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MIX DESIGN OF THE COMPOSITION OF GENERAL CONSTRUCTION CONCRETE BASED ON RECYCLED AGGREGATES

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This study's object is the concrete for general construction purposes that includes recycled aggregates formed from the processing and classification of residues from damaged or destroyed concrete buildings and structures, including those affected by military operations. The task addressed relates to the use of recycled concrete aggregates in conventional concrete, including the partial or complete replacement of natural aggregates. This area of research is aimed at devising a framework for the application of recycled concrete aggregates as a secondary raw material for the construction industry.

This paper describes the characteristics of recycled concrete aggregates from recycled concrete structures. It was found that these aggregates have significant structural defects such as cracks and pores of various origins. They are also characterized by compositional heterogeneity and an increased content of weak grains, at around 18%. Meanwhile, the content of fine fractions is almost 34%. This naturally worsens the physical and mechanical properties of concrete made with such aggregates.

However, a rational approach to using concrete mix components makes it possible to obtain concrete with appropriate performance characteristics, corresponding to class C20/25 (29.2 MPa) with 50% recycled concrete aggregate content.

Using this type of aggregate could conserve natural minerals, tackle the issue of disposing of large-tonnage industrial waste, as well as significantly improve the potential for large-scale reconstruction in Ukraine. This may be achieved by accelerating the construction of damaged and destroyed housing stock and by obtaining a substantial raw material resource in the form of recycled aggregate as an alternative to local materials

Keywords: recycled aggregate, granular composition, structural defects, physical and mechanical characteristics of concrete

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1. Introduction

One of the important issues of our time is the task to dispose of a huge number of destroyed building structures. According to preliminary estimates, the volume of such waste already reaches several million tons and continues to grow. Uncontrolled landfills with hazardous materials, such as asbestos, pose a serious threat to the environment and human health as they cause pollution of groundwater, air, and worsen the sanitary and epidemiological situation.

Modern technologies make it possible to convert construction waste into full-fledged building materials. Crushed concrete products and structures can successfully replace natural aggregates or even be part of cement. This significantly reduces the pressure on the environment, thereby reducing the need for the extraction of new materials and decreasing the amount of waste sent to landfills. It also makes construction more cost-effective and contributes to the development of the construction industry.

Thus, the production of aggregates from recycled concrete makes it possible to build a closed cycle in the construction industry and reduce the consumption of natural resources. However, the surface of secondary concrete aggregates has a porous structure with cement residues, which negatively affects their adhesion to the cement paste in new concrete. This leads to a decrease in the strength and durability of structures. For Ukraine, this issue is complicated by the presence of organic residues and combustion products formed as a result of military operations, which complicates the formation of concrete structures based on such materials.

Possible ways to reduce defects are the introduction of modifying additives that promote self-healing of concrete elements. In addition, it is advisable to use alternative cements that can withstand structural fluctuations caused by organic impurities, which in turn will contribute to the expansion of the raw material base. In addition, to improve the properties of secondary concrete aggregates, it is proposed to treat their surface with special additives. The use of pozzolanic additives and superplasticizers will make it possible to compact the surface of the aggregate and increase the strength of connection with the cement slurry.

An applied problem in this respect is to design concrete for general construction purposes based on recycled residues of concrete structures and buildings. Given the volume of destruction of housing stock, infrastructure facilities, and industrial complexes, as well as the need for their restoration, the specified research field is gaining relevance and priority in the construction industry and the domain of national security. This is reflected in several aspects, including the need to dispose of a significant amount of waste and the need for mass reconstruction and attracting a large amount of raw materials for this.

Considering the fact that construction waste is a problem in most countries, it can also be regarded as a local raw material. This will make it possible to resolve not only environmental issues but also optimize the logistical component of material supply.

2. Literature review and problem statement

As indicated in [1, 2], the recycling of construction waste and the creation of recycled aggregates are one of the sustainable solutions to the growing crisis of waste disposal and depletion of natural aggregate sources caused by the construction sector. However, so far, recycled aggregates have been mostly used in low-cost areas, such as the base of road pavements. Given that materials based on Portland cement systems are non-recyclable products, they are not subject to chemical decomposition and can be recycled only by mechanical processing. At the same time, the huge volumes of accumulated construction waste pose a serious threat to the environment. Therefore, the search for effective ways to recycle and reuse this waste is one of the most important tasks of our time. However, this process is complicated by both the heterogeneity of the composition of construction waste and its structural defects.

In world practice, studies are increasingly reported that are aimed at solving the problem of using aggregates from recycled concrete. Confirmation of this can be found in [3, 4], which consider the results of studies on the influence of recycled fine aggregates on permeability, shrinkage during drying, carbonation, penetration of chloride ions, acid resistance, and frost resistance of concrete based on them. The results show that the content of old mortar and the quality of recycled concrete are closely related to the durability of concrete based on recycled aggregates.

For example, the value of shrinkage during drying with a 100% replacement coefficient of recycled aggregate is twice that of conventional concrete. In addition, the durability of such concrete decreases with an increase in the replacement coefficient of recycled fine aggregate and water-cement ratio. These indicators can be improved by correcting mixing methods and/or using aggregates with optimized moisture content. According to the reported results, the optimal content is 30% of recycled fine aggregates, which, at an effective water-cement ratio of 0.41, makes it possible to obtain a shrinkage rate not exceeding 2.5%. In addition, the use of zeolite-like mineral additives has a positive effect on durability indicators. However, this approach is not economically justified in all cases. In addition, the use of coarse aggregate from recycled concrete is more appropriate in terms of the volumes required for disposal.

According to [5, 6], one of the approaches to reuse destroyed concrete is its conversion into both fine and coarse aggregates. Typically, recycled aggregate is obtained by crushing, but this process does not make it possible to isolate aggregate grains free from cement residue and dust. The amount of residual solution in recycled aggregates is considered one of the factors that directly reduce its properties. As noted in [7], because of the presence of residual solution, such aggregate has higher water absorption and lower density compared to natural analogs. This subsequently leads to a decrease in workability and compressive strength of concrete. The authors evaluated methods for removing adhering solution and sealing the pores of recycled aggregate, improving the quality of the material. However, for the production of high-quality recycled aggregates, it is necessary to devise or implement more effective methods of their processing, including reducing the content of cement dust.

This approach was used in [8, 9]. However, the presence of cement residue and cement dust formed during the crushing process are not the only disadvantages characteristic of recycled concrete aggregate. An important factor influencing the characteristics of recycled aggregate is the defectiveness of its structure. After all, during the processing and classification process, microcracks appear in the aggregate structure, which in turn worsens the properties of the final product. The methods for solving this problem reported in [10] include both impregnation of aggregate with a defective structure with mineral and alkaline solutions, and the use of modifying complex additives directly in the concrete production process. However, such methods are not always economically feasible and require reorganization of the technological process.

In addition, the composition of construction waste is quite diverse. The largest share is made up of concrete structures and stone materials, such as bricks and blocks. As noted in [11, 12], construction waste contains a significant amount of asphalt, metal, wood, and other materials. This significantly complicates the work with this type of raw material as it requires the introduction of additional preparation operations. One way to solve this problem is to devise an integrated approach to its processing with the mandatory use of separation after crushing.

It is evident that devising methods for processing and reusing aggregate from recycled concrete requires additional research into the properties of such aggregate for concrete mixtures and concretes.

This approach is used in [13, 14], which focus on the technology of grinding. However, residues of old cement or paint may remain on the surface of the formed fractions, which leads to a deterioration in the adhesion of the cement binder to the aggregate, an increase in porosity and a decrease in the indicators of physical and mechanical characteristics in general. It should be noted that the low quality of adhesion between the mortar and recycled aggregate leads to a deterioration in the structure of the concrete stone, which leads to fragility of the material, the formation of cracks, and high water absorption. This can be prevented by using such technical methods as sieving recycled aggregates to remove harmful impurities, coating with appropriate additives or calcination. However, these methods have a significant drawback in the form of time costs, re-equipment of the production line, and large capital investments.

According to [15, 16], concrete from recycled aggregates is a technologically complex material and has a lower quality. The amount of residual solution in such aggregates is one of the factors that directly reduce its properties. Due to the presence of residual solution, crushed stone has a higher water absorption and lower density compared to natural aggregate. However, a rational approach to the use of recycled concrete aggregates for the production of new generation concrete, primarily by taking into account the selection of initial compositions, makes it possible to mitigate the loss of concrete quality. The use of recycled concrete aggregates is beneficial from an environmental point of view, reducing the depletion of natural aggregate deposits and extending the life cycle of concrete.

Importantly, more research focused on this area is needed to identify a clear trend. Moreover, it is advisable to look for advanced technologies that make it possible to obtain aggregates from recycled concrete of higher quality with a significant amount of residual mortar removed. The result is concretes based on them, of corresponding or even higher quality compared to types of concrete with natural aggregate.

It is noted in [17] that when using recycled aggregate, there is a decrease in compressive strength, tensile strength, and modulus of elasticity. It was found that aggregate obtained on the basis of recycled concrete is characterized by higher absorption and water absorption (in the range from 3.0% to 10.0%). Therefore, to achieve a given ease of workability, it is necessary to increase the amount of water in the concrete mixture. And this, in turn, leads to an increase in porosity, deterioration of mechanical properties, and a decrease in the durability of such concretes.

In [18, 19] it is indicated that the use of up to 30.0% recycled aggregate in building mixtures has a slight effect on the physical, mechanical, and operational properties of concrete. However, it is noted that the sorption capacity of such concrete is 14% higher compared to concrete on conventional aggregates. With this content of recycled concrete and reinforced concrete aggregates, corrosion resistance does not decrease, but some concretes may contain a small amount of chlorides that affect the durability of reinforced concrete structures. If recycled aggregates are pre-wetted with water, this leads to an increase in the ease of placement of the construction mixture, but excess water contributes to an increase in shrinkage deformations.

Another technological technique that makes it possible to increase the efficiency of the aggregate based on recycled concrete is described in [20]. The study investigates the combined effect of washing the aggregate with its subsequent thermomechanical treatment on the properties of the recycled aggregate and the efficiency of its use in concrete. The combination of washing and thermomechanical treatment showed a more pronounced effect on the properties of the aggregate compared to the control sample of the aggregate. However, this technology is more resource-intensive because it requires additional energy consumption.

The results of the studies reported in [21, 22] focus on improving the grain structure of recycled aggregate by treating or soaking them again in alkali solutions or other aluminosilicate systems. This is aimed at ensuring increased adhesion between the recycled aggregate and the cement mortar and also contributes to reducing the number of cracks and compacting the structure of the recycled concrete aggregate.

This is also confirmed by the results described in [23], in which, when using recycled aggregates treated with alkali (NaOH), the compressive, flexural, tensile strength at split of concrete based on it with a cement content of 300 kg/m^3 was increased by 32.8%, 48.0%, and 38.9%, respectively. When using acid-treated (HCl) recycled aggregate with a cement content of 300 kg/m^3, these indicators increased by 30.1%, 40.0%, and 33.0%, respectively. However, these operations significantly complicate the manufacturability of the concrete production process as the main final product.

Considering all the advantages and disadvantages of the above techniques for using aggregate based on recycled concrete, the most economical and technically feasible one is its partial use with rationalization of the selection of the composition of starting components. In addition, research into this area will make it possible to control the structural processes and regularities related to the formation of the structure of cementing artificial stone, which can lead to self-healing of compositions.

3. The aim and objectives of the study

The aim of our research is to design concrete mixtures and concretes with partial use of aggregate based on recycled concrete. This will make it possible to solve the issue of recycling large-tonnage industrial waste, significantly increase the pace of construction and restoration of infrastructure, as well as damaged or destroyed housing stock.

To achieve this aim, the following objectives were accomplished:

– to investigate the main characteristics of recycled aggregate;

– to investigate the influence of the content of aggregate from recycled concrete on the rheological properties of the concrete mixture and the performance properties of concrete.

4. The study materials and methods

The object of this study is resource-efficient concrete based on aggregates from recycled concrete products and structures formed during hostilities.

The working hypothesis is as follows: by combining the features of the development of the structure and properties of cement, it is possible to ensure the directed development of the processes of structure formation of concretes based on recycled aggregate in order to obtain a low-defect material structure and high operational properties.

Devising new technological solutions to increase the functional properties of concretes based on recycled aggregates requires an in-depth study of the processes of material structure formation and self-healing processes of the defective structure in order to obtain reduced defects and, accordingly, improved material characteristics.

Portland cement with limestone L(B) – CEM II/A-LL 42.5R (PC II/A-B-500 R-N) was used as a binder during the research. The limestone content is 14%. The compressive strength indicators for 28 days are 54 MPa. The hardening times are characterized by the following indicators: the beginning of hardening – 170 min, the end of hardening – 240 min.

Granite rubble (a mixture of crushed stone fractions 5–20 mm) was used as a coarse aggregate for the control samples. The characteristics are given in Table 1.

The Dnieper river sand with a particle size modulus of M_s = 1.52 (according to DSTU B V.2.7.-32-95) was used as fine aggregate. The granular composition of the fine aggregate is shown in Fig. 1.

Sand particle size modulus is M_s = 1.52 (fine). The content of dusty and clay particles of siltation is 1.2%. Bulk density is 1520 kg/m^3.

As a plasticizing additive for Portland cement Type II, a superplasticizing additive (Superplasticizer of group I) STACHEMENT 2052/24 manufactured by TOV "Stakhema" (Lviv, Ukraine) was used. The average density of the superplasticizer is 1070 kg/m^3, and the acidity indicator pH is 5.

Table 1

Characteristics of coarse aggregate made of dense rocks (granite)

No. of entry	Property ID	DSTU B V. 2.7-75-98	Actual
1	Total sieve residue by weight, % *d*	90–100	99.2
	0.5(*d* + *D*)	30–80	69.8
	D	to 10	6.8
	1.25*D*	to 0.5	0.0
2	Content of plastic and needle-shaped grains %	≤15	8.3
3	Content of dust and clay particles %	to 1	0.6
4	Clay content in lumps %	to 0.25	0
5	Weak rock grain content %	to 5	0
6	Crushed stone grade by crushing ability	200–1400	1400
7	Frost resistance, F	15–400	400
8	Bulk density, kg/m^3	≥1100	1419
9	Crushed stone class by radionuclide content	class 1–3	first
10	Grade of strength of crushed stone by abrasion	C1–C4	C1

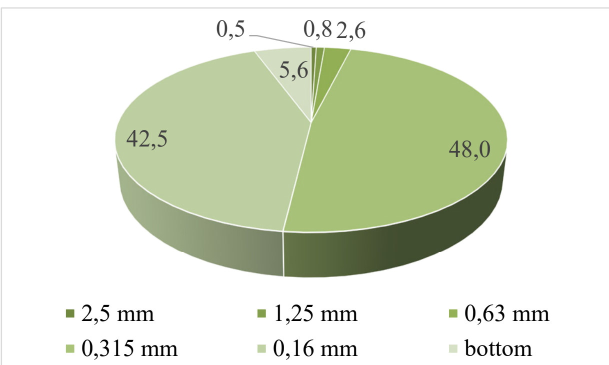


Fig. 1. Granular composition of natural river sand

Physical and mechanical characteristics of crushed stone from recycled concrete structures such as granular composition, content of grains of weak rocks, content of dusty and clay impurities, content of grains of plate (flaky) and needle shape, friability, frost resistance, water absorption were determined according to DSTU 9179:2022.

The frost resistance of crushed stone (DSTU 9179:2022, DSTU B V.2.7-75-98) was determined by the accelerated method, by alternately keeping the sample for 4 h in a sodium sulfate solution and drying it in a drying oven (temperature 105 ± 5°C) for the next 4 h. The criterion for assessing the frost resistance of the aggregate is the loss of sample mass in %, depending on the fraction size and the number of test cycles.

The determination of the structural defects of the coarse aggregate was carried out by electron microscopy using an electronic digital microscope, Digital Microscope.

The consistency of concrete mixtures was assessed by the values of the cone slump according to DSTU B V.2.7-114-2002. The determination of the compressive strength of concrete was carried out on cube samples with an edge size of 10 cm according to DSTU B V.2.7-223:2009. The samples hardened under normal conditions (20 ± 2°C and relative humidity 95 ± 5%). The frost resistance of concrete samples was determined according to DSTU B V. 2.7-49-96 by the first and third accelerated methods. The criterion for assessing the frost resistance of concrete was the loss of strength.

We determined water resistance according to DSTU B V.2.7-170:2008.

5. Results of research on concrete based on recycled concrete aggregates

5. 1. Results of research on the characteristics of recycled aggregate

The composition of recycled concrete aggregate is very complex as it contains fractions that are usually absent or almost absent in the composition of natural aggregate.

The content of weak rock grains in the composition of the recycled concrete aggregate is 18% by weight, which does not meet the requirements from the DSTU B V.2.7-75-98 standard, according to which this indicator should be 15% for an aggregate with a crushing capacity of 300.

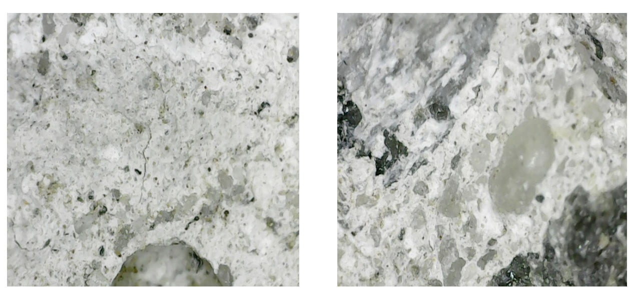
The content of dusty and clay impurities for the 5–20 mm fraction is 3.7% with a permissible value of up to 3% for grades with a crushing capacity of 200, 300, 400. The content of lamellar (vetch) and needle-shaped grains is 24%, which corresponds to the improved group (from 15 to 25%).

The pH value of the pore solution in the recycled concrete aggregate is 7, which corresponds to the indicator of a neutral environment and indicates its suitability for use in obtaining new concrete mixtures and concretes based on them.

The water absorption of recycled aggregate is 10.5% of the aggregate mass. This means that the water absorption of such an aggregate is significantly higher than that of conventional granite aggregate, which is less than 2%. This could potentially lead to high water consumption of concrete mixtures based on it and to a decrease in the properties of concrete.

The frost resistance of recycled aggregate corresponds to the F15 grade.

Such reduced characteristics of the aggregate from recycled concrete are a consequence of the weak structure of the recycled aggregate. As a result of the destruction of concrete structures, these recycled aggregates are characterized by various defects in the structure of the aggregate itself, which, first of all, leads to the appearance of cracks. The results of studying the structure of the artificial aggregate using microphotoanalysis are shown in Fig. 2.

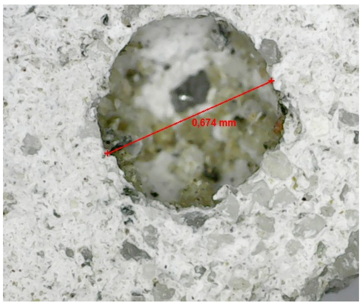


a *b*

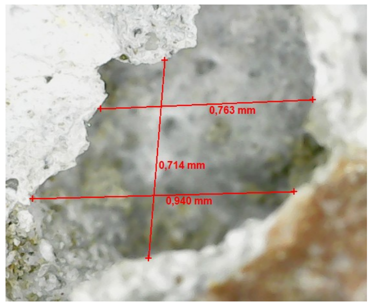
Fig. 2. Micrographs of aggregate grains from recycled concrete at 500x magnification: *a*, *b* – images of cracks on the surface of the aggregate grains

Moreover, cracks are not all structural defects of artificial aggregates from demolition waste. There are many other structural defects, first of all, pores of various origins. These can be pores from the former concrete structure or newly formed as a result of concrete destruction, or pores formed in place of lost natural aggregate. Various examples of such pores are shown in Fig. 3.

The size of such pores and voids can be from 0.5 to 1 mm. This reduces the properties of the aggregate structure and, in combination with cracks, leads to low performance properties of concrete based on such aggregates, which mostly negatively affects the flexural strength of concrete.



a



b

Fig. 3. Micrographs of aggregate grains from recycled concrete at 500x magnification: *a*, *b* – image of the aggregate structure with indication of pores of different diameters

The grain size composition of the recycled concrete aggregate was determined by sieving on a standard set of sieves. The total and partial sieve residues were determined. The test results are given in Table 2.

Table 2

Characteristics of the granular composition of recycled concrete aggregate

Sieve hole size, mm	Residues on sieves			Passage through sieves, %
	Partial		Complete	
	g	%	%	
50	774	7.74	7.74	92.26
40	210	2.10	9.84	97.90
30	497	4.97	14.81	85.19
25	440	4.40	19.21	80.79
20	630	6.30	25.51	74.49
15	875	8.75	34.26	65.74
12.5	470	4.70	38.96	61.04
10	436	4.36	43.32	56.68
7.5	496	4.96	48.28	51.72
5	550	5.50	53.78	46.22
2.5	503	5.03	58.81	41.19
1.25	727	7.27	66.08	33.92
0.63	339	3.39	69.47	30.53
0.315	2239	22.39	91.86	8.14
0.16	472	4.72	96.58	3.42
Bottom	342	3.42	100.00	100.00
Total	10000	100.00	100.00	100.0

Analysis of the results revealed that the main fraction of the aggregate is a fraction with a size of 0.315 mm. In the general case, the part of the aggregate with a size of less than 5 mm is 46.22%, including fractions less than 1.25 mm (fine fractions) – 33.92%.

Of the large fractions, a significant content of fractions larger than 20 mm (19.21 mm) is noteworthy, in particular, 7.74% above 40 mm. This requires additional classification of such aggregate for use in conventional concrete mix formulations to remove large fractions.

Thus, the content of the most popular fraction 5–20 mm for the production of ready-mixed concrete, which was used in further research, is less than 35%.

5. 2. Results of investigating the influence of the content of recycled aggregate on the operational properties of concrete

The development of formulation solutions and the study of the properties of concrete mixtures and concretes based on them were carried out in the system "Portland cement type II – recycled aggregate". In this case, it was necessary to obtain concretes that, in terms of their physical and mechanical characteristics, correspond to the C20/25 class concrete and are not inferior to the indicators of control compositions using conventional granite aggregate of fraction 5–20.

It was proposed to change the ratio of coarse and fine aggregate and to supplement the mixture with other types of aggregates, and if necessary, to remove fine aggregate altogether.

Experimental studies were carried out on concrete samples of concrete measuring 100 × 100 × ×100 mm, which hardened under normal conditions.

Concrete mixture based on recycled concrete aggregate is characterized by a significantly higher water-cement ratio and at the same time a significantly higher consumption of plasticizing additives, which subsequently should negatively affect the performance properties of concrete based on them. In addition, concrete mixtures using recycled concrete aggregate are characterized by lower average density compared to the control composition. This indicates the presence of additional pores, voids, and general structural defects, which in turn will affect the reduction of strength indicators, and, most likely, the reduction of frost resistance and durability of concrete in general.

The results of our studies are given in Table 3.

The workability of concretes of the studied compositions was studied by measuring the standard Abrams cone slump. To assess the slump retention index of the concrete mixture, the cone slump index after 120 minutes of storage was also studied. The mixture is considered to retain its properties if, during a period of 120 minutes, the cone slump decreases by no more than 3.5 cm. The results of our studies are shown in Fig. 4.

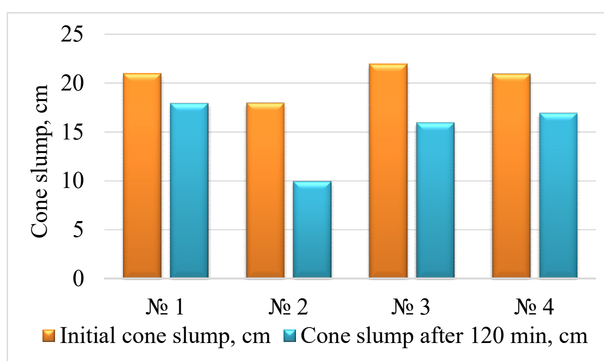


Fig. 4. Workability of concrete mixtures based on Portland cement and recycled concrete aggregate

Table 3

Formulation of concrete mixtures based on Portland cement and recycled concrete aggregate

Composition	Quartz river sand, kg	Granite crushed stone fr.5-20, kg	Recycled crushed stone fr.5-20, kg	Super plasticizer STACHEMENT 2052/24, kg	W/C	Average density, kg/m^3
No. 1	740	1120	–	2.64 (0.8%)	0.62	2397
No. 2	–	–	1495	6.6 (2%)	0.98	2148
No. 3	–	835	865	6.6 (2%)	0.74	2257
No. 4	–	1000	700	6.6 (2%)	0.7	2267

Note: the content of cement PC II/A-B-500 R-N for all compositions is 330 kg.

Determining concrete strength involves measuring the minimum forces that lead to the destruction of specially manufactured control samples of concrete when they are loaded at a constant rate of load growth and the subsequent calculation of stresses under these forces. The results of our studies are shown in Fig. 5.

As can be seen from the above data, the use of recycled aggregate in concrete mixtures significantly reduces the physical and mechanical performance of concrete based on them. Thus, when using conventional granite aggregate, the resulting concrete corresponds to the strength class C25/30. At the same time, when using only recycled aggregate, the concrete class is reduced to C8/10.

The use of mixed aggregate, represented by both conventional granite and recycled aggregate, results in the production of concrete of class C15/20, and with an increased content of granite aggregate in the mixture up to 50% – C20/25.

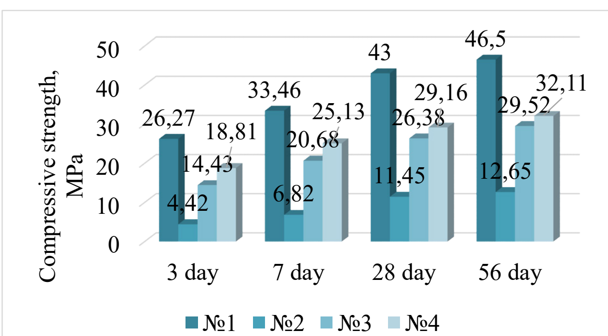


Fig. 5. Compressive strength of concrete based on Portland cement and recycled concrete aggregate

To determine frost resistance depending on the concrete compressive strength class, two test methods were used – the first basic and the third accelerated, in accordance with DSTU B V. 2.7-49-96. The results of our studies are given in Table 4.

According to the results obtained, concrete based on natural aggregate corresponds to the frost resistance grade F200, while the use of exclusively recycled concrete aggregate reduces this indicator to the F25 grade. Partial replacement of recycled aggregate with natural one improves the pattern. Thus, with the introduction of 50% recycled concrete aggregate, the frost resistance grade of concrete is F100.

The determination of water resistance was carried out by the "wet spot" method, in accordance with DSTU B V.2.7-170:2008.

Cylinders with an internal diameter of 150 mm and a height of 150 mm were used for testing. The results of our studies are given in Table 5.

The pressure indicators at which the samples are soaked with water confirm the general trend towards a decrease in the performance indicators of concretes using recycled aggregate. The use of only recycled aggregate in the concrete mix causes a decrease in the water resistance index of concrete from the W8 index for the control composition to the W2 index, which is a sufficiently low characteristic. At the same time, the use of a mixture of granite and recycled aggregates causes the production of concretes with a water resistance index of W6, which meets the requirements for most general-purpose concrete mixtures currently used on the market.

Thus, we have demonstrated the possibility of obtaining concretes with acceptable water resistance indices in the manufacture of concrete mixtures using recycled concrete aggregate.

Table 4

Frost resistance of concrete based on Portland cement and recycled concrete aggregate

Composition	Test method	Number of cycles	R_c, before testing, MPa	R_c, after testing, MPa	Strength reduction, %	Frost resistance grade
No. 1	3 accelerated	5	42.70	41.25	3.4	F200
No. 2	1 basic	25	11.13	10.65	4.3	F25
No. 3	1 basic	50	26.08	24.90	4.5	F50
No. 4	3 accelerated	3	31.24	30.27	3.1	F100

Table 5

Water resistance of concrete based on Portland cement and recycled concrete aggregate

Composition	Sample size, mm	Pressure at which water seepage was observed, MPa	Concrete grade for water resistance, W
No. 1	Ø150 h150	1.0	8
No. 2	Ø150 h150	0.4	2
No. 3	Ø150 h150	0.6	4
No. 4	Ø150 h150	0.8	6

6. Discussion of results based on investigating concretes made using recycled concrete aggregates

Analysis of the structure of recycled aggregates revealed the presence of cracks, holes, and pores that weaken the structure of the recycled aggregate, making it a poor choice for preparing concrete mixtures. The use of such aggregates leads to increased losses of cement and mortar components, as well as to higher water consumption of the concrete mixture. In addition, the concrete mixture formulation should be verified by practical experiments on the use of the mixture.

Unlike [7], in which the content of fine fractions does not exceed 15%, an increased content of fine fractions according to Table 2 is dangerous for the design of the composition of the concrete mixture since it provides increased water consumption of the aggregate and, accordingly, of the concrete mixture based on it. This, in turn, causes a decrease in both the strength properties of concrete based on such mixtures and a decrease in the remaining performance properties, in particular, water resistance, frost resistance, and others. That is why, at this stage of research, these fractions were screened out. However, given their increased percentage content, it is advisable to consider the possibilities of using aggregate from recycled concrete of a wide granulometric composition. This requires special efforts to compensate for the above-mentioned effect in order to obtain a concrete mixture with normal indicators of rheological properties, shrinkage, and contraction. This can be achieved by using compensating additives, in particular, water-retaining additives, plasticizers, etc.

The studied concrete mixtures using recycled aggregate are characterized by a decrease in cone slump greater than the standard values (Fig. 4). At the same time, the higher the content of aggregate from recycled concrete in the composition of the concrete mixture, the higher the slump index. This can be explained by the increased defectiveness of the aggregate, as well as the excessive content of cement dust on its surface, which over time absorbs water and reduces the overall mobility of the system.

The strength indicators shown in Fig. 5 demonstrate that the use of recycled aggregate, although it causes a decrease in the physical and mechanical indicators of concrete, reducing the content of artificial aggregate to 50%, ensures the production of concrete that meets the strength class C20/25. For comparison, in work [18], similar strength indicators were achieved without exceeding the content of aggregate based on recycled concrete in the amount of 30%.

As can be seen from analysis of our results given in Table 4, the assumption regarding the potential decrease in frost resistance of concretes based on recycled aggregate is fully consistent with reality. The resulting concretes are characterized by a frost resistance class of F25-F100, which is significantly inferior to the F200 indicator of the control composition. Possible options for increasing frost resistance are to optimize the concrete mix formulation in order to increase the average density and reduce the structural defects.

In addition, the obtained patterns regarding the decrease in frost resistance of concretes should be taken into account in the industrial application of concrete structures using the proposed formulations of concrete mixtures based on recycled concrete aggregate.

The limitation of our study relates to variable factors that affect the range of initial data, namely, the direct characteristics of the recycled concrete aggregate. The greatest influence in this case is dustiness, the content of weak rock grains, and friability. Given the lack of a current regulatory document that establishes clear limits for these indicators for recycled concrete aggregate, these parameters should be close to the corresponding values of natural analogues. These are the content of weak rock grains up to 15%, the content of dusty and clay impurities up to 3%, and the friability index corresponding to the D200, D300, D400 grades.

The main problems of systems based on Portland cement and recycled concrete aggregate are increased water consumption and a decrease in cone settlement over time. Eliminating these shortcomings is necessary for large-scale industrial implementation of such concretes. The solution to this problem is to select additives of modifiers of different nature or to use other types of binder.

Future research should involve conducting additional studies on the characteristics of the macro- and mesostructure of concretes based on recycled concrete aggregates to determine the degree of self-healing. It is also important to conduct studies on the physical and mechanical properties and durability of such concretes to determine the evolution of their operational properties over time.

7. Conclusions

1. We have investigated the granulometric composition and microstructure of recycled concrete aggregate. It was shown that such material is characterized by high structural defects and the presence of a high content of dust particles and weak fractions, which significantly reduces the potential properties of concretes based on it. The need to use a separated fraction (5–20 mm) was established to ensure optimal performance characteristics of concretes based on such aggregate.

2. The features in the production of concrete mixtures and concretes using recycled aggregates, which were formed as a result of the process of processing and classification of the remains of concrete buildings and structures, have been studied. It was established that despite the reduced performance characteristics of concrete based on recycled aggregates at 100% of its content, it is possible to obtain concretes of class C16/20 with a strength of 26.4 MPa when using 50% of such aggregate. Concrete strength of 29.2 MPa and compliance with class C20/25 is achieved with a 42% recycled concrete aggregate content. The frost resistance grade with this percentage of recycled concrete aggregate is F50 and F100, respectively.

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

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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