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# Experimental and theoretical studies of reinforced concrete structures using fine aggregates from iron ore beneficiation waste

Beneficiation waste from mining and processing plants possesses the characteristics of strong and inexpensive aggregates suitable for structural reinforced concrete. This enables the practical use of such waste in the production of precast reinforced concrete. Practice has demonstrated the feasibility of using iron ore beneficiation waste as fine aggregate in concrete. The authors conducted studies on the behavior of concrete structures incorporating fine aggregates derived from iron ore beneficiation waste. This article presents the results of research on concrete, elements, and structures with fine aggregates from iron ore beneficiation waste under low-cycle loading.

**Keywords:** beneficiation waste, fine aggregates, reinforced concrete structures, low-cycle loading, prestressing reinforcement.

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## Introduction

Improving the economy, reliability, and durability of structures is a key area of advancement in construction engineering both in Ukraine and internationally. Equally important is the reduction of concrete and reinforced concrete costs. One way to achieve this is through the development of construction materials utilizing waste from the mining industry

Iron ore basins hold significant reserves of aggregates from beneficiation waste, which can be used in the production of concrete and reinforced concrete structures. Utilizing such waste can help address the shortage of non-metallic construction materials and provide a supply of strong and affordable aggregates for structural reinforced concrete. Reclaiming land occupied by waste also addresses environmental protection concerns and promotes zero-waste processes in the mining industry.

Practice has confirmed the feasibility of using iron ore beneficiation waste as fine aggregate in concrete. At Kryvyi Rih National University, studies were conducted on the performance of concrete and reinforced concrete structures with concrete made using fine aggregates from iron ore beneficiation waste. The waste from all mining and processing plants has similar properties, making it viable for practical application in precast reinforced concrete production.

## Review of the latest research sources and publications

A review was conducted of domestic and international research dedicated to the theoretical and experimental study of the performance of concrete and reinforced concrete elements under low-cycle loading, as well as the reinforcement of the compressed concrete zone. The nature and physical essence of low-cycle repeated loading were also analyzed.

Researchers such as Soleimani, S. M., Boyd, A. J., Komar, A. J. K., & Roudsari, S. S. Han, B., Gao, H., Zhang, L. Li, J., Liu, H., Guo, Q., Dai, G., Zhou, J., & Xie, P. and others have contributed to the study of concrete and reinforced concrete elements under low-cycle loading.

The above studies confirm that low-cycle loading causes changes in the strength and deformation characteristics of both concrete and reinforcement.

The specific behavior of concrete and reinforced concrete structures made using beneficiation waste has been studied by researchers such as Valovoi, O. I., Eremenko, O. Yu., Valovoi, M. O., & Volkov, S. O., Arbili, M. M., Alqurashi, M., Majdi, A., Ahmad, J., & Deifalla, A. F. Evangelista, L., de Brito, J. Krishna, Y.M., Dhevasenaa, P.R., Srinivasan, G and others.

**Definition of unsolved aspects of the problem**

Improving the economy of reinforced concrete structures requires the development of concrete with higher strength properties and the creation of reliable methods for predicting their behavior under load.

This aligns with the economically efficient use of mineral resources in production. The current technical level of industry enables the complete processing of by-product minerals and production waste, 85% of which can be used in construction. Therefore, saving and optimizing the use of resources in precast reinforced concrete production can be viewed through the lens of comprehensive utilization of raw materials and mineral processing waste.

Currently, iron ore beneficiation waste is used as a substitute for sand in construction mortars and concrete. Studies have shown high efficiency and stable physical and mechanical properties in such concrete, along with good workability in construction.

The use of concrete and reinforced concrete has expanded significantly, and the average strength of materials used has increased. High-strength materials in structures often allow for the reduction of cross-sectional areas without compromising design load capacity.

The behavior of concrete and reinforced concrete under single static loads is well studied. However, a wide range of modern structures in real operating conditions are subjected to high-intensity. repetitive low-cycle loads (such as seismic or temperature effects). Operating modes of structures are becoming more demanding and complex. Therefore, studying the resistance of reinforced concrete elements to repeated high-intensity loading is a crucial issue both in reinforced concrete theory and in solving practical engineering problems for creating reliable and efficient structures.

**Problem statement**

The physical nature of the stress-strain state of concrete under repeated cyclic loading remains largely unexplored, and current views on the phenomenon are often contradictory. Despite extensive experimental and theoretical research aimed at studying the physical and mechanical properties of concrete under cyclic loading, there is still no unified modern physical theory that adequately explains the deformation process and changes in strength characteristics of concrete under such conditions.

Progress in the analysis of concrete and reinforced concrete structures under variable and cyclic loading should focus not so much on refining mathematical calculations, but rather on the experimental investigation and consideration of concrete and structural behavior. It is therefore essential to develop a comprehensive understanding of the behavior of such concretes to effectively integrate this knowledge into design practices.

In conclusion, scientifically accounting for the aforementioned factors in the design of reinforced concrete structures for strength, stiffness, and crack resistance will help avoid inefficient use of concrete and steel by refining safety factors.

**Basic material and results**

The research of concretes elements and constructions with fine aggregate from the ore-dressing waste products was carried out in the collation of analogical samples of heavy concrete with traditional fine aggregate – quartz sands.

Physical-mechanical properties of the concretes have been explored using cubes of 10 cm ribs and prisms of 10×10×40 cm size made of concrete of 400 projected make of 1:2.22:0.89 composition, with the addition of 1% plasticizer of cement mass and B/Z = 0.32.

In both concrete mixtures were used the portland cement of M 500 and granite rubble with a 10–20 mm fraction.

At axial compression, the concrete cubes made from waste products collapsed similar to the cubes produced from conventional concretes. The prisms collapsed along the longitudinal crecks or ruptures. Comparing the character of collopse (breaking) of waste products produced concrete with the conventional concrete, it was noticed that the first type is more brittle and breaks almost immediately. Besides, the strength of concrete produced from ore-dressing waste, after 28 days, practically doesn`t increase.

Waste produced concrete has 15–20% better grip on average. For estimation of waste produced concrete grip between concrete and steel we propose the following dependence [1]:

$$N_{\max} = K_1 K_2 K_3 UIR_{gr} \tag{1}$$

where $R_{gr}$ – average conventional value of grip; $I$ – length of reinforcement (steel) embedding, cm; $U$ – bar perimeter, cm; $K_1$ – coefficient regarding the steel (reinforcement) type: for smooth bars $K_1 = 1$, for periodical profiled bars $K_1 = 1.32$, for ropes K-7 of Ø 12-15 mm $K_1 = 1.2$; $K_2$ - coefficient regarding type of concrete: for conventional concretes $K_2 = 1$, for waste produced concrete $K_2 = 1.15$; $K_3$ –

coefficient regarding bar diameter: for Ø ≤10 mm – $K_3 = 1.1$, for Ø12-16 mm – $K_3 = 1$, for Ø18 mm – $K_3 = 0.9$.

The average discordance between test and theoretical out stresses (force) results for waste produced concrete, calculated on formula (1) doesn't exceed 7%.

The average values of waste (produced concrete limited deformations constituted 1.286 mm/m, and 1.683 mm/m for the conventional concrete). Waste produced concrete can be considered to be practically elastic material up to $0.8R_{np}$ tension (stress) (Fig. 1).

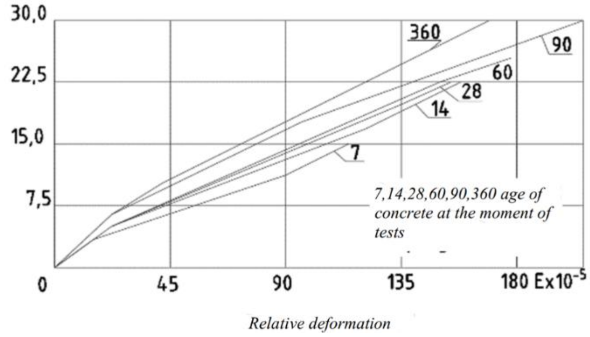



**Figure 1 - Prestressed constructions produced from concrete made of fine aggregate – ore-dressing waste.**

We propose to determine the waste produced concrete theoretical elastic modulus using the formula:

$$E_б = C\frac{5500\bar{R}}{27+\bar{R}} \tag{2}$$

where $C$ – coefficient obtained from experience, $C = 1.16$.

The values of waste produced concrete shrinking deformation don't exceed the shrinkage of conventional concrete.

Waste produced concrete creep characteristic is for 16% less than that of the conventional concrete. At the age of 300 days the values of the creep of concrete characteristic at 0.5 and $0.6R_{np}$ are corresponding $l_y$ – 1.49 and 2.02. The theoretical values of the said deformations on time are determined by the known formulas [2]:

$$\alpha_y(t) = \alpha_y\left(1-e^{-\alpha t}\right); \tag{3}$$

$$\varphi_t = \varphi_\infty\left(1-e^{-\beta t}\right), \tag{4}$$

where $\alpha$ – relative shrinkage deformation to arbitrary moment of time, t; $\alpha_y$ – limited relative shrinkage deformation the moment of its damping; $\varphi_\infty$ – limited value of creep characteristic related to the moment of time $t = \infty$; $\alpha$ and $\beta$ experimental parameters.

The average values of limited shrinkage and creep of concretes values and also the recommended coefficients $\alpha$ and $\beta$ are given in Table 1.

**Table 1- Coefficients value for the concrete under test in formula (3) and (4)**

| Types of concrete | $\varphi_\infty$ | $\alpha_y \times 10^{-5}$ | $\alpha$ | $\beta$ |
|---|---|---|---|---|
| Level of loading $0.5\bar{R}_{np}$ | | | | |
| On waste<br>Conventional | 1.27<br>1.66 | 28.5<br>24 | 0.0123<br>0.0132 | 0.0145<br>0.016 |
| Level of loading $0.6R_{np}$ | | | | |
| On waste<br>Conventional | 1.49<br>2.02 | 28.5<br>24 | 0.0123<br>0.0132 | 0.0145<br>0.016 |

To determine the low cyclic concrete fatique (Table 2) 9 series of prisms of old age were tested in the regime of soft loading with max level of stresses within the limits of 0.75-1.

The carried out tests showed that the less the level of loading (at low cycled loading) the higher the max deformations of concrete $\varepsilon_R$.

For determination of the low cycled fatique of waste produced concrete the following dependence is proposed:

$$N = \frac{\bar{R}_{np}\delta(1+\alpha)\alpha}{2E_0\varepsilon_R^\alpha}\sigma_a^{-\frac{1}{\delta}}, \tag{5}$$

where $R_{np}$ – concrete prism strength when subjected to monotonous by increasing loading: $\delta = \frac{\alpha}{1+\alpha}$; $\alpha = \frac{E_\delta \varepsilon_R}{\bar{R}_{np}} = \frac{1}{\upsilon}$; $E_0$ – modules of non-linearial concrete deformations; $E_R$ – concrete maximum deformations; $\sigma_\alpha$ – amplitude of stresses.

**Table 2- Results of low-cycle fatigue testing of waste-based concrete**

| № of series | Stresses Mа | Level of stresses | Max. deforma-tions of concrete $\varepsilon_R \times 10^{-5}$ | Cycle test number till break, $N$ | Theoretical value, $N$ |
|---|---|---|---|---|---|
| 1 | 25.3 | 1 | 114 | 0 | 0 |
| 2 | 24.8 | 0.98 | 119 | 4 | 2 |
| 3 | 24.3 | 0.97 | 123 | 5 | 3 |
| 4 | 22.8 | 0.9 | 131 | 11 | 8 |
| 5 | 20.7 | 0.82 | 137 | 18 | 18 |
| 6 | 20.2 | 0.8 | 138.5 | 21 | 22 |
| 7 | 19.7 | 0.78 | 140 | 30 | 28 |
| 8 | 19.5 | 0.77 | 141 | 33 | 32 |
| 9 | 19.0 | 0.75 | 141.5 | * | ∞ |
| * the prism didn`t collapse after 120 cycles | | | | | |

Experimental and theoretical results of low cycled fatigue of waste produced concrete are quite similar.

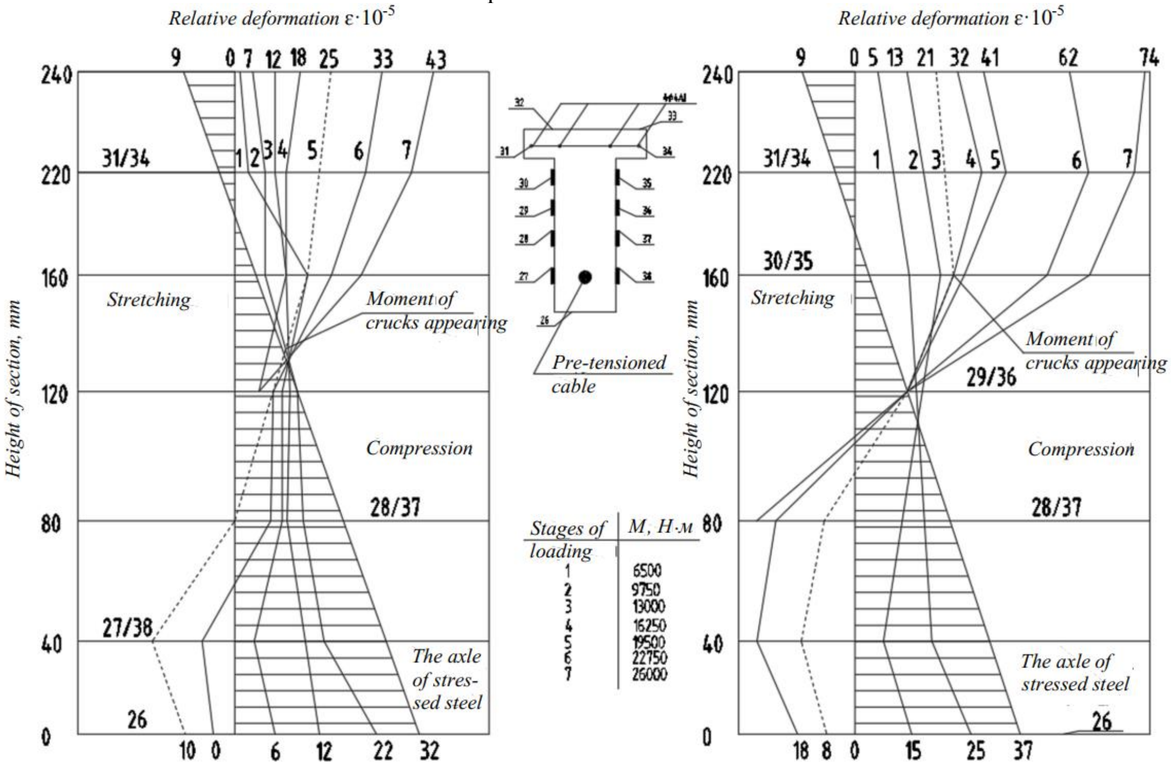
Prestressed T-beams were tested in laboratory conditions. The T-beams were treated with concrete simultaneously with cubes and prisms.

The steel initial stresses were specified in accordance with specifications and were transferred from the rests to concrete being 7 days of age (age of concrete). At the moment of the reinforcement tempering there were no cracks in the upper zone. The zone of clear bending free from lateral reinforcement was tested.

By monotonously increasing loading test process were checked and measured the concrete compressed zone edge deformations, as well as the deformation. At the stressed steel level deflections in the middle of the span and the width of the cracks opening.

The test results analysis of the stress distribution on high of the concrete compressed zone (Fig. 2) showed, that the strength analysis of the normal section beams made from waste produced concrete should be done regarding the triangular epure of stresses by formula:

$$M = 0,5R_{np}bx\left(h_0 - \frac{1}{3}x\right) \tag{6}$$




a b

**Figure 2 - Epure of longitudinal deformation of concrete on middle section height beams in dependance of the bending moment value.**

According to analysis the coefficient of elasticity $\nu$ in the collapse stage for waste produced beams can be taken as 0.8.

Crack resistance of the bending elements produced from waste can be determined regarding replacement of elastic-plastic moment of resistance WT by formula:

$$W_m = b(h-x)\left(\frac{h}{2}+\frac{x}{6}\right)+\frac{2F_{св}(x+\alpha_{св})}{h-x}\times \times\left(\frac{x}{3}-\alpha_{св}\right)+F_н\left(2n+\frac{\sigma_0}{R_p}\right)\left(h_0-\frac{x}{3}\right), \tag{5}$$

where all indices taken according to [4].

The values of crack formation moments regarding (7), determined from the premises of triangular epure of stresses, for experimental beams are shown in Table 3.

**Table 3- Values of test and theoretical index of $M_t$,$H{\cdot}м$**

| Concretes | σ0, Мпа | $M_m^{on}$ | $M_m^{теор.}$ with $W_m$ (7) | % difference |
|---|---|---|---|---|
| Produced from waste | 8361 | 19500 | 20016 | 2.6 |
| Conven-tional | 8072 | 16250 | 19126 | 17.7 |

The test values of crack opening in the beams of waste produced concrete with M≅0.6M are 27% less than in beams produced from conventional concrete.

Theoretical values of crack width opening of the beams made from waste produced concrete is necessary to determine by the known formula:

$$\alpha_m = KC_д\frac{\sigma_a}{E_a}\cdot 20(3,5-100\mu)\sqrt[3]{d}, \tag{8}$$

where $K = 0.8$ – coefficient obtained experimentally, the rest of values taken from [4].

The beams deflections of beams produced from waste are on average 20% less than that in the beams produced from concrete based on quartz.

That's why the flexure of these beams series beams, with $M \le M_m$ is recommended to determine by formula:

$$\frac{1}{p} = \frac{\bar{M}C}{K_n E_б J_n}, \qquad (9)$$

where coefficient $K_n = 0.95$ is obtained experimentally.

Experimental values of dressing waste produced concrete beams shrinkage deformation aging 480 days is lesser for 31-32%, and loss stress value for 35% lesser than, that in the analogical beams made of the conventional concrete. These stresses for the reinforced armored concrete elements are expedient to determine using the recommendations [2] according to formula:

$$\sigma_{ny} = \frac{\varepsilon_{\delta y}(t)}{\frac{1}{E_н} - F_н\left(\frac{1}{F_\delta} + \frac{Y_н^2}{J_\delta}\right)\frac{\gamma}{E_0}}, \qquad (10)$$

where $E_н$ and $F_н$ – module of elasticity and sectional area of stressing steel; $F_\delta$ – sectional area of concrete; $J_\delta$ – moment of beam inertia; $Y_н$ – distance from stressed steel to the centre of gravity of the beam section; $E_0 = E_\delta(\tau)$ ; τ – time of application of loading; $\gamma$ – is determined by the formula:

$$\gamma = \frac{\varphi_t}{1 - \exp\left(-\frac{\varphi_t}{1-\varphi_0}\right)}, \qquad (11)$$

where $\varphi_t$ - the characteristic of concrete creep; $\varphi_0$ – the value of the characteristic of the concrete creep charged in old age.

The value of $\varepsilon_{\delta y}(t)$ while calculating $\sigma_{ny}$, is taken from the test data. Supposing $\varepsilon_{\delta y}(t) = \alpha_y(t)$ determined by formula (3), $\alpha_y$ and $\alpha$ are known it is possible to calculate the stress losses at any moment of time.

The max. value of steel stress losses caused by the concrete creep in the BP-1 beams in average is for 18% less, than that in the analogical (similar) beams produced of conventional concrete. The prestressed losses in the beams, reinforced by single stressed steel is recommended to determine by the formula:

$$\sigma_{nn} = \frac{n\sigma_{бн}(1-\varphi_t) - \sigma_н}{1 - n\left(\frac{1}{F_\delta} + \frac{Y^2}{J_\delta}\right)F_н\gamma}, \qquad (12)$$

where $\sigma_{бн}$ – concrete initial stress; $\sigma_н$ – steel initial stress; $n = \frac{E_н}{E_\delta}$; the rest of the values are deciphered in formula (10). The formula (12) answers rather satisfactorily to the results of the experiment.

The applied calculation formulas and methods effectively approximate the experimental data, allowing for an assessment of the impact of fine aggregates derived from iron ore beneficiation waste on the performance characteristics of concrete and its structures. Further research will focus on evaluating the convergence between the obtained experimental data and theoretical calculations based on the deformation methodology.

To inculcate in industry the results of the research a series of tests on reinforced concrete constructions made from waste were carried out. There were tested eleven constructions altogether-floor slabs, roof truss, crane beams, cross-bar and foundation beam.

The constructions were produced from the materials, the physical mechanical properties of which had been described above.

The general geometrical size and reinforcing of the construction were taken from manuals.

Testing the hollow boards made from waste produced concrete the maximum permissible deflection $l/200$, or accordingly 2.75 and 3 cm, was reached with load on average of 20-30% higher than that with the boards made from conventional concrete.

At that the deformations of concrete compressed zone and the level of stressed concrete reinforcement is 30-40% lesser than the corresponding deformations in the conventional concrete made boards (than in the boards made from conventional concrete).

The boards made from waste produced concrete have exceeded the calculated index: on strength for 20-30% on harshness for 40-45% and deformation ability for 37-40 and 33-34%.

According to shop drawings demands the truss is to take up the test joint load of 297.3 kH (factum of calculated load of 178 kH and coefficient 1.67). At normative joint load of 148 kH the deflection of the truss is to be 9 mm, in case of calculated load of 178 kH – the deflection of the truss is 12 mm.

The test results showed that the truss deflection with testing load of 150 kH was 8.9 mm and with 180 kH load – 12 mm. The truss lost its carrying capacity at joint load of 440 kH.

The crane beam loaded with single concentrated force in the middle section took up load of P=633 kH, wich created stresses of M=934.5 кНм; Q=467 kH. The second beam, loaded with concentrated forces in the one third of the span, took up the load of P=920 kH which created stresses of M=920 kHm and Q=460 kH (the project demands are $M_{max}$=549 kНм, $Q_{max}$=419 kH).

The test of collar-beam was carried-out in accordance with working drawings demands. The actual load on the collar-beam was 840 kH (calculated breaking load 653 kH).

The collar-beam deflection at normal load of 528 kH has proved to be 8.5 mm. The standardized deflection for this load equals 13.3 mm.

The breaking load of the foundation beam proved to be 350 kH with calculated load of 128.6 kH.

The described here research is a striking evidence of the possibility of wide scale usage of ore-dressing waste for conventional and prestressed reinforced constructions production.

The effectiveness of reinforced constructions production made from the waste based concrete results from the profit gained by the ore-dressing plant, building companies and railway management.

**Conclusions**

Successful resolution of the issues discussed above will allow for the creation of reliable and cost-effective structures, preservation of land resources and the environment, and supply of strong and inexpensive fine concrete aggregates to precast concrete plants.

This study investigates concrete and flexural reinforced concrete elements and structures using fine aggregates from iron ore beneficiation waste under constant, variable, and alternating loads of varying intensity.

As a result of the research, a number of specific physical and mechanical properties were identified in concrete made from beneficiation waste (e.g. increased strength, reduced deformability), which must be taken into account when developing structural design approaches for such materials.

A comparison of experimental and theoretical results for the strength and deformation characteristics of reinforced concrete structures (e.g., strength, stiffness, cracking moment) demonstrates the feasibility of using standard design principles, provided the unique properties of the concrete in question are considered.

Laboratory testing of elements and field tests of typical reinforced concrete structures made with this concrete confirm the potential for wide application and high effectiveness of the recommended material.

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# Експериментальні та теоретичні дослідження залізобетонних конструкцій із використанням дрібного заповнювача з відходів збагачення залізної руди

Відходи збагачення гірничо-збагачувальних комбінатів характеризуються високою міцністю, однорідністю та низькою вартістю, що робить їх перспективними для використання як дрібного заповнювача у конструкційному залізобетоні. Це відкриває широкі можливості для практичного застосування таких техногенних матеріалів у виробництві збірного залізобетону, зокрема у регіонах з обмеженими запасами природних нерудних ресурсів. Практичний досвід і дослідження підтверджують доцільність заміни традиційних заповнювачів на відходи збагачення залізної руди. У дослідженні, виконаному на базі Криворізького національного університету, розглянуто особливості роботи бетону та залізобетонних конструкцій, що містять як дрібний заповнювач відходи збагачення залізної руди. Наведено результати фізико-механічних випробувань, проведених як у лабораторних умовах, так і у вигляді натурних експериментів на типових елементах конструкцій. Доведено, що бетон з техногенними заповнювачами характеризується підвищеною міцністю, зменшеною деформативністю та підвищеною тріщиностійкістю. Розглянуто поведінку таких конструкцій під дією постійного, змінного та малоциклового навантаження різної інтенсивності. На основі експериментальних даних проведено порівняння з теоретичними моделями, що дозволило підтвердити можливість використання діючих нормативних методик розрахунку за умови урахування особливих властивостей бетонної суміші. Зроблено висновки щодо ефективності використання відходів збагачення як альтернативного джерела заповнювачів, що одночасно сприяє підвищенню економічності, довговічності та екологічної безпечності будівельного виробництва.

**Ключові слова: в**ідходи збагачення, дрібний заповнювач, залізобетонні конструкції, малоциклове навантаження, попереднє напруження арматури.

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