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The influence of recycled ceramic aggregate on the strength characteristics of high-performance concrete

Wpływ recyklingowego kruszywa ceramicznego na cechy wytrzymałościowe betonu wysokowartościowego

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Abstract. The construction sector, especially the production of such a commonly used material as concrete, requires the implementation of solutions that reduce the carbon footprint. This is possible, among other things, by replacing coarse natural aggregate with secondary materials. The article presents the results of testing the strength characteristics of concrete, which the granite aggregate was replaced with recycled aggregate originating from the crushing of ceramic elements of sanitary fittings.
Keywords: circular economy; high-performance concrete; recycled aggregate; sanitary ceramics.

Streszczenie. Sektor budowlany, a szczególnie produkcja tak powszechnie stosowanego materiału, jakim jest beton, wymaga wdrażania rozwiązań pozwalających na ograniczenie śladu węglowego. Jest to możliwe m.in. przez zastąpienie grubego kruszywa naturalnego materiałami wtórnymi. W artykule przedstawiono wyniki badań cech wytrzymałościowych betonu, w którym kruszywo granitowe zastąpiono kruszywem recyklingowym, pochodzącym z rozkruszenia ceramicznych elementów armatury sanitarnej.
Słowa kluczowe: gospodarka cyrkularna; beton wysokowartościowy; kruszywo recyklingowe; ceramika sanitarna.

Sustainable development and environmental protection, and therefore rational waste management, are priority goals of the modern world [1]. The construction industry is struggling with the problem of disposing huge amounts of construction and demolition materials, as well as the continuous exploitation of natural resource deposits [2]. The vast majority of construction waste is classified as non-biodegradable waste, which means that it is difficult to recycle [3]. Concrete is one of the basic materials that is used in civil engineering. It gives an opportunity for the effective reuse of construction and industrial waste [4]. The introduction of recycled components into concrete enables the requirements regarding the construction parameters of concrete to be met. Moreover, the use of recycled materials reduces the amount of waste intended for storage [5, 6].

Recycled ceramic aggregate mainly includes properly crushed roof tiles, bricks (red ceramics), ceramic tiles, and sanitary ceramics. Sanitary ceramics were the subject of the research conducted as part of studies [7, 8]. Depending on the type of ceramic materials, the possibilities of recycling individual wastes should be examined. This is due to the fact that such materials are produced in different conditions and with the use of different raw materials, which affects their microstructure [9, 10].

The production of sanitary ware involves the forming, drying and glazing of semi-finished products made of ceramic mass, and then firing them at temperatures ranging from 1200 to 1290°C. The use of waste from sanitary ceramics in concrete technology requires an experimental approach to the design of the concrete mix, which is due to the lack of standards and guidelines that regulate the possibility of using waste from sanitary products [11, 12].

From a few studies covering the issue of introducing ceramic cullet into the concrete mix, it is known that it does not disturb the cement hydration processes. Moreover, it increases the resistance of concrete to the effects of elevated temperatures, which is due to the low thermal expansion coefficient of the ceramic aggregate [11, 13, 14]. These publications also demonstrated the beneficial effect of cullet on the strength properties of concrete. Such concrete can achieve a higher compressive strength than that produced only with natural aggregates. Moreover, the addition of this type of recycled aggregate guarantees the improvement of the tightness or resistance to crushing of the material [13, 15, 16].

Concrete, regardless of its composition, must meet requirements regarding the durability of the material throughout its entire period of use [17]. Introducing recycled aggregates into the concrete mix requires an analysis of the relationship between recycled materials, natural aggregates and other components of the concrete mix [18]. For this reason, the study presents the results of tests of concrete that was prepared with various levels of replacing the natural aggregate (made of natural raw material) with crushed sanitary ceramics.

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The article describes the influence of recycled aggregate on selected properties of concrete mixes and hardened concretes, as well as the usefulness of sanitary ceramics in obtaining high-quality concrete. When preparing the samples for testing, it was assumed that the construction conditions and the treatment of the concrete would be in accordance with standard procedures. The assumptions made regarding the production technology were intended to indicate the possibility of obtaining high-quality material with the use of ceramic recycled aggregate, without the need to use complex and difficult-to-access devices and materials.

Composition of the concrete mix

When preparing the samples needed for the tests, Portland cement CEM I 42.5R was used as the binder. Its use allows for the obtaining of high early strength and a rapid increase in the concrete's strength. It is used primarily for the production of ordinary concrete, but it can also be the binder for higher grades of concrete.

Granite was used as the coarse aggregate in the reference concrete. Its bulk density ρ_0 in the loose state was equal to 1.41 g/cm^3, and in the compacted state to 1.61 g/cm^3, while water absorption WA_{24} amounted to 0.73%. The density of the aggregate grains reached 2.56 g/cm^3, whereas in the saturated state and after initial drying it reached 2.61 g/cm^3. The aggregate that was used to replace part of the granite was sanitary ceramics obtained from crushing sanitary facilities intended for disposal. The ceramic cullet had a loose density of 1.17 g/cm^3 and a compacted density of 1.61 g/cm^3. The grain density of the dried ceramic aggregate was 2.38 g/cm^3, whereas in the saturated state and after initial drying it was 2.59 g/cm^3. The water absorption of the WA_{24} was 3.92%. The water absorbed by the aggregate is not included in the w/c calculations. Therefore, in order for the concretes to have the assumed value of the water-cement ratio, the aggregate (before being introduced into the mix) was moistened with the amount of water that results from the water absorption test for obtaining full saturation. The aggregate was then spread out and air-dried in laboratory conditions for an hour to remove the water that was coating the grains. Such water could disturb the water-cement ratio of the concrete mix. The method was developed experimentally by observing the water content in the aggregate when drying it over various time variants. A period of 60 minutes was considered to be the optimal time.

Sanitary ceramics are characterized by having a much higher level of water demand than granite aggregate. In the case of both the aggregates, only the 4 – 8 mm and 8 – 16 mm fractions were used (photo 1). Moreover, the concrete mix was made in two water-cement ratio variants: w/c = 0.30 and w/c = 0.40, with the consistency class being S3. The natural aggregate was replaced by 15, 30 and 45% of ceramic cullet.

In order to obtain the same consistency of all the mixes, it was necessary to introduce a fluidizing admixture into the concrete mix. The used admixture is a stabilized polycarboxylate superplasticizer. It allows a high early strength of the concrete to be achieved, the amount of mixing water (while maintaining proper workability) to be

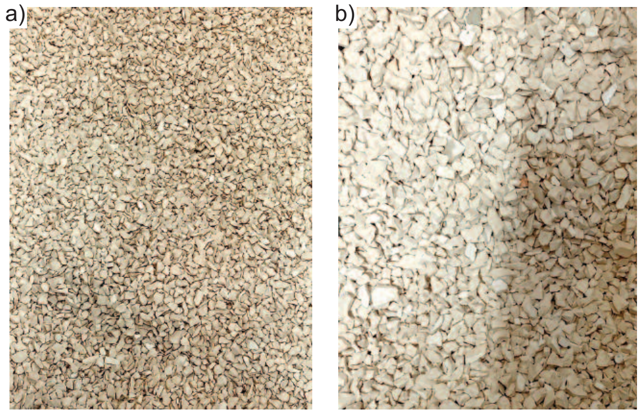

Photo 1. Ceramic recycled aggregate used in the research; fraction: a) 4 – 8 mm; b) 8 – 16 mm

Fot. 1. Ceramiczne kruszywo recyklingowe wykorzystywane w badaniach; frakcja: a) 4 – 8 mm; b) 8 – 16 mm

significantly reduced, the shrinkage to be decreased, and the segregation of the mix components to be limited. This in turn reduces the tendency of the concrete mix to crack due to drying.

Eight batches of concrete mixes were made, which differed in terms of the water-cement ratio and the level of replacement of the base aggregate with ceramic cullet. The following designations were adopted: for w/c = 0.40 – A0, A15, A30, A45 (where 0, 15, 30, 45 mean the percentage of the replacement of the granite aggregate by the recycled ceramic aggregate); for w/c = 0.30 – B0, B15, B30 and B45. The composition of the prepared concrete mixes is listed in Tables 1 and 2. As part of the research cycle, each mix was tested in order to assess its consistency. In addition, the density, compressive strength, splitting tensile strength, bending strength and elastic modulus were determined for the hardened concrete.

Research methods

The consistency of the concrete mix was tested using the concrete slump test in accordance with standard [19] 5 minutes after the end of mixing the ingredients. The formed test samples were stored in air-dry conditions for 48 hours from the moment of forming, then they were removed from the molds and placed in a tank filled with water.

The samples for the strength and density tests of the hardened concrete were made in accordance with standard [20]. In the case of the density tests, as well as the compressive and tensile splitting strength tests, cubic samples with an edge of 100 mm were tested immediately after being taken out of the water. Bending strength was tested on cuboidal samples with dimensions of 100 x 100 x 400 mm. Cylindrical samples with a diameter of 150 mm and a height of 300 mm were used to determine the elastic modulus. The strength characteristics were tested 28 days after their preparation.

The density of the water-saturated concrete was determined in accordance with standard [21], and the compressive strength was assessed in accordance with standard [22], by loading a sample in a testing machine until failure (photo 2). The tensile

Table 1. Composition of the concrete mixtures with w/c = 0.40
Tabela 1. Skład mieszanek betonowych o w/c = 0,40

Component	Amount in the concrete mix [kg/m³]
Ingredients in each series (with a constant content)	
Sand	469
Water	180
Superplasticizer	1,350
Cement	450
100% base aggregate – A0 mix	
Granite, fraction 4 – 8 mm	633
Granite, fraction 8 – 16 mm	633
15% ceramic cullet – A15 mix	
Granite, fraction 4 – 8 mm	538
Granite, fraction 8 – 16 mm	538
Cullet, fraction 4 – 8 mm	95
Cullet, fraction 8 – 16 mm	95
30% ceramic cullet – A30 mix	
Granite, fraction4 – 8 mm	443
Granite, fraction 8 – 16 mm	443
Cullet, fraction 4 – 8 mm	190
Cullet, fraction 8 – 16 mm	190
45% ceramic cullet – A45 mix	
Granite, fraction 4 – 8 mm	348
Granite, fraction 8 – 16 mm	348
Cullet, fraction 4 – 8 mm	285
Cullet, fraction 8 – 16 mm	285

Table 2. Composition of the concrete mixtures with w/c = 0.30
Tabela 2. Skład mieszanek betonowych o w/c = 0,30

Component	Amount in the concrete mix [kg/m³]
Ingredients in each series (with a constant content)	
Sand	501
Water	135
Superplasticizer	6,30
Cement	450
100% base aggregate – B0 mix	
Granite, fraction 4 – 8 mm	677
Granite, fraction 8 – 16 mm	677
15% ceramic cullet – B15 mix	
Granite, fraction 4 – 8 mm	575
Granite, fraction 8 – 16 mm	575
Cullet, fraction 4 – 8 mm	102
Cullet, fraction 8 – 16 mm	102
30% ceramic cullet – B30 mix	
Granite, fraction 4 – 8 mm	474
Granite, fraction 8 – 16 mm	474
Cullet, fraction 4 – 8 mm	203
Cullet, fraction 8 – 16 mm	203
45% ceramic cullet – B45 mix	
Granite, fraction 4 – 8 mm	372
Granite, fraction 8 – 16 mm	372
Cullet, fraction 4 – 8 mm	305
Cullet, fraction 8 – 16 mm	305

strength test required additional placement of the samples in frames that had pads made of hard fiberboards. Afterwards, the cubes were loaded in accordance with standard [23] until they lost their load-bearing capacity. In order to obtain the values for the analysis, the test results were converted using a scale factor of 0.90. This factor enables the strength value to be estimated on the standard samples with an edge of 150 mm, but the tests were performed on the samples with an edge of 100 mm [24].

The determination of the bending strength involved placing rectangular beam samples centrally in a testing machine, which was equipped with four rollers (two upper rollers – loading ones – and two lower rollers – loading and supporting ones). The samples were then loaded until they were destroyed [25].

Testing the elastic modulus in accordance with standard [26] can be carried out using two methods: Method A, which allows the initial and stabilized secant modulus of elasticity to be determined; and Method B, which allows only the stabilized modulus to be determined. Method A was used in the research program, and the loading and unloading cycles were carried out in accordance with Figure 1. The compressive strength tested on cylindrical samples, which are necessary to determine stresses σ_a and σ_b, was determined by calculating the strength of cubic samples with edges of 15 x 15 x 15 cm using scale factors of 0.80 [24].

Photo 2. The course of cracks in B0 samples subjected to compressive strength testing. Failure pattern typical of high-strength concrete
Fot. 2. Przebieg rys w próbkach B0 poddanych oznaczeniu wytrzymałości na ściskanie. Schemat zniszczenia charakterystyczny w przypadku betonu wysokiej wytrzymałości

Research results

Concrete density was determined as the arithmetic mean from the measurements of six cubic samples with an edge of 100 mm. Six samples were also used to determine the compressive strength, and three samples were used to test the splitting tensile strength. The bending strength test was carried out on three cuboid samples, and the secant modulus

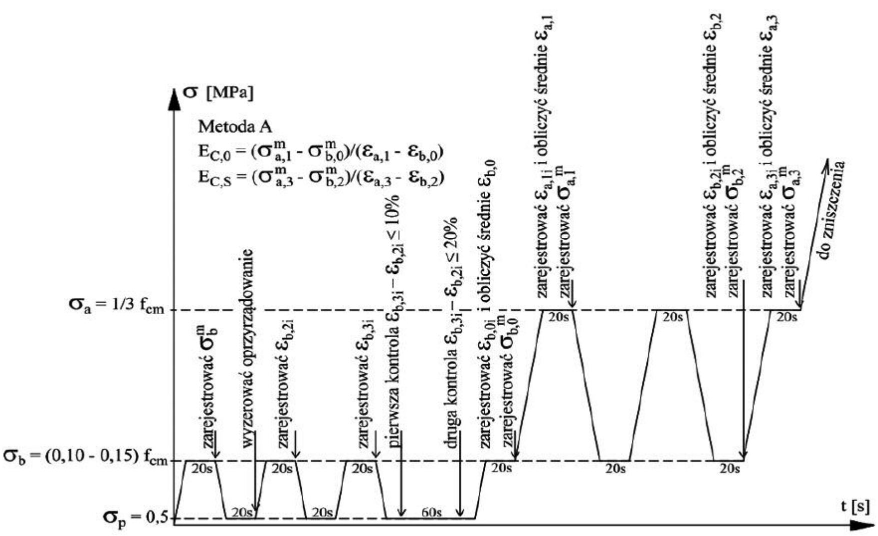

Fig. 1. Load diagram in method A for determining the initial and stabilized secant modulus of elasticity [27]
Rys. 1. Schemat obciążenia w metodzie A wyznaczania początkowego i ustabilizowanego siecznego modułu sprężystości [27]

Statistical analysis of the strength test results was only carried out for the tests that allowed for the determination of the strength class [28]. The remaining tests were performed using a minimal number of samples, and therefore the statistical analysis was omitted. Measurement uncertainties were determined using the Student's t-distribution with a confidence interval of 95%.

of elasticity was determined on the basis of the test results of three cylindrical samples. The results of all the performed determinations are summarized in Table 3.

Table 3. The concrete test results
Tabela 3. Wyniki badania betonu

Feature of concrete	100% of granite aggregate		15% of ceramic-cullet		30% of ceramic cullet		45% of ceramic cullet	
	A0	B0	A15	B15	A30	B30	A45	B45
w/c ratio	0,40	0,30	0,40	0,30	0,40	0,30	0,40	0,30
Density ρ_{28} [kg/m³]	2390	2460	2380	2420	2360	2420	2350	2390
Compressive strength f_{cm} [MPa]	65,3	95,9	65,3	78,2	65,4	78,7	66,8	76,9
Measurement uncertainty of compressive strength results [MPa]	±0,81	±2,43	±0,61	±1,27	±0,45	±1,04	±0,56	±0,81
Tensile strength when splitting f_{ctm} [MPa]	4,74	7,17	4,84	5,04	4,89	5,03	4,37	4,94
Flexural strength $f_{ctm,fl}$ [MPa]	6,92	8,89	6,99	8,74	6,94	8,93	7,37	9,41
Initial secant modulus of elasticity $E_{C,0}$ [GPa]	26,54	32,35	28,02	30,82	29,15	34,24	29,55	35,49
Stabilized secant modulus of elasticity $E_{C,S}$ [GPa]	35,41	42,86	35,30	37,20	35,29	37,31	34,64	37,30
Concrete strength class	C50/60	C70/85	C50/60	C55/67	C50/60	C55/67	C50/60	C55/67

Analysis of test results

Testing the consistency of the concrete mix using the concrete slump test shows that as the amount of ceramic cullet increases, the workability of the mix deteriorates, and the consistency becomes less liquid. The series of mixes with w/c = 0.30 is characterized by having a greater loss of consistency after replacing the granite aggregate with the ceramic aggregate when compared to the series with w/c = 0.40 (Figure 2).

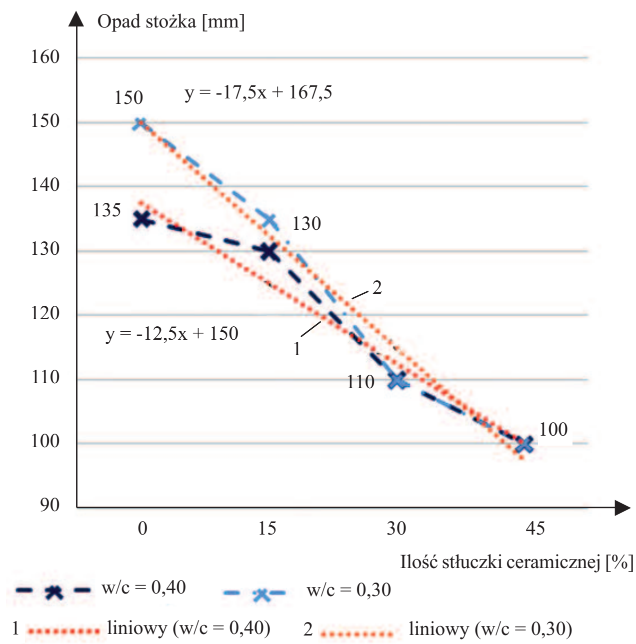

Fig. 2. The results of testing the consistency of the concrete mixture using the cone fall method
Rys. 2. Wyniki badania konsystencji mieszanki betonowej metodą opadu stożka

The hardened concretes with w/c = 0.30 had a higher density (by about 2 – 3%) when compared to the concretes with w/c = 0.40. It was also found that the density of the concrete decreases with an increase in the share of ceramic cullet in the composition of the concrete mix. This may be related to the small grain size of the prepared ceramic aggregate. However, it should be noted that the B0 concrete had the highest density, which is significantly different from the density of the series of concretes with w/c = 0.30. Replacing only 15% of the granite aggregate with ceramic aggregate caused a decrease in density by as much as 40 kg/m^3. This means that the presence of ceramic aggregate complicates the compaction of the concrete mix to some extent. This will result in differences in strength characteristics.

The compressive strength test results were at a similar level for all the series with w/c = 0.40 and for the three series with w/c = 0.30. The exception was the B0 concrete, which did not contain ceramic cullet, and which had a strength approximately 20% higher than the other concretes.

The tensile strength of the concrete with w/c = 0.30 decreased by more than 40% after adding the ceramic cullet into the concrete mix when compared to the reference concrete. The differences between the other concretes were insignificant. However, a tendency to decrease in strength can be observed as the content of the recycled aggregate in the mix increases. In the case of w/c = 0.40, this strength gradually increased with an increase in the amount of the ceramic aggregate in the concrete to 30%.

The results of the bending strength test were characterized by slight differences in the series without the ceramic cullet and those in which 15 and 30% of the granite aggregate was replaced. This applied to the concretes with a water-cement ratio of 0.3 and 0.4. In the concretes in which the largest amount of ceramic cullet was used (45%), there was an increase in strength when compared to the other samples.

The secant modulus of elasticity was tested in the case of two variants (Figure 3) – initial ($E_{C,}0$) and stabilized ($E_{C,S}$). The initial modulus of elasticity for the concrete with w/c = 0.4 increased gradually with an increase in the level of replacement of the granite aggregate by the recycled aggregate. In the case of the concrete samples with w/c = 0.3, this parameter was reduced after the introduction of cullet when compared to those without the ceramic aggregate. As the share of the cullet in the concrete composition increased, the secant modulus increased. The stabilized secant modulus for the series with w/c = 0.4 was at a similar level regardless of the degree of replacement of the aggregate with the ceramic cullet. However, in the case of w/c = 0.3, a slight decrease in the modulus was observed with an increased share of the ceramic aggregate in the concrete. The samples without the cullet achieved results that were approximately 15% higher than those in which the aggregate was replaced. However, almost identical results were obtained for the concrete containing 15, 30 and 45% of recycled ceramic aggregate.

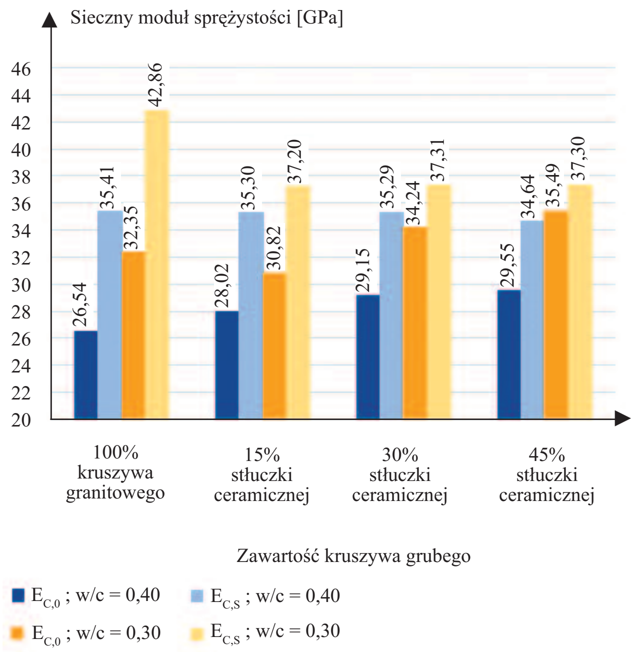

Fig. 3. The test results for the secant modulus of elasticity

Rys. 3. Wyniki badań siecznego modułu sprężystości

Conclusions

The density of the concretes with w/c = 0.40 was in each case lower when compared to the concretes with w/c = 0.30. This phenomenon was caused by a higher share of aggregate in the composition of the concrete mixes with a water-cement ratio of 0.30. Moreover, as the degree of replacement of the granite with the ceramics increased, the density decreased. This was due to the lower density of the ceramic aggregate when compared to the granite.

The compressive strength tests showed that at a w/c equal to 0.30, the introduction of ceramics into the concrete resulted in a reduction of this parameter by over 20%. In the case of the concrete with the cullet content of 15, 30 and 45%, the results were similar and oscillated around 78 MPa. The concrete with w/c = 0.40, made with the granite aggregate and with a partial replacement with ceramic recycled aggregate, obtained compressive strength results close to 66 MPa. Similar relationships were also observed after testing the splitting tensile strength. The addition of the cullet caused a decrease in strength when compared to the reference concrete with w/c = 0.30. An inverse relationship was observed after analyzing the bending strength test results. In the case of the reference concrete, and after replacing the aggregate with the ceramic cullet at the level of 15 and 30%, the results were at a similar level. However, the introduction of the cullet in the amount of 45% of the total coarse aggregate content caused a slight increase in bending strength (about 6% in the case of both w/c ratios). Based on the conducted research, it can be assumed that a high level of replacement of natural aggregate with recycled ceramic aggregate will be particularly beneficial for reinforced concrete structural elements under bending. However, assessing the usability of the material before its application requires additional durability tests.

The introduction of the recycled ceramic aggregate into the concrete mix generated an increase in the initial secant modulus of elasticity by approximately 10% in the case of replacing the granite with the ceramic cullet in the amount of 45% in both variants of the water-cement ratio. This parameter is used in the calculations of prestressed concrete structures (calculations of temporary losses of the prestressing force and the initial deflection of the element), which can be considered as another possible area of using concrete containing ceramic cullet [27]. In the case of the concrete with w/c = 0.4, the introduction of the ceramic cullet did not cause a significant difference in the test results for the stabilized secant modulus of elasticity. In turn, in the case of the concrete with w/c = 0.3, the introduction of the ceramics caused a decrease in the modulus value, regardless of the amount of ceramic aggregate that was introduced (15, 30 and 45%). The results were at a similar level. The modulus of elasticity largely depends on the adhesion between the aggregate and the cement matrix, and also the elasticity of the aggregate itself. This means that the introduction of sanitary ceramics makes it possible to maintain the stress-strain relationship in concrete at a level similar to that of granite aggregate.

The results of the conducted research confirm that sanitary ceramics can be considered as a replacement coarse aggregate in high-quality concrete, but only after previously determining the durability of such concrete in the expected operating conditions. Determining the composition of concrete made with the addition of ceramic recycling aggregate requires an experimental analysis of the properties of the concrete mix and hardened concrete.

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