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# The influence of the type and grain size of glass waste on the physical and mechanical properties of cement mortars

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Abstract: Due to the problem of dwindling natural resources and increasing waste volumes, the use of various waste materials as a substitute in cement-based products is gaining particular importance. This study compared the effect of two types of waste glass – transparent and blue – in two fractions (<0.063 mm and 2 mm - 0.063 mm), used as a partial sand substitute, on the physical and mechanical properties of cement mortars. Thirteen sample series were prepared, including a control sample (CS) and samples with glass added at 10 %, 20 %, and 30 % by weight of cement as a substitute for aggregate (standard sand). The tests were conducted in accordance with applicable PN-EN standards, assessing workability (flow table method), flexural and compressive strength after 7 and 28 days, water absorption, and frost resistance. The study showed that glass additives reduced the workability of mortars, particularly in the case of fine fractions, although some of the mixtures improved mechanical properties. After 28 days, the highest compressive strength was achieved for mortars with 10 % - 20 % blue glass (over 62 MPa), exceeding the reference sample. Flexural strength was also highest for samples with 10 % blue glass (<0.063 mm). The results suggest that appropriately selected glass type and amount can positively influence the performance of cement mortars, supporting the concept of sustainable construction.

Keywords: glass waste, cement mortar, recycling, sustainable construction



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## Introduction

The production of cement is expected to increase to 5.0 billion metric tons by 2030 worldwide (Ahmad et al., 2022), which will significantly contribute to $CO_2$

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emissions and accelerate the depletion of natural resources. Therefore, incorporating waste and recycled materials into cement-based composites is important, both from an environmental and economic perspective. In the face of the growing shortage of natural resources, replacing traditional materials with waste and recycled waste is becoming increasingly necessary, particularly in the construction industry. One of the most common solutions is the use of waste in cement-based materials, which allows for the management of difficult-to-dispose industrial residues. Fly ash and slag from coal combustion are most commonly used in the power, heating, and metallurgical sectors (Ankur & Singh, 2021; Murtaza et al., 2024; Pormmoon et al., 2024; Voshell et al., 2018). In addition to these typical waste materials, ash from coal and biomass co-combustion is also used in laboratory tests (Langier, 2022; Rutkowska & Małuszyńska, 2014) as well as from the combustion of biomass itself (Agrela et al., 2019; Bonfim & de Paula, 2021; Fořt et al., 2024; Jura & Ulewicz, 2025, 2021, 2017; Voshell et al., 2018), made of polymer composites and ash (Ulewicz et al., 2024a) and ashes obtained from the combustion of other materials (Pietrzak et al., 2025). Other wastes are also being used in research as additives and substitutes for cement composites. This is intended to reduce the amount of natural materials used, but also to utilize landfill waste. Such materials may include construction waste (Cai et al., 2025; Modi & Bhogayata, 2023; Sobuz et al., 2025; Tanash et al., 2023; Zhao et al., 2025), sludge waste (Ulewicz et al., 2024b) or polymer (Han et al., 2025; Pietrzak, 2024; Pietrzak & Ulewicz, 2023).

At the same time (to reduce the amount of glass waste in landfills) the reuse of glass in cementitious materials is becoming increasingly important – both in finely ground and crushed form, as cement additives and aggregate substitutes. Additionally, glass takes an extremely long time to degrade naturally (approximately 4,000 years) which raises further environmental concerns regarding its accumulation in landfills and thus the need for sustainable reuse strategies. The EU average recycling rate of glass packaging reached 80.8 % in 2023, with over 12 million tonnes collected. In 2023, approximately 1.3 million tonnes of glass packaging were introduced to the market in Poland, but only around 700,000 tonnes were collected. After about 20 % contamination, this results in actual recycling of less than 50 %, far below EU targets (Recycling in Poland, 2025).

Artificial pozzolans, such as finely ground glass powder (GGP), alongside natural pozzolans – including pumice, perlite, and volcanic ash – are characterized by amorphous aluminosilicate phases that react with calcium hydroxide ($Ca(OH)_2$) in the presence of water to form calcium silicate hydrate (C–S–H) gel, thereby serving as potential substitutes for fly ash (FA) (Kasaniya et al., 2021). While natural pozzolans contribute to enhanced durability and sustainability of concrete, their application is often limited by variability in chemical and physical properties, restricted availability, slow pozzolanic reactivity, potential contamination, processing difficulties, and associated transportation costs. In contrast, glass exhibits reduced variability in chemical composition, greater purity, and lower water demand relative to FA and conventional supplementary cementitious materials (SCMs) (Nassar & Soroushian, 2012).

When used in cement-based materials, preparation and fragmentation are crucial. Studies (Islam et al., 2017) have confirmed that ground glass as a partial substitute for cement (up to 20 %) improves compressive strength by 10 % - 14 %, which may be due to its pozzolanic activity and the increased amount of C–S–H gel. At the same time, it was found that crushed glass used as a substitute for fine aggregate has a different effect on the properties of mortars. Research conducted by (Harrison et al., 2020) showed that glass is not suitable as a raw material for the production of clinker or as a coarse aggregate, but fine glass particles can positively influence the mechanical properties of mortars and concretes due to the pozzolanic reaction. According to the authors, up to 20 % of cement can be replaced with 20 µm glass without compromising mechanical properties. Higher substitution rates (above 30 %) can negatively impact the material. When replacing fine aggregate with glass, rates up to 20 % also do not degrade performance compared to traditional mixtures. In laboratory tests (Chen et al., 2022) showed that replacing 20 % of sand with glass resulted in a reduction in porosity by 16.5 %, an increase in compressive strength by 3 % and an increase in the modulus of elasticity by 5.9 %, which was confirmed by SEM analyses and porosimetry tests, this effect was attributed to effective hydration and better filling of the structure. In his research (Czapik, 2020) showed that the use of crushed glass up to 20 % in the mortar has a positive effect on resistance to gas penetration and on the microstructure. Son et al. (2024) focused on the type of crushed glass (clear vs. green) and found that up to 20 % glass in the mortar, especially for fine particles (<500 µm), the effect on the strength and expansion of the ASR was acceptable, although the type of glass and the surface condition were important. The topic of glass in cement matrix materials was also taken up by (Małek et al., 2020). The authors examined the effect of adding finely ground glass from post-consumer waste as a substitute for fine aggregate in cement mortar. The researchers concluded that adding up to 20 % glass improved the mortar's mechanical properties, although it caused a slight decrease in density and workability, confirming the potential of using glass waste in sustainable construction. A literature review revealed that ground transparent glass (up to 300 µm) acts as a proven cement substitute (in amounts of 10 % - 20 %), improving the strength properties of mortars. When crushed and used as aggregate, such glass improved its microstructure, strength, and airtightness to approximately 20 %. Both forms support sustainable development goals by reducing the consumption of cement, sand, and the amount of glass waste in landfills.

In this study, the authors investigated the impact of different types of glass on basic mechanical properties.

## 1. Materials and methodology

The research presented in this article aimed to investigate and compare the effect of different types and fractions of recycled waste glass on the basic physical and mechanical properties of cement mortars. Two types of recycled packaging glass from glassworks were used in the study. The first type was clear glass, while the second was blue glass produced by adding cobalt oxide (CoO) during production. Each type of glass was sieved (Table 1) and then divided into two fractions used in cement mortar tests (2 mm - 0.063 mm and <0.063 mm) (Fig. 1). Sieving tests of the glass waste showed that both wastes had very similar percentages on the individual sieves, meaning that the grain composition of both wastes was similar. The density of both glass wastes was 2.53 g/cm$^3$.

**Table 1.** Sieve analysis of glasses (*own research*)

| Fraction [mm] | Transparent glass | Blue glass |
|---|---|---|
| | Contents [%] | |
| 16.0-8.0 | 14.78 | 17.06 |
| 8.0-4.0 | 43.71 | 35.65 |
| 4.0-2.0 | 23.17 | 26.73 |
| 2.0-1.0 | 11.48 | 10.04 |
| 1.0-0.5 | 4.48 | 5.78 |
| 0.5-0.25 | 1.46 | 2.51 |
| 0.25-0.125 | 0.66 | 1.34 |
| 0.125-0.063 | 0.22 | 0.66 |
| <0.063 | 0.04 | 0.23 |

Fractions up to 2 mm were used for the tests due to the size of standard natural aggregates used in mortars. TGS refers to clear glass with fractions of 2 mm - 0.063 mm, TGA refers to a fraction of <0.063 mm, BGS refers to blue glass with a fraction of 2 mm - 0.063 mm, and BGA refers to <0.063 mm.

**Fig. 1.** Waste glass used for testing before sieving (*own research*)

Table 2 presents the percentages of individual fractions in the prepared glass samples. Comparing the percentages of both glass wastes with a fraction of 2 mm - 0.063 mm after sifting out the oversized and undersized fractions, it can be seen that TGS has a slightly higher proportion of the 2 mm - 1 mm fractions, while BGS has a higher proportion of the finer fractions <1 mm.

**Table 2.** Percentage of fractions in prepared glass samples (*own research*)

| Fraction [mm] | Type of glass | | | |
|---|---|---|---|---|
| | TGS | TGA | BGS | BGA |
| | Contents [%] | | | |
| 2.0-1.0 | 62.71 | – | 49.36 | – |
| 1.0-0.5 | 24.50 | – | 28.44 | – |
| 0.5-0.25 | 7.96 | – | 12.37 | – |
| 0.25-0.125 | 3.62 | – | 6.59 | – |
| 0.125-0.063 | 1.21 | – | 3.24 | – |
| <0.063 | – | 100.00 | – | 100.00 |

The tests were performed using cement mortars formed into rectangular specimens measuring 160 × 40 × 40 mm. In addition to glass waste, Portland cement CEM I 42.5 R, standard sand, and tap water were also used. All tests were performed in accordance with applicable standards. Compressive strength test specimens were prepared in accordance with the PN-EN 196-1:2016-07 standard, which specifies the method for sample production, storage, and guidelines for compressive and flexural strength tests. Bending and compressive strength tests were performed based on the PN-EN 1015-11:2020-04 standard.

Thirteen series of specimens were prepared for the tests. A series of control samples were prepared in accordance with the guidelines for standard mortar, as well as series using each type of waste glass. Based on the research presented in the scientific literature, it was decided to use waste glass in the amount of 10 %, 20 %, and 30 % by weight of cement as a substitute for aggregate, i.e., standard sand, by volume. The compositions of the individual mixtures are presented in Tables 3 and 4.

**Table 3.** Composition of cement mortar mixtures with transparent glass (*own research*)

| Component [g] | CS | TGS10 | TGS20 | TGS30 | TGA10 | TGA20 | TGA30 |
|---|---|---|---|---|---|---|---|
| Cement | 450 | 450 | 450 | 450 | 450 | 450 | 450 |
| Water | 225 | 225 | 225 | 225 | 225 | 225 | 225 |
| Standard sand | 1350 | 1302.8 | 1255.7 | 1208.6 | 1302.8 | 1255.7 | 1208.6 |
| TGS | – | 45 | 90 | 135 | – | – | – |
| TGA | – | – | – | – | 45 | 90 | 135 |

**Table 4.** Composition of cement mortar mixtures with blue glass (*own research*)

| Component [g] | BGS10 | BGS20 | BGS30 | BGA10 | BGA20 | BGA30 |
|---|---|---|---|---|---|---|
| Cement | 450 | 450 | 450 | 450 | 450 | 450 |
| Water | 225 | 225 | 225 | 225 | 225 | 225 |
| Standard sand | 1302.8 | 1255.7 | 1208.6 | 1302.8 | 1255.7 | 1208.6 |
| BGS | 45 | 90 | 135 | – | – | – |
| BGA | – | – | – | 45 | 90 | 135 |

## 2. Results

During sample preparation at the stage of making the cement mortar mixtures, their consistency was tested (Fig. 2). The test was performed in accordance with the PN-EN 1015-3 standard using the flow table method. The results presented are the arithmetic mean for three prepared samples. Mortar consistency, expressed as the flow value, systematically decreased with increasing glass additive content, regardless of the glass type. The CS reference sample had the highest flow (155 mm), confirming its highest workability. For the TGS series, this value dropped to 131 mm at 30 % additive content. In the TGA series, the effect was even more noticeable, with only 119 mm obtained at 30 % additive content, indicating a significant deterioration in workability. A similar trend was observed for BGS and BGA additives, although their impact was somewhat milder. The decrease in consistency results from the larger specific surface area of glass additives, particularly in fractions <0.063 mm (TGA, BGA), which increases their water requirement.

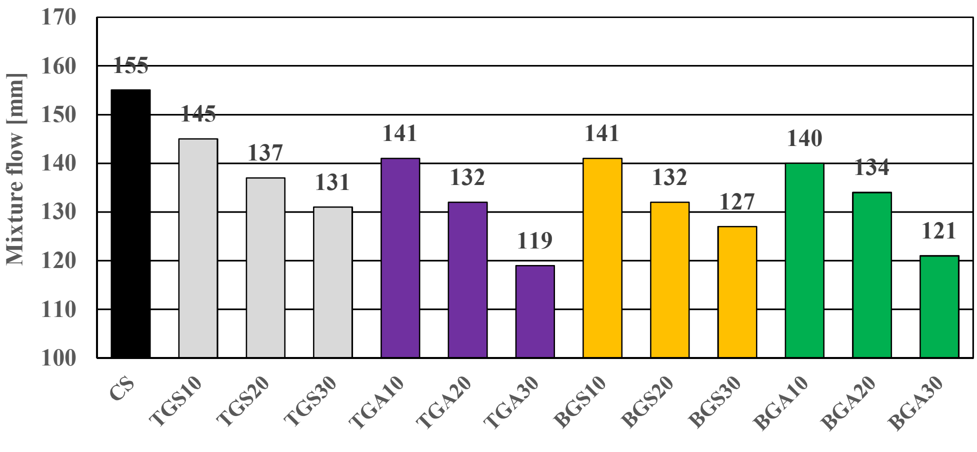


**Fig. 2.** Consistency of the tested cement mortars (*own research*)

Flexural and compressive strength tests were carried out in accordance with the PN-EN 1015-11:2020-04 standard. Flexural strength tests were performed on 6 samples and compressive strength tests on 12 samples from each series and presented as an arithmetic mean. The standard deviation of the results was a maximum of 4 % and was similar across all series. After 7 days, the highest flexural strength was achieved by the control sample CS (6.97 MPa) (Fig. 3). Among the mortars with waste glass additives, the best results were achieved by mixtures with BGS10 (6.89 MPa) and BGA30 (6.78 MPa), which were similar to the control value. The addition of TGS and TGA resulted in a greater decrease in flexural strength. The lowest results were recorded for TGA10 (5.78 MPa) and TGS30 (6.12 MPa). This indicates that blue glass has a more favorable effect on early strength development than clear glass.

After 28 days of curing, the samples with the BGA addition achieved the highest flexural strength. BGA10 reached 8.82 MPa, which is higher than the control sample

(8.55 MPa) (Fig. 4). Mortars with BGS also showed a beneficial effect, with samples from the BGS10 series achieving an average of 8.53 MPa. TGS and TGA additions gave lower results than those with blue glass, but these results were similar to those of the control series. This suggests that tinted glass additives improve the standard flexural strength of cement mortars.

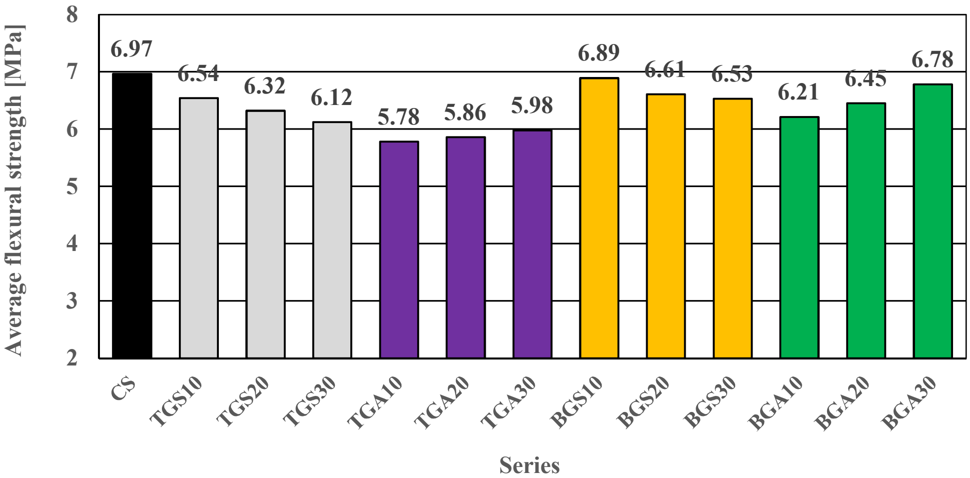


**Fig. 3.** Average flexural strength of the tested cement mortars after 7 days (*own research*)

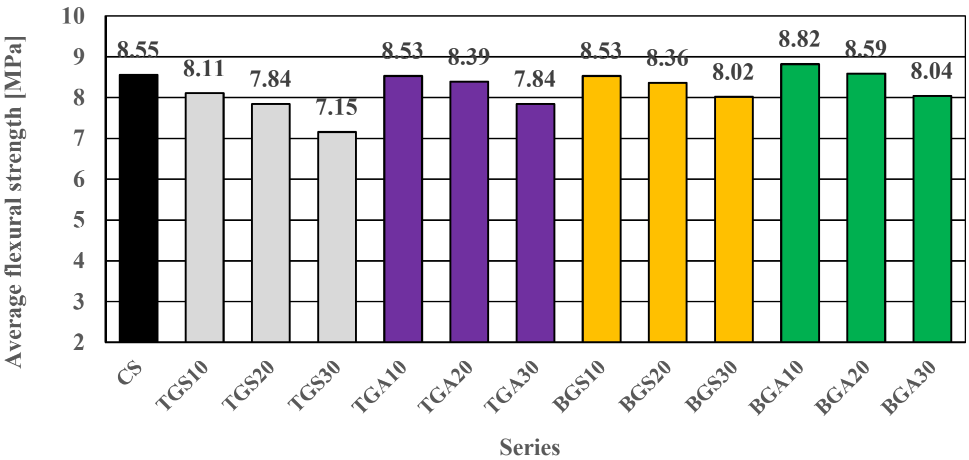


**Fig. 4.** Average flexural strength of the tested cement mortars after 28 days (*own research*)

The highest compressive strength after 7 days was observed in the control sample CS (40.88 MPa), but mortars with the addition of BGS10 achieved very similar values of 40.24 MPa (Fig. 5). The poorest results were achieved by all mixtures containing 30 % of the additive (34 MPa - 35 MPa). This means that glass only slightly worsens the development of early compressive strength. After 28 days of curing, the best compressive strength was achieved by mortars from the BGS10 (62.4 MPa) and BGA20 (62.25 MPa) series, even surpassing the control sample CS (59.79 MPa).

Furthermore, all series containing 10 % or 20 % glass added achieved higher compressive strength values after 28 days than the control samples. Additions of 30 % glass generated lower strength values than the control samples, up to over 4 MPa relative to CS.

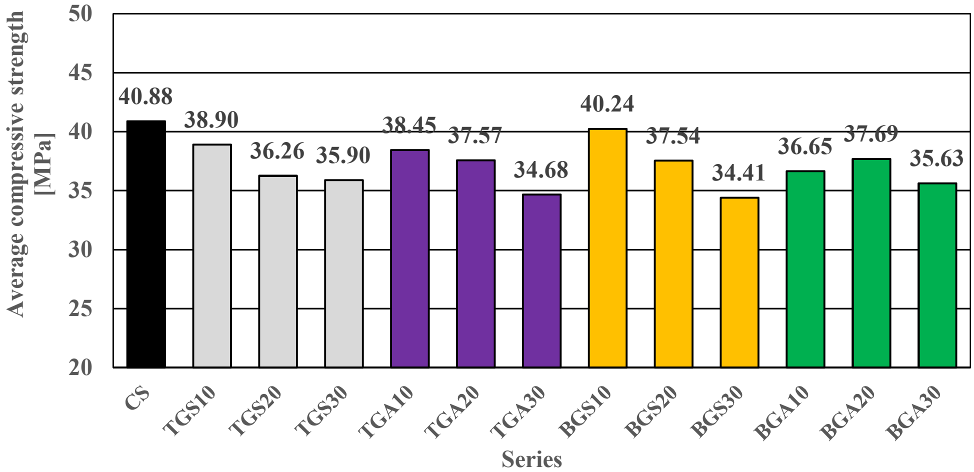


**Fig. 5.** Average compressive strength of the tested cement mortars after 7 days (*own research*)

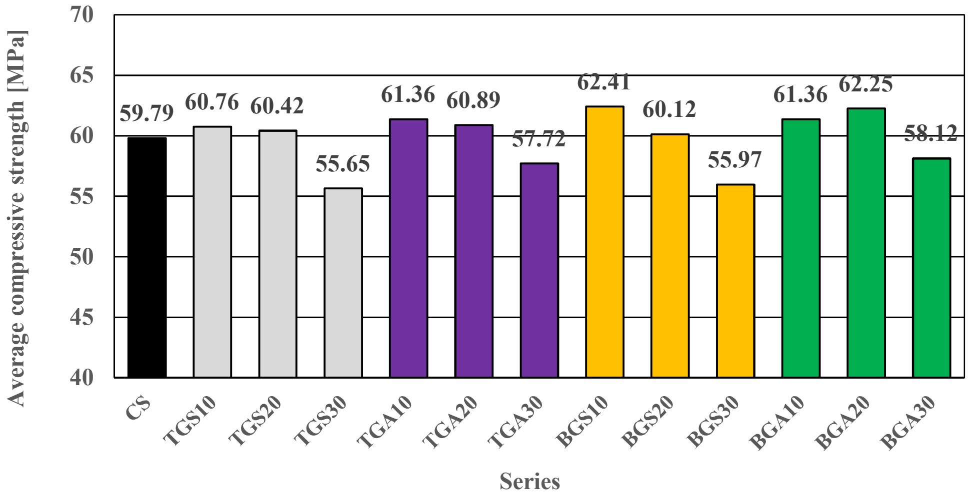


**Fig. 6.** Average compressive strength of the tested cement mortars after 28 days (*own research*)

As part of the research, tests were also carried out on the water absorption of mortars in accordance with the PN-EN 1015-18 standard. The incorporation of recycled glass generally led to a reduction in water absorption compared to the control sample (6.67 %), indicating the formation of a denser and less porous microstructure. This suggests that both fine and coarse glass particles, when applied in appropriate proportions, can enhance the packing density of the matrix and limit capillary pore formation. The fine glass fractions (TGA and BGA, <0.063 mm) primarily function as microfillers, contributing to improved particle distribution and matrix densification. In the case of BGA, the additional refinement in pore structure may also be attributed to pozzolanic reactivity, wherein the amorphous silica content reacts with calcium hydroxide to form additional calcium silicate hydrate (C–S–H) and further reducing the porosity. Coarse glass particles (TGS and BGS, 2.0 mm - 0.063 mm), characterized by angular morphology, contribute mechanically by enhancing interparticle interlock and physically filling voids within the mortar matrix. Notably, samples containing 20 % - 30 % of these additives demonstrated favorable reductions in water absorption.

Conversely, the BGA30 sample exhibited the highest water absorption value (7.71 %), which may be attributed to the excessive replacement of cementitious material with fine glass particles (Fig. 7). Such high dosages may disrupt the paste-to-aggregate ratio, hinder effective dispersion, and result in unreacted glass residues and increased capillary porosity. These findings underscore the importance of optimizing both the particle size and dosage of glass additives. While moderate additions (10 % - 20 %) enhance the compactness and durability of the mortar, excessive amounts can adversely affect the microstructure and compromise long-term performance.

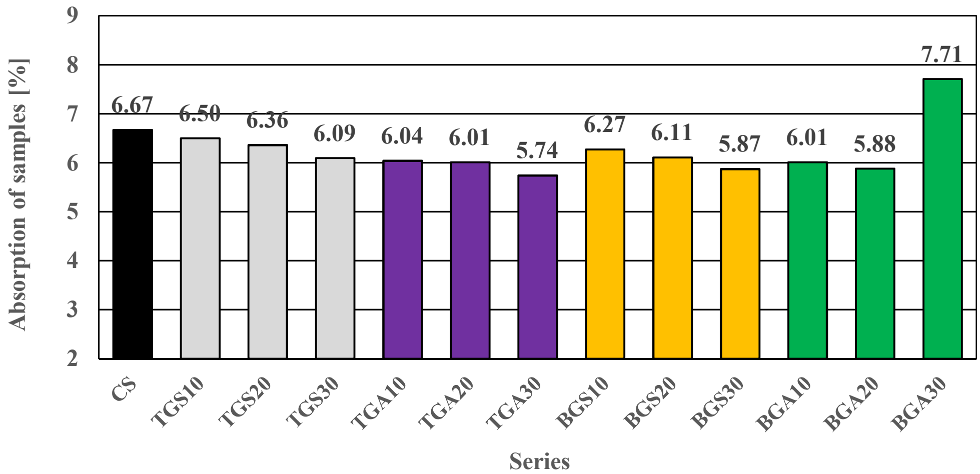


**Fig. 7.** Average water absorption of samples (*own research*)

The prepared mortar samples were also subjected to 25 freeze-thaw cycles in accordance with the PN-B-04500 standard. An analysis was then conducted of the loss of compressive strength after these frost resistance tests (Fig. 8). The smallest decrease in compressive strength after the frost resistance tests was observed for BGS20 (9.84 %) and BGS10 (10.57 %), indicating very good resistance to freeze-thaw cycles. The control sample recorded a 12.32 % decrease, while the highest strength losses were observed for the series with the TGS additive. All samples with TGS and TGA had greater decreases than the corresponding series with the BGS and BGA additives. This confirms that blue glass positively affects the frost resistance of cement mortars.

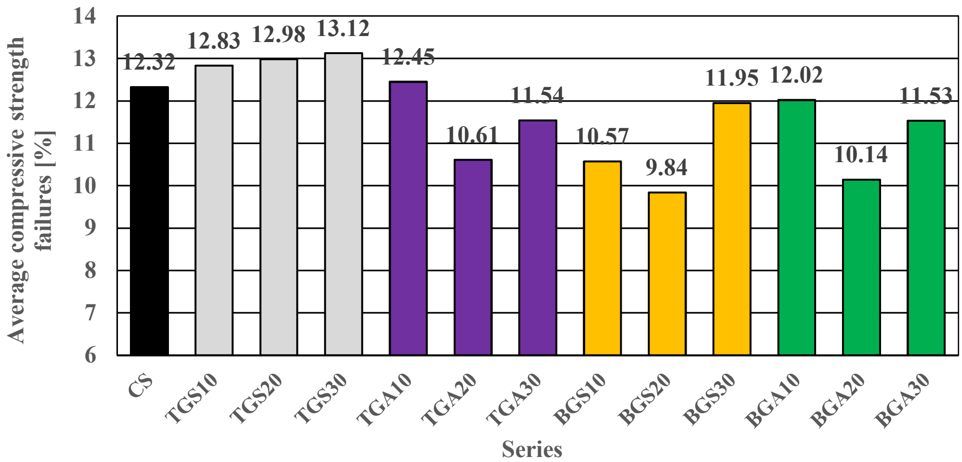


**Fig. 8.** Percent decrease of average value of compressive strength (*own research*)

## Conclusions

Based on the conducted research, it can be concluded that using waste glass, both transparent and tinted, as a partial aggregate substitute in cement mortars ensures comparable or even improved mechanical performance compared to control mixtures. Tinted (blue) glass demonstrated a more favorable effect on both flexural and compressive strength than transparent glass, with the best results observed for BGS10 and BGA20 mixtures. Finer fractions (<0.063 mm) increased water demand and affected workability, but also contributed to improving microstructure and long-term strength. An optimal substitution level of up to 20 % of the cement mass was identified, which maintains or enhances strength without compromising mixture consistency or durability, aligning with findings from other studies.

Beyond the mechanical performance, these results highlight the broader sustainability benefits of incorporating waste glass in mortars: reducing natural aggregate consumption, diverting glass from landfills, and offering a cost-effective, locally available raw material for construction.

Overall, the study confirms that waste glass is a valuable resource for sustainable construction, supporting both environmental protection and the development of efficient, high-performance building materials.

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