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DEVELOPMENT OF GEOPOLYMER CONCRETE FORMULATIONS BASED ON ACTIVATED STONE PROCESSING SLUDGE TO REDUCE NATURAL RESOURCE CONSUMPTION

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This study investigates concrete mixtures modified by partial or complete replacement of cement and sand with granite and gabbro sludge from stone-processing plants, activated with a 12M NaOH solution to improve their mechanical properties and microstructure.

The task addressed relates to the excessive accumulation of sludge waste from the stone-processing industry, which pollutes the environment and predetermines the need to reduce the consumption of natural resources (cement and sand) in concrete production. This production is accompanied by high CO_2 emissions and significant costs. All these factors necessitate designing environmentally friendly and economically viable construction materials.

The study investigated the effect of replacing cement (0–100%) and sand (0–100%) with a mixture of granite and gabbro sludge on compressive strength and ultrasonic pulse velocity after 7, 14, and 28 days of curing. Replacing up to 30% of sand provides a compressive strength of 45–50 MPa while replacing up to 20% of cement provides 30–32 MPa on day 28, meeting structural requirements (>10 MPa). The ultrasonic velocity (4200–4300 m/s at 30% sand replacement and 3800–4000 m/s at 20% cement replacement) indicates the preservation of a dense structure.

Distinguishing features of the results are attributed to the combination of granite and gabbro sludge activated with NaOH that produces a microfiller effect and enables pozzolanic activity. This makes it possible to reduce sand consumption by 30% and cement by 20% without a significant loss of strength. Unlike conventional mixtures or solutions using only one type of sludge, strength reduction proceeds more slowly due to fewer microcracks.

The results are suitable for producing environmentally friendly concrete for road and residential construction under moderately aggressive environmental conditions. The optimal replacement (30% sand or 20% cement) is effective under both laboratory and industrial conditions, provided that the sludge has a homogeneous composition and is activated with NaOH

Keywords: stone-processing sludge, geopolymer concrete, waste utilization, mechanical strength, ultrasonic properties, material nano activation

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1. Introduction

In the modern world where industrial production is rapidly growing and the planet's resources are being depleted, the issue of industrial waste disposal is becoming critically urgent. In particular, the stone processing industry generates significant amounts of sludge – finely dispersed waste from the processing of granite, gabbro, and other natural stones, which often accumulate at landfills, thereby polluting soils, water, and air. According to research, more than 2.59 billion tons of solid waste are generated in the world annually. A significant part of this waste is industrial, including mining and processing industries [1]. About 63.35 million tons of waste are generated in stone processing alone per year. At the same time, 30–40 tons of sludge are formed for every 100 tons of processed granite [2, 3].

In Ukraine, a country with developed stone processing (for example, in Zhytomyr and Vinnytsia oblasts), the problem of sludge waste is particularly acute. It is not only about taking valuable land resources, but it also leads to soil erosion, heavy metal pollution, and environmental degradation. As noted in [4, 5], such waste not only occupies valuable land resources but also leads to soil erosion, heavy metal pollution, and environmental degradation [6], which requires the implementation of European waste management standards. Conducting scientific research on the use of sludge in concrete is relevant under current conditions since global challenges such as climate change and the shortage of natural resources require a transition to the principles of a circular economy, in which waste from some processes becomes raw material for others.

The production of conventional concrete requires significant amounts of cement, sand, and crushed stone, which leads to depletion of quarries and increased CO_2 emissions (the cement industry is responsible for approximately 8% of global greenhouse gases) [7, 8]. Research aimed at replacing these components with sludge contributes to reducing the environmental burden and achieving the UN Sustainable Development Goals, in particular No. 9 (innovation and infrastructure) and No. 12 (responsible consumption and production). In addition, under conditions of economic instability and rising costs of construction materials, such research enables cost optimization and increased sustainability of the construction industry.

Results of such studies could provide a number of significant advantages to practice. First of all, they allow the development of new geoconcrete formulations, where sludge partially or completely replaces cement or sand. At the same time, the mechanical properties of the material, such as compressive strength and ultrasound propagation velocity, are maintained or even improved. As shown in experimental data, replacing up to 25% of sand with granite sludge increases the strength of concrete [9, 10]. This will lead to designing environmentally friendly building materials that reduce the use of primary raw materials by 10–100%, reduce the cost of concrete production by 9–30%, as well as minimize waste. In practice, this means the possibility of building more sustainable structures – from roads and bridges to residential buildings – with less impact on the environment, as well as solving the problem of sludge disposal for enterprises, thereby turning costs into profits. In addition, the introduction of such technologies could stimulate innovation in construction, creating new jobs in the field of waste processing and contributing to the transition to a green economy.

Summarizing the above, the relevance of our study is due to the need to solve environmental and resource crises through innovative approaches to waste processing, as well as the potential for practical application to design sustainable and economically viable materials. Therefore, research on the use of stone processing sludge in concrete is relevant.

2. Literature review and problem statement

The use of waste from the stone processing industry, in particular granite and gabbro sludge, is a promising direction in the development of building materials, which makes it possible to combine environmental safety and technological efficiency. Studies show that granite sludge can be used as an aggregate in concrete and cement compositions, partially replacing sand or cement, which reduces the consumption of natural resources and increases the environmental efficiency of production.

Thus, it is shown in work [1] that self-compacting mortars with a replacement of up to 40% of the aggregate with granite sludge retain strength and durability, although there is an increased water consumption and a slightly reduced density of the mixture. This confirms the prospects for the use of granite sludge in high-performance mortars. In [2], it was established that replacing cement with granite dust in an amount of 10–20% ensures proper durability of concretes. However, at higher levels of replacement, microcracks appear. This may limit the use of such mixtures in structures operated in aggressive environments.

In work [3], it is emphasized that the use of granite dust in cement composites improves the microstructure and physical and mechanical properties of the material, while reducing the negative environmental impact.

Study [4] showed that cements with granite sludge at 10% cement replacement demonstrate satisfactory durability, while at 20% microcracks appear.

Paper [5] demonstrated that at a low level of granite sludge replacement in concrete, the properties of the mixtures remain acceptable, while the consumption of natural materials and disposal costs are reduced.

The authors of [6] showed that the hydration properties of the system based on enrichment sludge and OPC 42.5 cement allow for the effective use of such mixtures in dry building materials without losing their functional characteristics.

The set of studies indicates that granite sludge can be an effective component of cement and concrete compositions [8]; however, to ensure optimal properties of the mixtures, it is necessary to correctly select the concentration of sludge and take into account its mineralogical composition.

Thus, the integration of granite and other stone-working sludges into concrete compositions makes it possible to simultaneously solve environmental and technological problems but requires further research into the combined use of different types of sludges, their effect on the microstructure and durability of the material.

3. The aim and objectives of the study

The aim of our study is to design environmentally friendly concrete mixtures by combined use of granite and gabbro sludge as a substitute for cement and sand. This could make it possible to optimize the mechanical properties, microstructure, and durability of concrete. Such an approach will contribute to the disposal of industrial waste in accordance with the principles of circular economy.

To achieve the goal, the following tasks were set:

– to investigate the effect of partial replacement of cement (0–100% in increments of 10%) with a mixture of granite and gabbro sludge on the compressive strength, ultrasound propagation velocity, and microstructure of concrete samples after 7, 14, and 28 days of hardening;

– to investigate the effect of partial replacement of sand (0–100% in increments of 10%) with a mixture of granite and gabbro sludge on the compressive strength, ultrasound propagation velocity, and microstructure of concrete samples after 7, 14, and 28 days of hardening.

4. The study materials and methods

The object of our study is concrete mixtures modified by partial or complete replacement of conventional components (cement, sand) with sludge from stone processing enterprises, in particular a mixture of granite and gabbro sludge. The study focuses on analyzing the influence of such sludge on the mechanical properties (compressive strength, ultrasound propagation velocity), microstructure, and durability of concrete under conditions of long-term hardening (7, 14, 28 days).

The principal hypothesis assumes that the combined use of granite and gabbro sludge as a substitute for cement or sand provides concrete with satisfactory mechanical characteristics and strength not lower than 10 MPa. This makes it possible to increase the durability of the material and, at the same time, reduce the environmental load through the disposal of industrial waste. Our hypothesis assumes that the optimal replacement fraction (up to 40%) provides a balance between strength, economic feasibility, and environmental benefits.

Assumptions accepted in the work:

– granite and gabbro sludge have sufficient pozzolanic activity to partially replace cement, which contributes to the formation of a dense microstructure of concrete;

– the chemical composition of the mixture of granite and gabbro sludge is compatible with the cement matrix and does not cause significant negative reactions (for example, alkaline corrosion);

– the mechanical properties of concrete (compressive strength, ultrasound propagation velocity) correlate with the percentage of sludge replacement and the duration of hardening (7, 14, 28 days);

– activation of sludge with a 12M NaOH solution increases its reactivity and contributes to improving the strength of concrete mixtures.

Simplifications adopted in our work:

– the study does not take into account the influence of external factors (temperature, humidity, aggressive environments such as sulfates or chlorides) on the durability of concrete outside laboratory conditions;

– analysis of the microstructure of concrete is limited to the assessment of compressive strength and ultrasonic propagation velocity, without a detailed study of the phase composition or microcracking using methods such as X-ray diffraction or electron microscopy;

– the chemical composition of granite and gabbro sludge is assumed to be homogeneous, without taking into account possible variations in the mineralogical composition depending on the source of origin;

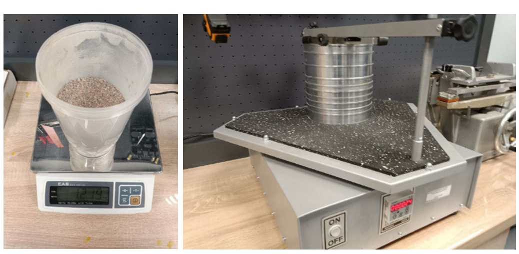
– the economic assessment of the replacement of components with sludge is based on the assumption of a stable cost of raw materials and does not take into account the logistical costs of transporting sludge to the concrete production site.

Research methodology.

The research was conducted to study the effect of the combined use of granite and gabbro sludge as a substitute for cement and sand on the properties of concrete mixtures. Our experiments included the preparation of concrete samples, sludge activation, measurement of mechanical characteristics, and microstructure analysis. The equipment, materials, theoretical methods and conditions for conducting experiments are described in detail below.

Preparation of materials and sludge activation.

For the preparation of concrete mixtures, Portland cement of the PC II/A-Sh 500 brand (CEM II/A-S 52.5), natural quartz sand with a fraction of 0.16–2 mm, granite crushed stone with a fraction of 5–20 mm, and distilled water were used. Granite and gabbro sludge obtained from stone processing enterprises in the Zhytomyr oblast were sieved through a sieve with a mesh size of 100 μm (0.1 mm) using a laboratory vibrating sieve (Fig. 1, *b*).



a *b*

Fig. 1. Laboratory instruments: *a* — laboratory scales CAS SW-2.DD; *b* — sieve with a mesh size of 100 μm

To activate the sludge, a 12M sodium hydroxide (NaOH) solution was used, which was prepared by dissolving 480 g of NaOH (analytical grade) in 500 ml of distilled water and then making up to 1 l in a 2-l heat-resistant laboratory beaker.

Then, the 12M solution was added to the sludge in an amount of 10% of the sludge weight. The mixing process was carried out using a stirrer at a temperature of 20±2°C. The solution was left for 2–3 hours to stabilize, as specified in the procedure. The activated sludge was mixed with other components under controlled conditions to avoid excess moisture, using a CAS SW-2.DD laboratory balance (Fig. 1, *a*) with an accuracy of ±1 g for weighing materials.

Technology for manufacturing concrete samples.

Concrete mixtures were prepared with different percentages of cement and sand replacement with sludge (0–100% in 10% increments), as specified in the experimental data. A laboratory concrete mixer with a drum volume of 185 l was used to mix the components. The mixtures were molded into standard cubic molds measuring 100 × 100 × 100 mm (Fig. 2), made of metal, in accordance with the standards of DSTU B V.2.7-214:2009. After molding, the samples were kept under standard hardening conditions at a temperature of 20 ± 2°C for 7, 14, and 28 days.

The following proportions were taken to prepare concrete: in some mixtures, cement was replaced by sludge (Table 1), in others, sand was replaced by sludge (Table 2).

Table 1

Composition of concrete mixtures with different levels of cement replacement by stone slurry

Cement replacement, %	Cement (kg)	Stone slurry (kg)	Sand (kg)	Crushed stone (kg)	Water (l)
0	0.84	0	2.25	3.6	0.48
10	0.756	0.084	2.25	3.6	0.48
20	0.672	0.168	2.25	3.6	0.48
30	0.588	0.252	2.25	3.6	0.48
40	0.504	0.336	2.25	3.6	0.48
50	0.42	0.42	2.25	3.6	0.48
60	0.336	0.504	2.25	3.6	0.48
70	0.252	0.588	2.25	3.6	0.48
80	0.168	0.672	2.25	3.6	0.48
90	0.084	0.756	2.25	3.6	0.48
100	0	0.84	2.25	3.6	0.48
Total:	4.62	4.62	24.75	39.6	5.28

Table 2

Composition of concrete mixtures with different levels of sand replacement by stone slurry

Sand replacement, %	Cement (kg)	Stone slurry (kg)	Sand (kg)	Crushed stone (kg)	Water (l)
0	0.84	0	2.25	3.6	0.48
10	0.84	0.225	2.025	3.6	0.48
20	0.84	0.45	1.8	3.6	0.48
30	0.84	0.675	1.575	3.6	0.48
40	0.84	0.9	1.35	3.6	0.48
50	0.84	1.125	1.125	3.6	0.48
60	0.84	1.35	0.9	3.6	0.48
70	0.84	1.575	0.675	3.6	0.48
80	0.84	1.8	0.45	3.6	0.48
90	0.84	2.025	0.225	3.6	0.48
100	0.84	2.25	0	3.6	0.48
Total:	9.24	12.375	12.375	39.6	5.28

The chemical composition of fine-dispersed waste from stone processing production is given in Table 3.

Table 3

Chemical composition of fine-dispersed waste from stone processing production

Component	wt. %
SiO_2	56.71
Al_2O_3	17.84
Fe_2O_3	7.38
CaO	7.29
Na_2O	3.69
MgO	2.42
K_2O	2.09
TiO_2	1.42
P_2O_5	0.21
SO_3	0.20
Mn_2O_3	0.09
SrO	0.06
ZnO	0.02
Cr_2O_3	–
As_2O_3	–
Cl	0.06
Total:	99.48
Si/Al	3.17

Measurement of mechanical properties.

Two main methods were used to evaluate the mechanical properties of the samples: measuring the compressive strength and the speed of propagation of ultrasound. The compressive strength was determined using a MATEST hydraulic press (Fig. 2), which complies with EN 12390-3 standards, with a maximum force of 2000 kN and an accuracy of ±1%.

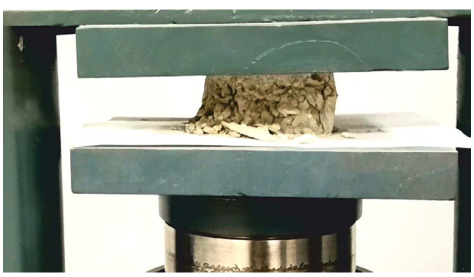
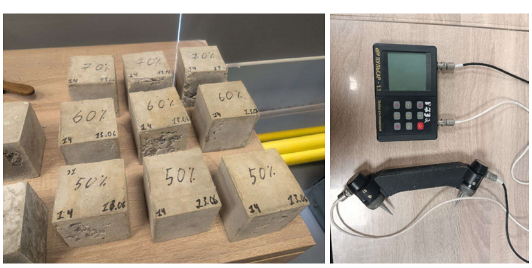


Fig. 2. Testing on a MATEST hydraulic press

The samples (Fig. 3, *a*) were tested after the corresponding curing periods (7, 14, 28 days).



a *b*

Fig. 3. Kit for studying the speed of ultrasonic waves in concrete: *a* — general view of concrete samples; *b* — ultrasonic device Pulsar 1.1

The speed of ultrasound propagation was measured using an ultrasonic tester Pulsar 1.1 (Fig. 3, *b*) with a sensor frequency of 54 kHz. Measurements were performed in three directions on each sample to ensure data accuracy, and the pulse transit time (t) was recorded with an accuracy of 0.1 μs. All tests were performed under laboratory conditions at a temperature of 20±2°C and a relative humidity of 60±5%.

Theoretical methods and data processing.

The theoretical basis of our study is the principles of pozzolanic activity of sludge and its effect on cement hydration. To assess the microstructure and mechanical properties, a correlation analysis between the percentage of sludge replacement, compressive strength, and ultrasound propagation speed was used. Data processing was performed using Microsoft Excel software (USA) to organize data and perform basic statistical calculations. For trend analysis and plotting, OriginPro 2025b software (USA) was used, which allowed us to build correlation models between variables. No specialized software for microstructure modeling (e.g., using X-ray diffraction methods) was used, which is a simplification within the scope of this study.

5. Results of investigating the effect of replacing cement and sand with activated stone processing sludge on the mechanical properties of geoconcrete

5. 1. Assessing the effect of replacing cement with granite and gabbro sludge on the mechanical properties of concrete

The results of determining the strength of concrete at different levels of cement replacement with a sludge mixture are shown in Fig. 4.

Our results indicate a pronounced effect of partial replacement of cement with a mixture of granite and gabbro sludge on the compressive strength of concrete samples (Fig. 4). It was found that with increasing sludge content, there is a systematic decrease in strength regardless of the hardening period.

In control samples (0% sludge), the strength reached maximum values: more than 55 MPa after 7 days and about 50 MPa after 14 and 28 days of hardening. This confirms that conventional Portland cement provides intensive hydration reactions and the formation of a dense cement matrix with high bearing capacity.

When replacing cement by 10–20% sludge, a significant decrease in strength was observed – 1.5–2 times compared to the control values. At the same time, for samples with 20% sludge, a certain increase in strength was observed on day 28 (up to 30–32 MPa), which exceeded the indicators on day 14. This may be due to the late effect of secondary reactions between the active components of the sludge and the products of cement hydration, which to some extent compensates for the initial decrease in strength.

Further increase in the sludge content (30–40%) led to an even greater drop in strength – to the level of 15–25 MPa, which is only 30–40% of the control composition. At 50–70% cement replacement, the strength decreased below 10–12 MPa, and at 80–90% sludge – it did not exceed 2–5 MPa. This level is insufficient for structural use, which is explained by a sharp decrease in the amount of cement clinker capable of hydration, and a decrease in the amount of calcium hydro silicates that form the main framework of concrete.

During the experiments, an ultrasonic examination of concrete samples was carried out, the results of which are shown in Fig. 5.

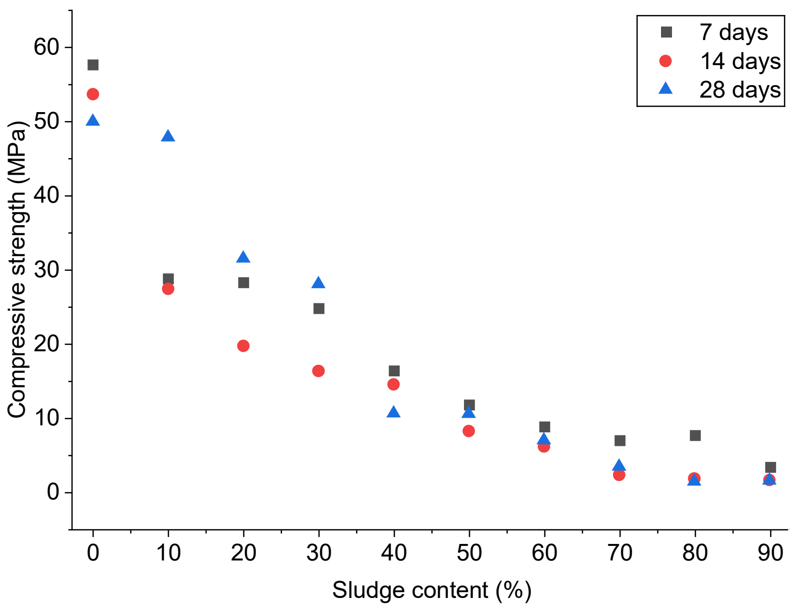


Fig. 5. Dependence of the propagation velocity of ultrasonic waves in concrete samples on the sludge content at different hardening times

5. 2. Assessing the effect of replacing sand with granite and gabbro sludge on the mechanical properties of concrete

The results of determining the effect of partial replacement of sand with a mixture of granite and gabbro sludge on the strength of concrete are shown in Fig. 6.

The obtained data show that the control samples (0% sludge) have the highest strength – over 50 MPa on day 28 due to the optimal ratio of cement and sand, which provides a dense microstructure.

Partial replacement of sand by 10–30% maintains strength at 45–50 MPa due to the microfiller effect of small sludge particles, which reduce capillary porosity.

At 40–50% replacement, the strength decreases to 35–40 MPa due to the lack of quartz sand, which weakens the rigidity of the aggregate.

At 60–70%, the strength drops to 25–30 MPa with increasing porosity and defects.

At 80–100% replacement, the strength is less than 15 MPa, which makes the concrete unsuitable for structural work.

Control samples (0% sludge) are characterized by the highest speed of propagation of ultrasonic waves – about 4400–4600 m/s, which corresponds to a dense and homogeneous structure of cement stone with a minimum number of defects. With an increase in the sludge content, the speed gradually decreases, which is consistent with the results of compression tests (Fig. 4). At 20–40% cement replacement, the speed of propagation of ultrasound is 3800–4000 m/s, which indicates the formation of a more porous and heterogeneous structure.

At the level of 60–70%, it decreases to 3200–3500 m/s, which corresponds to concrete with high defects and microcracks.

At 80–90% sludge, the speed drops to 2000–2500 m/s, i.e., the material acquires a developed porous structure and loses the characteristics of dense structural concrete. Unlike compressive strength, the differences between 7-, 14-, and 28-day samples are minimal since the ultrasonic method primarily reflects the overall density and structural defects, and not the increase in strength due to late hydration. Thus, regardless of the hardening period, the key factor determining the wave speed is the volume of cement clinker and the number of formed hydrates, which provide the density of the material. The resulting dependences confirm the close relationship between the mechanical characteristics of concrete and its structural parameters recorded by the ultrasonic method. A decrease in the wave speed with an increase in the sludge content reflects the degradation of the cement stone structure due to a deficiency of hydration products and the development of microporosity. This indicates that ultrasonic testing can be effectively used as an operational non-destructive method for assessing the quality of concrete, which makes it possible to predict its strength without conducting additional destructive tests.

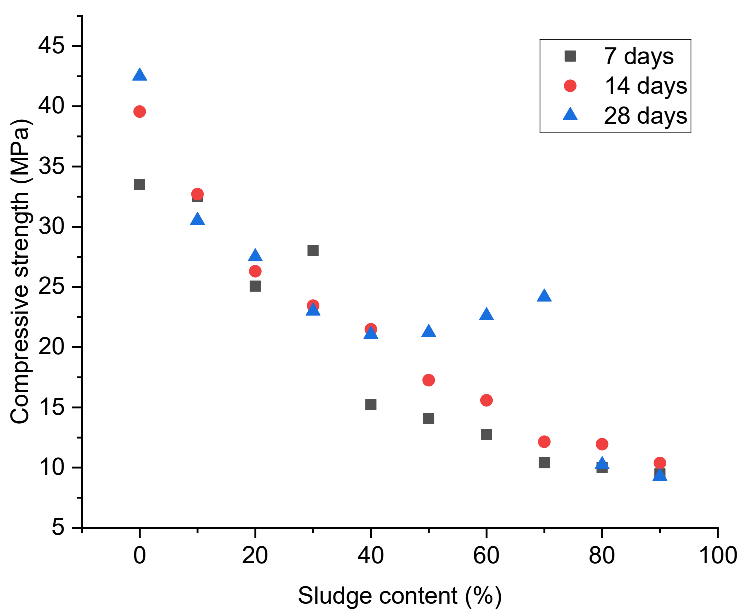


Fig. 6. Compressive strength of concrete specimens in which sand was replaced by sludge at different curing times

Therefore, replacing sand with sludge is advisable up to 30%, as it provides high strength characteristics and structural improvement due to compaction.

The results of ultrasonic testing (Fig. 7) correlate well with the compression tests.

At 0% sludge, the velocity is 4400–4600 m/s, which corresponds to a dense cement stone with minimal defects.

At 10–30%, the velocity is 4200–4300 m/s, which indicates the preservation of a high density structure.

At 40–50%, a drop to 3700–3900 m/s is observed, which indicates a more porous and heterogeneous composition.

At 60–70%, the velocity decreases to 3200–3500 m/s, which reflects the development of microcavities and microcracks.

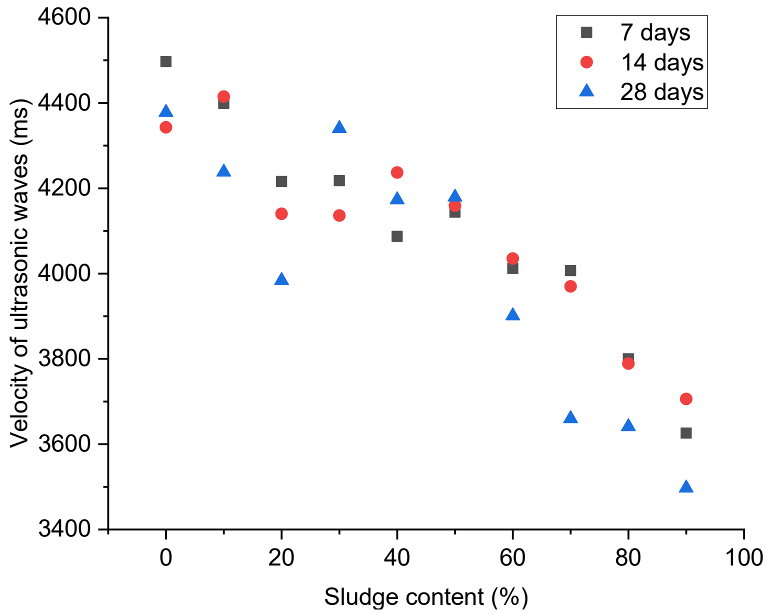


Fig. 7. Dependence of ultrasound velocity in concrete samples on sludge content when replacing sand

At 80–100%, it drops to 2500–2800 m/s, which indicates a loss of density and the transition of the material to a state with developed defects.

It is worth emphasizing that, unlike compressive strength, which increases with time due to late hydration, ultrasonic velocity is a more stable parameter and reflects primarily the density and integrity of the structure, rather than the strength gain itself. This makes ultrasonic testing a convenient non-destructive method for monitoring the condition of concrete.

6. Results of the influence of granite-gabbro sludge on the properties and structure of concrete: discussion

Our results can be explained as follows. Replacing cement with sludge leads to a systematic decrease in compressive strength with increasing sludge content (Fig. 4), which is associated with a decrease in the amount of cement clinker, which provides the main hydration reactions and the formation of calcium hydro silicates (C-S-H), which is the basis of concrete strength. For example, at 0% replacement, the strength reaches 55 MPa after 7 days, while at 50% it drops below 10 MPa, which is explained by the insufficient pozzolanic activity of the sludge, which does not compensate for the loss of binder, as can be seen from Table 1, where the mass of cement decreases proportionally. Similarly, the decrease in the ultrasonic propagation velocity (Fig. 5) from 4600 m/s (0%) to 2000 m/s (90%) reflects the increase in porosity and structural defects due to the deficiency of hydrates, which correlates with mechanical tests, since ultrasound is sensitive to the density of the material. When replacing sand with sludge, the compressive strength (Fig. 6) remains high up to 30% replacement (45–50 MPa), which is explained by the microfiller effect of the finely dispersed sludge, which fills the pore space between the grains, reducing capillary porosity and improving compaction, as shown in Table 2, where sludge replaces sand without changing the cement. At higher percentages (80–100%), the strength drops below 15 MPa due to the loss of the rigid skeleton of the aggregate. The ultrasonic velocity (Fig. 7) decreases less sharply (from 4600 m/s to 2500 m/s), which confirms the preservation of density at low replacement levels due to the filler role of the sludge. Comparing both tasks, sand replacement appears to be more effective.

The sludge acts better as a filler than as a binder due to its mineralogical composition (quartz, feldspar), which does not provide full hydration but promotes compaction.

The advantages of the proposed solutions are the combined use of granite and gabbro sludge with 12M NaOH activation, which provides a balance between environmental friendliness and mechanical properties. In contrast to [1], in which replacing up to 40% of the aggregate with granite sludge in self-compacting mortars leads to increased water consumption and reduced density, this result (maintaining strength up to 50 MPa with 30% sand replacement, Fig. 6) makes it possible to for concrete with improved durability without significant loss of rheological properties. This is made possible by NaOH activation, which increases the reactivity of the sludge and promotes the formation of additional hydrates. In contrast to [2], in which 10–20% cement replacement with granite dust induces microcracking at higher levels, our result (ultrasonic velocity 4200–4300 m/s at 10–30% sand replacement, Fig. 7) provides better structural integrity, allowing the concrete to be used in structures with a lower risk of corrosion. This is achieved by combining the two types of slurry, which optimizes the mineralogical composition and reduces porosity. In contrast to [4], in which 20% cement replacement with granite sludge reduces sulfate resistance due to microcracking, our result (strength increase on day 28 at 20% cement replacement, Fig. 4) favors late reactions, allowing the material to be used in moderately aggressive environments. The advantage is economic feasibility, as the activation of the sludge reduces disposal costs, in contrast to [5], in which the focus on low replacement levels without activation limits the savings.

Our results are aimed at solving the problem of environmental burden caused by the accumulation of sludge waste and excessive use of natural resources in the production of building materials. The use of activated sludge partially compensates for the shortage of conventional components and improves the microstructure of concrete. Up to 30% of sand replacement, the problem is solved through the microfiller effect, which reduces the consumption of natural resources and the negative environmental impact, as shown in Fig. 6, 7, when the properties remain acceptable; this is explained by the pozzolanic activity of activated sludge, which compensates for the shortage of conventional components. For cement replacement, the problem is resolved to a lesser extent (up to 20%) since the strength drops sharply (Fig. 4), but this contributes to the disposal of waste, reducing the environmental burden, due to late hydration reactions.

The limitations of our study include the failure to take into account external factors such as temperature, humidity, or aggressive environments (sulfates, chlorides), which may overestimate laboratory strength indicators (Fig. 4–7) in practical applications; therefore, under real-world conditions (e.g., in bridge construction), additional durability testing is required. In addition, the simplification in microstructure analysis (only strength and ultrasound, without X-ray diffraction or electron microscopy) limits the understanding of the phase composition, which should be taken into account in further theoretical studies for more accurate modeling. The chemical composition of the sludge was assumed to be homogeneous, without variations by source, which may affect reproducibility when using sludge from other regions. The economic assessment does not include logistics, therefore, in practical implementation (e.g., at enterprises in the Zhytomyr oblast), transportation costs should be estimated.

The limitations of the study are the limited range of tests – only mechanical properties without analysis of the rheology of the mixtures or corrosion resistance, which limits the assessment of suitability for specialized applications. The lack of statistical processing of the data (e.g., variance) reduces the reliability of conclusions. The focus on laboratory samples (100 × 100 × 100 mm) does not reflect industrial conditions.

Future studies may investigate combined replacements of cement and sand simultaneously. It is advisable to add superplasticizers to the mixture composition to improve rheology and durability in aggressive environments. Our results (Fig. 4–7) show the potential for up to 30% component replacement. However, they need to be expanded to reach higher levels without losing properties. This is important for the transition to a circular economy. This approach will enable the integration of sludge into a wider range of construction materials.

7. Conclusions

1. The combined use of granite and gabbro sludge with 12M NaOH activation as a cement substitute makes it possible to optimize mechanical properties up to 30–32 MPa at 20% replacement on day 28 of hardening. This exceeds the indicators on the 14th day and provides a balance between strength and economic feasibility, unlike solutions with granite dust where strength drops more sharply due to microcracks. This is explained by late reactions between activated sludge and cement hydration products, which compensates for the clinker deficit and makes it possible to reduce cement consumption by 20% without losing structural suitability (strength >10 MPa). The ultrasound velocity is 3800–4000 m/s, which is 13–17% lower than the control samples, but indicates an acceptable density of the structure.

2. Replacing sand with a mixture of granite and gabbro sludge activated by 12M NaOH in concretes provides a compressive strength of 45–50 MPa at 10–30% replacement at 28 days. This exceeds the control values in some cases due to the microfiller effect, solving the problem of porosity better than conventional aggregates, and makes it possible to reduce the consumption of natural sand by 30% with improved durability. Sealing the pore space with fine sludge particles fills the capillaries without significant loss of stiffness. The ultrasound velocity reaches 4200–4300 m/s, which is only 4–9% lower than the control samples, providing higher structural integrity compared to full replacement.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors used artificial intelligence technologies within the permissible limits in the “Introduction” chapter; the entire text was checked and supplemented by the authors.

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