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The evaluation of the possible utilization of waste glass in sustainable mortars

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Abstract: The assumptions of the low-carbon economy and sustainable development in construction leads to the search for ecological solutions in materials whose production generates significant amounts of carbon dioxide. Cement substitution with waste glass powder used in building mortars is part of this trending solution. This paper describes the results on the selective properties of mortars containing powdered waste glass in the amount of 0-20% by weight. The proposed modification gives satisfactory physical and mechanical properties to the cement mortars used in the building industry.

Keywords: glass waste, cement mortars, mechanical properties, absorbability

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Introduction

Glass is one of the oldest and most important materials used in everyday life. Despite the strong competition from plastics, it remains an irreplaceable material in many people's lives. Being an inert material, it is widely used in packaging production (Ismail & Al-Hashmi, 2009; Lu et al., 2017a; Lu et al., 2017b; Rashad, 2014; Saccani et al., 2017; Serpa et al., 2013). According to Eurostat data, in 2016 in the EU glass was among the most popular packaging materials with a usage share of 19% (Fig. 1). The mass use of this material also leads to the formation of a huge amount of glass waste. Due to its unique features, such as not losing its properties despite repeated processing, glass has the ability to be recycled in many ways. In some European countries, nearly 85% of glass packaging (bottles and jars) is made from recycled materials. This is extremely important for society and the environment, because despite the fact that glass is fragile, it is also very durable, it can survive intact for thousands of years (Khmiri et al., 2013). Unfortunately, the advantageous features of glass packaging, especially in relation to used packaging and the resulting cullet, are not often rationally used. The majority of waste packaging and the resulting cullet end up in landfills (Kuśnierz, 2011).

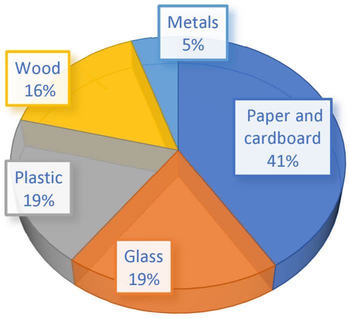

Fig. 1. The most popular types of packaging waste in the EU in 2016 (Eurostat, 2019)

Therefore, it is extremely important to look for ways to manage glass cullet created outside the glass production process, i.e. recycled cullet. One such option is the use of glass waste in the process of creating popular building materials such as concrete and mortar that are used as floor underlays, to repair materials or as adhesive mortars (Azevedo et al., 2017; Du & Tan, 2013).

Modifying the composition of a mix with waste glass cullet can take place in two ways. The first is by substituting the aggregate or binder. This method is important because resources of natural aggregates are drastically shrinking. Replacing natural aggregates with waste materials is also part of the sustainable development trend in construction (Dębska, 2017). One of the barriers to substituting glass for natural aggregate is the problem associated with the reaction of alkaline silica (ASR). ASR is one of the best-studied harmful mechanisms of concrete degradation and is particularly harmful. Once detected in the concrete structure, the ASR process is very difficult to stop. Serpa et al. (2013) showed, however, that waste glass can be used as a replacement for natural non-reactive aggregates up to 20% by weight. The reactions of alkaline silica in such a composite depends on the degree of substitution and the size of the particles. These parameters, as well as the mortar maturation time, also affect strength properties (Ismail & Al-Hashmi, 2009). With a short maturation time, a small addition (up to 5%) of glass waste can increase strength, while with 20% substitution, the positive effect of modification only becomes apparent after a longer maturation period. Ismail and Al-Hashmi (2009) and Calmon et al. (2014) confirmed that the mechanical behavior of cement composites with the addition of glass waste depends on the shape of the modifier grains. Tan & Du (2013) replaced aggregate in mortars with waste glass particles in an amount of 0 to as much as 100% by mass. The irregular shape and lower density of glass particles caused a higher content of air in the mortar, which resulted in a decrease in its density. The use of glass waste in the mortar caused a decrease in compressive strength, bending and modulus of elasticity due to weakened bonds in the transition zone between glass particles and cement paste. Conversely, the negligible water absorption capacity of the glass particles has led to an improvement in dimensional stability and thus to less shrinkage when drying modified mortars.

Glass is an amorphous solid with pozzolanic properties, which is why it can be used as a partial replacement for ordinary Portland cement in cement-based composites (Šimonová et al., 2017). This fact is particularly relevant because it is possible to use waste and at the same time reduce the consumption of cement, which is also important because in its production a significant amount of carbon dioxide, harmful to the environment, is emitted. This approach is integral to the low-carbon economy. Nassar & Soroushian (2012) showed that waste glass, after milling to micro-scale particle sizes, undergoes pozzolanic reactions with cement hydrates, forming secondary calcium silicate hydrate (C-S-H). These reactions cause favorable changes in the structure of the hydrated cement paste and the interfacial transition zones in recycled aggregate concrete. It was also found that ground waste glass suppresses alkaline-silica reactions. Test results for compressive strength, modulus of elasticity, linear contraction and tensile strength conducted by Calmon et al. (2014) indicate the possibility of using ground glass waste in the process of obtaining cement mortars with a 5% cement substitution rate. This fact is also confirmed by the results of research by Pan et al. (2017). In turn, Šimonová et al. (2017) proved that replacing cement with waste glass powder while maintaining a constant fresh consistency of the mixture causes a decrease in the value of all monitored parameters of hardened mortars. Compared with the reference cement mortar, the compressive and flexural strength as well as the effective crack resistance of the tested mortars are gradually reduced. However, for the modulus of elasticity, a small increase was observed for smaller amounts of waste glass powder.

The examples described confirm that research should continue in order to find practical ways to recycle used glass in building materials such as mortars and concretes. This article presents the results of research on selected properties of cement mortars in which glass powder derived from waste was a cement substitute in an amount of 0-20% by weight. The goal was to demonstrate the possibility of obtaining composites with good physical and mechanical properties, with replacement of binder by waste. The positive environmental impacts from this substitution should not be ignored.

1. Materials and methods

1.1. Materials

The tests were carried out on cement mortars with the addition of waste glass powder (Fig. 2).

Five mortar compositions were prepared for testing (see Table 1). To determine the composition, a standard mortar recipe was used, which consists of the following proportions: 1 part cement, 3 parts standard sand, 0.5 part water.

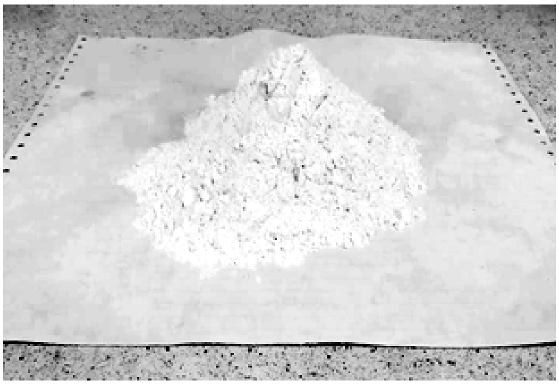

Fig. 2. Waste glass powder (*own photo*)

Table 1. Composition of mortar compositions (*own research*)

Mortar designation	The content of ingredients				
	Glass waste	Glass waste	Cement	Standard sand	Water
	[%]	[g]	[g]	[g]	[g]
WG0	0	0	450	1350	225
WG5	5	22.5	427.5	1350	225
WG10	10	45	405	1350	225
WG15	15	67.5	382.5	1350	225
WG20	20	90	360	1350	225

CEM I 42.5 N, meeting the requirements specified in the PN-EN 197-1 standard, was used. The aggregate was in a form of standardized sand prepared according to PN-EN 196-1. Water from the municipal water supply system was used. Waste glass powder with a density of 2.5 g/cm^3 was added to the mixes.

1.2. Preparation and testing of samples

Three samples of 40x40x160 mm were made for each series of mortars, and separately tested for flexural strength (f_f) and water absorption (N). The compressive strength (f_c) test was carried out on 6 samples from each series that remained from the bending strength test. A standard mixing and casting procedure was utilized for the preparation of specimens for the strength tests. Molds of mortar were stored for 24 hours in a laboratory cabinet under the conditions of required temperature 20.0±1.0°C and humidity over 90%. After 24 hours, the samples were demoulded, marked and placed in a water bath, where they matured for 7 and 28 days, respectively.

The absorbability was tested using 3 mortar samples of each composition. Samples were measured and placed in the dryer, until constant weight was achieved, then the samples were weighed and immersed in water until they were fully saturated with water. Water absorption was determined using the formula (1):

$$N = ((m_n - m_s)/m_s) \cdot 100 \qquad (1)$$

where:
N – mortar absorptivity [%],
m_n – mass of saturated samples [g],
m_s – mass of dried sample [g].

2. Results and discussion

Data analysis was performed using statistical software. The average values and standard deviation of the results of flexural and compressive strength and water absorption are summarized in Table 2.

Table 2. List of mean values and standard deviation of results obtained during tests (*own research*)

Mortar designation	f_{f7} ± st. dev.	f_{f28} ± st. dev.	f_{c7} ± st. dev.	f_{c28} ± st. dev.	N ± st. dev.
	[MPa]	[MPa]	[MPa]	[MPa]	[%]
WG0	8.32±0.76	10.18±0.23	35.80±2.21	47.57±1.59	8.07±0.05
WG5	8.24±0.20	9.64±0.09	33.70±1.78	44.92±1.69	7.89±0.09
WG10	7.31±0.49	9.29±0.44	28.52±1.24	43.00±0.36	8.11±0.04
WG15	6.81±0.23	9.33±0.11	27.15±1.22	39.02±0.89	8.29±0.17
WG20	6.42±0.26	8.18±0.29	23.08±1.06	34.85±1.21	8.27±0.09
Total	7.42±0.87	9.33±0.71	29.65±4.88	41.87±4.70	8.13±0.17

With the increase in the degree of cement substitution by waste glass powder, the values of marked strength parameters decreased, while the absorbability slightly increased. The nature of the changes could be assessed by presenting the results in graphic form and then determining the regression curve equations. Equations of functions were fitted to empirical data, which are presented in Figures 3-5.

A linear model of the approximation function was fitted to the test results (2):

$$y = a + b \cdot x \qquad (2)$$

For both tested strengths, this model well describes the empirical data, as evidenced by high values of R^2 determination coefficients, ranging from 0.7765 to 0.9182.

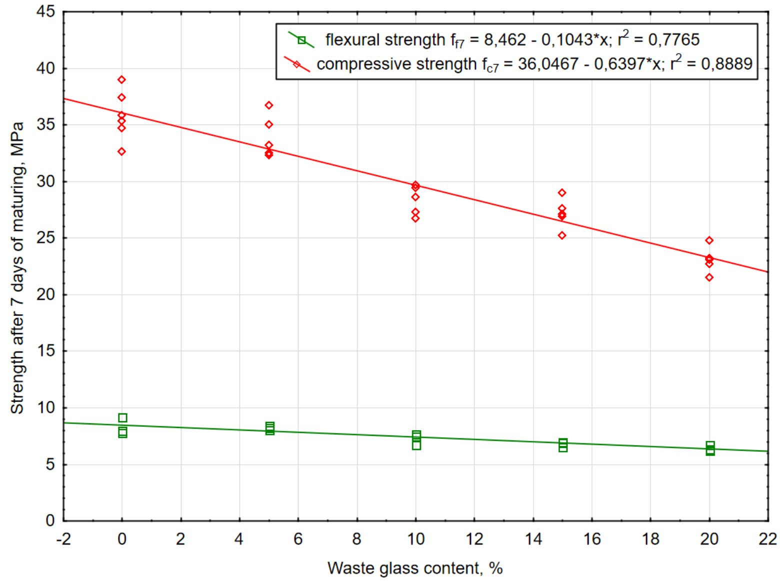

Fig. 3. Function graphs describing the dependence of flexural and compressive strength after 7 days of maturation on the percentage of glass waste in mortar (*own research*)

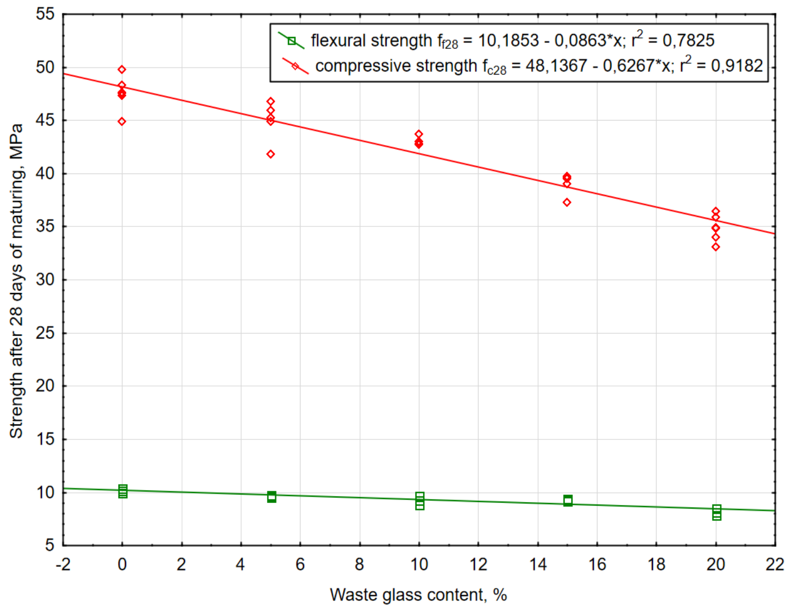

Fig. 4. Function graphs describing the dependence of flexural and compressive strength after 28 days of maturation on the percentage of glass waste in mortar (*own research*)

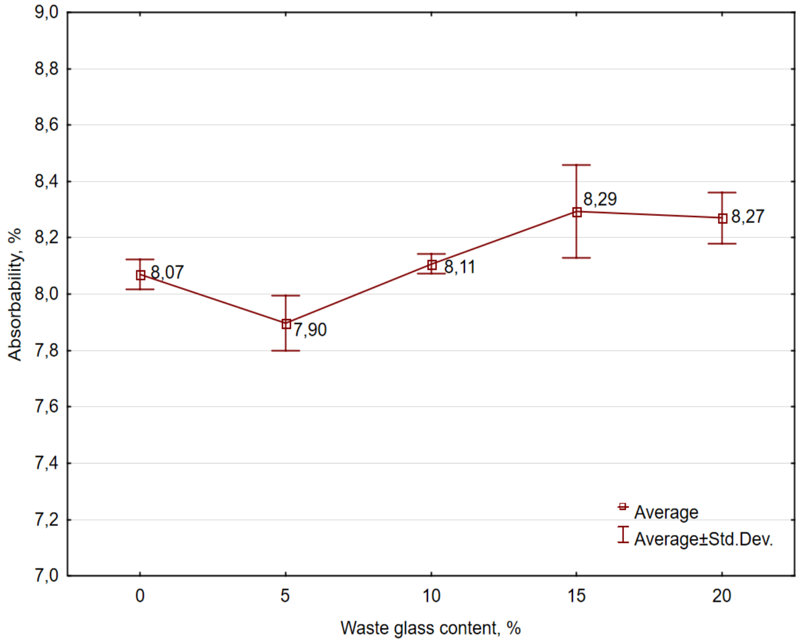

Fig. 5. Function graph describing the dependence of absorbability on the percentage share of glass waste in mortar (*own research*)

Both flexural and compressive strength decreases as the waste content increases. The lowest values of determined parameters were recorded at 20% cement substitution. The average flexural strength values were 7.42 and 9.33 MPa, after 7 and 28 days of ripening, respectively. At 20% cement substitution with waste, a decrease of 22.8% after 7 days and of 19.65% after 28 days of sample storage was recorded. However, with a 5% cement replacement, the flexural strength was reduced by just 0.08 MPa (0.96%) and 0.52 MPa (5.3%) respectively for increasing maturing time. A similar tendency can be observed by analyzing the results of the compressive strength tests. At 20% substitution, the decrease in this parameter was 35.5% (after 7 days) and 26.7% (after 28 days), respectively, which is 12.72 MPa in both cases. On the other hand, with a 5% cement swap glass waste, after 7 days there was a decrease in compressive strength by 2.1 MPa (5.87%), and after 28 days by 2.65 MPa (5.57%). The results presented are therefore consistent with those obtained by Pan et al. (2017) and Šimonová et al. (2017), which confirms that with a small (5%) degree of cement substitution with waste material, mortars with high strength parameters can be obtained. Higher or comparable to the strength properties attributed to cement concretes, for which the bending strength was assumed at the level of 1.1-7.2 MPa, and compressive strength – 15-60 MPa (Czarnecki, 2010). The results presented in Table 2 and Figure 5 show that the modifier used does not significantly affect the absorbability of the mortars obtained. At a 5% waste addition, this property turned out to be even 0.18% lower on average compared to control samples and was 7.89%.

Conclusions

Despite ongoing campaigns encouraging pro-ecological behavior, the amount of waste at landfills is still huge. The method of modifying cement mortars proposed in this article is in line with the main assumptions of rational waste management, it also reduces carbon dioxide emissions to the environment. Based on the conducted research, the following conclusions can be made:

- Substitution of cement in mortars causes a decrease in strength parameters, however, even with the use of 20% glass waste, a composite can be obtained that can compete with traditional cement mortars.
- Addition of waste material does not significantly reduce mortar absorbability and remains at the level of approx. 8%.
- The issue requires further long-term tests and determination of adhesion to the ground in order to fully assess the possibility of using glass cullet to obtain adhesive mortars or those used for repairs.

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