Assessment of sustainable cement composites with waste material incorporation: Resistance to sulphate attack and property changes

Miriama Cambal Holosova[1*], *Adriana* Estokova[1], and *Alena* Sicakova[1]

[1]Institute for Sustainable and Circular Construction, Faculty of Civil Engineering, Technical University of Kosice, Vysokoskolska 4, 04200 Kosice, Slovakia

Abstract. This study investigates the performance of cement composites incorporating waste materials—blast furnace slag, bypass dust, eggshells, and recycled glass—as partial replacements for cement, following their exposure to sulphate attack in a corrosion chamber. It assesses changes in compressive strength, water absorbency, specific surface area, and degree of hydration post-exposure. A point evaluation system was used to compare the samples based on their resistance to the aggressive environment and the resultant property changes. While scoring differences among the samples were minimal, the reference sample without waste, slag sample and eggshells sample exhibited the best overall performance, whereas the glass-containing sample was the least effective. These results enhance our comprehension of the feasibility of employing specific waste materials as sustainable alternatives in cement composites.

1 Introduction

In the face of escalating environmental concerns, the construction industry stands at a crossroads, seeking sustainable practices that not only address the urgent need for reducing carbon dioxide (CO_2) emissions but also tackle the growing problem of waste management [1]. Among the most significant contributors to CO_2 emissions is the production of Portland cement, a fundamental ingredient in concrete, which accounts for approximately 8% of global CO_2 emissions [2]. This stark reality drives the imperative for innovative approaches to cement production and utilization. This research paper explores the potential of incorporating alternative materials—blast furnace slag, cement kiln dust, eggshells (as a source of calcium carbonate, $CaCO_3$), and recycled glass—into cement, aiming to reduce the carbon footprint associated with its production and decrease the reliance on landfilling for waste management.

The utilization of these supplementary cementitious materials (SCMs) not only offers a pathway to decrease the environmental impact of cement production by reducing CO_2 emissions but also addresses the challenge of managing industrial by-products and waste materials. Blast furnace slag, a by-product of iron manufacturing, and cement kiln dust, produced during cement production, present valuable opportunities for recycling and reuse in cementitious applications, thus diverting them from landfills [3, 4]. Similarly, eggshells,

* Corresponding author: miriama.cambal.holosova@tuke.sk

an organic waste product rich in $CaCO_3$, and recycled glass, offer unique chemical and physical properties that can enhance the performance of cementitious materials [5]. By integrating these SCMs into cement production, this research aims to contribute to the development of more sustainable construction materials, which is vital for the global effort to combat climate change and promote circular economy principles [6].

This study not only evaluates the technical viability of these alternative materials as partial replacements for Portland cement but also assesses their impact on the mechanical properties and durability of the resulting cementitious composites. Through analysis, this research endeavours to provide a foundation for the broader adoption of these SCMs in the construction industry.

An essential aspect of this research is the investigation into the durability of cement composites, particularly their resistance to sulphate attack, a prevalent form of chemical degradation that compromises the longevity and structural integrity of concrete structures. Sulphate attack occurs when concrete is exposed to external sources of sulphate ions, leading to expansive reactions that result in cracking, spalling, and ultimately, structural failure [7]. This challenge is exacerbated in environments with high sulphate content, such as soils, groundwater, sewage pipes and certain industrial effluents [8]. The incorporation of alternative materials like blast furnace slag, cement kiln dust, eggshells, and recycled glass into cement formulations presents an opportunity not only to enhance the environmental profile of construction materials but also to potentially improve their resistance to sulphate-induced degradation. By examining the sulphate resistance of these novel cementitious composites, this study seeks to address a critical aspect of material durability that is vital for the development of more sustainable and resilient infrastructure. The findings on the sulphate resistance properties of these composites will provide valuable insights into their suitability for use in sulphate-rich environments, contributing to the body of knowledge on sustainable construction materials designed for enhanced durability and longevity.

Presented paper focuses on changes in properties that are related to the durability of the material after exposure to an aggressive environment, contributes to the studies on sustainable construction practices, offering insights into the challenges and opportunities of utilizing waste materials as SCMs. It underscores the necessity for an interdisciplinary approach, combining insights from materials science, environmental engineering, and sustainability studies, to address the pressing environmental issues associated with cement production. Ultimately, this research aims to pave the way for a more sustainable construction industry, where the reduction of CO_2 emissions and the effective management of waste materials are central to its practices.

2 Materials and Methods

Changes in properties after exposure of cement composite samples sulphate attack were observed and investigated. The samples, prepared according to the EN 196-1 (2016) standard [9], consisted of cement, drinking water, natural river fine sand, and—apart from the reference sample (C) —included 20% substitutes from blast furnace slag (S), bypass dust (B), eggshells (E), and recycled glass (G). Observations were made on changes in compressive strength, absorbency, specific surface area, and degree of hydration. The compressive strength tests were conducted using a mechanical press (ADR 2000, International Ltd, UK) according to the EN 196-1 (2016) standard [9], the measurement was performed on samples with dimensions 40x40x160 mm, and the results were calculated according to EN 12390-3:2019-07 [10]. Water absorption tests were performed in accordance with STN 73 1316 (1989) [11]. To gather information on the specific surface area, particle analysis was conducted using a Quantachrome Instruments Nova 1000e, utilizing the BET method. The degree of hydration was calculated based on data obtained from thermogravimetric analysis using an STA 449 F3 Jupiter analyzer (Netzsch, Germany). The simulation of sulphate attack was performed in a corrosion chamber (Ascott i120p), using a sulphate solution with a pH of 4. The chamber's cycle was divided into six cycles, occurring four times per day, utilizing a total of 190 litres over three months.

3 Results and Discussion

Changes observed in the properties of cement composite samples, which included cement replacements, after being subjected to simulated sulphate attack in a corrosion chamber are presents on Fig. 1. Fig. 1 displays four graphs illustrating the changes in properties following exposure and their impact on compressive strength, water absorption, specific surface area, and degree of hydration.

An increase in water absorption by the samples suggests a rise in the pore volume within the porous system, as these pores become filled with water. This expansion in pore volume can result from the internal structure's disruption caused by the formation of new compounds, whose increased volume exerts pressure on the matrix walls. This scenario was observed exclusively in the sample containing bypass dust.

A decrease in water absorption signals a reduction in pore volume within the porous system, potentially due to the filling of these pores with hydration products or sulphate compounds. Notably, the slag sample exhibited the most significant reduction in water absorption, surpassing even the performance of the reference sample. The samples containing eggshells and recycled glass followed in the third and fourth positions, respectively (Fig. 1b)).

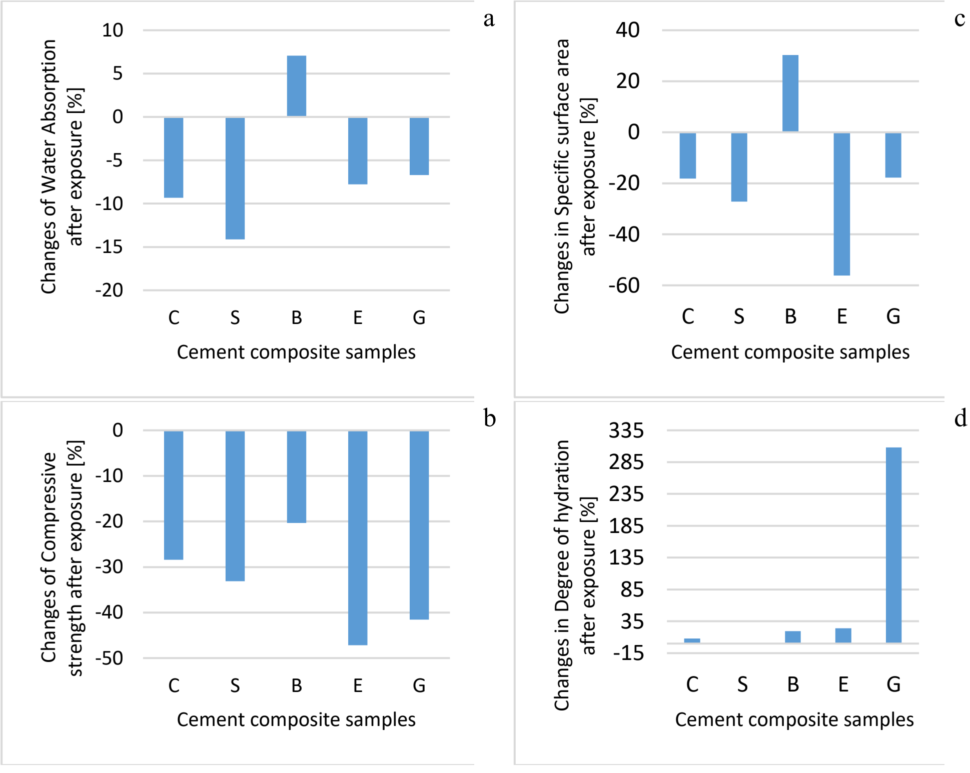

Fig. 1. Changes in properties of cement composite samples after sulphate attack exposure of a) Compressive strength, b) Water absorption, c) Specific surface area, d) Degree of hydration.

The evaluation of changes in strength (Fig. 1a)) is straightforward: an increase in strength, or minimally, the smallest possible decrease, is desirable. Regarding the behaviour of the samples after sulphate attack, the one containing bypass dust exhibited the smallest reduction in strength [12], while the specimen with slag experienced the most significant decrease. The reference sample ranked second in terms of strength retention, whereas the samples with eggshells content suffered larger decrease in strength than the sample containing glass which in this case showed improved performance compared with water absorption ranking.

Like water absorption, the specific surface area is intricately linked to the pore structure of the material. Variations in this property are influenced by whether hydration has occurred, leading to the formation of hydration products, or if corrosion has resulted in the creation of sulphate compounds, or if dissolution and recrystallization processes have occurred. These events can either fill the pores, reducing the specific surface area, or cause leaching of material, which increases porosity and, consequently, the specific surface area [13].

Among the examined samples, the only occurrence of an increase in the specific surface is in the case of bypass dust. This outcome aligns with the water absorption results, suggesting that leaching or matrix degradation occurred. However, it does not account for the minimal reduction in strength observed. The continuation of the hydration process could lead to a reduced specific surface area. Notably, among the samples, the one containing eggshell exhibited the most significant decrease in specific surface area. Given that both water absorption and strength have decreased, this could indicate the formation of new compounds resulting from corrosion processes.

The findings related to the degree of hydration (Fig. 1d)) reveal the extent of hydration within the calcium silicate hydrate (C-S-H) phase following sulphate corrosion. A significant increase is represented by the sample with glass, as it also contains the highest content of SiO_2, which therefore contributed to a significantly greater extent to the calcium silicate hydration phase [14]. The creation of other products in this process is not included, therefore we can say that it is a positive effect on durability parameters. In each case the degree of hydration increased except of sample with slag, where the decrease was very small. It still indicates that hydration of product was depleted in this case.

The evaluation system consists in scoring the samples based on the comparison of individual results with each other for a certain property. At the end, the points for all four properties were summed up, with the lowest number of points indicating the best results. Evaluation points of properties changes after sulphate attack are represented in Table 1.

An interesting observation is that the reference sample does not dominate in either case, which is a good prerequisite for the use of cement replacement with wastes in achieving resistance to aggressive environments.

Table 1. Evaluation points of compressive strength, water absorption, specific surface area and degree of hydration changes after sulphate attack.

	Evaluation points of properties changes after sulphate attack				Sum of Evalution points
	Compressive strenght	Water absoprtion	Specific Surface Area	Degree of hydration	
C	↓ 2	↓ 2	↓ 3	↑ 4	11
S	↓ 3	↓ 1	↓ 2	↓ 5	11
B	↓ 1	↑ 4	↑ 5	↑ 3	13
E	↓ 5	↓ 3	↓ 1	↑ 2	11
G	↓ 4	↓ 5	↓ 4	↑ 1	14

Table 1 presents the ranking of the samples based on the evaluation system, which identifies the most suitable ones according to their individual properties. These rankings reflect how well each sample performed relative to the others after being subjected to sulphate attack. Table 2 presents the order of the samples based on the number of points obtained, where the fewest points mean the best results. The minimal differences in points suggest variability in how the samples responded to individual tests, each demonstrating a mix of strengths and weaknesses. Consequently, they may serve as viable substitutes for cement.

Table 2. Order of samples according to evaluation points.

Composite samples	Evalution points
C	11
S	11
E	11
B	13
G	14

Samples with bypass dust and eggshells seem to have a greater potential as a cement partial replacement to resist aggressive environments.

4 Conclusion

This study explored the use of waste materials—blast furnace slag, bypass dust, eggshells, and recycled glass—as cement replacements in cementitious composites, assessing their performance under simulated sulphate attack in a corrosion chamber. Focusing on changes in compressive strength, water absorption, specific surface area, and degree of hydration after exposure revealed nuanced responses across the samples.

Compressive strength decreased across all samples, with bypass dust showing the least reduction, while eggshell samples experienced the most significant decline.

Water absorption patterns varied, increasing for bypass dust but decreasing for others, particularly in slag samples, which is desirable feature.

A notable correlation between changes in absorbency and specific surface area underscored the interconnected nature of the pore system; bypass dust samples saw increases, whereas eggshell samples showed the most considerable decreases.

The glass sample exhibited the highest degree of hydration, attributed to its siliceous character, contrasting with the varied hydration degrees in other samples, excluding the slag sample which did not show an increase.

Comparative analysis based on an evaluation system assessing resistance to the aggressive sulphate environment showed minimal differences in scores, highlighting the potential of these waste materials as viable cement replacements. Notably, the bypass and glass samples scored only marginally lower than the reference, suggesting that with proper formulation, waste materials can significantly contribute to sustainable cementitious composites.

This paper was supported by VEGA Grant No. 1/0230/21 and 2/0108/23.

References

1. A.G. Araújo, A.M.P. Carneiro, R.P. Palha, J. Clean. Prod. **256** (2020)
2. R.M. Andrew, Earth Syst. Sci. Data **10**, 4 (2018)
3. Y. Li, Y. Liu, X. Gong, Z. Nie, S. Cui, Z. Wang, W. Chen, J. Clean. Prod. **120** (2016)
4. D. Barnat-Hunek, J. Góra, Z. Suchorab, G. Łagód, W. Sup. Cement. Mater. Conc. (2018)
5. S. Paruthi, A.H. Khan, A. Kumar, F. Kumar, M.A. Hasan, H.M. Magbool, M.S. Manzar, CSCM **18** (2023)

6. M. Nodehi, V.M. Taghvaee, CES **2**, 3 (2022)
7. M. Whittaker, L. Black, Adv. Cem. Res. **27**, 9 (2015)
8. S. Moharana, B. Garg, LCES Emph. Sust. Civ. Infrastr. (2016)
9. EN 196-1: 2016, Methods of Testing Cement, Determination of strength. British Standards Institution. (2016)
10. EN 12390-3:2019-07. Testing Hardened Concrete-Part 3: Compressive Strength of Test Specimens; European Committee for Standardization: Brussels, Belgium (2019)
11. STN 731316:1989-05. Determination of Moisture Content, Absorptivity and Capillarity of Concrete (in Czech); Federal Bureau for Standardization and Metrology: Prague, Czech Republic (1989)
12. R.A. Alhorani, S.A. Asaad, R.M. Abendeh, Int. J. Pavement Eng. **23**, 10 (2022)
13. J.J. Thomas, H.M. Jennings, A.J. Allen, CSE **1**, 1 (1999)
14. K. Baltakys, R. Jauberthie, R. Siauciunas, R. Kaminskas, Mater. Sci.-Pol. **25**, 3 (2007)