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MECHANICAL PROPERTIES OF CEMENT COMPOSITES WITH PLASMA-TREATED WASTE GLASS AGGREGATE

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Abstract. This research focuses on evaluating the effect of low-temperature plasma surface treatment of finely ground recycled glass on the mechanical properties of cement composites. The use of waste glass in construction represents an environmentally friendly alternative, but its application may cause alkali-silica reaction (ASR), leading to material degradation. To prevent this phenomenon, plasma treatment was applied with the aim of improving the adhesion of glass particles to the cement matrix, enabling the partial replacement of traditional filler materials. In cement composites, glass primarily functions as an alternative fine aggregate. Its use offers several potential advantages, including improving the pozzolanic properties of the composite, meaning it reacts with calcium hydroxide, thereby contributing to the formation of additional binding phases. In this way, glass not only replaces traditional fillers but also enhances the long-term mechanical properties of the material. However, inappropriate particle size or high reactivity of the glass may lead to ASR, which causes cracking and degradation of the material. Plasma treatment was employed to mitigate these negative effects by enhancing the adhesion between glass particles and the cement matrix, thereby increasing the overall cohesion, strength, and resistance of the composite to environmental influences and degradation. The samples were tested for compressive strength and bulk density after 28, and 168 days of curing. The results indicated that plasma treatment, particularly with oxygen, led to a moderate improvement in mechanical properties compared to untreated samples, but the values did not reach the levels observed in the reference sample without glass powder.

Keywords: Waste glass, cold plasma, surface treatment, mechanical properties, cement composite.

1. Introduction

Waste glass has been extensively studied as a replacement for traditional fillers in cement composites, primarily due to its potential for reducing environmental impact. Its application is particularly significant in cases where recycling is difficult. However, waste glass can negatively affect the strength and durability of cementitious materials, mainly due to alkali-silica reaction (ASR). Studies have shown that finely ground glass can enhance the strength of the composite due to its pozzolanic properties, which react with calcium hydroxide [1, 2]. However, larger glass particles often lead to cracks caused by ASR, which degrade the material. To minimize this negative effect, various material treatments have been tested, including the addition of chemical admixtures [3, 4]. Plasma treatment of waste glass has proven to be an effective approach to improving the interaction between glass and the cement matrix. Low-temperature plasma can modify the chemical structure of the glass surface, increasing its adhesion and reducing surface contamination by carbon. These modifications promote better bonding between the glass powder and cement, thus improving the mechanical properties of the resulting material [2, 5]. The experiment examines the mechanical properties of plasma-treated glass powder, utilizing oxygen and hydrogen plasma. The results build on previous studies that demonstrated the promising potential of replacing traditional filler with ground glass powder at up to 20 % content [6].

Before production, the glass powder was treated using plasma technology, which is gaining popularity due to its ability to modify the surface properties of materials without altering their internal structure. In practice, plasma coatings are applied to concrete surfaces to enhance the durability of the concrete against wear, chemical influences, and reduce porosity, which extends the lifespan of structures in highly demanding conditions, such as water management infrastructure [7, 8]. Plasma surface treatment of glass improves adhesion between glass and coatings or adhesives, thereby increasing the wettability of the glass surface [9]. In agriculture, low-temperature plasma is used for seed treatment to enhance germination and plant growth, with plasma generating reactive oxygen species that inactivate pathogens and reduce the need for chemicals [10–12].

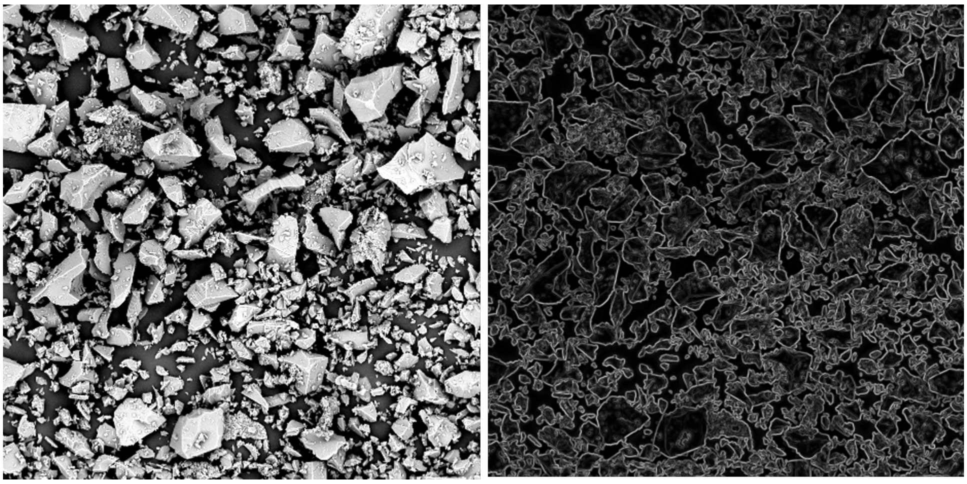

Figure 1. SEM micrograph showing the microstructural characteristics of the composite material,at 500× magnification. The left image shows an overview of the surface morphology, while the right highlights particle boundaries for the purpose of quantitative image-based particle size analysis.

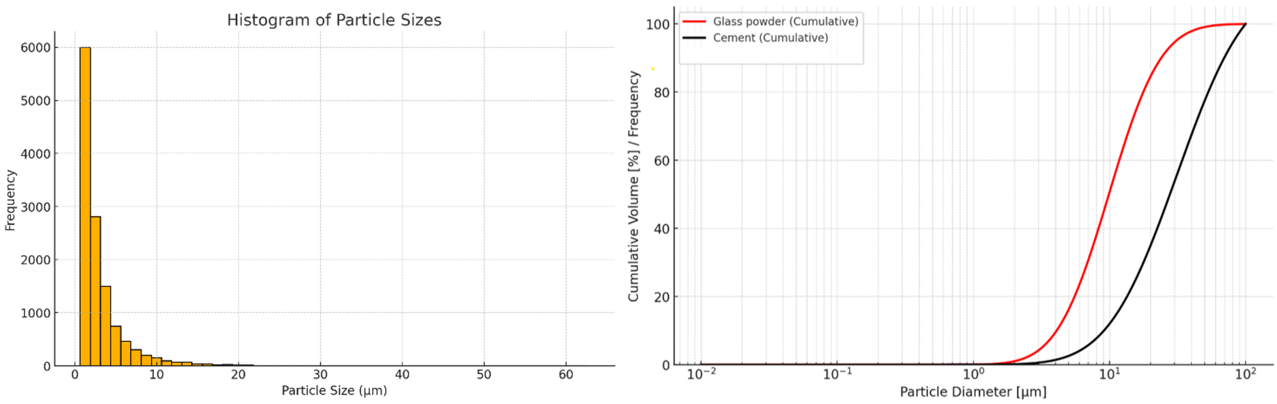

Figure 2. Particle size distribution: histogram for glass powder is based on data obtained using SEM microscopy – left, for glass powder and cement obtained by laser granulometry – right.

Low-temperature plasma is an ionized gas containing electrons, ions, and neutral particles, and at low temperatures, it does not alter the basic structure of the material. The application of plasma to fine waste glass additives causes chemical and physical changes on the surface, increasing surface reactivity and improving adhesion between the glass and the cement matrix. This process is carried out in a special chamber.

2. Materials and samples

For this experiment, low-temperature plasma technology utilizing oxygen and hydrogen was selected, considering the particle size of the finely ground glass powder and its compatibility with this process. This method was chosen because it allows for effective surface treatment of fine glass particles without affecting their internal structure.

The materials used included Portland cement CEM I 42.5R from the Radotín production plant (Českomoravský cement, a.s.), characterized by rapid strength development and fast heat evolution during hydration, making it suitable as a binder for this type of application. As an alternative filler based on silicon dioxide (SiO_2), finely ground waste glass was used, originating from shards intended for disposal. The reference material was sourced from Recifa, a.s., specifically the Refaglass Vintířov product from silo no. 5. This was finely ground waste glass with a particle size of less than 90 μm. This waste glass, derived from glass shards that would otherwise end up in landfills, was used as an alternative binder for this research. This alternative not only contributes to environmentally friendly waste disposal but also offers the potential for innovative use of waste materials in modern construction composites.

Sample preparation for SEM analysis may result in the displacement of ultrafine particles due to air flow, causing partial segregation and the appearance of a superficial particulate layer. This phenomenon is recognized as a preparation-induced artifact. The glass powder exhibited a relatively narrow particle size distribution, with the majority of particles falling within the 1–10 μm. range, as corroborated by image analysis of SEM micrographs see Figure 1 and Figure 2. In the sub-20 μm fraction, the particle size

Marking	CEM I 42.5R [kg]	SiO_2 [kg]	Water [kg]	Type of waste materials treatment
REF	0.300	-	0.105	without treatment
S1_10_ref	0.270	0.030	0.105	without treatment
S2_20_ref	0.240	0.060	0.105	without treatment
S1_10_O	0.270	0.030	0.105	Oxygen plasma treatment
S2_20_O	0.240	0.060	0.105	Oxygen plasma treatment
S1_10_H	0.270	0.030	0.105	Hydrogen plasma treatment
S2_20_H	0.240	0.060	0.105	Hydrogen plasma treatment

Table 1. Composition of test mixtures.

distribution curve closely aligns with that obtained from laser diffraction granulometry, indicating consistency between both analytical techniques. The analysis was conducted using five out of six available SEM micrographs acquired at 500× magnification. Under these imaging conditions, the lower detection limit for particle size was estimated to be approximately 0.5 µm. The total evaluated area for image analysis was $100\,\mu m^2$.

The grain geometry of the particles was characterized as angular to sub-angular, ranging from circular to oval, with an aspect ratio of 1.0 to 1.4. These morphological traits reflect the processing and preparation of the materials, as well as their influence on the overall composite properties.

As shown in Table 1, the samples were prepared by precisely weighing the raw materials, including water, cement, and waste glass powder, according to the specified proportions and treatment type. The treatments included reference samples without modification, plasma-treated samples using oxygen, and plasma-treated samples using hydrogen. The weighing was conducted using a laboratory scale with an accuracy of ±1 g.

All mixtures were prepared with the same water-to-cement ratio (w/c = 0.35) to maintain consistent mechanical properties. After mixing, the mixtures were poured into molds with dimensions of 20 × 20 × 100 mm and allowed to set at 20 °C. After 24 hours, the samples were demolded, labeled, and stored in a water bath at 20 °C until testing. A total of 28 samples were prepared, each of which was divided into smaller blocks of 20 × 20 × 20 mm for later testing at 28 and 168 days. The sample dimensions are not standardized, but literature indicates that the "size effect" does not influence the final properties [6].

3. Experimental method

The experiment was conducted to test the compressive strength of samples in the form of beams with dimensions of 20 × 20 × 100 mm, which were cut into smaller blocks of 20 × 20 × 20 mm. After processing, the samples were measured and weighed. The prepared sample was then placed into a hydraulic press. Using specialized software, the measurement was initiated, with the hydraulic press moving at a speed of $0.5\ \mathrm{mm\,min^{-1}}$. The test continued until the sample lost its structural integrity, and the maximum force was recorded.

The compressive strength was calculated using the following equation:

$$f = \frac{F_{\max}}{A}, \tag{1}$$

where f is the compressive strength (in Pa), $F_{\max}$ is the maximum force applied during the compression test (in N), and A is the cross-sectional area of the specimen (in m^2).

4. Results and discussion

This experiment builds upon previous research. In the first phase, mixtures containing glass powder were tested, and it was found that substitutions of up to 20 % could achieve acceptable mechanical properties compared to the reference sample [6]. However, higher proportions of glass powder led to a significant decrease in strength, particularly at the 20 % substitution level, where values below 60 MPa were recorded. At 28 days, all samples showed an increase in strength; however, samples containing untreated glass continued to exhibit lower strength values compared to the reference compound.

The samples, after 28 days of curing, were subjected to low-temperature plasma treatment using oxygen and hydrogen. The results demonstrated a moderate improvement in compressive strength following oxygen plasma treatment, with the treated samples approaching the strength levels of the reference sample. In contrast, the samples treated with hydrogen plasma showed slightly lower compressive strength values.

Final measurement, conducted after 168 days of curing, showed a continued increase in strength for the oxygen plasma-treated samples, while the hydrogen-treated samples stagnated or slightly decreased. This decline may be attributed to the alkali-silica reaction (ASR), which can cause microcracking in the pores of the material. To further investigate this, the samples will undergo microscopic analysis to detect the presence of any potential cracks caused by ASR.

In Figure 3, the comparison of the mechanical properties of cement composites with different waste glass additives and the effect of plasma treatment (oxygen and hydrogen) on compressive strength can be observed. The reference sample exhibits the highest

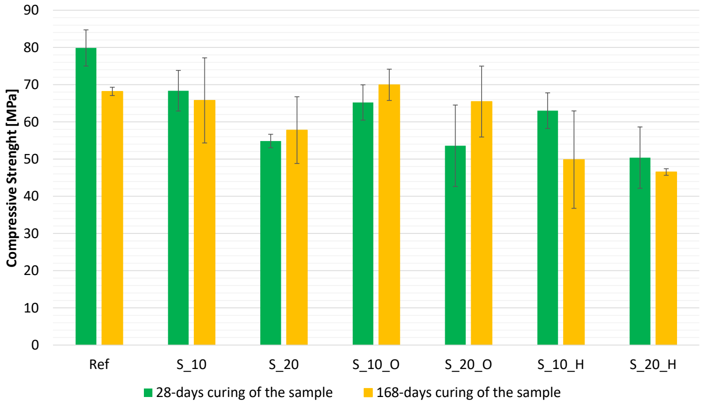

Figure 3. Comparison of the mechanical properties of cement composites with different waste glass additives and the effect of plasma treatment (oxygen and hydrogen) on compressive strength, with the standard deviation indicated in the results..

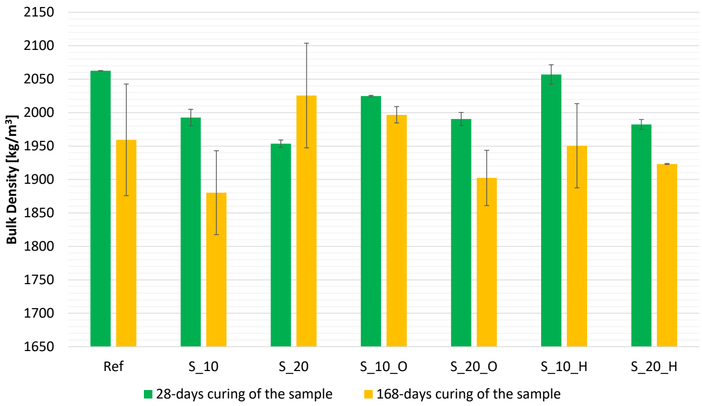

Figure 4. Bulk density values of cement composites after 28 days and 168 days of curing, with the standard deviation indicated in the results.

strength, confirming that the addition of untreated glass powder reduces the mechanical properties of the material (S_10 and S_20). After the application of low-temperature oxygen plasma (S_10_O, S_20_O), an improvement in strength was observed compared to untreated samples, with compressive strength reaching around 70 MPa. Hydrogen plasma (S_10_H, S_20_H) has a similar effect, although some samples achieve lower strength values than those treated with oxygen plasma. This difference may suggest that different types of plasma have varying effects on the microstructure of the material.

When examining the bulk density values shown in Figure 4, the reference sample exhibits the highest bulk density, exceeding $2\,050 \pm 48\,\mathrm{kg\,m^{-3}}$ across all time periods (28 days, 168 days). This result confirms the expected properties of a cement composite without glass additives. Samples containing 10 % (S_10) and 20 % (S_20) glass powder show a slight decrease in bulk density, particularly after 6 months of curing. This decrease can be attributed to the lower density of glass, which is less compact than the cement matrix.

Differences are observed in the samples subjected to plasma treatment. The oxygen plasma treatment (S_10_O, S_20_O) shows a slight increase in bulk density compared to untreated samples, suggesting that plasma treatment may have improved the material's cohesion and density. In contrast, the hydrogen plasma treatment (S_10_H, S_20_H) shows greater variability in the results, especially after 168 days of curing. This may be due to the increased reactivity of the glass surface after treatment and subsequent reactions within the cement matrix, which may have affected the material's stability.

When comparing these findings with the compressive strength results in Figure 3, it is evident that the microstructure, including particle size and morphology, plays a critical role. Untreated glass powder, despite its fine size, showed a detrimental effect on strength at higher substitution levels, e.g., 20 %, likely due to its incompatibility with the cement matrix. However, plasma treatment, particularly with oxygen, improved the interaction between the matrix and glass particles, as demonstrated by increased compressive strength and bulk density values.

The distribution of cement particles, primarily ranging between 10 and 50 µm, ensures adequate binding in the matrix. However, the finer particles of the glass powder enhance the matrix's packing density to some extent. Notably, untreated glass powder exhibits a lower degree of particle interaction with the cement matrix, leading to reduced mechanical properties.

Plasma treatments showed potential to improve these interactions. Specifically, oxygen plasma-treated samples demonstrated improved compressive strength and bulk density, suggesting enhanced cohesion at the particle-matrix interface. On the other hand, hydrogen plasma-treated samples showed less consistent results, potentially influenced by microstructural changes such as alkali-silica reaction (ASR)-induced microcracking, as indicated by future microscopic analyses.

5. Conclusion

The results of this study confirm that low-temperature plasma treatment of finely ground waste glass can significantly enhance the mechanical properties of cement composites. The impact of plasma treatment depends on the type of medium used and the proportion of glass powder in the mixture. The reference sample, without any glass additives, demonstrated the highest compressive strength values exceeding 80 MPa and a bulk density above $2\,050 \pm 48\,\mathrm{kg\,m^{-3}}$, reflecting an optimal microstructure of the cement matrix. In contrast, samples containing 10 % and 20 % glass powder exhibited reduced mechanical performance, highlighting the challenges of efficiently integrating glass powder into composites.

The use of oxygen plasma led to an improvement in the mechanical properties of glass-containing samples, with strength increases of up to 10 % compared to untreated samples. This improvement is attributed to enhanced surface properties and better adhesion between the glass particles and the cement matrix. Conversely, hydrogen plasma treatment yielded mixed results. While some samples (S_10_H) showed improvements in compressive strength and bulk density, others (S_20_H) experienced a decline, likely due to accelerated alkali-silica reaction (ASR), which causes microcracking and destabilization of the composite.

Future research should focus on detailed microstructural analysis using advanced techniques such as scanning electron microscopy (SEM). Understanding the effects of plasma treatment on the surface modifications of glass particles and their interaction with the cement matrix is essential for optimizing the process. Moreover, investigating the effects of ASR-induced microcracking and proposing mitigation strategies will be critical. Long-term testing over a one-year cycle will be vital to validate these findings and support the practical application of plasma-treated waste glass in sustainable construction materials.

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