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ANALYSIS OF CONCRETE PERFORMANCE UTILIZING LOCALLY SOURCED MATERIALS IN LIGHTWEIGHT PERMANENT FORMWORK SYSTEMS

АНАЛІЗ МІЦНІСНИХ ХАРАКТЕРИСТИК БЕТОНУ ІЗ ВИКОРИСТАННЯМ МІСЦЕВИХ МАТЕРІАЛІВ У ЛЕГКИХ СИСТЕМАХ ІЗ НЕЗНІМНИХ ОПАЛУБОК

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Abstract. *The large-scale invasion of Ukraine has resulted in the destruction or severe damage of over 236,000 residential buildings, yielding more than 700,000 tons of construction debris. This situation has created an urgent need for rapid, economical, and sustainable reconstruction methods. The reduced labor force, coupled with the abundance of local byproducts (such as slag and granite screenings), presents a unique opportunity to develop permanent formwork blocks tailored for efficient on-site assembly. By transforming locally available materials into structurally viable components, the proposed approach aims to reduce overall costs while promoting debris reuse.*

In this study, laboratory tests were conducted to assess compressive strength, flexural strength, and durability of formwork blocks containing varying proportions of slag and granite screenings. The experimental results indicate that these composites attain compressive strengths in the range of 9.5 – 11 MPa and flexural strengths of approximately 2 MPa, demonstrating their suitability for formwork applications. Concurrently, finite element modeling (ANSYS) was employed to optimize block geometry, ensuring both adequate load-bearing capacity and a mass below 25 kg – thereby allowing single-person handling in field conditions. This design consideration is especially critical in post-conflict rebuilding scenarios, where both labor availability and on-site safety are paramount.

The findings underscore the viability of using low-cost, easily accessible materials for permanent formwork production, which has the added benefit of diverting substantial amounts of debris from landfills. Moreover, the use of locally sourced materials is likely to reduce transportation and manufacturing expenses, further boosting economic feasibility. To validate the practicality of this solution, future research will entail field testing that assesses installation efficiency, labor intensity, and life-cycle performance under realistic construction conditions. By integrating resource reuse, labor minimization, and sustainable design principles, this approach offers a promising pathway for rebuilding Ukrainian infrastructure in the aftermath of widespread damage.

Keywords: *permanent formwork, local materials, rapid reconstruction*

Introduction

Ukraine's population decline[1, 3, 5, 6], driven by low birth rates and emigration, accelerated significantly due to Russia's 2022 invasion. By late 2024, approximately

10 million people had left Ukraine[4, 7, 8] or died, representing a 25% reduction in population. Fertility rates fell to around 1.0 child per woman, among the lowest globally, and mortality rates surged due to conflict and disrupted healthcare.

The war triggered Europe's largest displacement since WWII, displacing nearly a third of the population at its peak, with millions remaining abroad by 2025, notably women and children. This mass emigration resulted in a significant "brain drain" of highly educated and skilled individuals, complicating future economic recovery. Concurrently, economic disruption led to severe job losses and structural unemployment, highlighting ongoing challenges for post-war reconstruction and demographic stabilization[2].

As of early 2025, approximately 236,000 residential buildings have been damaged or destroyed, affecting over 3 million civilians nationwide. Infrastructure damage includes severe impacts on energy infrastructure, such as major power stations. Public buildings and facilities have also suffered extensively, with around 3,800 educational institutions, 784 healthcare facilities (including hospitals and clinics), and nearly 500 cultural heritage sites damaged. Destruction has been concentrated primarily in eastern and southern oblasts like Donetsk, Kharkiv, Luhansk, Zaporizhzhia, Kherson, and to a lesser extent Chernihiv and Sumy, reflecting frontline intensity[9-13].

Ukraine currently faces the urgent task of rapidly reconstructing residential, infrastructural, and industrial buildings damaged or destroyed due to the ongoing conflict. Accelerating the rebuilding process is critical for restoring societal functions, economic activity, and overall stability. One viable strategy to expedite reconstruction efforts involves the implementation of a permanent structural framework. Such a framework would standardize construction practices, streamline project planning, and enhance resource allocation efficiency. Moreover, adopting standardized design and engineering protocols within this framework could significantly reduce construction timelines, minimize logistical complexities, and promote sustainability through durable, long-lasting structures. Consequently, utilizing a permanent structural framework may offer tangible benefits, facilitating quicker recovery and helping Ukraine rebuild more resilient communities in a shorter timeframe.

Permanent formwork overview

Permanent formwork, also known as stay-in-place formwork, refers to molds that remain integrated within the concrete structure after curing, unlike traditional temporary formwork[14,15]. Common materials used include concrete, plastic, fabric, fiber-reinforced polymer (FRP) composites[18], and metal, each contributing unique properties such as structural support, insulation, or environmental protection[16,17]. Concrete-based systems, such as precast twin-wall panels and ultra-high-performance concrete (UHPC) shells offer exceptional durability, fire resistance, and high-quality finishes, yet their weight and potential brittleness in thin sections pose challenges. Plastic formwork systems, notably insulating concrete forms (ICF) and modular polymer panels, excel in thermal insulation, ease of installation, and moisture protection, although their structural contribution is minimal. Fabric-based permanent formwork[19], involving textile sheets or membranes, is beneficial for creating complex geometries and enhanced surface quality, but requires meticulous execution to prevent deformation or damage. Composite formworks, like concrete-filled FRP tubes, enhance concrete's strength, ductility, and durability, making them advantageous in aggressive environments, though their high cost and limited fire resistance pose significant limitations. Metal systems, such as steel decking and hollow steel columns, offer high structural performance through composite action and rapid construction but face challenges related to weight, corrosion risk, and inflexibility. Across all types, permanent formwork systems reduce labor and waste, speeding up construction and contributing positively to sustainability. However, each material also has trade-offs in terms of initial cost, environmental impact, construction complexity, and long-term maintenance requirements. Current innovations, including ultra-high-performance concrete shells, hybrid composite forms, and sustainable bio-based materials, continue to evolve the field, aiming for improved performance, environmental benefits, and ease of construction.

However, most existing research does not adequately address strategies for reducing the cost of implementing permanent structural frameworks, nor does it sufficiently explore possibilities for reusing construction materials for ecological sustainability. Cost-efficiency remains a critical consideration for large-scale reconstruction efforts, yet current methodologies often overlook innovative approaches to minimize expenses through material optimization or recycling. Additionally, incorporating environmentally conscious practices, such as reusing materials from damaged structures, could significantly reduce waste and environmental impact. Therefore, future research should prioritize examining economically viable methods to integrate reusable and recyclable components into permanent frameworks. Addressing these gaps would not only enhance affordability but also support Ukraine's reconstruction efforts in becoming environmentally sustainable and resource-efficient.

Local materials overview

The Dnipropetrovsk region possesses significant geological resources and hosts a robust heavy industrial base. Situated atop the Ukrainian Shield, the region is geologically characterized by extensive deposits of granite, iron, and manganese ores. Local quarries capitalize on these granite reserves, generating substantial quantities of crushed stone and granite screenings suitable for construction purposes. Concurrently, the region's prominent mining and metallurgical industries, particularly concentrated around Kryvyi Rih, produce substantial volumes of iron and steel. This industrial activity results in millions of tons of slag annually as a byproduct, notably from major facilities such as ArcelorMittal Kryvyi Rih, Ukraine's largest steel plant. Consequently, the region's geological and industrial profiles collectively yield significant supplies of granite-derived construction materials and metallurgical slag, providing opportunities for their utilization in sustainable reconstruction and industrial applications.

Granite aggregate production in Ukraine's Dnipropetrovsk region has maintained stable output, typically around several hundred thousand cubic meters annually, with production closely aligned to construction demand cycles. For instance, quarry output near Dnipro city was approximately 0.5 million cubic meters (approximately 1–1.3 million tons) around 2017. Increased infrastructure investments in the late 2010s and early 2020s moderately boosted production of crushed granite and screenings. Simultaneously, the region's extensive steel industry, notably ArcelorMittal Kryvyi Rih and other plants, has historically produced several million tons of steel annually, resulting in substantial slag generation. With blast furnace slag yields ranging between 300–600 kg per ton of pig iron, significant slag volumes accumulate yearly, with utilization for construction steadily rising but still underutilized – about 5 million tons used nationwide in 2021, only 10% of available material. Consequently, large stockpiles of slag remain in Dnipropetrovsk, ensuring abundant and cost-effective supplies of both granite screenings and metallurgical slag for future construction and infrastructure development.

Laboratory investigation of concrete produced from locally sourced materials

A total of 36 concrete cubes measuring 100×100×100 mm were produced using granite screenings to evaluate their compressive strength. The concrete mixture was prepared with proportions of 1 part cement, 2 parts sand, and 2 parts granite screenings by weight. After a curing period of 28 days, dimensional measurements were performed on each specimen to assess size consistency. The resulting size distribution of these samples is illustrated in the histogram presented in Figure 1. A Pearson correlation coefficient approaching 1 indicates an exceptionally high consistency and uniformity among sample dimensions. This result is beneficial as it confirms the reliability of the concrete preparation method and ensures accurate and reproducible test outcomes.

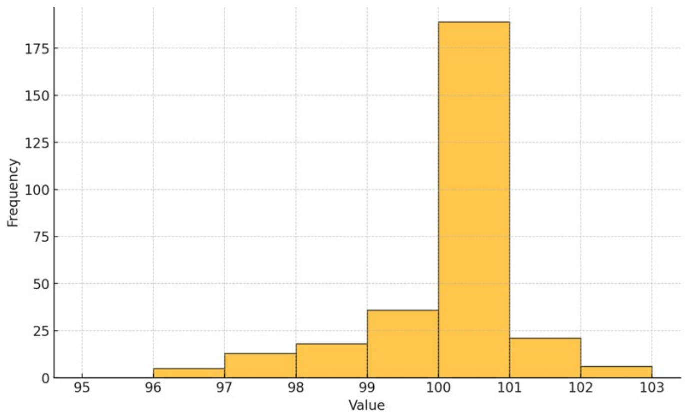

Figure 1 – Distribution of cube sample dimensions

As a result, the average compressive strength of the tested concrete samples was determined to range between 9.5 and 11 MPa, indicating satisfactory compression structural performance for certain construction applications.

Subsequently, eight concrete prisms were produced for flexural testing: four specimens measuring 100×100×400 mm and four specimens measuring 70×70×280 mm. Both prism dimensions yielded a consistent flexural strength of approximately 2 MPa, demonstrating strong correlation between different specimen sizes. This consistency confirms the reliability of the obtained flexural strength results, suggesting suitability for specific construction purposes.

As a result, the average Young's modulus for the tested concrete samples was determined to be 23×10^3 MPa, reflecting adequate stiffness and suitability for structural applications requiring moderate elastic deformation under load.

Similarly, an additional set of concrete samples was produced utilizing metallurgical slag as an aggregate component. Specifically, 18 concrete cubes, each measuring 100×100×100 mm, were prepared with a solution ratio consisting of 1 part cement, 2 parts sand, and 2 parts slag by weight. After a curing period of 28 days, dimensional measurements of the specimens yielded a Pearson correlation coefficient approaching 1, indicating an exceptionally high consistency and dimensional uniformity across all samples. This high correlation value confirms the accuracy and reliability of the concrete manufacturing process and assures reproducibility of future experimental outcomes.

Subsequent laboratory tests provided the following results: the average compressive strength achieved by the slag-based samples was determined to be approximately 9.5 MPa, suggesting suitability for moderate-load-bearing construction applications. Additionally, flexural strength was consistently measured at 2 MPa, reflecting adequate performance for scenarios involving tensile stresses and bending loads. Lastly, the average Young's modulus was calculated as 21×10^3 MPa, indicating sufficient stiffness for structural uses where controlled elastic deformation is desirable. Overall, these outcomes demonstrate that slag-based concrete can reliably achieve structural characteristics comparable to conventional aggregates, thus confirming its potential for sustainable and economically feasible construction practices.

Figure 2 – Destroyed samples

In conclusion, the experimental comparison of concrete produced from granite screenings and metallurgical slag demonstrates similar structural performance characteristics, albeit with slight variations. Both aggregate types yielded compressive strength results suitable for moderate-load-bearing construction, with granite-based samples averaging between 9.5 and 11 MPa and slag-based samples averaging approximately 9.5 MPa. Flexural strengths for both materials were equivalent, consistently measured at around 2 MPa, indicating comparable resistance to tensile and bending stresses. Regarding stiffness, the granite screenings concrete exhibited a slightly higher average Young's modulus (23×10^3 MPa) compared to slag-based concrete (21×10^3 MPa), implying marginally superior resistance to deformation. Overall, both aggregates offer viable and reliable options for construction, but granite screenings appear slightly advantageous in terms of compressive strength variability and stiffness, whereas slag provides a sustainable alternative with consistent and satisfactory performance.

Proposal for permanent formwork blocks

The central objective of this research is to develop lightweight permanent formwork blocks designed to be easily handled by one or, at most, two individuals. These blocks should be intuitive and straightforward to assemble, allowing the construction of frameworks without the necessity for specialized training or prior construction experience. Additionally, the formwork system will integrate simple yet effective mechanisms or tools to establish secure, stable, and reliable joint connections between blocks. A critical aspect of the proposed solution is its capacity to be assembled entirely without mechanical equipment, significantly simplifying construction logistics. By prioritizing ease of handling, simplicity of assembly, and reliable joint connectivity, this innovative formwork approach aims to optimize construction efficiency, cost-effectiveness, and accessibility, particularly in regions with limited technical resources.

a. Columns

In developing permanent formwork blocks specifically intended for constructing columns, the research focused on modularity and ease of assembly. Two standardized block heights, 300 mm and 600 mm (Figure 2.1) were selected to promote efficient handling and accommodate various construction scenarios. Additionally, a universal block was introduced to further enhance flexibility and facilitate optimal bonding between different block configurations. A specially designed tongue-and-groove joint mechanism was incorporated to ensure accurate vertical alignment and secure connections without the need for complex tools. To reinforce these joints and provide additional stability, an innovative clamping system was integrated, significantly improving overall structural integrity. These combined design considerations enable workers to construct columns (Figure 2.2) quickly, reliably, and without specialized training. As a result, this modular formwork approach reduces labor requirements and enhances safety on-site, supporting more efficient and cost-effective building practices.

To facilitate accurate and stable construction of columns using permanent formwork blocks, a specialized clamping system was developed employing steel angle profiles (Figure 4). These angle profiles are welded on one side to create a rigid connection, while the opposite side is secured using adjustable clamps, enabling precise alignment and efficient assembly. Additionally, a robust basement support system was designed following the same principle, utilizing welded connections on one side complemented by clamps or adjustable bolts on the other. This approach ensures that each column remains strictly vertical throughout the construction process, thereby guaranteeing structural accuracy and stability. The integration of adjustable clamps or bolts provides flexibility, allowing for fine adjustments to accommodate construction tolerances or minor inconsistencies. Overall, this clamping methodology significantly enhances ease of assembly, ensures reliable vertical alignment, and reduces dependence on specialized construction skills or sophisticated equipment.

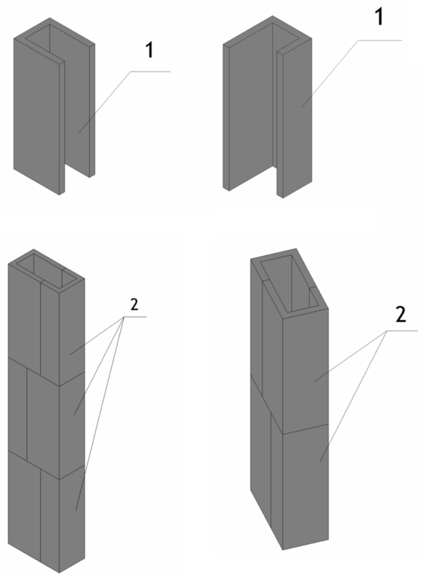

Figure 3. Permanent formwork blocks for column construction.

1 – individual blocks, 2 – assembled column structure.

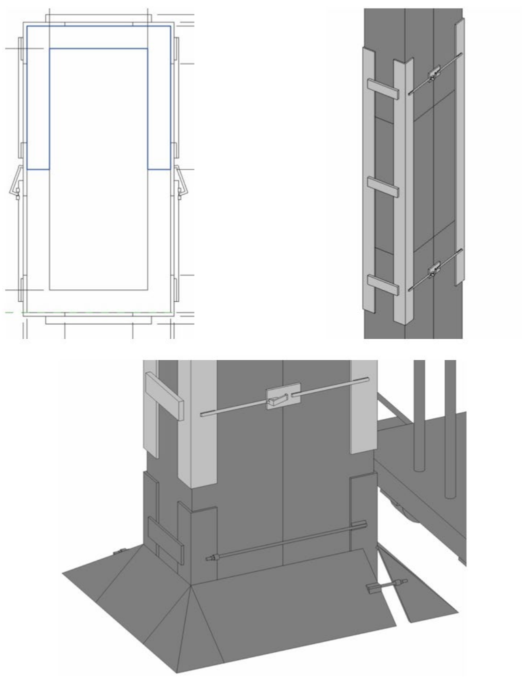

Figure 4. Column structure clamping system

b. Beams

Permanent formwork beam blocks were developed as U-shaped structural elements (Figure 5) specifically intended for simplified assembly and efficient beam construction. To enhance their spatial stability and overall structural performance, additional reinforcement was integrated into the side walls of each block. This reinforcement not only strengthens individual components but also improves load distribution within assembled beams. The standardized U-shaped design facilitates rapid, accurate assembly, minimizing labor and specialized equipment requirements. Collectively, these features enhance both structural reliability and ease of use in construction applications.

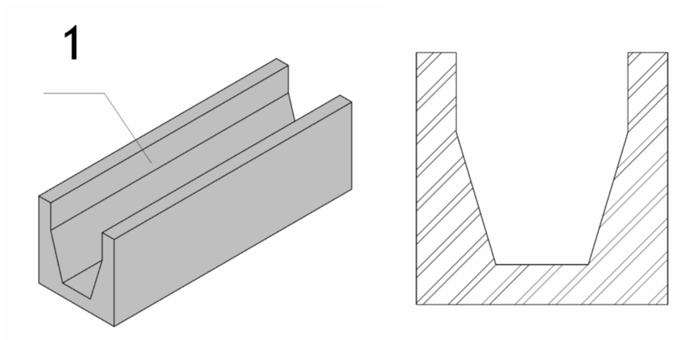

Figure 5 - Permanent formwork blocks for beams construction.

1 – individual block.

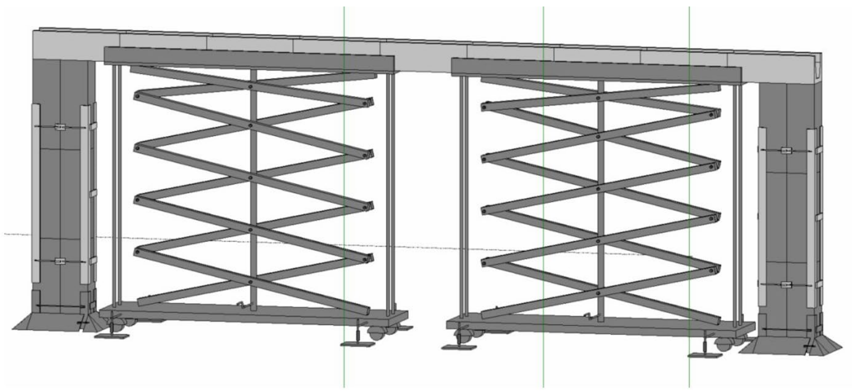

Figure 6 - Beams construction support system.

To ensure structural stability during construction, a specialized support system was developed for use with beam formwork blocks (Figure 6). This system incorporates lightweight, adjustable components designed to maintain positional accuracy and structural integrity throughout concrete placement and curing. Its modular nature enables easy assembly and disassembly without specialized tools or equipment. Collectively, these features facilitate efficient installation and enhance safety by ensuring beams remain stable and precisely positioned until the concrete achieves sufficient strength.

Numerical analysis of structural performance using finite element modeling

Finite element modeling was performed using ANSYS software to analyze the structural performance of the designed beam blocks, incorporating concrete characteristics determined experimentally. The modeled beam had overall dimensions of 250 mm height, 300 mm width, and 600 mm length, with a uniform wall thickness of 20 mm. Under the simulated loading conditions, the maximum deformation observed for the beam filled with concrete was only 0.02 mm, indicating negligible deflection and high rigidity. Additionally, the maximum calculated stress reached 1.06 MPa, which is approximately half of the experimentally determined flexural strength of 2 MPa, signifying a comfortable margin of safety against structural failure. The stress distribution analysis revealed uniform stress dispersion throughout the beam, with localized stress concentrations within permissible limits. Collectively, these simulation results demonstrate that the designed beam formwork blocks offer robust structural performance, confirming their reliability and suitability for practical construction applications.

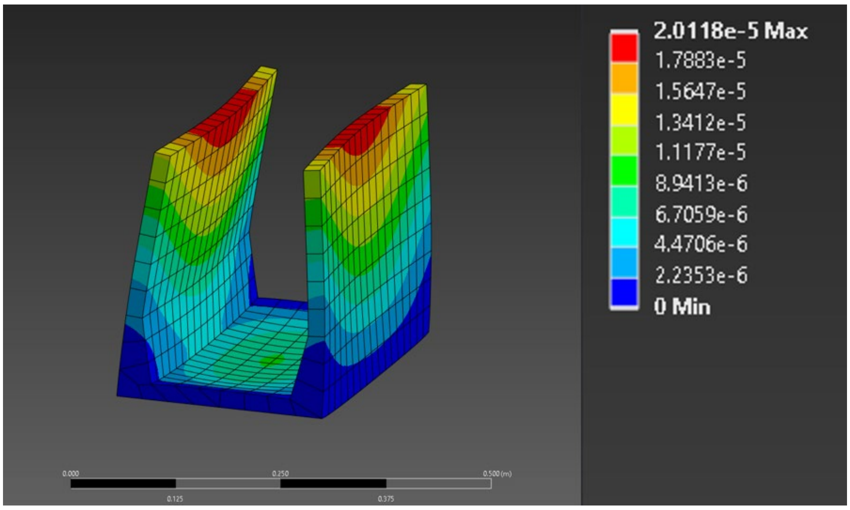

Figure 7 - Beams deformation results.

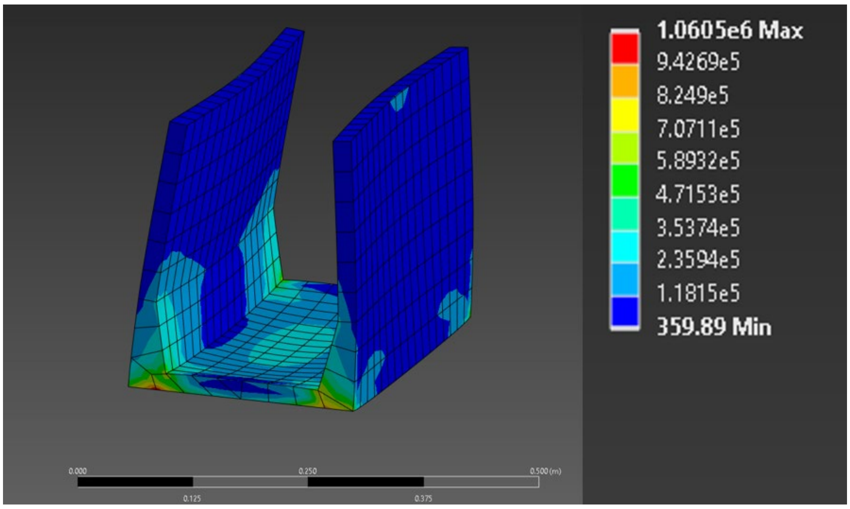

Figure 8 - Beams stress results.

Conclusions

Based on the investigations carried out, locally sourced aggregates – such as granite screenings and metallurgical slag – demonstrate viable properties for use in permanent formwork-based concrete construction. Laboratory tests indicate that concrete samples with granite screenings and slag achieve compressive strengths ranging from approximately 9.5 to 11 MPa and flexural strengths of around 2 MPa, thus meeting the basic requirements for moderate-load applications. Dimensional consistency of the specimens was confirmed via Pearson correlation coefficients approaching 1, while Young's module ranging from 21×10^3 to 23×10^3 MPa further corroborate the structural adequacy of the materials. The development of lightweight formwork blocks, featuring tongue-and-groove joints and clamping systems for both columns and beams, enhances overall assembly efficiency and accuracy. ANSYS finite element simulations of a beam model (250×300×600 mm, 20 mm wall thickness) revealed minimal deformation (0.02 mm) and a maximum stress of 1.06 MPa – approximately half the experimentally observed flexural strength. Such results underscore the structural reliability of the proposed design, confirming sufficient safety margins under standard loading conditions. Consequently, this research substantiates the practicality of using local aggregates and innovative permanent formwork blocks to facilitate cost-effective, sustainable, and structurally sound construction.

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Анотація. *Масштабне вторгнення в Україну призвело до знищення або серйозного пошкодження понад 236 000 житлових будівель, що спричинило утворення понад 700 000 тонн будівельного сміття. Виникла нагальна потреба у швидких, економічно вигідних і сталих методах відбудови. Скорочення трудових ресурсів у поєднанні з наявністю місцевих побічних продуктів (таких як шлак і гранітний відсів) створює унікальну можливість для розробки блоків незнімної опалубки, оптимізованих для ефективного складання безпосередньо на будівельному майданчику. Перетворюючи доступні місцеві матеріали на конструктивно придатні елементи, запропонований підхід спрямований на зниження загальних витрат та сприяння повторному використанню будівельного сміття.*

У цьому дослідженні проведено лабораторні випробування для оцінки міцності на стиск, міцності на вигин і довговічності блоків опалубки, що містять різні пропорції шлаку та гранітного відсіву. Отримані експериментальні результати свідчать, що такі композити *досягають міцності на стиск у межах 9,5–11 МПа та міцності на вигин близько 2 МПа, що підтверджує їхню придатність для застосування в опалубці. Одночасно було проведено моделювання методом кінцевих елементів (ANSYS) для оптимізації геометрії блоків, що забезпечує як достатню несучу здатність, так і масу менше 25 кг, що дозволяє здійснювати монтаж однією людиною в польових умовах. Цей аспект особливо критичний у процесі відбудови після конфлікту, коли доступність робочої сили та безпека на будівельному майданчику мають першочергове значення.*

Отримані результати підтверджують доцільність використання недорогих і легко доступних матеріалів для виготовлення незнімної опалубки, що також сприяє значному зменшенню обсягів відходів, які потрапляють на звалища. Крім того, застосування місцевої сировини може суттєво знизити транспортні та виробничі витрати, що підвищує економічну ефективність. Для подальшої перевірки практичності запропонованого рішення планується проведення польових випробувань, спрямованих на оцінку ефективності монтажу, трудомісткості та довговічності конструкцій в реальних умовах будівництва. Інтегруючи повторне використання ресурсів, мінімізацію трудових витрат і принципи сталого проєктування, цей підхід відкриває перспективний шлях для відбудови української інфраструктури після масштабних руйнувань.

Ключові слова: *незнімна опалубка, локальні матеріали, швидка відбудова*