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Experimental Investigation of Concrete with Recycled Aggregates for Suitability in Concrete Structures

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Abstract: This paper presents the experimental tests of concrete made on the recycled aggregates basis. Tests were carried out to determine the concrete suitability for construction purposes. The physical and strength properties were determined for three types of recycling aggregates. The aggregates were obtained from sanitary ceramics ‘SC’ (washbasins and toilet bowls), building ceramics ‘BC’ (solid bricks), and concrete rubble ‘CR’. The results obtained in tests of compressive strength, bending tensile strength, water absorption, total shrinkage, watertightness, and frost resistance of concrete made of SC and CR aggregates gave grounds for stating its suitability for structural purposes. Concrete based on the BC aggregates is not recommended for structural applications.

Keywords: concrete; recycling aggregate; laboratory tests

1. Introduction

Environmental regulations and policies increasingly address the issue of conscious waste management. At the same time, consumers are encouraged to be environmentally responsible by means of promotional programmes, guidelines (segregation of municipal waste into coloured containers), or legal requirements. Almost all materials from which raw materials, such as glass, metals, plastics and minerals, paper, textiles, and others can be recovered, can be reused (recycled). Recycling is also becoming an increasingly common concept in the construction sector. According to the definition contained in PN-EN 12620 [1] standard, recycled aggregate is the aggregate coming from the processing of inorganic material previously used in the construction industry. Such materials include, for example, building rubble, road and street demolition debris, or earth and rock masses. The Polish Aggregate Producers Association estimates that the recycling process produces approx. 4.5 million tons of aggregate annually. This amount translates only into approx 2.5% of all building materials used in Poland. Considering the situation in other countries, a thesis can be made that this value will have an upward trend [2]. The problem of environmental pollution with construction waste and depletion of natural resources is not only a Polish problem, but also a global problem [3]. In European countries, 320–380 million tons of this type of waste is generated every year [4] and in China alone this is about 640 million tons annually [5,6]. A lot of research has been conducted all over the world on recycled aggregates and their application in the production of structural concrete [7–26]. Nevertheless, new possibilities of using various types of waste for the production of aggregates used in structural concrete are constantly being sought. The authors of the work [27] showed that the use of recycled glass as a substitute for

coarse aggregate in architecturally oriented concrete is possible from a mechanical point of view. They received the compressive strength in the range 19.89–25.26 MPa. The strength is comparable to C25 concrete. Gawenda et al. [28] studied the properties of concrete made on the basis of aggregate prepared from ceramic tiles. The results of the research show that the samples made of natural aggregate showed better strength parameters. The compressive strength of a concrete with natural aggregates is equal about 49 MPa, and with artificial aggregates it is about 33 MPa. Halicka and Zegardło [29–31] focused on the use of sanitary ceramics in the production of aggregate. Their tests showed better strength parameters of the samples made on the basis of recycled aggregate. They received higher compressive strength (about 10%) and tensile strength (about 3%) of a concrete with ceramic aggregates (the compressive strength is equal 42.8 MPa and the tensile strength under bending is 6.35 MPa) in the comparison to concrete with natural aggregates (the compressive strength is equal to 46.95 MPa and the tensile strength under bending is 6.52 MPa). The scrub resistance of concrete with ceramic aggregates is about 20% higher than with natural aggregates. The work of Zegardło et al. [32] concluded that the use of sanitary ceramic cullet as aggregate is the most advantageous in the production of concrete that is resistant to aggressive environments and is recommended for the production of concrete sewage pipes. The influence of an aggressive chemical environment reduces the compressive strength of concrete with ceramic aggregates by about 13.4% and with basaltic aggregates by about 27.8%. In this context, it is very important to recognize the properties and possibilities of using such ecological aggregates in building structures. In this paper, the formulas of three concrete mixtures based on recycled aggregates were developed and their selected parameters, such as compressive strength, bending tensile strength, total shrinkage, water absorption, watertightness, and frost resistance, were examined. The problem of watertightness and frost resistance for concretes made of recycled aggregates is poorly described in the literature. The frost resistance is considered by authors in [33,34], but it requires further researches.

2. Materials and Methods

2.1. Aggregate

Three types of recycled aggregates were prepared for the purposes of the study. Aggregate with SC marking was prepared from sanitary ceramics, which included washbasins and toilet bowls of various origins, the BC aggregate was made of building ceramics, which included solid bricks of various origins, and CR aggregate was made on the basis of concrete rubble. In each case, the material intended for a given aggregate was crushed and the three groups of fractions were obtained: 0–4 mm, 0–8 mm, and 8–16 mm (Figure 1).



Figure 1. Recycled aggregates (a) sanitary ceramics (SC), (b) building ceramics (BC), (c) concrete rubble (CR).

For each of the fractions, the volumetric density was determined (Table 1).

Table 1. Volumetric density of the used aggregates.

Symbol	Fraction [mm]	Volumetric Density [kg/m ³]	Average Volumetric Density [kg/m ³]
SC	0–4	1463.3	1274.3
	0–8	1212.2	
	8–16	1147.3	
BC	0–4	1067.2	932.9
	0–8	976.6	
	8–16	755.1	
CR	0–4	1518.1	1347.1
	0–8	1376.1	
	8–16	1147.0	

All of the prepared aggregates can be classified as lightweight aggregates of density below 2000 kg/m³. For the 0–4 mm and 0–8 mm fractions, screen analysis was carried out (Figure 2). The sample for grain size distribution testing was taken by means of the quartering method.

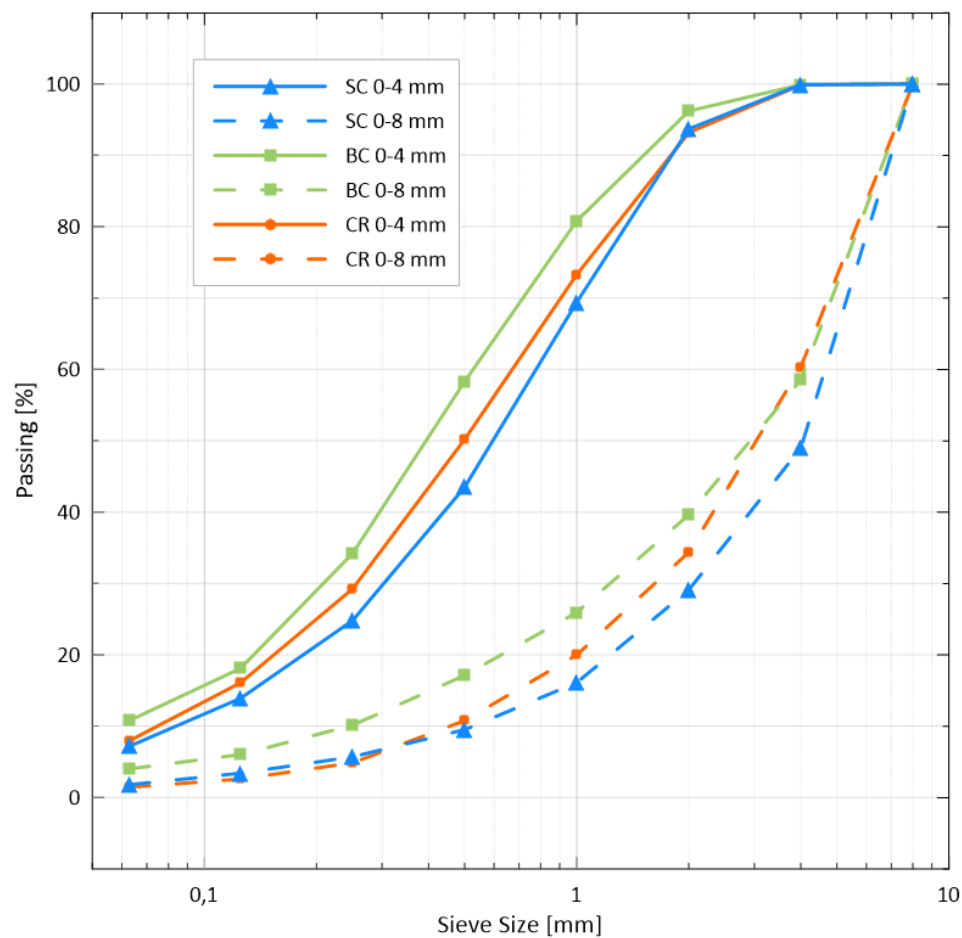


Figure 2. The grain-size distribution curves of the aggregates used.

2.2. Mix Design

When using alternative aggregates obtained from recycled materials, the formula is most often created on the basis of experimental composition of concrete ingredients. This is mainly due to the lack of knowledge of the physical properties of the aggregate and its high variability, while striving to obtain a small water–binder ratio. Equation (1) was used as an aid in estimating the necessary amount of cement and silica fume, assuming the expected strength in a similar way as for high-strength concrete [35,36].

$$f_c = \frac{188.4}{21.7 \left(\frac{W}{C+P_k} - 0.15 \frac{P_k}{C} \right)} \quad (1)$$

Properly designed recipes must also satisfy the equation tightness, which has the form:

$$\frac{C}{\rho_c} + \frac{P_k}{\rho_{pk}} + \frac{K}{\rho_k} + \frac{W}{\rho} + \frac{P}{\rho_p} = 1 \quad (2)$$

where: f_c —compressive strength of concrete [MPa], W —amount of mixing water [kg/m³], C —amount of cement [kg/m³], P_k —amount of silica fume [kg/m³], P —amount of plasticizer [kg/m³], K —amount aggregate [kg/m³], $\rho_c, \rho_{pk}, \rho_k, \rho_p, \rho$ —density [kg/m³]: cement, silica fume, aggregate, plasticizer, water.

After the preparation of preliminary formulas for concrete mixtures, test batches were made. The tests showed that it is not possible to maintain the water–binder ratio for all mixtures at the same assumed level of $w/b = 0.40$. The BC aggregate showed much higher water demand than the others. Assuming a constant amount of plasticizer addition, it was decided to change the water–binder ratio for BC mixture from 0.40 to 0.65. As a result of the conducted tests, the use of 8–16 mm fractions in mixtures with SC and BC aggregates was also abandoned as it adversely affected the strength of the finished concrete. Finally, the samples of concrete were prepared in the composition as presented in Table 2.

The following components were used for the preparation of the mixtures: Portland cement CEM I 42,5R compliant with [37], non-concentrated silica fume compliant with [38] with SiO₂ content of 85% and specific surface area of 15 m²/g, plasticizer based on lignosulfonates and urea improving wetting of cement grains with batched water compliant with [39]. The designed concrete recipes contains higher amount of cement (600 kg/m³). The recipes are performed as a first step for preparing the ultra-high performance concrete (UHPC) on the base of recycled aggregates. UHPC is characterized by low w/b (water–binder) ratio. It is the reason for testing the concrete with a high amount of cement.

Table 2. Formulas of concrete mixtures.

	Mixture SC [kg/m ³]	Mixture BC [kg/m ³]	Mixture CR [kg/m ³]
Cement CEM I 42,5R	600	600	600
Silica fume	150	150	150
Water	300	490	300
Plasticizer	20	20	20
SC 0–4 mm	760	-	-
SC 0–8 mm	330	-	-
BC 0–4 mm	-	460	-
BC 0–8 mm	-	150	-
CR 0–4 mm	-	-	740
CR 0–8 mm	-	-	250
CR 8–16 mm	-	-	100
Tightness	1.0	1.0	1.0
Strength estimated using Formula (1) [Mpa]	61.8	28.3	61.8
w/c	0.50	0.82	0.50
w/b	0.40	0.65	0.40
Pk/C	0.25	0.25	0.25
P/c [%]	3.33	3.33	3.33
P/s [%]	2.67	2.67	2.67
w/c—water–cement ratio			
S—binder = cement + silica fume			
w/b—water–binder ratio			
Pk/C—silica fume–cement ratio			
P/C—plasticizer–cement ratio			
P/S—plasticizer–binder ratio			

2.3. Types of Samples and Research Methods

A total of 39 concrete samples in the form of $10 \times 10 \times 10$ cm and $15 \times 15 \times 15$ cm cubes and $10 \times 10 \times 46$ cm beams were prepared for the study. The following marking of the samples was adopted (Figure 3):

- SC—concrete based on fine aggregate (fractions 0–4 mm and 0–8 mm) made of sanitary ceramics,
- BC—concrete based on fine aggregate (fractions 0–4 mm and 0–8 mm) made of building ceramics,
- CR—concrete based on aggregate made of concrete rubble (fractions 0–4 mm, 0–8 mm, and 8–16 mm).



Figure 3. Damage samples from left to right: BC, SC, CR.

The research included: water absorption, total shrinkage within 30 days from moulding carried out on Amsler's apparatus (Figure 4). Determination of compressive strength and bending tensile strength after 28 days of curing, carried out on a hydraulic press with a load capacity of 3000 kN produced by PROETI S.A. MADRID ESPAÑA. The watertightness test was carried out on standard apparatus for testing concrete water tightness produced by ratioTEC Prüfsysteme GmbH. Frost resistance test carried out on low temperature chamber Toropol K-010. All tests carried out in accordance with [40].



Figure 4. Specimen in Amsler's apparatus.

3. Results

3.1. Shrinkage

Samples in the form of $10 \times 10 \times 46$ cm beams were subjected to shrinkage tests 48 h after moulding. Earlier, they were placed in a bathtub of high humidity in order to prevent water loss. The test lasted 30 days during which the changes were measured every 2 days on average, and at a later stage, every 3 days. Amsler's apparatus (Figure 4) was used in measurements.

During the study, samples were stored at an average temperature of 21.9°C and air humidity of 54%. The exact distribution of these values is shown in Figure 5. Samples made of concrete based on recycled aggregate from building ceramics BC showed the largest final shrinkage of about 51% greater than the samples made of SC and 39% greater than the samples made of CR (Figure 6).

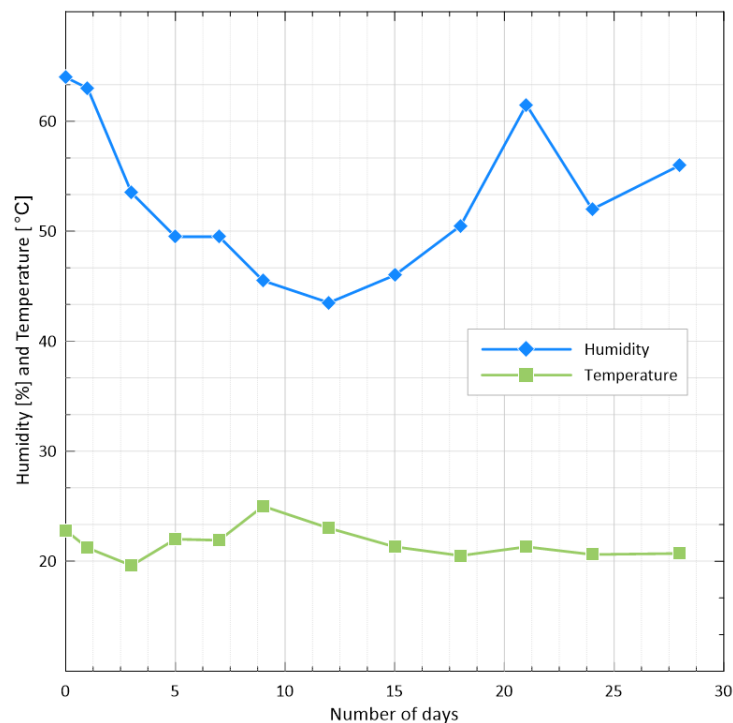


Figure 5. Temperature and humidity during shrinkage test.

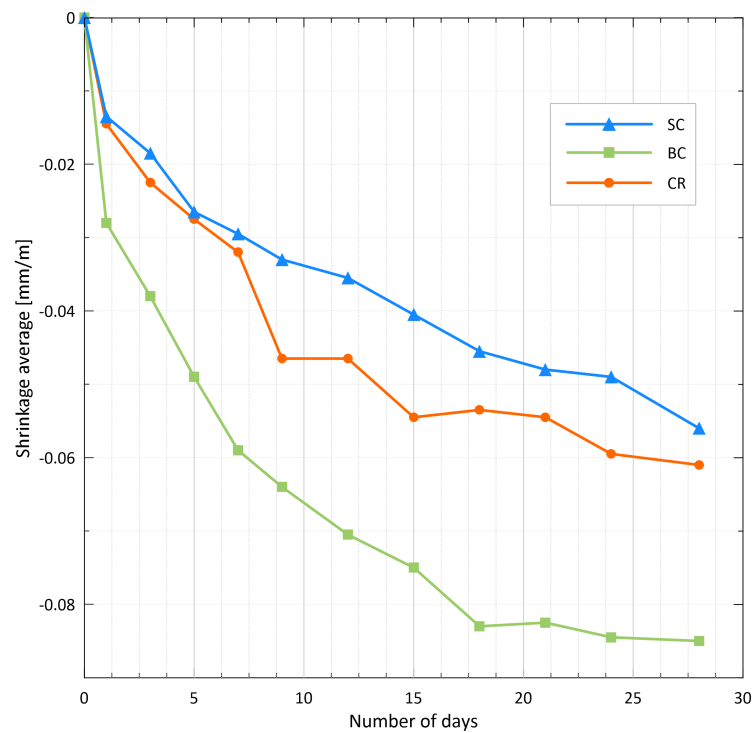


Figure 6. The measurement results of shrinkage.

3.2. Strength

The compressive strength test was carried out on cubic samples with a 10 cm side. Load speed during the test was 0.1 kN/s. Average compressive strength (Figure 7) was calculated based on 5 samples for SC and 4 for BC and CR. Average bending tensile strength (Figure 7) was calculated based on 2 samples for SC, BC, and CR.

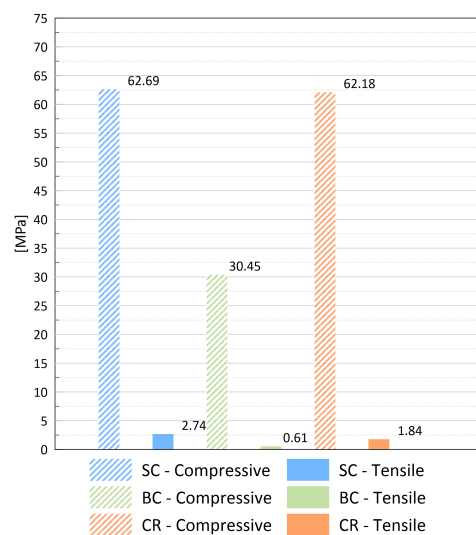


Figure 7. Compressive strength and tensile strength in bending.

During the compressive test, it was noted that the BC aggregate samples clearly showed a different nature of destruction, compared with the behaviour of SC and CR samples. The BC samples did not disintegrate after destruction and plastic deformations were clearly visible (Figure 8).



Figure 8. Damage samples BC.

The bending tensile strength was tested on $10 \times 10 \times 46$ cm rectangular samples during a three-point bending test (Figure 9). Load speed during the test was 0.1 kN/s.



Figure 9. Sample during test of compression and tensile strength in bending.

3.3. Water Absorption

The water absorption test was carried out on 12 cubes with dimensions $10 \times 10 \times 10$ cm, 3 specimens of each mixture, according to [40]. The results were presented in Figure 10. The highest absorption was demonstrated by BC samples, which is the result of the high water demand of the aggregate made of building ceramics. The absorption for SC samples is comparable with the results of other authors [32].

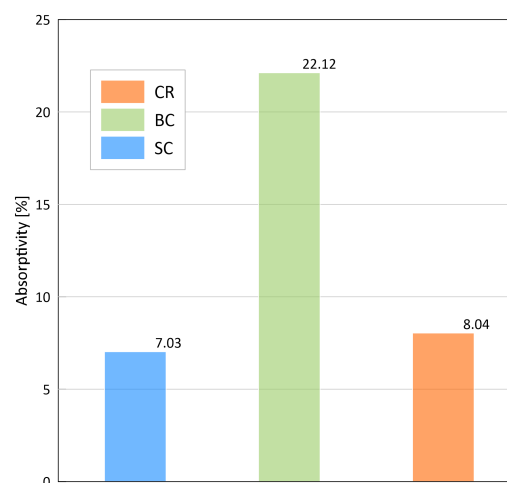


Figure 10. Water absorption.

3.4. Water Tightness

The watertightness test was carried out on cubes with dimensions $15 \times 15 \times 15$ cm, with the use of a standard apparatus for testing the watertightness of concrete (Figure 11). The samples were dried to obtain a constant weight before the test. The experiment consisted of pressuring water with controlled pressure under 1.2 MPa on the specimen area with 100 mm diameter. The constant temperature of water and air was established and equal 18 ± 2 °C. The possible water leaks were observing during the test on the specimen surface.



Figure 11. Samples during watertightness test.

During the test, the samples were subjected to water pressure from 0.2 MPa to 1.2 MPa. The pressure was increased from 0.2 MPa by 0.2 MPa every 24 h. The final pressure value was kept during 24 h. By the end of the test, no leakages were detected on the samples. In order to assess the degree of saturation, the samples were split during the compressive strength test and the height of saturation at the centre and at the edges of the samples was measured (Figure 12). The results were summarized in Table 3.

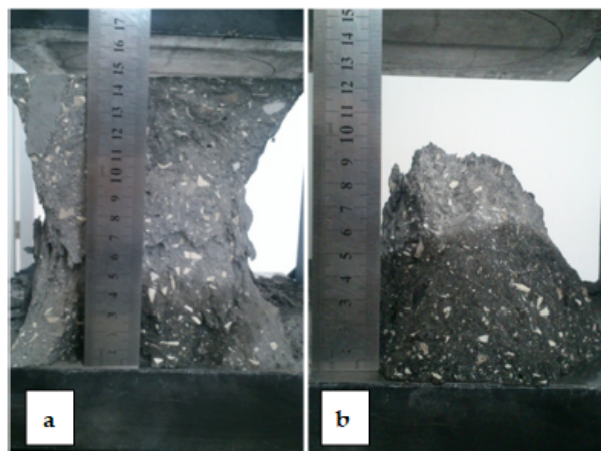


Figure 12. Measuring watertightness SC; **a**—measuring at the edge, **b**—measurement in the middle.

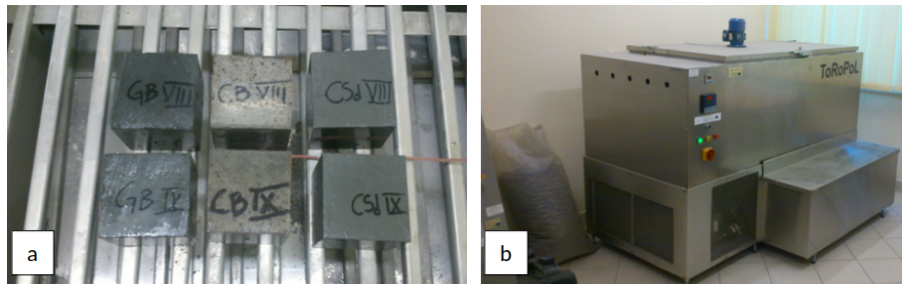
Table 3. Results of watertightness tests.

Sample	Compressive Strength		Maximum Height of Water Absorption [mm]			
	F_m [kN]	R_m [N/mm ²]	At the Edge	Average	In the Middle	Average
SC III	1437.5	63.9	47		65	
SC IV	956.8	42.5	40	39	47	57
SC V	930.7	41.4	30		59	
CR III	1242.2	55.2	40		68	
CR IV	1206.3	53.6	55	44	80	69
CR V	1437.7	63.9	38		60	
BC III	641.6	28.5	58		100	
BC IV	760.8	33.8	50	54	60	86
BC V	699.1	31.1	54		97	

According to the requirements of the standard [40], all samples shall be classified in W12 watertightness class. The value behind the letter “W” means the ten times water pressure value during the for the specimen without the leak. At the same time, on the basis of the conducted test, it can be stated that the highest average tightness was observed for samples made on the basis of the SC aggregate, by about 21% higher to CR and about 51% higher to BC.

3.5. Frost Resistance

The resistance of concrete to frost (Table 4), i.e., the ability to maintain proper structure and strength with the use of a specified number of freezing and defrosting cycles, was tested according to the standard [40]. The test was carried out in a low-temperature chamber (Figure 13), which allows for cyclic freezing and defrosting of the tested material. The samples were subjected to 25 freezing and defrosting cycles.

**Figure 13.** Test of frost resistance (a) samples in the chamber, (b) low-temperature chamber.

After completion of the test, the samples were inspected in the low-temperature chamber and no visible damage was found. Then, the average weight loss was examined:

$$\Delta G = \frac{G_1 - G_2}{G_1} \cdot 100\% \quad (3)$$

where: G_1 —average sample weight before freezing (saturated with water); G_2 —average sample weight after freezing (saturated with water);

The average decrease of compressive strength is calculated by

$$\Delta R = \frac{R_1 - R_2}{R_1} \cdot 100\% \quad (4)$$

where: R_1 —average compressive strength of unfrozen samples; R_2 —average compressive strength of the cubes after the last cycle is thawing.

Table 4. Results of frost resistance tests.

Sample	G_1 [g]	G_2 [g]	ΔG [%]	R_1 [MPa]	R_2 [MPa]	ΔR [%]
SC	1942.9	1933.3	0.5	50.5	45.3	10.3
CR	2121.8	2076.1	2.2	55.3	53.5	3.3
BC	1674.0	1632.7	2.5	26.7	23.5	11.9

The recommendations of the standard [40] state that the frost resistance test should be carried out on 12 samples. However, due to the limited amount of aggregate available, it was decided to limit the number of samples to four for each mixture. According to the recommendations of the standard [40], in order to classify concrete to a given frost resistance class (number of cycles), samples after the test must not show visible signs of damage, weight loss must not exceed 5%, and compressive strength loss must not exceed 20% in relation to samples not subjected to cyclic freezing and defrosting. All tested samples met the requirements for minimum F25 frost resistance class.

4. Discussion

Table 5 shows the basic parameters of tested concretes performed with three kinds of recycled aggregates: SC—sanitary ceramics, CR—concrete rubble, and BC—building ceramic. The range of tests carried out permits to estimate the suitability of the aggregates as a main ingredient of structural concrete. The aggregates SC and CR are suitable for construction concrete. The water absorption for concrete exposed to the atmospheric humidity should be lower than 5% and for concrete shielded against the direct influence of the rainfall 9% [40].

Table 5. Basic parameters of tested concretes.

Parameter	SC	CR	BC
Water–cement ratio	0.5	0.5	0.82
Consistency class	S1	S1	S3
Compressive strength [Mpa]	62.7	62.2	30.5
Tensile strength in bending [Mpa]	2.7	1.8	0.6
Water absorption [%]	8	7	22
Watertightness	W12	W12	W12
Frost resistance class	≥F25	≥F25	≥F25

Concrete with recycled aggregates is studied in the work [30] and the received values of water absorption are similar to ours (6–10%). Taking into account the absorbability criterion, it could be stated that the BC aggregates are not suitable for structural concrete (water absorption = 22%). The high value of absorbability is affected by the high porosity of the aggregates (volumetric density of the BC aggregate 932.9 kg/m³) and high water demand. This leads to high demand of water with a constant amount of plasticizers and decreases the strength parameters. The specimens made of BC indicate the highest shrinkage, about 51% higher than SC and 39% higher than CR. BC aggregates could be used as a main ingredient of light or insulating concretes. The observed failure mode of specimens with BC aggregates is characteristic for plastic materials. It could be of significant benefit for light or insulating concretes and needs further researches to prove it. The SC recycled aggregates have strength parameters similar to natural aggregates and could be used as a substitute for them. This is proved by our own results and by the results of other authors [29–31]. It should be noted that not all kinds of ceramic could be suitable as an

ingredient in concrete. For instance, in paper [28] concrete on a base of aggregates made of ceramic tiles is demonstrated. The concrete had a much lower compressive strength than concrete based on natural aggregates, by about 33%.

The results of water absorption and frost resistance tests of concrete with SC, CR, and BC allow to rank them as W12 and F25 class, respectively. Table 3 shows the average height of water absorption in the middle of the sample. Analyzing the results, it is concluded that the highest average tightness was observed for samples made on the basis of the SC aggregate, by about 21% higher compared to CR and about 51% higher than BC.

The frost resistance tests showed the average decrease of compressive strength after cyclic freezing and thawing (25 cycles) to be 3.3% for samples with CR aggregates. The concretes made of SC and BS aggregates showed 10.3% and 11.9% decreases, respectively.

5. Conclusions

The concrete made of concrete rubble and sanitary ceramics was characterized by high and similar strength parameters (the CR compressive strength is equal to 62.2 MPa and SC to 62.7 MPa, the tensile strength under bending for CR was 1.8 MPa and for SC 2.7 MPa). All tested concretes fit into water absorption class W12 and frost resistance class F25. The features of concrete composed on the basis of aggregates from building ceramics proved to be relatively weak (compressive strength 30.5 MPa and tensile strength under bending 0.6 MPa). It was found that the strength of this material was lower by approximately 40% in comparison to the other two materials. The reason for this lies mainly in the high porosity of the aggregate, and thus its absorbability, which contributes to a significant increase in the aggregate's water demand, and consequently to the necessity to add more batched water, which makes the value of the water–binder ratio higher and adversely affects the strength of the finished concrete. Therefore, it is not recommended to use this material as a component of structural concretes. Due to the low volumetric density of the BC aggregate (932.9 kg/m³), concrete made on the basis of this material could be used to make elements where low weight is more important than high strength parameters. BC aggregates could be used in insulating concrete with low thermal conductivity coefficient.

The research also showed that larger fractions of sanitary ceramics (8–16 mm) are not suitable for use, as they have a worse adhesion to the cement matrix due to their flat, very smooth grains. The use of 8–16 mm fractions of the SC aggregate in the mixture results in the reduction of strength parameters of the finished concrete. A similar situation occurs in the case of 8–16 mm fractions of the aggregate made of building ceramics.

Aggregates obtained by means of recycling of concrete rubble and sanitary ceramics (smaller fractions) are suitable for use in production of concrete for structural purposes. Concrete made of these materials meets the recommendations of the standards [40,41].

Further investigations will be concentrated on the use of SC and CR aggregates to prepare ultra-high performance concrete (HPC and UHPC) and the use of BC aggregates for insulating concrete.

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