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Influence of ground waste glass addition on concrete prepared with their participation properties

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Abstract

Caring for the environment, in accordance with the principles of sustainable development, as well as the increase in the standard of living of society, introduces the need to conduct proper waste management. Construction is an industry with great potential for the management of glass waste as part of material recycling. The construction sector is characterized by high material consumption, with a limited amount of natural resources, meaning that research is constantly being performed on the possibility of replacing them with other common ingredients. A feature of the building materials industry is also the pursuit of continuous improvement of the properties of manufactured materials.

The paper presents the research results on the impact of the partial replacement of Portland cement and aggregate with glass waste on strength parameters and frost resistance. For the purpose of experimental work, a concrete mix based on the C20/25 standard concrete with CEM I 42.5R Portland cement, in which from 0 to 20% of the cement or aggregate weight is replaced with glass waste (i.e., glass flour and glass cullet), is designed.

In the test range, the glass flour slightly affected the deterioration of the compressive strength, while the glass cullet had no effect on the compressive strength after 56 days of maturation. Moreover, the addition of glass flour increases the bending strength, while the addition of glass cullet maintains a comparable bending strength compared to the reference concrete. The obtained concretes are frost-resistant concrete F150.

Introduction

In recent years, the priority of the European Union's policy has become to improve the condition of the natural environment, which translates into a number of regulations in many areas of the economy. According to the document of the European Environment Agency – EEA-EIONET Strategy for 2021–2030 – one of the five main goals to be achieved at that time is to support the implementation of the circular economy plan adopted by the European Commission (European Environment Agency, 2021). In the construction sector, this translates into at least two levels: obtaining electricity and proper management of the production of building materials. According to the data of the International Energy Agency, in 2018, the global construction sector was responsible for 36% of final energy consumption and 39% of carbon dioxide emissions, of which approximately 11% is related to the production of construction materials and products; this data is constantly growing (International Energy Agency, 2019). Therefore, it becomes justifiable to examine alternative building materials with the lowest possible carbon footprint and to modify the already used materials to contribute to improving the natural environment.

Another aspect of environmental protection is proper waste management, which is growing every year. Along with the escalating costs of waste disposal, specialized, environmentally friendly forms of disposal are sought, which would contribute to reducing the costs of storage and, thus, lowering the prices of manufactured products. One of the forms of waste disposal is its reuse. In the case of post-production waste, it is possible in the production processes of building materials. Currently, we can observe a number of research works aimed at looking for substitutes for commercial components of building materials, mainly concrete or ceramic components, through the use of various types of post-production waste, such as glass granules, polymer granules, polymer waste fibers or fibrous materials derived from metal processing (Flores Medina et al., 2017; Ogrodnik & Szulej, 2018; Szulej, Ogrodnik & Klimek, 2019; Bahij et al., 2020; Mhaya et al., 2020; Łasica & Małek, 2021b).

One of the waste materials that can be utilized in the process of concrete production, while modifying their reference composition, is glass granulate obtained from the mechanical crushing of waste glass. The process of mechanical crushing is a process that is increasingly appreciated in relation to the melting of glass in metallurgical furnaces due to the much lower electricity demand and, thus, the reduction of carbon dioxide emissions into the atmosphere; it is used for a wide range of raw materials – e.g., cullet, glass flour or dust that is used in construction and architecture (Łasica & Małek, 2021a).

Research on the possibility of using glass granules in the production of concrete is mainly performed in relation to glass cullet as a potential aggregate substitute and glass flour as a potential cement substitute. According to previous research (Łasica & Małek, 2021b), glass cullet can form a crumb pile of the resulting composite, while glass flour can act as a sealant for the internal structure and as a particle size distributor. The conducted works relate to the determination of the optimal content of substitutes in relation to the physical and mechanical properties of the obtained composites, which is also influenced by the graining, shape, and chemical composition of glass waste. The influence of different contents of broken glass (5–25%) on concrete properties, in the form of flour as a cement substitute, was presented previously (Belebchouche et al., 2021). The results obtained from these tests show that replacing cement in the amount of 15% with glass flour improves the mechanical strength and reduces the porosity of the concrete. The tests were performed on the 7th and 28th day of concrete maturation.

In other studies (Gimenez-Carbo et al., 2021), the impact of replacing cement in the amounts of 25% and 40% on the properties of mortar and concrete was examined. This work also analyzed the shape and size of glass powder particles. The addition of glass flour to the composition of concrete without reducing the amount of cement, in relation to the mechanical properties and frost resistance of concrete, is presented in another paper (Jurczak et al., 2021). On the other hand, an article (Małek et al., 2020) examines the effect of replacing traditional aggregate with glass cullet of four different contents (i.e., 5, 10, 15, and 20%) (glass cullet for four contents) on the compressive, bending, and tensile strength. In this work, the modulus of elasticity and Poisson's ratio are also determined. A similar subject was presented previously (Devaraj et al., 2021), in which a glass cullet replaced the aggregate in the amounts of 10, 15, 30, 50, and 100%.

Despite many other studies on the use of glass waste in concrete production (Weng, Lin & Chiang, 2003; Hendi et al., 2019; Mohammadinia et al., 2019; Ramdani et al., 2019), we can observe various gaps in this area of the research. The tests are fragmented and concern equal types of waste and different types of concrete. To gain a deeper understanding and create a universal model illustrating the relationship between the glass waste content and the mechanical/chemical properties of the obtained composites, the analysis should be continued to supplement the existing research cases in the literature. The main objective of this research is to determine the effect of replacing Portland cement and aggregate with glass waste, in the form of flour and glass cullet, on the compressive strength after 7, 14, 28, and 56 days of maturation and frost resistance of the composite.

Materials and methods

The composition of the concrete mix of ordinary concrete of C20/25 class with thick-plastic consistency was designed by the method of three equations as provided by Bukowski in accordance with PN-EN

206 + A2: 2021-08 (PKN, 2013). Portland cement CEM I 42.5 R (Cement Ożarów SA, Poland), natural, pebble aggregate, a grain size of 0–16 mm – selected by the iteration method (Table 1) with a density of 2.65 kg/m^3 – and water were used to make individual mixtures. A glass cullet fraction of size 2–4 mm and glass flour with a density of 2.70 kg/m^3 were used as mineral additives. The aggregate composition was kept constant in all the samples. The chemical and physical parameters and phase composition of the cement, in accordance with the requirements of PN-EN 197-1: 2012 (PKN, 2012), are presented in Table 2. The chemical composition of the glass cullet, according to the product properties sheet (FHU Eko-Glass – Poland), is as follows: 70–74% SiO_2, 0.5–2.0% Al_2O_3, 7–11% CaO, 3–5% MgO, 13–15% Na_2O + K_2O, and a maximum of 0.2% Fe_2O_3 and 0.1% TiO_2.

To determine the effect of glass waste on the bending strength, compressive strength, and frost resistance of ordinary concretes, the following types of samples were prepared:

- CB – no additive,
- MI – with the addition of glass flour in the amount of 5% to 20% of the cement mass,
- MII – with the addition of glass cullet in the amount of 5% to 20% of the aggregate weight.

Table 1. Percentage ratio of the aggregates selected by iterations

Fraction	Fraction mixing percentage ratio (for sand and gravel)			Grain composition of [%]	
	And stage	II stage	III stage	Sand	Gravel
0.0–0.125				1.93	0.58
0.0125–0.25				17.82	5.34
0.25–0.50			thirty	28.62	8.59
0.50–1.0				24.32	7.30
1.0–2.0				27.31	8.19
2.0–4.0		34			23.80
4.0–8.0	50	66	70		23.10
8.0–16.0	50				23.10

The composition of the prepared concrete townspeople per 1 m^3 is shown in Table 3.

For a fresh concrete mix, the following was checked: air content using the pressure method in accordance with PN-EN 12350-7: 2011 (PKN, 2011a), consistency by the drop cone method in accordance with PN-EN 12350-2: 2011 (PKN, 2011b), and apparent density using the mass and volume measurement in accordance with PN-EN 12350-6: 2011 (PKN, 2011c). The compressive

Table 2. Physical properties, phase composition, and chemical properties of cement CEM I 42.5 R

Blaine's specific surface area [cm^2/g]	Beginning of binding time [min]	Compressive strength after 2 days [MPa]	Compressive strength after 28 days [MPa]	
3330	219	21.3	49.6	
The share of mineral phases CEM I [% mass]				
C_3S – 55.54	C_2S – 14.59	C_3A – 8.15	C_4AF – 6.85	
Roasting loss [%]	Sulfate content SO_3 [%]	Chloride content Cl [%]	Alkali content Na_2O_{eq} [%]	SiO_2 [%]
3.19	2.94	0.05	0.78	20.10
Al_2O_3	Fe_2O_3	CaO	CaO	MgO
4.40	2.40	64.35	1.97	1.95

Table 3. Mass fraction of ingredients per 1 m^3

Components		Concrete mix						
		BZ	Replacement of cement [kg]			Replacement of aggregate 2–4 mm [kg]		
			MI 5	MI 10	MI 15	MII 5	MII 10	MII 15
Cement		438.80				438.80	438.80	438.80
Water		179.84	179.84	179.84	179.84	179.84	179.84	179.84
Aggregate	0–2 mm	539.51	539.51	539.51	539.51	539.51	539.51	539.51
	2–4 mm	428.01	428.01	428.01	428.01			
	4–8 mm	415.42	415.42	415.42	415.42	415.42	415.42	415.42
	8–6 mm	415.42	415.42	415.42	415.42	415.42	415.42	415.42
Glass powder 0.1 mm		0.00	21.94	43.88	65.82	–	–	–
Cullet 2–4 mm		0.00	–	–	–	21.40	43.88	64.20

strength test was carried out after 7, 14, 28, and 56 days of maturation on samples with dimensions of 10×10×10 cm in accordance with PN-EN 12390-3: 2011 (PKN, 2011d). For the test, 12 samples were prepared for each type of mixture. The bending strength tests were performed on a sample of 10×10×50 cm (3 pieces each) in accordance with PN-EN 12390-5: 2011 (PKN, 2011e) after 28 days of maturation. Frost resistance tests were carried out on 15×15×15 cm samples using the direct method according to the procedure described in the PN-B-06265: 2004 standard (PKN, 2004). For the test, 12 samples were made. Compressive strength tests were performed in a hydraulic testing machine H011 by Matest, for bending in a testing machine ZD-40, and frost resistance in a Toropol chamber. All samples intended for testing were cultivated in water. The research was carried out at the Institute of Civil Engineering at the Warsaw University of Life Sciences. Based on the obtained average strengths, the result was converted into cubic samples with a side of 15 cm (according to formula 1), and the concrete classes were determined from the following:

$$f_{c,\text{cub }150} = 0.90\, f_{c,\text{cub }100} \quad (1)$$

where $f_{c,\text{ cub}150}$ and $f_{c,\text{ cub}100}$ are the compressive strength observed on cubic samples with an edge length of 15 and 10 cm, respectively.

Results and discussion

Properties of concrete mix

Based on the results of tests performed on the concrete mix, it was found that glass waste affects its individual parameters – i.e., density, consistency, and air content. The density of the concrete mix was from 2369 to 2387 kg/m^3 for the MI samples with the addition of glass flour and, for the MII samples with the addition of glass cullet, from 2342 to 2371 kg/m^3. The air content in concrete mixtures depended on the amount of the added additive instead of the cement/aggregate, and it increased with a higher content of the additive. The lowest air content was obtained for BZ samples, equal to 1.8%, while the highest air content (2.8%) was recorded in concrete mixes in which the aggregate was replaced in the amount of 20%. When replacing the cement, the highest air content of 2.5% was obtained with a replacement of 20%. The consistency test results obtained are very consistent. It is evident that the additive used changes the consistency from plastic to thick-plastic. In addition, the fall of the cone is smaller with an increasing amount of additive.

Properties of concrete

Compressive strength

The assumed compressive strength, which meets the requirements of normal concrete class C20/25 acc. PN-EN 206 +A2:2021-08 (PKN, 2013), was obtained for all the tested concrete mixtures following 28 maturing courses. Figures 1 and 2 show the results of measurements of the average compressive strength of concrete samples with different additive content – i.e., glass flour and cullet – and with different maturation times of the concrete mix. Figures 3 and 4 show the same results but relate to the trends in the change of compression resistance over time.

In the case of samples with the addition of glass flour, the compressive strength of the tested concretes was lower than that of the BZ reference samples, regardless of the concrete maturation time. It is noticeable that, up to the flour content of 15%, the

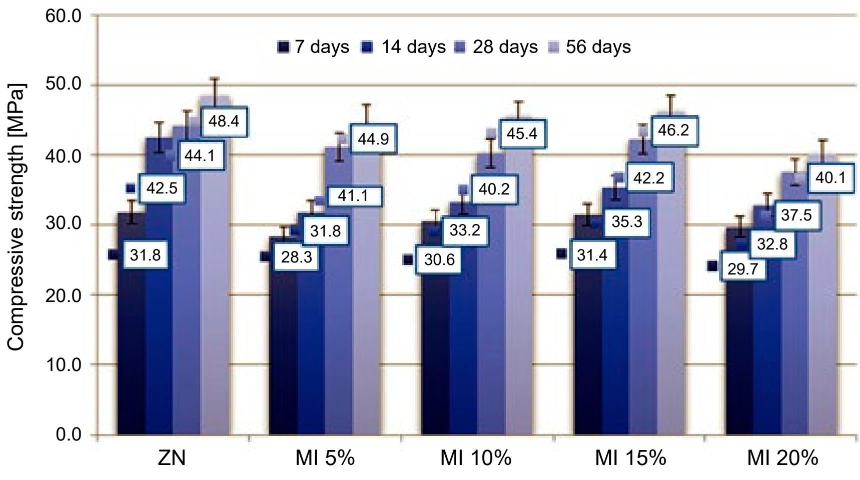

Figure 1. Compressive strength in different maturation periods for concrete with the addition of glass flour

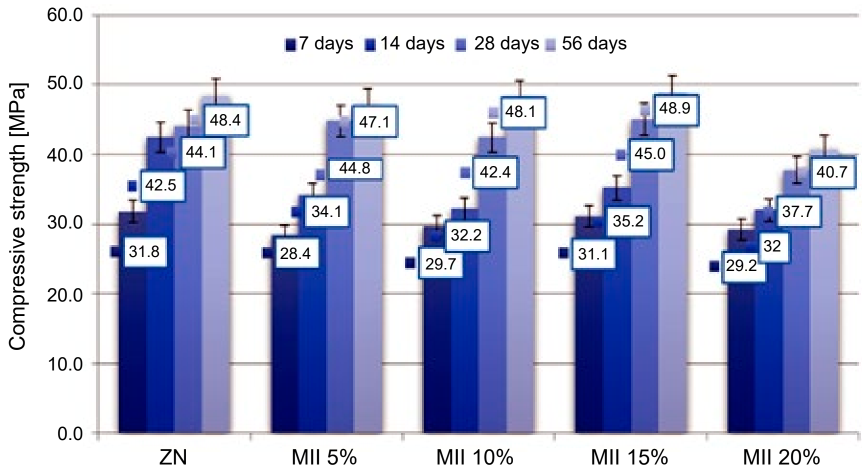

Figure 2. As Figure 1, but for concrete with the addition of glass cullet

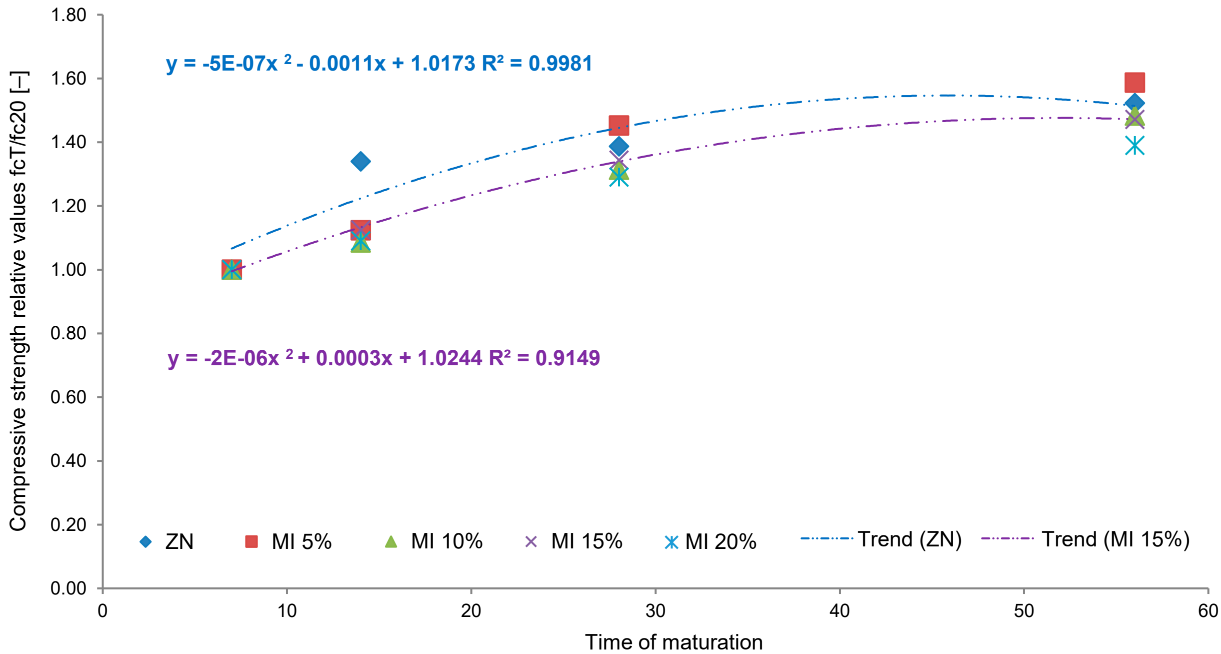

Figure 3. Changes in the compressive strength of samples with the addition of flour in different maturation periods

compressive strength increases with the growth of the flour content (the lowest for 5% and the highest for 15%).

For samples in which the aggregate was replaced with a glass cullet, the load capacity values were lower than the load capacity of the reference samples for the maturation time of 7 and 14 days. However, for 28 and 56 days, the load-bearing capacity values have comparable or higher values up to 15% of the cullet content.

In both cases, for glass contents above 15% in the samples, the load capacity significantly decreased compared to the reference samples. This can be explained by a reduction in the amount of binder in the material and, thus, a reduction in the amount of hydrates that affect the compressive strength of the concrete. The presence of chromium in the glass flour further explains this. According to the literature on the subject, the addition of chromium, after exceeding a certain amount in the cement materials, causes a decrease in strength and, consequently, slows down the hydration of cement grains (Golonka, Nocuń & Nocuń-Wczelik, 2017).

The highest compressive strength, equal to 45.0 MPa after 28 days of maturation, was obtained for concrete samples (MII 15%), in which the aggregate was replaced by a glass cullet in the amount of 15%. While the lowest compressive strength of 37.5 MPa was obtained by samples (MI 20%) in which the cement was replaced by glass flour in the amount of 20%. Compared to the reference concrete samples, the increase in strength was 2%,

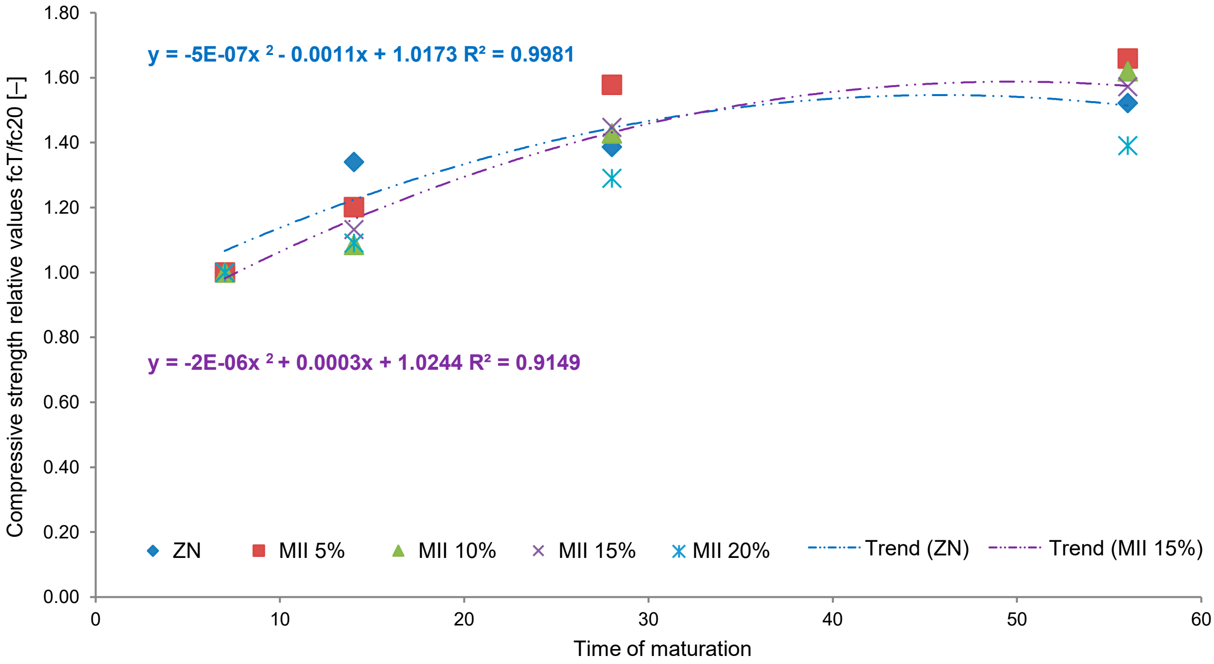

Figure 4. As Figure 3, but for the addition of cullet

and the decrease was 17.6%. The highest compressive strength after 56 days of maturation, equal to 48.9 MPa, was achieved by the MII 15% samples, while the lowest compressive strength (40.1 MPa) was obtained for the MI 20% samples.

Flexural strength

The bending strength increased in all the samples on the replacement of cement with glass flour in relation to the reference samples. The lowest value was 2.01 MPa, and the highest was 2.35 MPa for the sample with 5% glass flour. The amount of glass cullet, with a fraction of 2–4 mm, did not affect the bending strength in the tested range of cullet content. A comparable value was recorded for all tested samples. Table 4 shows the obtained results.

Table 4. Bending strength results

Type samples	BZ	MI 5%	MI 10%	MI 15%	MI 20%
Resilience on bending [MPa]	2.01	2.35	2.16	2.19	2.25
Type samples	BZ	MII 5%	MII 10%	MII 15%	MII 20%
Resilience on bending [MPa]	2.01	2.01	1.98	2.01	2.20

Frost resistance

Table 5 shows the obtained results for the compressive strength of reference concrete samples and samples after 150 freezing cycles. According to the PN-88/B-06250 standard, samples subjected to freezing should not have cracks or damage, and their weight loss should not exceed 5%. Additionally, the

Table 5. Summary of the average strength of the samples before and after freezing and the average weight loss of the samples

Sample	Average compressive strength		Average strength decrease of frozen sample	Average mass		Average loss in mass
	Before freezing	After 150 freeze-thaw cycles		Before freezing	After 150 freeze-thaw cycles	
	[MPa]	[MPa]	[%]	[g]	[g]	[%]
BZ	50.6	47.8	–5.53	2412	2409	0.12
MI 5%	46.8	44.6	–4.70	2411	2408	0.12
MI 10%	47.8	45.4	–5.02	2414	2401	0.67
MI 15%	49.0	44.9	–8.38	2398	2382	0.54
MI 20%	43.7	39.7	–9.15	2406	2390	0.17
MII 5%	49.6	47.3	–4.64	2385	2381	0.50
MII 10%	50.5	48.1	–4.75	2395	2379	0.67
MII 15%	50.9	47.7	–6.29	2411	2370	1.70
MII 20%	43.5	40.5	–6.90	2416	2368	1.98

decrease in compressive strength should not exceed 20%.

Table 5 presents the obtained results for the average compressive strength before and after freezing and average masses. The values shown in Table 5 are the average measurements made on the 6 samples after 78 days. In the case of comparative samples, the BZ concrete, for which the strength value is 50.6 MPa, had the highest compressive strength, and the MII 20% samples had the lowest strength of 43.5 MPa. When considering the compressive strength of the samples after 150 freezing cycles, it is noted that the 10% MII samples are the most resistant. The average strength here is 48.1 MPa. Concrete MI 20% – 39.7 MPa is characterized by the lowest strength after 150 freezing cycles. The average strength loss of the frozen samples exceeded 20% in none of the cases. The lowest decrease in strength occurred in the MII 5% sample and the highest in the MI 20% sample. The values are 4.64% and 9.15%, respectively. The average weight loss in the tested samples after 150 freezing cycles ranged from 0.12% for the BZ sample to 1.98% for the MII 20% sample. The samples used in this study were subjected to 150 cycles of freezing and thawing and water action; therefore, they can be assigned the degree of frost resistance F150.

Conclusions

This research revealed the possibility of using glass waste, in the form of flour and cullet, as a partial replacement for traditional components of concrete mix – i.e., cement and natural aggregate. It also ascertained the impact of such changes on the basic mechanical properties of concrete – i.e., its compressive and bending strength, and frost resistance.

For the purposes of this research, the composition of the concrete mix was developed based on the composition of the B20/25 concrete mix, in which two independent changes were made: glass flour replaced CEM 42.5 R cement in the amount of 5, 10, 15, and 20%, and glass cullet replaced the aggregate in the same proportions. The obtained samples were subjected to strength and frost resistance tests.

The compressive strength results indicate that the most optimal amount of additive, both in the case of flour and glass cullet, is the content of 15% of the cement/aggregate content. The addition of glass waste above the above-mentioned value causes a significant decrease in compressive strength in both cases.

In the case of the partial replacement of cement with glass flour, the obtained strength values were lower than those of the reference samples; however, the differences do not exceed 10% with a concrete maturation time of 28 days. The obtained results also indicate a smaller increase in strength as a function of time for samples with the addition of glass flour; the least noticeable is for samples with 15% glass flour.

The results for the partial replacement of natural aggregate with glass cullet showed that the strength values for the 5% and 10% content are slightly lower than the strength of the reference samples. However, for the cullet content of 15% of the aggregate, the compressive strength values, after exceeding 28 days of maturation, exceeded the strength of the reference samples.

In both test cases, the replacement of components to the amount of 20% has contributed to a significant reduction in the strength of the samples. Bending strength tests have shown that partial replacement of the cement/aggregate with glass waste will not reduce its strength and, in certain contents, even increase it. The frost resistance tests showed that, with an increase of glass addition in the sample, the loss of average concrete compressive strength grew after 150 freezing cycles. However, these losses are greater for samples where cement was replaced with glass flour. The greatest decrease in endurance was found to be 9.15%.

After conducting the tests (the obtained results were presented in the previous section), it can be concluded that the glass waste (i.e., the subject of the analysis) may be an additive that reduces the consumption of cement and natural aggregate in the concrete mix. The method of utilizing glass waste by adding it to the concrete mix is completely ecological and environmentally friendly, and it prevents the costly accumulation of this type of waste in landfills.

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