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ASSESSMENT OF THE RESISTANCE OF CONCRETE WITH RECYCLED AGGREGATE TO FREEZE-THAW CYCLES

The object of research is a concrete mix in which 50% of the natural coarse aggregate is replaced with recycled aggregate (RA) obtained by crushing demolished buildings and structures. This research was aimed at assessing the compressive strength and freeze-thaw resistance in a 5% NaCl solution of C30/37 concrete in which 50% of the natural coarse aggregate in the 4–8 and 8–16 mm fractions was replaced by RA from two regions of Ukraine.

The research problem concerns the recycling of construction and demolition waste into new building materials that can meet strength and durability requirements. This approach enables the broader use of RA without compromising the performance characteristics of concrete produced with its incorporation.

Two concrete mixes were prepared using RA from different regions: TN-218 (Kharkiv, Ukraine) and TN-249 (Mykolaiv, Ukraine). Both mixtures used CEM II/A-M (S-LL) 42.5 R cement and had the same water-cement ratio (w/c ≈ 0.43). A superplasticizer and an air-entraining admixture were added to the mix.

The resulting concrete mixes demonstrated stable technological properties: the slump corresponded to class S5; the air content was 5.5–5.7%; and the density of compacted fresh concrete was 2444 kg/m^3. The 28-day compressive strength of both mixes exceeded 54 MPa, confirming that the regional origin of the RA did not significantly affect strength parameters.

Freeze-thaw resistance was evaluated using an accelerated method in a 5% NaCl solution. Both mixes achieved frost-resistance grade F200: the loss of compressive strength after freeze-thaw cycles was 4.04% for TN-218 and 4.35% for TN-249, while mass change remained minimal – 0.14% and 0.29%, respectively.

The results confirm the feasibility of using 50% RA in the production of C30/37 strength-class concrete intended for exterior exposure to freezing and chloride environments, provided that the aggregate grading, RA water absorption, and air-entrainment level are properly controlled. In practice, such mixes can be recommended for the manufacture of concrete and reinforced concrete products without prestressing, intended for use in environments subject to repeated freezing and thawing.

Keywords: *concrete, durability, recycling, aggregates, freeze-thaw, chlorides, strength, circularity, debris, PSD.*

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1. Introduction

The War in Ukraine has created an unprecedented need for reconstruction, which will inevitably translate into a sharp increase in demand for concrete, aggregates, and mineral binders. According to a joint assessment by RDNA4, the total cost of rebuilding and reconstructing Ukraine over the next decade is estimated at 524 billion USD, while direct physical damage as of 31 December 2024 has reached 176 billion USD [1].

Alongside the need for reconstruction, significant amounts of debris (concrete, brick, mortar, plaster, etc.) are rapidly accumulating, creating a separate infrastructure challenge: dismantling and clearing, logistics, sorting, temporary storage, and safe processing. According to estimates by the United Nations Development Program, the approximate cost of debris removal and management (including dismantling where necessary) is around 13 billion USD; at the same time, around 13% of the housing stock has been damaged or destroyed, affecting more than 2.5 million households (United Nations Development Program) [2].

In terms of the circular economy, construction and demolition waste is the largest waste stream in the construction sector and a strategic source of secondary mineral raw materials. In the European Union, this stream accounts for more than a third of all waste generated [3]. However, for Ukraine, these challenges are exacerbated by the military context: mixed debris flows, potentially hazardous contaminants, and the high risk of uncontrolled storage can have a long-term negative environmental impact if proper handling procedures are not implemented [4].

The categorization of debris waste forms the basis for decisions on its subsequent management. The actual composition of the waste depends on the type of natural disaster or armed conflict, the area's characteristics (urban/rural, residential/industrial/commercial), and the climate zone. Destruction results in a mix of solid household waste and debris from destroyed buildings. Such waste requires initial sorting, followed by reuse, recycling, or disposal [5].

In the initial stages, materials contaminated with hazardous substances and scrap metal are separated. Metal scrap can be detected using magnetic systems, which allows it to be reused or recycled.

Other waste forms a temporary landfill that requires further sorting and processing. Debris, such as concrete, brick, and wood, is primarily cleaned and recycled, rather than being disposed of.

For the regulation of waste management in Ukraine, the Cabinet of Ministers of Ukraine Resolution No. 1073 dated 27 September 2022 [6] approved the "Procedure for the management of waste generated in connection with damage (destruction) to buildings and structures as a result of hostilities, terrorist acts, sabotage or work to eliminate their consequences". The document contains a list of components from waste generated by destruction, along with possible directions for their reuse. All construction products, including those obtained because of the use of recycled waste from destruction, must comply with the requirements of the Technical Regulations for Construction Products (Products).

In CEN member countries, the use of recycled aggregates is common practice and is regulated by standards EN 12620, EN 206, and EN 13369.

Ukrainian national standards are largely harmonized with the relevant EN standards, particularly in the areas of aggregates, concrete, and precast reinforced concrete products. However, the fact that most of these standards (13 out of 18 existing documents) are adopted in English may be an obstacle to the introduction of technologies for the use of secondary raw materials.

Standard DSTU B EN 12620:2013 (EN 12620:2002 + A1:2008, IDT) Aggregates for concrete [7] regulates the requirements for aggregates obtained by processing natural materials, industrial processing products, or recycled materials. It defines reclaimed aggregate (RA) as aggregate obtained by processing inorganic material previously used in construction.

The key factors determining the actual use of recycled aggregate are the availability of high-quality secondary raw materials and the presence of economic incentives.

General requirements for concrete are regulated by the standard DSTU EN 206:2022 (EN 206:2013 + A2:2021, IDT) [8]. It allows for the use of recycled aggregates if their quality meets the requirements of DSTU B EN 12620:2013.

Restrictions on replacing natural coarse aggregate with recycled aggregate are imposed based on the exposure class and type of recycled aggregate.

The exposure class is determined according to the characteristics of the environment in which the concrete product will be located [8]:

- X0 – No risk of corrosion or damage;
- XC1–XC4 – Concrete containing reinforcement or other embedded metal and exposed to air and moisture;
- XD1–XD3 – Concrete containing reinforcement or other embedded metal, in contact with water containing chlorides, including de-icing salts, from sources other than seawater;
- XS1–XS3 – Concrete containing reinforcement or other embedded metal, in contact with chlorides from seawater or air containing sea salt;
- XF1–XF4 – Concrete subject to significant freeze/thaw cycles in a wet state;
- XA1–XA3 – Concrete exposed to chemical attack from natural soils and groundwater.

By type, recycled aggregates are divided into:

- type A (Rc90, Rcu95, Rb10-, Ra1-, FL2-, XRg1-) – characterized by higher uniformity and predictability of characteristics, can be used in more critical structures and for more severe exposure classes;
- type B (Rc50, Rcu70, Rb30-, Ra5-, FL2-, XRg2-) – characterized by a higher level of impurities, not recommended for concrete with a compressive strength class > C30/37.

The concept of "Exposure Classes" is based on the prescriptive method. Under this approach, a concrete structure is considered durable if all requirements of the selected exposure class are satisfied. These requirements range from limitations on concrete composition to the control of crack openings. When they are met, the structure is expected to resist environmental actions throughout its service life [9].

This approach differs from the "descriptive" method accepted in Ukraine, which involves measuring characteristics that determine concrete durability: water resistance (W), frost resistance (F), and sulphate resistance. It should be noted that, in certain complex cases, the EU also uses "descriptive" methods, such as the CDF method, as specified in DSTU CEN/TS 12390-9:2019 "Testing of hardened concrete. Part 9. Resistance to freeze-thaw cycles using de-icing salts (CEN/TS 12390-9:2016, IDT)" [10].

The use of demolition waste, in Ukraine's context – debris, as recycled aggregates aligns with broader research trends exploring alternative resources in cement and concrete technology. Studies have shown that non-conventional materials, such as rice husk ash, can modify phase formation and performance parameters in cement systems [11], reinforcing the potential of waste-derived components to contribute to sustainable mix design strategies.

International experience from countries affected by armed conflict Lebanon, Syria, Gaza demonstrates the absence of robust regulatory frameworks for dealing with war-related debris. Their cases highlight the complexity of managing destruction waste under unstable conditions, limited logistics, and environmental hazards. Therefore, global literature does not yet offer tested approaches for integrating such debris into sustainable construction-material cycles.

The object of research is a concrete mix in which 50% of the natural coarse aggregate is replaced with recycled aggregate (RA) obtained by crushing demolished buildings and structures.

The aim of this research is to evaluate the compressive strength and freeze–thaw resistance in a 5% NaCl solution of C30/37 concrete containing 50% recycled coarse aggregate in the 4–8 and 8–16 mm fractions sourced from Kharkiv and Mykolaiv.

Thus, the research tasks were as follows:

1) characterize the physical and mechanical properties of cement used;
2) characterize the physical and mechanical properties of recycled aggregates originating from different regions of Ukraine;
3) determine the technological properties of fresh concrete mixes containing 50% RA (workability, air content, density);
4) assess the compressive strength and freeze-thaw resistance of concrete in a 5% NaCl solution using an accelerated test method.

2. Materials and Methods

2.1. Methodology and experimental approach

In this research, several scientific methods were applied to investigate the properties and performance of concrete containing recycled coarse aggregates:

- the *method of analysis* was used to evaluate the physical and mechanical properties of cement, natural aggregates, recycled aggregates and characteristics of admixtures;
- the *method of classification* was applied to group recycled materials according to origin, fraction size, and physical characteristics;
- the *experimental method* was used to prepare, test, and compare concrete mixes containing 50% recycled aggregates;
- the *comparative method* was applied to analyze differences between concretes made with recycled aggregates from two regions of Ukraine;
- the *accelerated testing method* was used to assess freeze-thaw resistance in a 5% NaCl solution.

Each method supported the step-by-step investigation of material properties, mix design, and durability performance.

Investigation of freeze-thaw resistance in concrete begins with defining the further construction requirements. Classification of performance characteristics will depend on the field of application. For the aim of this article, ready-mix concrete, which will be used for four ordinary structural units in severe conditions (outdoor), was designed.

To meet the requirements for resistance to freeze-thaw cycles, the concrete mix must comply with DSTU EN 206:2022

(EN 206:2013 + A2:2021, IDT), with a minimum strength class C30/37, namely containing at least 340 kg of cement, a maximum water-cement ratio of 0.45, and 4% entrained air [8].

2.2. Evaluation of the physical and mechanical properties of cement, natural aggregates, recycled aggregates, and characteristics of admixtures

Raw materials from various sources were used for testing to simulate the potential use of recycled materials from different regions of Ukraine (the Center and the South). Two concrete mixes were produced and tested; throughout the paper, they are identified by the laboratory protocol codes TN-218 and TN-249. TN-218 corresponds to the concrete mix incorporating recycled concrete aggregate (RCA) sourced from Kharkiv (fractions 4–8 and 8–16 mm), whereas TN-249 corresponds to the concrete mix incorporating RCA sourced from Mykolaiv (fractions 4–8 and 8–16 mm). The complete mix design (constituents, grades/types, material sources/manufacturers, and mass per 1 m^3 of concrete) is summarized in Table 1.

The target technical requirements for both mixes (strength class, water-cement ratio limit, entrained air content, and durability performance) are summarized in Table 2.

Table 1

Concrete mix design and material sources for mixes TN-218 (Kharkiv RCA) and TN-249 (Mykolaiv RCA)

Material	Grade/Type	Deposit/Manufacturer		Material amount per 1 m^3, kg
		TN-218	TN-249	
Cement	CEM II/A-M (S-LL) 42.5 R	Cemark, POD	Cemark, ODE	380
Water	Technical	–	–	165
Sand	River port/Southern region	Dnipro River	Voznesenske	745
Crushed stone 4–8	Granite	Koshchiivske	Mykytivske	300
Crushed stone 4–8	Recycled	Kharkiv	Mykolaiv	300
Crushed stone 8–16	Granite	Koshchiivske	Mykytivske	275
Crushed stone 8–16	Recycled	Kharkiv	Mykolaiv	275
Chemical admixture No. 1	Centrament Air 202	MC-Bauchemie	MC-Bauchemie	0.57 (0.15%)
Chemical admixture No. 2	MC-Powerflow 6425			3.80 (1%)

Table 2

Target technical requirements for the concrete mixes
(applicable to both TN-218 and TN-249)

Parameter	Value
Concrete strength class (design)	C30/37
Required strength, MPa	39.96
Workability (design)	S4
Frost resistance (design)	F200
Water resistance (design)	W8
Consistency	Non-stiff
W/C	0.43

Cement type CEM II/A-M (S-LL) 42.5 R, which meets the requirements of DSTU B EN 197-1:2015 (EN 197-1:2011, IDT) [12], was selected to produce the concrete mix. Quality characteristics were measured in accordance with DSTU EN 196-1:2019 (EN 196-1:2016, IDT) [13], DSTU EN 196-3:2022 (EN 196-3:2016, IDT) [14], DSTU EN 196-6:2019 (EN 196-6:2018, IDT) [15].

The quality acceptance of aggregates was determined in accordance with the requirements of DSTU B EN 12620:2013 [7] and methods described in DSTU EN 933-1:2021 (EN 933-1:2012, IDT) [16].

Granite crushed stone fractions of 4–8 mm and 8–16 mm were used as the reference coarse aggregate and were partially replaced with recycled aggregate at *50% by mass in each fraction* (Table 1).

Two sources of fine aggregate were used in the research: for the concrete mix, with RA from Kharkiv TN-218 – Dnipro River sand; for the concrete mix with RA from Mykolaiv TN-249 – sand from the South of Ukraine.

Replacement of natural aggregates in the concrete mix was on the next scheme: 50% of natural aggregate (granite) in fractions 4–8 mm and 8–16 mm was replaced by 50% of RA aggregate.

Using this approach, the frame density of the concrete mix was achieved without a negative impact on porosity.

For the water-cement ratio reduction, rheological stability, and workability improvement of the concrete mix MC-Powerflow 6425 a modern polycarboxylate superplasticizer, was added. It also helps to compensate for the increased water absorption of RA aggregate and prevents the addition of excessive water.

According to EN 206 requirements, to ensure frost resistance, an air-entraining admixture should be used. For testing purposes, Centrament Air 202 admixture was also added to the concrete mixes. This admixture forms a system of air microcapsules (10–300 μm in diameter), which help to create an additional pore structure to compensate internal pressure during ice crystallization, reducing the risk of microcracking of concrete at low temperatures.

Concrete mix preparation for frost resistance test:

1. Dry components (cement, fine and coarse natural aggregates, RA aggregates) mixed for uniformity and avoidance of grains formation.
2. MC-Powerflow 6425 mixed with water and added to uniform dry components.
3. After achieving the targeted plasticity of the concrete mix, Centrament Air 202 was added.
4. The consistency was adjusted, and the cone slump was checked.
5. The fresh concrete mix was formed into samples for further testing for strength and frost resistance.

2.3. Assessment of freeze-thaw resistance in a 5% NaCl solution

Since DSTU EN 206:2022 (EN 206:2013 + A2:2021, IDT) [8] defines requirements using a prescriptive approach, Ukraine tends to use a more traditional descriptive approach to determine frost resistance. For this purpose, an accelerated method exists for determining concrete's resistance to freeze-thaw cycles.

The essence of the method lies in the production of concrete cube samples with sides measuring 100 × 100 × 100 mm, including 12 main cube samples and 6 control cube samples.

The main samples, saturated with a 5% aqueous solution of sodium chloride, are placed in a container filled with the same solution to test their frost resistance. The samples are placed on two wooden spacers, with the distance between the samples and the container walls equal to (10 ± 2) mm, and with a layer of solution at least 10 mm above the sample surface.

This means that concrete that has withstood 5 freeze-thaw cycles under the conditions specified by the method will withstand 200 cycles under actual operating conditions in the environment.

The sodium chloride solution in the container for freezing and thawing is changed every 20 cycles.

The main samples shall be placed in a freezer at an air temperature not exceeding 10°C in containers closed at the top, with the distance between the container walls and the chamber not less than 50 mm. After the temperature in the closed chamber reaches minus 10°C, the temperature is lowered over a period of (2.5 ± 0.5) hours to minus (50 ± 5)°C and maintained for (2.5 ± 0.5) hours. Then the temperature in the chamber is increased over a period of (1.5 ± 0.5) hours to –10°C, and at this temperature, the containers with samples are removed from the chamber.

Cubes with an edge length of 100 mm thaw within (2.5 ± 0.5) hours, in a bath containing a 5% aqueous solution of sodium chloride at a temperature of (18 ± 2)°C. The containers are immersed in the bath so that each of them is surrounded by a layer of solution at least 50 mm thick.

The main samples tested for compression in accordance with DSTU EN 12390-3:2024 (EN 12390-3:2019, IDT) [17] after 2–4 hours after removal from the container. For concrete used in road and airfield pavements, the mass of the samples is determined in advance.

3. Results and Discussion

3.1. Characterization of the physical and mechanical properties of cement used

The experimental results confirm that both concretes meet the targeted performance requirements for binder quality, workability retention, strength development, and frost resistance. The physical-mechanical characteristics of the cements used are summarized in Table 3, showing comparable 2-day and 28-day strengths (28.4–28.7 MPa and 57.3–59.0 MPa, respectively), as well as similar fineness and setting times (initial setting 150–160 min; final setting 200–220 min).

3.2. Characterization of the physical and mechanical properties of recycled aggregates originating from different regions of Ukraine

Particle size distribution results for recycled aggregates from Mykolaiv fractions 4–8 mm and 8–16 mm are provided in Tables 4, 5, respectively.

Recycled aggregates from Mykolaiv for fraction 4–8 mm demonstrate stable, well-graded particle size distributions, as shown in Fig. 1, with low fines content (0.51%), ensuring minimal dust.

In RA fraction 8–16 from Mykolaiv, the main volume of the material is concentrated in the medium and coarse fractions (16 and 22.4 mm). This is reflected in Fig. 2, where the curve generally falls within the acceptable range. However, it is below the control limits on the finer sieves, indicating that the material is coarser than typically expected.

Particle size distribution results for recycled aggregates from Kharkiv fractions 4–8 mm and 8–16 mm are provided in Tables 6, 7, respectively.

The particle-size curve of RA from the Kharkiv 4–8 fraction in Fig. 3 shows a material dominated by coarse fractions, with very few fines. While the remains are within acceptable control measures, they consistently fall below the limits on the finer sieves, indicating a noticeably coarser grading. At larger sieve sizes, the material aligns closely with the upper control limit, confirming that its main mass is concentrated in the coarse fraction range.

Table 3

Cement physical and mechanical test results

Cement type	Producer	Strength, 2 days	Strength, 28 days	Sieve residue 32 µm	Water for consistency	Blaine	Initial setting	Final setting
		MPa	MPa	%	%	cm^2/g	min	min
CEM II/A-M(S-LL) 42.5 R	JSC "Podilskyi Cement"	28.7	59.0	4.9	28.4	4860	150	200
CEM II/A-M(S-LL) 42.5 R	LCC "Cement"	28.4	57.3	6.1	30.0	4687	160	220

Table 4

Sieving results of RA from Mykolaiv 4–8 fraction

Sieve size	Residual mass Ri, g	Residual percent $100 \cdot Ri/M_1$, %	Complete passage through a sieve $100 - \sum(100 \cdot Ri/M_1)$, %
11.2	170.55	6.56	93.44
8.0	1530.14	58.85	34.59
5.6	796.73	30.64	3.95
4.0	32.77	1.26	2.69
0.063	56.56	2.18	0.51
Material in the receiver	13.25	0.51	–

Note: M_1 – initial mass of the dried test sample; Ri – mass of dry sifted material remaining on each sieve

Table 5

Sieving results of RA from Mykolaiv 8–16 fraction

Sieve size	Residual mass Ri, g	Residual percent $100 \cdot Ri/M_1$, %	Complete passage through a sieve $100 - \sum(100 \cdot Ri/M_1)$, %
22.4	591.2	5.91	94.09
16	3517.8	35.18	58.91
11.2	4883.01	48.83	10.08
8.0	852.07	8.52	1.56
0.063	151.61	0.16	0.04
Material in the receiver	4.31	0.04	–

Note: M_1 – initial mass of the dried test sample; Ri – mass of dry sifted material remaining on each sieve

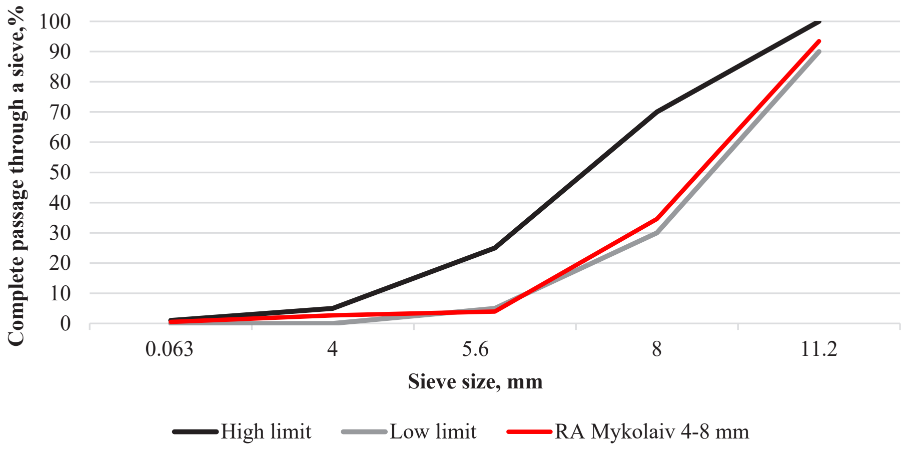

Fig. 1. Curve of particle size distribution of RA from Mykolaiv 4–8 fraction

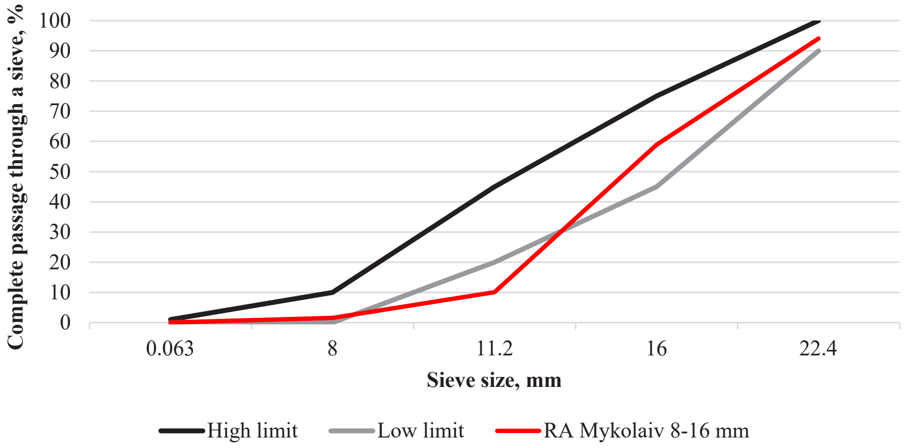

Fig. 2. Curve of particle size distribution of RA from Mykolaiv 8–16 fraction

Table 6

Sieving results of RA from Kharkiv 4–8 fraction

Sieve size	Residual mass Ri, g	Residual percent $100 \cdot Ri/M_1$, %	Complete passage through a sieve $100 - \sum(100 \cdot Ri/M_1)$, %
11.2	138.98	5.35	94.65
8.0	1326.46	51.02	43.64
5.6	1060.57	40.79	2.85
4.0	49.66	1.91	0.94
0.063	14.57	0.56	0.38
Material in the receiver	9.76	0.38	–

Table 7

Sieving results of RA from Kharkiv 8–16 fraction

Sieve size	Residual mass Ri, g	Residual percent $100 \cdot Ri/M_1$, %	Complete passage through a sieve $100 - \sum(100 \cdot Ri/M_1)$, %
16	1246.64	12.47	87.53
11.2	7737.11	77.37	10.16
8.0	868.27	8.68	1.48
4	85.4	0.85	0.63
0.063	39.91	0.4	0.23
Material in the receiver	22.67	0.23	–

The particle-size curve of RA from the Kharkiv 8–16 fraction in Fig. 4 falls within the acceptable envelope at the larger sieve sizes; it remains well below both control limits on the finer sieves, confirming that the material is significantly coarser than the target specification. The majority of the mass is concentrated in the 16 mm fraction, where the curve approaches the upper boundary.

Such a particle-size distribution requires balancing the overall grading of the concrete mix to achieve a dense concrete structure, which can be achieved by using two coarse aggregate fractions.

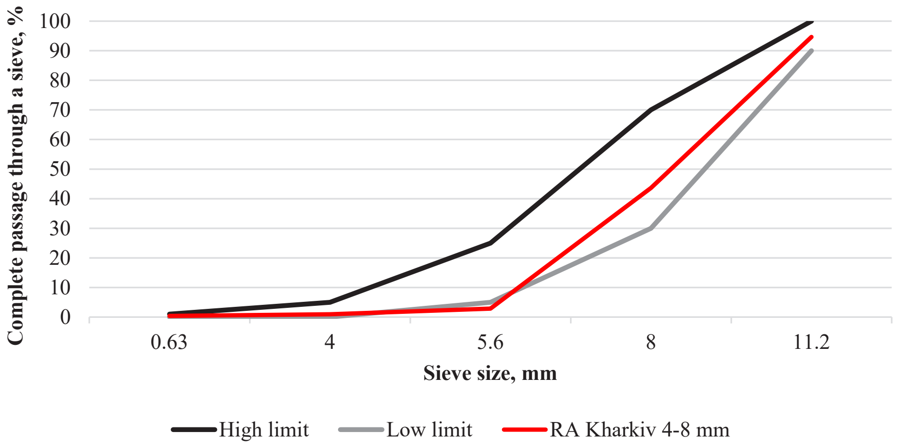

Fig. 3. Curve of particle size distribution of RA from Kharkiv 4–8 fraction

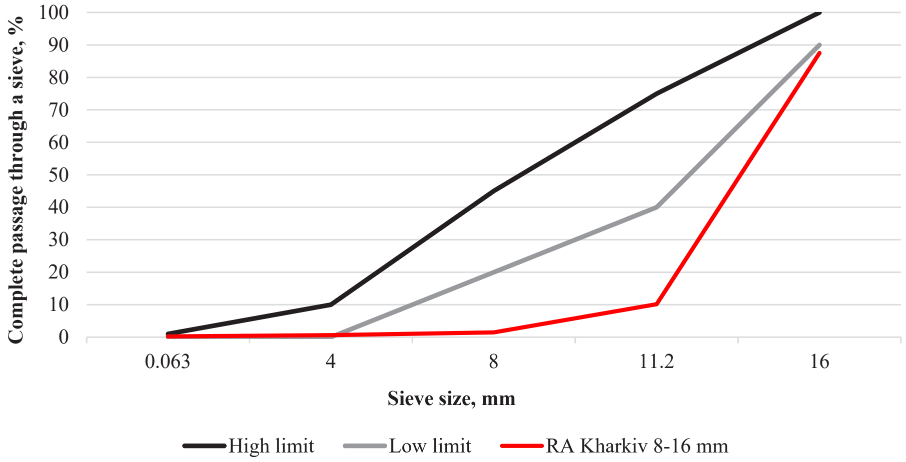

Fig. 4. Curve of particle size distribution of RA from Kharkiv 8–16 fraction

3.3. Determination of the technological properties of fresh concrete mixes containing 50% RA (workability, air content, density)

Fresh concrete properties are provided in Table 8. Both mixes demonstrated the designed workability class and stable rheology over time: the slump decreased from 22 cm (10 min) to 18–18.5 cm after 2 h. The entrained air content was 5.5% and 5.7%, while the fresh density remained 2444 kg/m^3 at a mix temperature of 20°C. Such values are consistent with an air-entrained, frost-resistant concrete concept and indicate that the regional aggregate origin did not cause a critical loss of workability or excessive air variability under the adopted mixing procedure.

Strength development is summarized in Table 9. The average compressive strengths at 1 day were 20.81 MPa and 20.76 MPa; at 7 days, 45.59 MPa and 43.62 MPa; and at 28 days, 54.31 MPa and 54.22 MPa, which exceeded the required level (39.96 MPa). The 28-day strengths correspond to values commonly observed for high-strength concrete made with recycled aggregates. Studies indicate that such aggregates may reduce compressive strength, occasionally by as much as 25%. Nevertheless, reported strengths generally range from 40 to 70 MPa, depending on mix composition and the degree of replacement [18]. This agreement suggests that the selected w/b ratio and admixture system compensated for the higher porosity of recycled aggregates, and the recycled coarse aggregate quality was sufficient to avoid a pronounced mechanical penalty. At the same time, the literature consistently emphasizes that the durability and strength of concrete with RA are sensitive to the content of adhered mortar, aggregate absorption, and w/c ratio; increasing RA content generally increases porosity and can weaken durability unless countermeasures (e. g., SCMs or aggregate treatments) are applied [19].

Table 8

Test results of fresh concrete mixes (TN-218 and TN-249)

Test name	10 min	1 h	2 h
Slump, cm	22/22	20/20	18/18.5
Air content, %	5.5/5.7	–/–	–/–
Fresh density, kg/m^3	2444/2444	–/–	–/–
Mix temperature, °C	20/20	20/20	20/20

Note: numerator – TN-218; denominator – TN-249

Table 9

Compressive strength and specimen mass at 1, 7, and 28 days

Name	Mass, 1 day, g		Strength, 1 day, MPa		Mass, 7 days, g		Strength, 7 days, MPa		Mass, 28 days, g		Strength, 28 days, MPa	
TN-218												
Test results	2290	2310	20.48	21.13	2290	2270	45.07	46.10	2280	2270	54.71	53.90
Average value	2300		20.81		2280		45.59		2275		54.31	
TN-249												
Test results	2310	2320	20.99	20.53	2290	2290	43.83	43.41	2300	2290	54.68	53.75
Average value	2315		20.76		2290		43.62		2295		54.22	

3.4. Assessment of the compressive strength and freeze-thaw resistance of concrete in a 5% NaCl solution using an accelerated test method

Freeze-thaw resistance results are presented in Table 10. After the accelerated freeze–thaw exposure, the relative compressive strength reduction remained limited (4.04% and 4.35%), while mass change was small (0.14% and 0.29%). Both concretes achieved the frost resistance grade F200 according to the national accelerated procedure applied. These outcomes indicate that the adopted air-entrainment and overall mixture compactness were effective in controlling internal frost damage under the test conditions. The finding is also consistent with the broader view that frost performance of recycled aggregate concrete may vary widely and depends strongly on saturation degree, pore structure, and recycled aggregate characteristics, hence the absence of a universal consensus across studies [20].

Table 10

Freeze–thaw resistance after 5 accelerated cycles in 5% NaCl solution

Indicator	Control specimens (avg.)	Main specimens after 5 cycles (avg.)	Mass change, %	Strength loss, %	Frost resistance grade
Average mass, g	2294.67/2310.50	2296.50/2303.83	0.14/0.29	4.04/4.35	F200/F200
Average compressive strength, MPa	53.93/53.18	51.75/50.87	–/–	–/–	–/–

Note: numerator – TN-218; denominator – TN-249

When interpreting these results, it is important to distinguish internal frost damage from surface scaling caused by chlorides. Internationally, the CDF approach is widely used to quantify scaling per unit surface area under freezing-thawing cycles in a sodium chloride solution, explicitly targeting freeze-thaw + de-icing salt action [21].

Many studies indicate that de-icing salts greatly intensify deterioration mechanisms. For recycled aggregate concrete, salt-assisted freeze-thaw resistance often decreases as the share of recycled aggregate increases. As a result, structures exposed to salts may need extra protection, even if the material performs well in freeze-thaw cycles without salts [22].

Moreover, surface scaling may become more severe even when internal freeze-thaw cracking resistance remains satisfactory, which is particularly relevant for recycled aggregate systems due to their near-surface saturation sensitivity [23]. In this context, the limited mass change and modest strength loss observed in Table 10 are encouraging; however, they should be considered as evidence of good resistance within the applied accelerated framework rather than a direct equivalence to long-duration, high-cycle salt-scaling regimes (e. g., CDF-type scaling protocols).

Finally, the literature also indicates practical routes to further improve the salt-scaling performance of concrete with RA, including pretreatment of RA (e. g., with silica fume slurry) and optimized binder systems, which can reduce scaling and improve durability indicators under combined freeze-thaw and de-icer action [24]. If the intended application includes severe de-icing salt exposure, integrating such mitigation strategies (or confirming performance through a dedicated salt-scaling protocol in addition to the accelerated frost method) would strengthen the durability justification of the developed concretes.

The confirmed frost resistance in a 5% NaCl solution indicates that concrete with 50% RA can be applied in civil engineering exposed to freeze-thaw cycles and chloride action. In particular, the developed compositions can be considered for non-prestressed exterior concrete and reinforced-concrete products, intended for use in environments subject to repeated freezing and thawing. Designers and producers may use the developed mix-design methodology to create concretes with partial RA replacement. This supports reduced natural aggregate extraction.

3.5. Discussion

Durability assessment of the regional origin of recycled aggregate did not lead to significant differences in performance when the water-cement ratio and air-entrainment system were properly controlled, confirming the feasibility of producing durable recycled-aggregate concretes for environments subject to cyclic freezing and exposure to de-icing salts. The developed concretes may therefore be recommended for non-prestressed exterior concrete and reinforced-concrete products, intended for use in environments subject to repeated freezing and thawing.

The obtained data can also serve as a basis for preparing standards or technical guidelines on RA use, support recommendations for ready-mix plants, and promote the scaling of circular construction technologies in Ukraine.

The research did not evaluate other durability mechanisms, such as carbonation, chloride penetration, chemical corrosion, or behavior under repeated loading. For applications in highly demanding structures, extended durability testing is necessary.

Future research should examine RA sourced from additional regions, as their properties may differ significantly in strength, absorption, and adhered mortar content. It is also important to study pre-treatment techniques (e. g., mineral slurry coating, carbonation, impregnation) to improve concrete durability.

Further freeze-thaw and salt-scaling tests are required to confirm long-term behavior under exposure to de-icing salt. Mix optimization with higher RA contents and different water-binder ratios, superplasticizers, and secondary cementitious materials (SCM) combinations remains a promising research direction.

Evaluation of environmental performance, including life-cycle assessment (LCA), is another relevant topic, as it can help quantify the sustainability benefits of circular technologies in concrete production.

4. Conclusions

1. Physical and mechanical properties of both cement samples of CEM II/A-M (S-LL) 42,5 R tested according to DSTU EN testing methods demonstrate nearly identical performance: 2-day strength results ranged from 28.4 to 28.7 MPa; 28-day strength ranged from 57.3 to 59.0 MPa; initial setting time ranged from 150 to 160 minutes; final setting time ranged from 200 to 220 minutes; fineness according to Blaine method ranged from 4687 to 4860 cm^2/g; water for consistency ranged from 28.4 to 30.0 percent. These results enable the correct interpretation of concrete behavior, mitigating influence of cement characteristics inconsistency.

2. Particle size distribution of RA aggregates indicates well-graded curves for the RA from Mykolaiv source with a low quantity of fines, 0.51% in 4–8 mm fraction and 0.04% in 8–16 fraction.

RA from Kharkiv source shows a coarser grading, where 77.37% of the particles concentrated in 11.2 mm sieve for 8–16 fraction. This may affect the compactness of the concrete structure and should be compensated by adjusting the 4–8 and 8–16 mm fraction ratio in the concrete mix.

3. Developed concrete mixes TN-218 (Kharkiv RA) and TN-249 (Mykolaiv RA) containing 50% by mass RA aggregates. Water-cement ratio 0.43, achieved by adding a combination of the chemical admixtures MC-Powerflow 6425 and Centrament Air 202.

Slump loss test shows the workability of the concrete mixes, which starts at 22 cm in the first 10 minutes after concrete preparation and stops at 18 cm after 2 hours of storage under normal conditions, which demonstrates good plasticity retention.

Entrained air in concrete mixes was 5.5–5.7%, which complies with the requirements of the standard. Fresh concrete density was consistently 2444 kg/m^3 under normal conditions.

4. Compressive strength of the concrete samples TN-218 and TN-249 after freeze-thaw cycles in 5% NaCl solution was 51.75 MPa and 50.87 MPa, respectively. Strength loss compared to the reference samples was 4.04% for TN-218 and 4.35% for TN-249, while mass change was only 0.14% and 0.29%, respectively.

Both concrete samples have achieved frost resistance grade F200, which ensures the durability of concrete structures based on the designed recipes in freeze-thaw conditions.

Conflict of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship, or any other interests that could have influenced the research and the results presented in this paper.

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Data availability

Data will be provided upon reasonable request.

Use of artificial intelligence

The authors used an artificial intelligence language model (GPT-5.2, OpenAI) to edit the manuscript and improve its clarity (e. g., phrasing, grammar, and formatting). The authors prepared all numerical data, calculations, tables, and interpretations. The authors reviewed and verified all AI-assisted edits against the original experimental records and applicable standards. The use of AI did not affect the experimental design, data analysis, or the research scientific conclusions.

Authors' contributions

Anastasiia Bielohrad: Conceptualization, Methodology, Validation, Investigation, Resources, Visualization, Writing – review and editing, Supervision, Project administration; ***Liubov Melnyk***: Conceptualization, Methodology, Supervision; Writing – original draft, Project administration; ***Oleksandr Hizhevskyi***: Validation, Investigation, Data Curation, Validation, Visualization; ***Denys Dudarevych***: Validation, Investigation, Data curation, Validation, Visualization.

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