease in its prism strength.

## 4 Conclusions

1) Under cyclic exposure to elevated temperatures and subsequent moistening at normal temperature, there are significant changes in the compressive strength of concrete at various stages of each cycle. At the short-term heating stage, the decrease in the prismatic strength of concrete amounted to 15 - 22% of the concrete strength before heating. Prolonged isothermal heating results in a 13 - 25% increase in concrete strength. At the stage of subsequent moistening of concrete after heating, there is a 25 - 27% decrease in strength, while the relative strength reduction does not significantly depend on the number of previous cycles.

2) In the investigated interval of up to twenty-five cycles of elevated temperatures and moistening, the greatest reduction in concrete strength was observed in the first and last cycles. For cycles with heating temperature up to 90°C at short-term heating at the beginning of the second cycle, the drop in concrete strength was 45.5%, and the drop in concrete strength at short-term heating for the 25th cycle was 9.7%. For cycles with heating temperature of 150°C, the strength drop was 45.9% and 52.5% respectively. The accepted test mode according to the formula of cycle (6+1) + (6+1) is the most unfavorable for the strength of concrete under cyclic influences of elevated temperatures and subsequent moistening.

3) To define the calculated strength of concrete during cyclic heating and moistening it's recommended to use: formulas (4) – (5) for the first heating and heating on subsequent cycles, formulas (6) – (7) for the moistened concrete.

## References

1. Aleksandrovsky S.V., Stroyizdat, **444** (2006).
2. Bushnev N.S., VNIPO, **547** (2011).
3. Krichevsky A.P., Res. of Rel. And Qual. Of Rein. Conc. Str. J. 1978, V.3. Pp.43-54.
4. Krichevsky A.P., Conc. And Reinf. Conc. J. 1980. V.1. Pp. 23-24.
5. Krichevsky A.P., Conc. And Reinf. Conc. J. 1982. V.11. Pp.18-19.
6. Krichevsky A.P., Peredereyi V.D., Conc. And Reinf. Conc. J. 1998. V.3. Pp.16-18.
7. Deutscher M, Market M., Scheerer S., Struc. Conc. J. 2021. V.23(2). Pp. 1-10.  
<https://doi.org/10.1002/suco.202100153>
8. Deutscher M., Tran N., Scheerer S. Appl. Sci. J. 2019. V.9(1). 4087.  
<https://doi.org/10.3390/app9194087>
9. Phan L.T., Carino N.L. Mat. Struc. J. 2003. V.36(2). Pp.1–8.  
<https://doi.org/10.1007/BF02479522>
10. Nekrasov K.D., Zhukov V.V., Gulaeva V.F., Stroyizdat, **128** (1992)c.
11. Korsun V.I., DNACEA, **153** (2013).
12. V. Korsun, N. Vatin, A. Korsun, D. Nemova. Appl. Mech. and Mat. J. 2014. V.633-634. Pp. 1013-1017. <https://doi.org/10.4028/www.scientific.net/AMM.633-634.1013>

13. Korsun V.I., Korsun, A.V. In Improving Performance of Concrete Structures. Vol. II. : The 4th International FIB Congress 2014. Proceedings. Mumbai, India, 10-14.02.2014. 2014. Pp. 849-852.
14. V. Korsun, A. Korsun, A. Volkov. MATEC Web of Conf. J. 2013. V.6. 07002. <https://doi.org/10.1051/matecconf/20130607002>
15. Deutscher M., Tran N., Scheerer S. Appl Sci. J. 2020. V.**10**(17). 5845. <https://doi.org/10.3390/app10175845>

RETRACTED