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UTILIZATION OF LOCAL MATERIALS FOR PERMANENT FORMWORK PRODUCTION FOR LOW-RISE BUILDING CONSTRUCTION

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Abstract. *Problem Statement.* Ukraine’s construction industry has been severely impacted after russian full-scale invasion, with more than 167,000 residential buildings destroyed and a significant reduction in the workforce. Additionally, the country faces a massive accumulation of construction waste due to widespread destruction. Traditional construction methods are labor-intensive and costly, further hindered by the shortage of skilled labor. There is an urgent need for innovative solutions to reduce construction time and costs while addressing environmental sustainability by recycling building debris. ***Objective.*** This research aims to explore the feasibility of using local materials, such as granite screenings, slag, and recycled concrete, to produce permanent formwork in low-rise building construction. It seeks to evaluate the mechanical properties of these materials through compression and flexural tests, compare the labor and cost efficiency of permanent formwork to conventional systems, and propose methods to optimize the formwork design to reduce construction labor intensity and material costs. ***Conclusion.*** The study demonstrated that local materials, such as granite screenings can be used for permanent framework production and reducing final costs. Mechanical characteristics of samples from local materials were tested and the research found some correlations between material density and structural strength in part of samples, indicating that higher-density materials can improve durability. This approach presents a cost-effective and environmentally sustainable alternative for Ukraine’s reconstruction efforts, reducing reliance on skilled labor and mitigating the challenges posed by the war-damaged construction sector.

Keywords: *permanent formwork; local materials; granite screenings*

ВИКОРИСТАННЯ ЛОКАЛЬНИХ МАТЕРІАЛІВ ДЛЯ ВИРОБНИЦТВА НЕЗНІМНОЇ ОПАЛУБКИ ДЛЯ ЗВЕДЕННЯ МАЛОПОВЕРХОВИХ БУДІВЕЛЬ

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Анотація. *Вступ.* Будівельна галузь України зазнав значних втрат унаслідок повномасштабного військового вторгнення, що призвело до руйнування понад 167 000 житлових будинків і суттєвого скорочення робочої сили. Масштабні руйнування спричинили також значне накопичення будівельних відходів. Традиційні методи будівництва характеризуються високою трудомісткістю та вартістю, що посилюється дефіцитом кваліфікованих кадрів. Отже, існує нагальна потреба в інноваційних рішеннях, які зможуть зменшити час і витрати на будівництво, одночасно сприяючи екологічній стійкості через переробку будівельних відходів. ***Мета дослідження.*** Метою цього дослідження є вивчення можливості використання локальних матеріалів, таких як гранітний відсів, шлак, перероблена цегла та бетон, для виготовлення незнімної опалубки та використання її в малоповерховому будівництві. Дослідження передбачає оцінку механічних властивостей зазначених матеріалів шляхом випробувань на стиснення та згин, виготовлення прототипів опалубки та тестування зразків на міцність. Крім того, планується порівняння ефективності праці та вартості незнімної опалубки з традиційними системами, а також розробка методів оптимізації дизайну опалубки для зниження трудомісткості та витрат на будівництво. ***Висновки.*** Результати дослідження показали, що локальні матеріали, зокрема гранітний відсів, можуть ефективно використовуватися для виготовлення незнімної опалубки, що сприяє зниженню її собівартості. Аналіз механічних властивостей зразків із використанням локальних матеріалів виявив кореляцію між щільністю матеріалу та міцністю конструкції, що свідчить про те, що матеріали з вищою щільністю можуть підвищувати міцність виробів. Запропонований підхід надає економічно вигідну та екологічно стійку альтернативу для відбудови України, зменшуючи залежність від кваліфікованої робочої сили та вирішуючи проблеми, пов'язані з наслідками військових дій у будівельній галузі. Подальші напрями дослідження включають вивчення властивостей інших локальних матеріалів, таких як шлак, перероблена цегла та бетон, порівняння їх механічних характеристик та виготовлення повномасштабних прототипів опалубки.

Ключові слова: *незнімна опалубка; локальні матеріали; гранітний відсів*

Introduction. According to the Kyiv School of Economics, as of June 2023, the total damage inflicted on Ukraine due to Russian aggression and the full-scale invasion is estimated at $150.5 billion. This includes more than 167,000 residential buildings and 426 large and medium-sized enterprises [1]. Additionally, IMF data indicates that Ukraine's population decreased by 19 % from 2021 to April 2024 due to military actions and the temporary occupation of territories [2]. This reduction in population proportionally decreases the number of construction industry specialists available in Ukraine.

One approach to reduce construction time is the use of permanent formwork. Permanent formwork consists of blocks or panels made from various materials, which are assembled into a unified monolithic formwork structure. A key characteristic of permanent formwork is that it is not removed after the concrete hardens, but instead remains as an integral part of the structure [3; 6−7].

The main objectives of this research are to:

- Investigate and establish the relevance of using permanent formwork in low-rise construction.
- Conduct a technical and economic comparison of different types of formwork.
- Explore the potential use of local materials to reduce production costs.
- Examine the feasibility of reusing construction waste where applicable.
- Minimize the need for skilled labor.
- Perform compression and flexural tests on samples to determine mechanical properties.

Ukraine ranks first in the world in terms of the volume of waste resulting from destruction. According to official statistics, at least 700,000 tons of construction waste are in areas under Ukrainian control, generated because of Russian aggression. However, experts believe the actual figure is much higher, and by the end of the war, it could increase hundreds of times [4; 5].

To prevent being overwhelmed by construction debris, pilot projects for the disposal and recycling of construction waste have already been initiated. This recycled material has the potential to be used in the reconstruction of Ukraine.

Most recycled building materials can be utilized in the construction of buildings and structures. For example, crushed (sorted by fractions) concrete, brick, and natural or artificial stone can serve as aggregate in concrete or be used in the production of permanent formwork.

Our comparative analysis of using permanent formwork for ceiling installations shows that permanent formwork for floors can reduce the labor intensity of the construction process by an average of 31 % compared to traditional beam-panel formwork. When using permanent beam formwork for floors, labor intensity can be reduced by as much as 44 %.

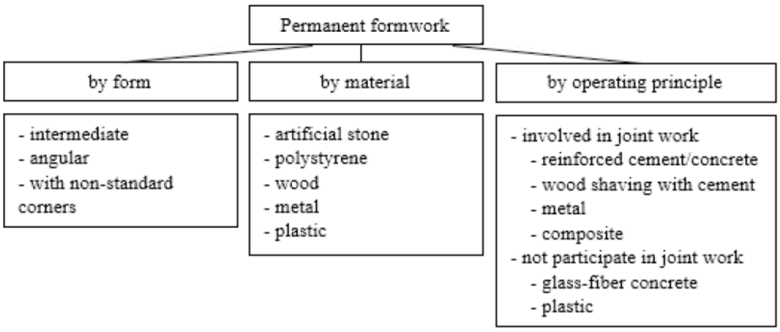

Fig. 1. Permanent formwork classification

The purpose of the work. We plan to focus on studying permanent formwork made from local materials, such as granite screenings and waste slag, or building debris, including recycled concrete and brick.

The main results of the research. We conducted mechanical experiments using potential materials. For the compression tests, we prepared a total of 20 cubes with dimensions of 100×100×100 mm for each of the three types of materials listed in Table 1. The geometrical characteristics, mass and density are presented in Table 2, the results of the compression tests are presented in Table 3.

Table 1

Mark	Cement, kg	Granite screenings, fraction 0−5, parts	Sand, kg	Number of cubes
1/8.4	25	8.4	30	6
1/9	25	9	30	7
1/9.6	25	9.6	30	7

Table 2

№	Type	a top, mm	b top, mm	S top, mm^2	a btm, mm	b btm, mm	S btm, mm^2	S avg, mm^2	h1, mm	h2, mm	h3, mm	h4, mm	h avg, mm	V, cm^3	mass, g	ρ, kg/m^3
1	1/8.4	100	97	9700	100	98	9800	9750	97	97	98	100	98	956	1810	1894
2	1/8.4	98	97	9506	100	97	9700	9603	98	97	98	99	98	941	1795	1907
3	1/8.4	96	96	9216	97	98	9506	9361	98	98	100	99	99	924	1755	1899
4	1/8.4	97	97	9409	100	98	9800	9605	99	98	100	99	99	951	1805	1898
5	1/8.4	95	100	9500	97	100	9700	9600	98	100	101	98	99	953	1820	1910
6	1/8.4	95	96	9120	95	97	9215	9168	95	97	100	97	97	892	1705	1912
7	1/9	100	106	10600	100	107	10700	10650	100	100	100	98	100	1060	2050	1935
8	1/9	101	105	10605	100	106	10600	10603	100	101	100	98	100	1058	2075	1962
9	1/9	104	104	10816	101	103	10403	10610	101	100	98	100	100	1058	2085	1970
10	1/9	100	95	9500	95	95	9025	9263	105	103	105	100	103	956	1980	2070
11	1/9	100	98	9800	96	98	9408	9604	104	103	99	105	103	987	2005	2032
12	1/9	101	96	9696	101	99	9999	9848	98	101	105	101	101	997	2010	2016
13	1/9	102	95	9690	100	100	10000	9845	100	100	100	101	100	987	1895	1920
14	1/9.6	96	102	9792	100	101	10100	9946	98	98	98	100	99	980	1930	1970
15	1/9.6	98	101	9898	100	98	9800	9849	97	98	99	99	98	968	1920	1984
16	1/9.6	101	98	9898	101	101	10201	10050	98	99	98	101	99	995	1975	1985
17	1/9.6	100	98	9800	101	98	9898	9849	100	95	95	100	98	960	1915	1994
18	1/9.6	100	98	9800	98	100	9800	9800	98	99	99	101	99	973	1920	1974
19	1/9.6	100	98	9800	99	99	9801	9801	95	98	98	95	97	946	1895	2004
20	1/9.6	100	98	9800	100	98	9800	9800	95	95	95	95	95	931	1880	2019

Table 3

№	Type	F, kgf	F, kN	P, kPa	P, MPa	P, MPa (average)
1	1/8.4	3059	30.0	3077	3.08	3.12
2	1/8.4	3100	30.4	3164	3.16	
3	1/8.4	2950	28.9	3088	3.09	
4	1/8.4	3100	30.4	3163	3.16	
5	1/8.4	3030	29.7	3093	3.09	
6	1/8.4	2960	29.0	3164	3.16	
7	1/9	4635	45.4	4265	4.27	4.10
8	1/9	4340	42.5	4012	4.01	
9	1/9	4450	43.6	4110	4.11	
10	1/9	4300	42.1	4550	4.55	
11	1/9	4200	41.2	4286	4.29	
12	1/9	4000	39.2	3981	3.98	
13	1/9	3500	34.3	3484	3.48	
14	1/9.6	3525	34.5	3473	3.47	3.34
15	1/9.6	3420	33.5	3403	3.40	
16	1/9.6	3340	32.7	3257	3.26	
17	1/9.6	3730	36.6	3711	3.71	
18	1/9.6	3840	37.6	3840	3.84	
19	1/9.6	2850	27.9	2850	2.85	
20	1/9.6	2840	27.8	2840	2.84	

Next essential part of experiment was building histograms of size distribution to understand possible errors. We built separate histograms for each cube type. As it is shown below, dimension errors are up to 7 mm, that is 7 % of standard cube dimension.

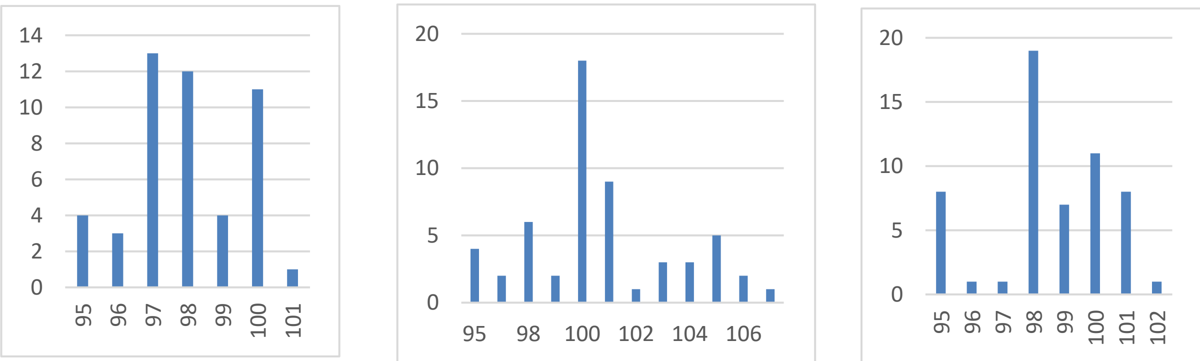

Fig. 2. Distribution of dimensions for samples 1/8.4, 1/9 and 1/9.6

Fig. 3. Part of destroyed samples

We also investigated dependency of destructive pressure, MPa on density kg/m^3. For samples 1/8.6 the Pearson correlation coefficient is approximately 0.396, that suggests a weak positive correlation between the two variables. Also, p-value is 0.438 that indicates that the correlation is not statistically significant at common significance levels, meaning we cannot confidently assert that the observed relationship isn't due to random chance.

For samples 1/9 Pearson Coefficient is 0.703 that indicates a moderate to strong positive correlation between density and destructive pressure. As the density increases, the destructive pressure tends to increase as well. For this type of samples p-value is 0.078 that is greater than 0.05 but close to it. This means the result is not statistically significant at the conventional 0.05 level, but it does suggest a potential relationship that might become significant with more data points or a larger sample size. The moderate to strong positive correlation shows a trend that higher densities are associated with higher destructive pressures. However, the p-value of 0.078 implies that there is still some uncertainty, and we can't confidently conclude the relationship is statistically significant with this data alone.

For samples 1/9.6 Pearson Coefficient is −0.761 that indicates a strong negative correlation between density and destructive pressure. As the density increases, the destructive pressure tends to decrease. For this type of samples p-value is 0.047. Since the p-value is less than 0.05, the result is statistically significant. This means the negative correlation is unlikely to be due to random chance, and there is strong evidence of an inverse relationship between the two variables. There is a significant negative relationship between density and destructive pressure, meaning that as density increases, the destructive pressure decreases.

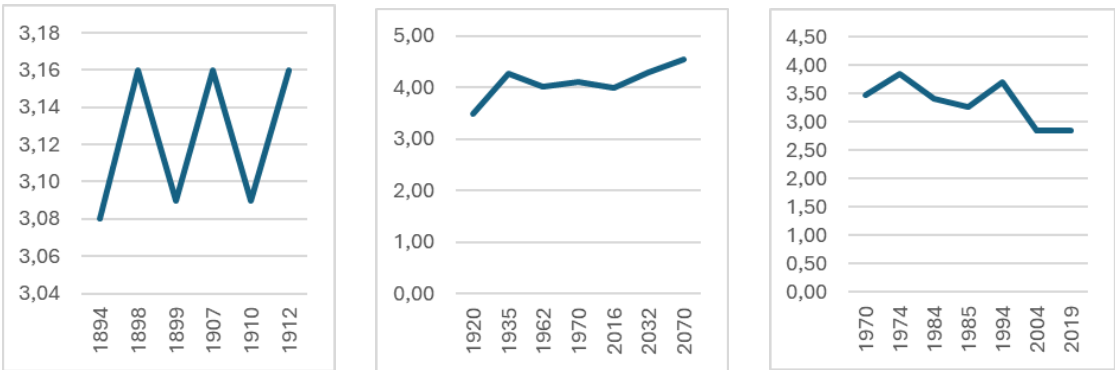

Fig. 4. Dependency of P,MPa on density kg/m^3 for samples 1/8.4, 1/9 and 1/9.6

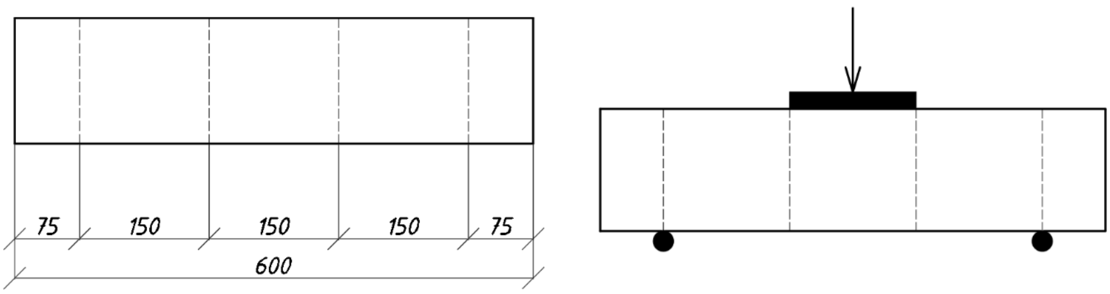

Fig. 5. Scheme of flexural tests performing

We also conducted flexural tests on a total of six beams, each measuring 145×145×600 mm. Two types of materials were tested, with three beams used for each material type:

1. 1/5 – 1 part of cement : 2 parts of sand : 2 parts of granite screenings of fraction 0−5

2. 1/5a – 1 part of cement : 4 parts of granite screenings of fraction 0−5.

The geometrical characteristics, mass and density are presented in Table 4, the results of the flexural tests are presented in Table 5.

Table 4

№	Type	a st., mm	b st., mm	S st., mm^2	a end, mm	b end, mm	S st., mm^2	S avg, mm^2	l1, mm	l2, mm	l3, mm	l4, mm	l avg, mm	V, cm^3	mass, g	ρ, kg/m^3
1	1/5	144	145	20880	145	143	20735	20808	601	605	603	598	602	12521	27740	2215
2	1/5	145	145	21025	144	143	20592	20809	599	600	602	601	601	12496	28120	2250
3	1/5	144	144	20736	143	146	20878	20807	600	600	601	601	601	12495	27980	2239
4	1/5a	143	146	20878	144	145	20880	20879	601	600	600	601	601	12538	30700	2449
5	1/5a	145	145	21025	144	144	20736	20881	599	602	598	605	601	12549	29980	2389
6	1/5a	144	145	20880	146	144	21024	20952	600	601	600	599	600	12571	30800	2450

Table 5

№	Type	F, kN	f_{ctk}, MPa	P, MPa (average)
1	1/5	19.4	2.86	2.87
2	1/5	19.6	2.89	
3	1/5	19.5	2.87	
4	1/5a	23.0	3.40	3.33
5	1/5a	21.7	3.21	
6	1/5a	22.9	3.39	

For these beams, we also constructed histograms to analyze the size distribution and assess potential errors. The results show dimensional errors of up to 3 mm for widths (*a* and *b*), which corresponds to 2 % of the standard beam dimensions. Length deviations reached up to 5 mm, representing less than 1% of the total length.

The same as for cubes, we investigated dependency of destructive pressure, MPa on density kg/m^3. For the samples 1/5 Pearson Coefficient is 0.921 that indicates a strong positive correlation between density and destructive pressure. As the density increases, the destructive pressure tends to increase. P-value is 0.256 and since the p-value is greater than 0.05, the result is not statistically significant. This means that, although there is a strong correlation, we do not have enough evidence to confidently say that this relationship is not due to random chance, likely due to the small sample size. There is a strong positive correlation between density and destructive pressure in this dataset, but the relationship is not statistically significant due to the small number of data points. More data would be needed to confirm this trend.

For samples 1/5a Pearson Coefficient is 0.998 that indicates an extremely strong positive correlation between density and destructive pressure. As density increases, destructive pressure also increases almost perfectly in tandem. The p-value is 0.039. As we can see, the p-value is less than 0.05, the correlation is statistically significant. This means there is strong evidence of a real, meaningful relationship between density and destructive pressure. The data shows a very strong positive and statistically significant correlation between density and destructive pressure. This suggests that in this dataset, the increase in density is closely associated with an increase in destructive pressure.

Next, we successfully fabricated a beam formwork with a cross-sectional dimension of 190×190 mm (Fig. 6). The geometric characteristics of the section were determined as follows: cross-sectional area A = 183 cm^2, moment of inertia I_y = 5 524 cm^4, and section modulus W_y = 581 cm^3. Given an average density of 1 960 kg/m^3, the weight of a 600 mm-long formwork is approximately 21.5 kg, which can be handled by a single person.

We then developed a universal model of the section, and the next phase involves optimizing the section to achieve a better Wy/mass ratio. Our next objective is to develop multiple universal shapes with optimal characteristics, aimed at minimizing the setup time for formwork.

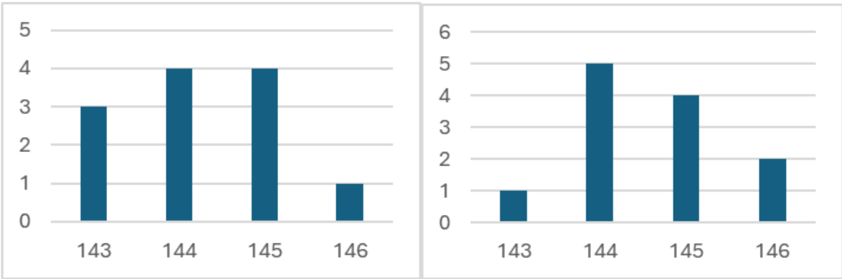

Fig. 6. Distribution of a and b dimensions for samples 1/5 and 1/5a

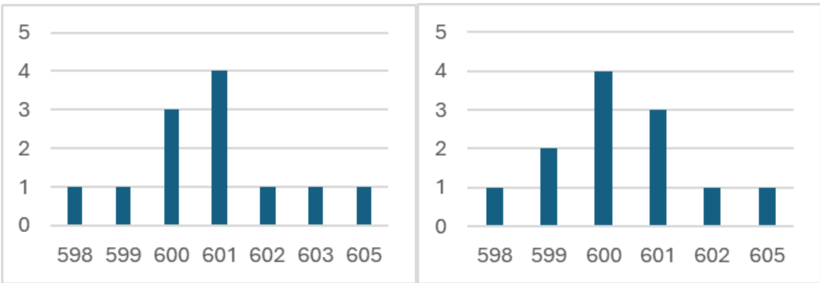

Fig. 7. Distribution of length dimensions for samples 1/5 and 1/5a

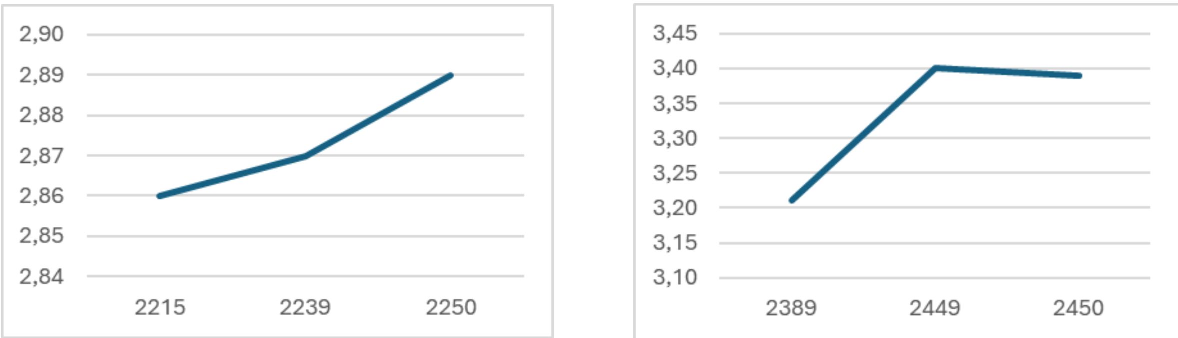

Fig. 8. Dependency of f_{ctk}, MPa on density kg/m^3 for samples 1/5 and 1/5a

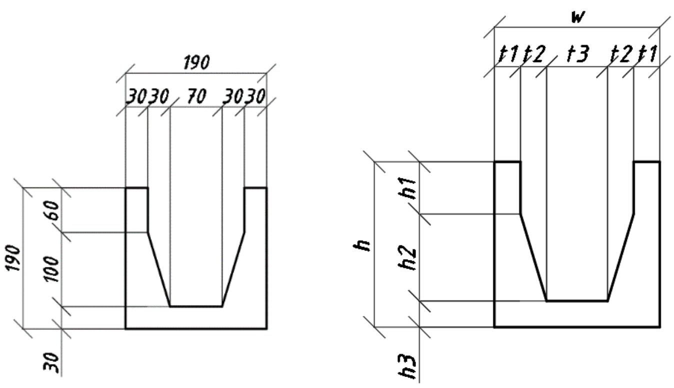

Fig. 9. Sections of beam formwork

Our upcoming experimental objectives are:

– Improve sample quality and minimize dimensional errors to within ±1 mm.

– Conduct additional tests to gain a deeper understanding of the mechanical properties of the materials and to achieve better correlation of experimental results.

– Conduct tensile (traction) experiments on prism-shaped samples.

– Test samples with varying proportions to identify the optimal load-to-mass ratio.

– Optimize cross-sections to achieve the best Wy-to-mass ratio.

– Perform flexural tests on formwork samples.

Conclusions

Following this research, we determined that local materials are suitable for permanent formwork production, as their mechanical properties meet the necessary requirements.

For further investigation into strength characteristics, experimental cubes and prisms will be fabricated using concrete that incorporates locally sourced materials, such as crushed stone, slag, recycled concrete, and brick.

The objective is to design and produce permanent formwork using these materials, aiming to reduce both the cost and labor demands of structural construction while also addressing environmental sustainability.

Additionally, time standards for the installation of permanent formwork made from local materials will be analyzed and compared to those associated with conventional formwork systems.

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