EXPERIMENTAL INVESTIGATION AND THEORETICAL BACKGROUND OF THE OPTIMAL CONTROL OF THE CONCRETE MIXTURE FORMING

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Resume
Concrete belongs to the most used building materials, applied in almost all types of constructions (civil, industrial, road, hydraulic, subway constructions, etc.). Currently, the most common is the vibration method of molding concrete and reinforced concrete products.
However, the issues of choosing a rational mode for compacting concrete mixtures, its effect on density and, accordingly, strength, water resistance, frost resistance and deformation properties of concrete, remain insufficiently studied. The best results are obtained by using the optimal frequentative vibratory influence method. In this case, concrete strength is increased by 25-30 % in comparison to the factor of concrete compacted by traditional method.

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1 Introduction

For the construction industry, the development and improvement of methods of compaction of concrete mixtures in forming of the reinforced concrete products is one of the leading areas in the concrete technology. At the forming stage, the necessary concrete structure is created, its required density, homogeneity and, accordingly, the quality of the product have to be secured. Therefore, we have modernized and substantiated the optimal mode of compaction of concrete mixtures during the products' forming. This would make it possible to significantly reduce the duration of the products' forming and the consumption of the energy can be reduced too. Such implementations are one of the actual solutions in concrete technology at the companies of the construction industry.

Achievements in theoretical physics and analytical mechanics were used to develop the foundations of the theory of optimal control of the process of vibration compaction of concrete mixture [1-4].

Some researchers represent the concrete mixture as a system of aggregate particles connected by elastic or elastic-plastic connections [5]. The role of such connections is assigned to the layers of cement paste. It is assumed that each particle of a certain mass, connected by an elastic connection, must have some frequency of natural vibrations and vibration will be the most effective when the period of the vibrator's perturbing force coincides with the period of natural vibrations of the aggregate particles, i.e. at resonance. It has been proven that a low vibrations frequency is necessary for the resonance of large aggregate particles and a higher frequency for the small ones. Since the aggregate particles, of different sizes, weights and shapes, are usually present in the concrete mixture, the multifrequency vibrations should be the most effective [5].

One of the main parameters of compaction of concrete mixtures is the optimal duration of compaction, after which the density and strength of concrete are practically not increasing. For durations of compactions below this value, the mixture would be uncompacted and the strength and other properties of concrete would not be fully utilized. The same degree of compaction can be achieved with different combinations of intensity and duration of vibrations. As the intensity increases, the time required for compaction of the mixture decreases and vice versa. The increased duration of the compaction does not provide a noticeable improvement of strength and other properties of concrete. Such a measure is ineffective and sometimes even harmful (overconsumption of energy, unproductive use of equipment, longer exposure to noise) [3, 5-6].

Currently, the vibrations are the most common method of compaction of concrete products. However, despite the available developments in this field, the issues of choosing a rational mode of compaction of concrete mixtures, its effect on density and, accordingly, strength, waterproofing, frost resistance and deformable properties of concrete remain insufficiently studied [5].

2 Experimental material and methods

The paper aimed at developing the scientific and technical principles of optimal management of the reinforced concrete products' forming process by the vibrating method. This would significantly improve the quality of reinforced concrete (in terms of strength, waterproofing, frost resistance, deformation indicators, etc.).

Portland cement M400, 20-40 mm fraction gravel and the fine Dnieper sand (Mkr = 1.2-1.3) were used in the research.

The composition of the concrete was characterized by the ratio of components Cement: Sand: Crushed stone: Water = 1:1.63:3.68:0.59 (C:S:C:W = 1:1.63:3.68:0.59; (C = 357 kg/m^3, S = 582 kg/m^3, C = 1314 kg/m^3, W = 210 l/m^3)), the mobility of the concrete mixture - the slump of a standard cone of 30 - 40 mm (S1 = 30 - 40 mm), concrete class B 15 (C12/15).

For compaction of concrete mixtures when forming samples of 100 × 100 × 100 mm, a laboratory vibrating table VT-1 was used (oscillation frequency 2860 cycles/min, amplitude under load - 0.35 mm).

3 Research methodology

Vibrations compaction of concrete mixtures with a constant intensity of vibrations (at a constant energy flow) results in voids (jamming of aggregates and especially crushed stone or gravel). This significantly reduces the sealing efficiency. To increase the efficiency of compaction, it is suggested to apply optimal management of the forming process, which includes multiple vibrations actions. This would contribute to the destruction of voids, as well as directed capillaries, which are formed as a result of air removal, redistribution of cement paste and soluble component. The technology of manufacturing reinforced concrete products by the optimal molding control allows to significantly increase the physical and mechanical properties of concrete and reduce their cost.

Compaction of concrete mixtures by the vibrations method can be carried out under different modes (the intensity value, its change over time, the duration of compaction, etc.), however, after the end of the process, a concrete mixture of different densities will be obtained [5-6]. The task is to develop and theoretically justify such a mode of vibrations compaction, in which compaction of the concrete mixture (achieving the minimum possible volume) would take place in the shortest time.

Significant factors, characterizing the quality and speed of compaction of the concrete mixture, are the change in the volume of the compacted mixture and the speed of removal of the air phase. Therefore, using the terms «theory of optimal control», the phase plane is defined by the coordinate X_1^y - the volume of the compacted concrete mixture and the coordinate X_2^y - the rate of air removal during vibrations compaction, water removal during vibrovacuum, centrifugation, etc. The origin of the coordinates will be characterized by the minimum possible volume of the compacted mixture and the removal rate of the air and liquid phase, which is equal to zero. Admissible control has the following components: pressure in the concrete mixture without vibrations, during the vacuuming etc. and pressure in the concrete mixture during the vibrations compaction, vibrations vacuuming etc.

The phase state of the concrete mixture (terms of "theory of optimal control") at the initial moment of time $(X_1^y(t_0), X_2^y(t_0))$ and the control function $\overline{P}(t)$ uniquely determine the phase trajectory of the state of the concrete mixture during the compaction. Based on this, a dependence was obtained, which gives the optimal control in terms of speed, which turns out to be piecewise-continuous (relay) - it changes periodically [7-8]. The number of switches (or control stability intervals) for the linear systems is always normal and depends on the control field, initial and final conditions. We have proven that the optimal control of the forming is carried out by rational regulation of the pressure inside the compacting concrete mixture [7, 9-10]:

$$\overline{P_a}(t) = K^Y(t) sign\psi(t) = K^Y(t) sign\psi(c_1 - c_2 t), \quad (1)$$

where:
P_a - pressure in the concrete mixture (active pressure);
ψ - amount of movement (impulse of the system);
t - compaction time;
c_1, c_2 - constant integrations;
K^Y - coefficient depending on the type of compacted mixture.

Taking into account the obtained results of theoretical studies, as well as developments [8], a structural diagram of the concrete mixture vibrations compaction control with feedback was developed (Figure 1).

Thus, the optimal forming control is carried out by the rational pressure regulation inside the concrete mixture compacted by the vibrations method by means

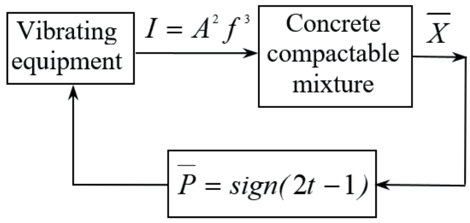

Figure 1 *Block diagram of the concrete mixture vibrations compaction control with feedback, where: I - is the intensity of compaction, A - is the vibrations amplitude of the vibrations device, f - is the vibrations frequency of the vibrations device*

Table 1 *Density and strength of concrete depending on the method of vibrations*

Type of sealing	Duration of operation of the included vibrating table, s	The average density of concrete, ρ_0, kg/m^3	Concrete strength limit, f^{28}_{6}, MPa
Without inertial intensity flow (energy flow)	20	2343	19.5
With inertial intensity flow (energy flow)	10	2357	21.2
Without inertial intensity flow (energy flow)	30	2357	19.2
With inertial intensity flow (energy flow)	20	2263	20.9
Without inertial intensity flow (energy flow)	40	2352	19.1
With inertial intensity flow (energy flow)	30	2360	22.2

of multiple vibrational influences (multiple intensity pulses).

With this mode of compaction, the inertial intensity flow (inertial energy flow) will significantly affect the quality of compaction of the concrete mixture. To reveal its role, two batches of samples were formed using different methods of vibrations.

4 Results and discussion

The first batch of samples was formed without an inertial intensity flow (energy flow), the duration of forming was 20, 30 and 40 s, respectively. In this case, the form with the concrete mixture was installed on the vibrating table, the vibrating table was turned on and after the set time, the form was removed from the vibrating table without turning it off.

The second batch - taking into account the inertial energy flow: the duration of the vibrations effect in this case was only 10, 20 and 30 s - here the form with the concrete mixture was installed on the vibrating table, the vibrating table was turned on and turned off after a certain period of time, the form was removed only after a complete stop of the vibrating table The density of concrete at the age of one day and the strength limit after 28 days were determined (Table 1, Figure 2).

The results of the research show that the inertial energy flow has an important impact on both the density and strength of concrete, as well as on the forming duration, which is significantly increased if this flow is excluded from the technological process of compaction of the concrete mixtures. It should be noted that with the help of an additional inertial intensity flow (energy flow), it is possible to increase the concrete strength by 10-15 %, relative to the strength of concrete compacted by the standard molding method. Repeated use (application) of the inertial energy flow can significantly improve the quality of concrete compaction.

In the course of research, a comparative assessment of various modes of vibrations compaction of concrete mixtures was carried out. Materials used for production of the concrete mixtures were the same as in previous studies.

Optimal control of the forming process of concrete and reinforced concrete products is an inertial energy flow under vibrations. That is, the general cycle of product molding is divided into several segments: when the concrete is exposed to vibrations and when the vibrations are interrupted. The time interval between the vibrations impact was 2-3 s and duration of vibrations (with optimal control) was 6-18 s. The entire cycle of compaction of the concrete mixture is 30 s.

Molded samples were hardened under the normal conditions. At the age of 28 days, the density and compressive strength of concrete were determined. The results of the research are given in Table 2, which confirmed the conclusions obtained during the theoretical development of optimal forming control [8]. A comparative assessment of various methods and regimes of the concrete mixtures compaction showed that the best results were obtained by applying the optimal control, which uses the mode with multiple vibrations effects. In this case, the greatest increase in concrete strength was achieved in comparison to the indicators of the concrete compacted by the traditional method.

Since the frost resistance is one of the most important properties of concrete for determining its durability, we have carried out research on the frost resistance of concrete compacted with the commonly used method of vibrations compaction and optimal management

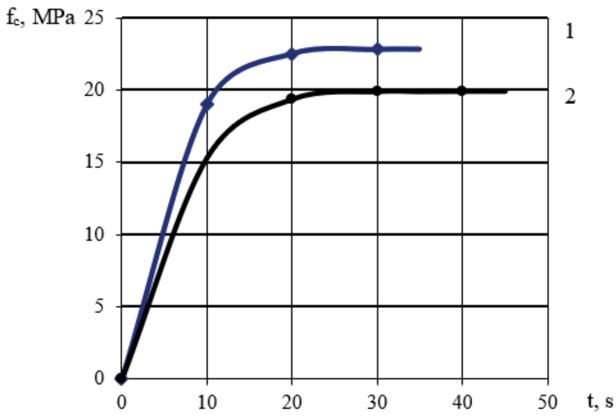

***Figure 2** Influence of the method of vibration exposure during the molding of products on the strength characteristics of concrete: 1 - with inertia energy flow; 2 - without inertial energy flow*

***Table 2** Density and strength of concrete depending on the compaction mode*

Type of sealing	Vibro-sealing at the maximum possible intensity		Concrete density mixture, ρ_0, kg/m^3	Strength of concrete, f^{28}_c, MPa
	Duration of vibrations actions, s	Number of vibrations		
Existing method of vibrations compaction (at constant intensity)	30	1	2384	19.4
The proposed method of vibrations compaction (with multiple vibrations)	13	2	2466	23.0
	8	3	2505	25.8
	6	4	2507	25.9

according to standard DSTU B.V.2.7-47-96. A freezer was used to test for frost equipment. The tests were carried out at a temperature of -50^0 C. Duration of the test cycle in the freezer was 2.5 hours. The main samples are tested for strength 2 hours after being removed from the freezer. In the experimental studies, used concrete mixes and concretes, as well as the materials for their preparation, were the same as in the previous experiments.

The degree of the frost resistance was judged by changes in sample weight and compressive strength after 50, 100, 150 and 200 freezing cycles.

The results of the research are shown in Figures 3 and 4. During the period of testing for the frost resistance (273 days), the control samples that were stored in water hardened, increased their mass and strength. At the same time, the largest increase in mass (3.5 %) and strength (10 MPa) was observed in samples of concrete compacted at a constant intensity of vibrations.

Samples of concrete compacted with optimal control of forming showed a smaller increase in mass due to lower water absorption (within 2 %), the increase in strength was 9 MPa on average

Samples subjected to freeze-thaw cycles within 100 cycles increased mass and strength with greater intensity than the control ones. The strength of samples molded by vibration in the usual mode (at constant intensity), after 200 cycles, decreased by 16% compared to control samples.

After 200 cycles the compressive strength of the concrete compacted by the optimal control of the compaction (with repeated vibrations effects) was almost at the same level as that of the control samples (the decrease was only 5-6.5 %).

The research results show that concrete compacted under optimal control of forming has higher frost resistance compared to concrete compacted under constant vibrations intensity. The results of our studies of the main properties of concrete, compacted by different modes of vibrations, have shown that in addition to the increased frost resistance, the optimal control of forming also significantly increased the water resistance of concrete (by 1.3-1.6 times) and on the other hand, it significantly reduced the value of capillary moistening and water absorption, as well as deformation, shrinkage and swelling.

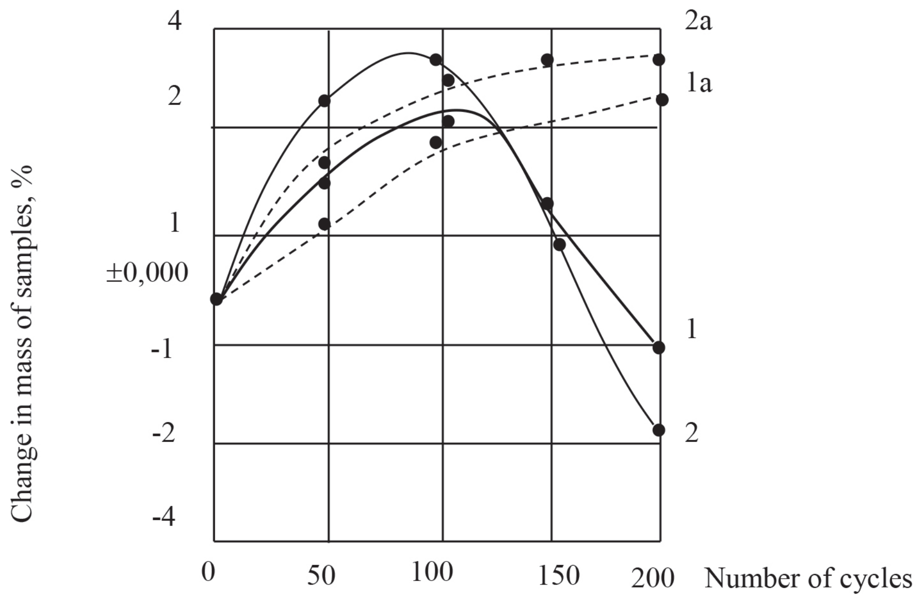

Figure 3 *The mass of concrete samples depending on the duration of hardening, the number of freezing and thawing cycles: 1 - for samples formed with optimal control and freezing-thawing; 1a - the same, for control samples; 2 - for samples molded according to the traditional mode (with constant vibrations intensity) and subjected to freezing-thawing; 2a - the same, for control samples*

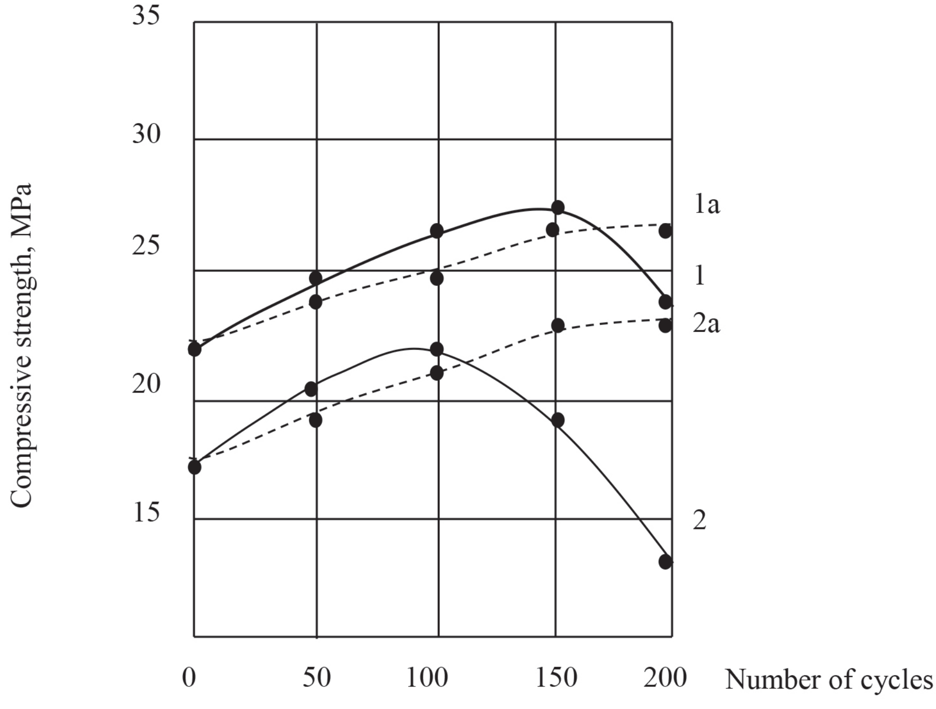

Figure 4 *Compressive strength of concrete samples depending on the duration of hardening, the number of freezing and thawing cycles: 1 - for samples formed with optimal control and freezing-thawing; 1a - the same, for control samples; 2 - for samples molded according to the traditional mode (with constant vibrations intensity) and subjected to freezing-thawing; 2a - the same, for control samples*

5 Conclusions

Experimental research has confirmed the conclusions obtained during the theoretical considerations, regarding the improvement of the compaction mode of concrete mixtures:

- A comparative assessment of different methods and regimes of compaction showed that the better results were obtained by application of the optimal control of forming, i.e. when using the mode with multiple vibrations effects. In that case, the increase in strength of concrete was 25-30 %, compared to the indicators of concrete compacted by the traditional method;
- When obtaining the full-strength concretes, it is possible to reduce the cement consumption. At the same time, the duration of forming is significantly reduced and the proposed forming method does not require additional capital costs for implementation - it requires just the standard mechanical equipment widely used in the construction industry.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] STOROZHUK, N., DEKHTA, T. On the inertial energy flow with optimal control of the formation of reinforced concrete structures. *Bulletin of the Prydniprovska State Academy of Civil Engineering and Architecture*. 2003, 1, p. 24-31. ISSN 2312-2676.
[2] STOROZHUK, N., DEKHTA, T. *Optimal control of the compaction of concrete mixtures in the production of reinforced concrete*. Monograph. Dnepropetrovsk: Thresholds, 2012. ISBN 978-617-518-197-3.
[3] STOROZHUK, N., DEKHTA, T. Optimal control of compaction of concrete mixtures by vibration method and its features. *Bulletin of the Bulletin of the Prydniprovska State Academy of Civil Engineering and Architecture* [online]. 2018, 4, p. 56-64, ISSN 2312-2676. Available from: https://doi.org/10.30838/J.BPSACEA.2312.231018.56.311
[4] PSHINKO O., KRASNYUK A., HROMOVA O., Theoretical study of the conditions of combined action of materials of old and new concrete in the repair and restoration of the structures of transport facilities. In: 23-nd International Scientific Conference Transport Means 2019: Sustainability: Research and Solutions: proceedings. Part I. 2019. ISSN 1822-296X, eISSN 2351-7034, p. 508-513.
[5] DEKHTA T. Optimal control molding in technology concrete structures. *Promising Scientific Researches of Eurasian Scholars.* 2021, 8, p. 8-11. ISSN 2709-183X
[6] PSHINKO O., HROMOVA O., RUDENKO D., Study of rheological properties of modified concrete mixtures at vibration. *Material Science Forum*. 2019, 968, p. 96-106. ISSN 1662-9752. Available from: https://doi.org/10.4028/www.scientific.net/MSF.968.96
[7] STOROZHUK, N. *Vibrovacuumization of concrete mixtures and properties of vacuum concrete*. Dnepropetrovsk: Thresholds, 2008. ISBN 978-966-525-966-4.
[8] STOROZHUK, N., DEKHTA, T. The problem of optimal control of the compaction of concrete mixtures. *Bulletin of the Prydniprovska State Academy of Life and Architecture*. 2001, 1, p. 46-53. ISSN 2312-2676.
[9] STOROZHUK, N. On the issue of compaction of concrete mixtures by vibro-vacuum. *Izvestiya VUZov. Construction and Architecture*. 1976, 2, p. 110-115.
[10] STOROZHUK, N. Investigation of a new method of compaction of concrete mixtures under the action of vacuum. *Izvestiya VUZov. Construction and Architecture*. 1982, 11, p. 67-71.