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ORIGINAL PAPER

Micromechanism of partial replacement of cement by glass powder and analysis of reasonable replacement rate

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Abstract
The inclusion of glass powder in concrete can have an impact on its performance. However, by using an appropriate amount, it is possible to effectively address the issue of cement energy consumption and achieve favorable economic outcomes. The slump test and rheological performance test demonstrate that replacing cement with glass powder can enhance the workability of mortar through improved mixing properties. As the amount of cement replaced by glass powder increases, the slump of the mortar tends to increase as well, while maintaining the same total water consumption due to the low water absorption of glass powder. The addition of glass powder affects both the early and late strength of the mortar. Early inductively coupled plasma mass spectrometry reveals that glass powder dissolves in water, thus influencing the reaction. Nanoindentation and scanning electron microscope-energy dispersive spectrometer analysis demonstrate that glass powder also impacts the nature of hydration products. Furthermore, thermodynamic simulation indicates that the presence of glass powder initially increases and then decreases the amount of calcium hydroxide, while the hydration product C-S-H continues to decrease. Over time, the detrimental voids in the mortar mixed with glass powder gradually diminish. Higher replacement ratios of glass powder result in greater overall porosity. However, as the age of the mixture increases, the discrepancy in total porosity diminishes. Full-cycle analysis suggests that incorporating glass powder can yield positive economic and environmental benefits.

Keywords Glass powder · Concrete · Workability · Mechanical properties · Durability

Introduction

The production of glass is increasing along with industrialization and improved living standards. Consequently, the amount of waste glass is also on the rise. Since glass is non-biodegradable, it takes up a significant amount of space in landfills and contributes to environmental pollution. The proper management of waste glass has become a pressing global environmental issue. One effective solution is to reuse waste glass by partially replacing cementitious materials with glass powder in the production of environmentally friendly and structurally suitable mortars. This approach proves to be feasible and beneficial (Kumar et al. 2022; Nweke et al. 2023).

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A large amount of waste is generated by various industrial activities worldwide. It was found that the permeability and water absorption of glass powder mortar were improved and the ability of sulfate and acid attack was significantly better than that of the control mortar (Mejdi et al. 2022; Mohammed and Hama 2022). Although glass can theoretically be fully recycled, there are still limitations in meeting the quality standards for glass remanufacturing. As a result, the non-recyclable fraction is often discarded and disposed of in landfills. Worldwide landfill glass is estimated to be about 200 Mt/year, with very low recycling rates (Abendeh et al. 2021; Al-Kheetan et al. 2021; Ali et al. 2021; Bayraktar 2021).

The quantity and particle size of waste glass powder added to the mortar have an impact on its durability performance. Mortars with glass powder exhibit favorable characteristics, including low dry shrinkage. There are indications that the inclusion of glass powder reduces the permeability of chloride ions in the mortar, which consequently lowers the risk of reinforcement-induced corrosion. By incorporating glass powder as an admixture at a range of 20–30% in 40 MPa mortars, the utilization of waste glass in mortars can generate significant value and contribute to a reduction in greenhouse gas emissions from the cement industry (Borges et al. 2021; Bilgen 2022). The glass powder used replaces the active powder to make the active powder mortar, which can make the mortar with the maximum compressive strength value of 90 MPa (Boukhelkhal 2021; Bueno et al. 2021; Cercel et al. 2021).

Incorporating glass powder in mortars can result in a decrease in early compressive strength and modulus of elasticity. However, when the glass powder content is kept below 20%, it can enhance the later compressive strength and modulus of elasticity. Moreover, using glass powder content below 20% can significantly reduce creep, with the optimal amount for minimizing creep appearing to be at 20% glass powder content. Therefore, careful consideration should be given to the glass powder content to achieve the desired balance between strength, elasticity, and reduced creep in the mortar (Darwich Higuchi et al. 2021; Dawood and Abdullah 2021; Deng et al. 2021; Dong et al. 2021).

Li and Tier (Li and Tier 2022) found that the partial replacement of cement with glass powder helps to improve the workability of mortar, but due to the replacement of glass powder, it leads to the reduction of hydrated cementitious material and an increase in porosity. Tremino et al. (n.d.) found that the compressive strength and ultrasonic pulse velocity of the specimens with added glass powder were similar to or even higher than those of the reference specimens. Barkauskas and Nagrockiene (Barkauskas and Nagrockiene 2022) showed better physical and mechanical properties and higher resistance to alkali-aggregate reaction in specimens containing 20% composite zeolite additions compared to the reference specimens without additions.

In this paper, the effects of glass powder with different substitution rates on the properties of mortar were studied. The microscopic mechanism was analyzed by ICP-MS and other microscopic analysis methods, and the economic and environmental benefits brought by glass powder were analyzed by the LCA method.

Materials and methods

Materials

PII42.5 silicate cement was used, and the recycled glass was ground. In order to reduce the influence of glass powder particle size on the test, the particle size distribution of raw materials was analyzed by laser particle size meter, and glass powder with particle size similar to that of cement was used (Fig. 1). The main chemical compositions of cement and glass powder are shown in materials

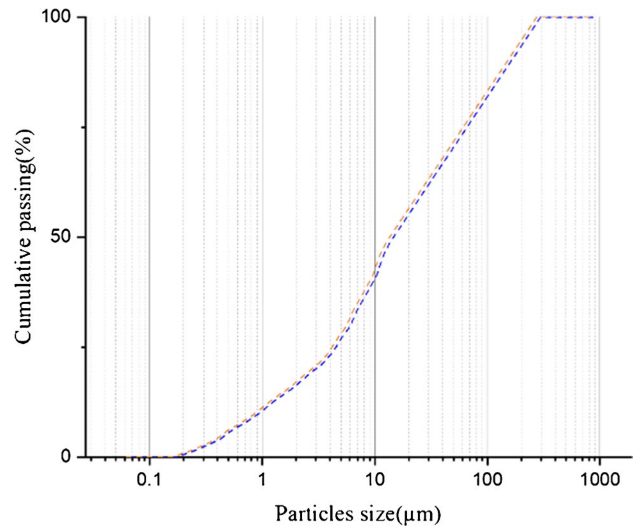

Fig. 1 Particle size distribution of materials

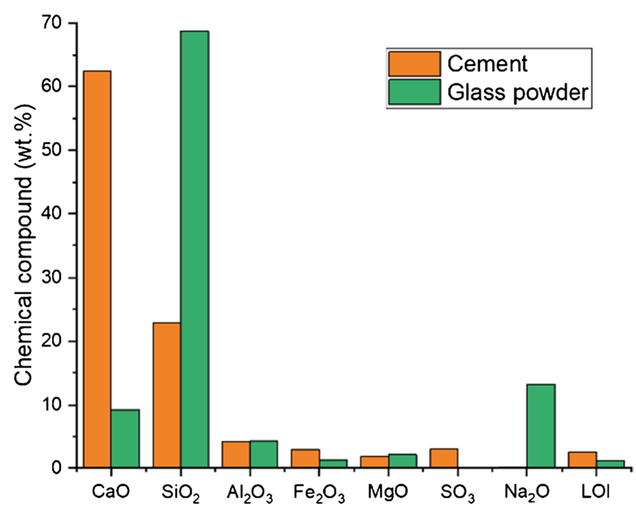

Fig. 2 Chemical composition of cement and glass powder

Fig. 2. The silica content of glass powder is higher, and the calcium oxide content of cement is higher.

Mix proportion

The blending amount of glass powder is 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%. In order to reduce the effect of water absorption of glass powder, the water absorption of glass powder is measured to be 4%, and the glass powder is wetted first, and then, the corresponding water is added, and the matching ratio is shown in Table 1.

Table 1 Proportion of concrete

Substitution	Glass powder (g)	Water (g)	Cement (g)	Standard sand (g)
0%	0	225	450	1350
10%	45	202.5	405	1350
20%	90	180	360	1350
30%	135	157.5	315	1350
40%	180	135	270	1350
50%	225	112.5	225	1350
60%	270	90	180	1350
70%	315	67.5	135	1350
80%	360	45	90	1350
90%	405	22.5	45	1350
100%	450	0	0	1350

Workability and compressive strength

The impact of glass powder on mortar workability was assessed by evaluating the flow rate of the cement-sand mixture. The setting time was also determined based on applicable standards. Specimens measuring 70.7 mm × 70.7 mm × 70.7 mm were manufactured and cured for 7, 28, and 90 days. The compressive strength of the cement mortar specimens was then tested using a pressure testing machine (UTM-69).

Inductively coupled plasma mass spectrometry

To understand how glass powder affects the early hydration of the cement paste, the early pore solution of the paste was characterized using PerkinElmer's NexION 2000.

Scanning electron microscope-energy dispersive spectrometer

Hitachi S-3400 N scanning electron microscope equipped with Oxford Inca Energy 250 energy dispersive spectrometer was used for inspection. The accelerating voltage and magnification are set to 15 kV and × 400, respectively, allowing analysis of 300 μm × 240 μm surfaces. Energy dispersive spectrometer spot analysis is performed on approximately 100 micro-volumes, using a 20-s dwell time to achieve a count of more than 100,000 times per spectrum.

Mercury intrusion porosimetry and ultrasonic pulse velocity

The pore structure of the mortar samples at 28 days and 90 days was analyzed using the mercury intrusion porosimetry test conducted with the Quantachrome Poremaster GT-60 Instrument. It is important to note that mercury intrusion porosimetry can only measure connected pores. To gain a comprehensive understanding of the cement's durability, the ultrasonic pulse velocity test was employed as a non-destructive method. This test measures the velocity of ultrasonic pulses traveling through the cement and helps assess its durability. The ultrasonic pulse velocity device consists of a transmitting and receiving transducer, along with an indicator that displays the arrival time. All ultrasonic pulse velocity tests were conducted using the Pundit Lab instrument.

Life cycle assessment

A full-cycle analysis of glass powder was conducted according to the methodology provided by Tucker et al. to determine the environmental and economic benefits obtained (Tucker et al. 2018).

Thermodynamic modeling

Thermodynamic modeling was performed using the Gibbs free energy minimization software (GEMS), which calculates the phase combinations at equilibrium based on the initial volume composition of the system. The default PSI-Nagra thermodynamic database of hydration products and solids was extended with additional data related to cementitious materials, namely, Cemdata18. According to the CSHQ model originally proposed by Kulik, C-S-H was modeled as an ideal solid solution between jennite, tobermorite, NaSH, and KSH.

Results and discussions

Workability

Under the condition of constant water binder ratio, the influence of different glass powder content on the fluidity of cement mortar is shown in Fig. 3. It can be seen from Fig. 3 that the expansion of the mixture increases with the increase of the amount of glass powder replacing cement. Due to the small water absorption of glass powder, the free water that does not participate in cement hydration increases under the condition that the total water consumption remains unchanged, resulting in an increase in the expansion of the mortar. When the substitution rate is 100%, although the glass powder does not have cohesion, a degree of expansion can still be obtained according to the same experimental steps. A formula can be obtained by fitting

$$y = y_0 + A_1\left(1 - e^{-\frac{x}{t_1}}\right) + A_2\left(1 - e^{-\frac{x}{t_2}}\right) \quad (1\text{-}1)$$

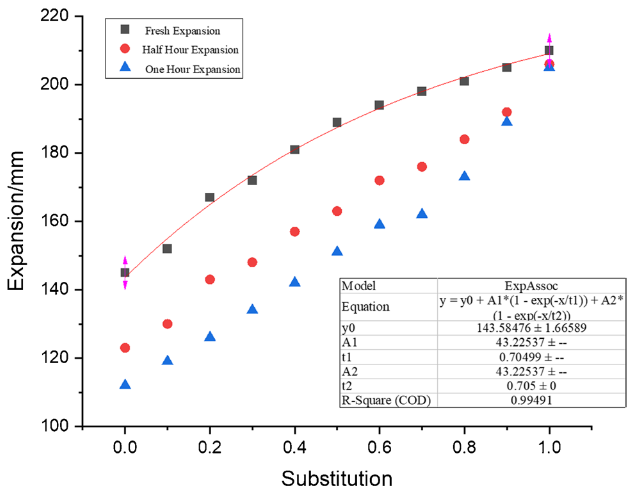

Fig. 3 Effect of glass powder on expansion

The influence of the expansion degree may be two, in which A_1 may represent the influence of the substitution rate, A_2 may represent the influence of the friction force, and the influence of the two determines the influence of the glass powder on the slump.

It can be seen from Fig. 4 that the more glass powder is added, the longer the setting time of the composite cementitious material is. The utilization of glass powder in place of cement leads to a decrease in the concentration of cement particles within the composite cementitious material. As a result, the effective water-cement ratio increases, which negatively impacts the hydration rate of the cement. This reduction in the hydration rate subsequently decreases the formation rate of C-S-H gel and slows down the development of the spatial network structure in the cement-based system. Consequently, both the initial setting time and final setting time of the cement are increased to a certain extent. It is worth noting that the higher the replacement rate of glass powder, the lower the content of cement paste in the composite cementitious material, further slowing down the hydration rate and therefore prolonging the initial and final setting time of the cementitious material.

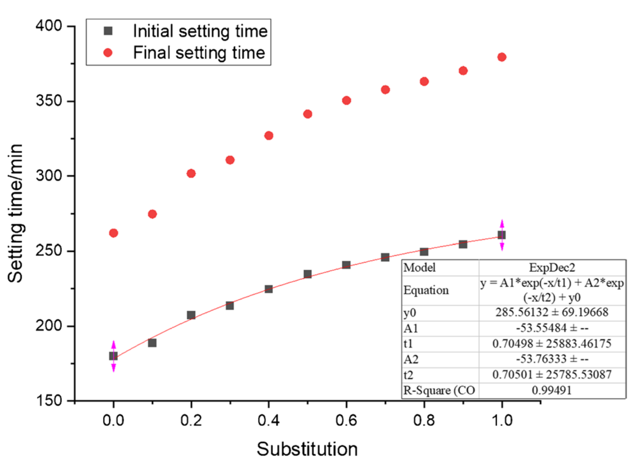

Fig. 4 Effect of glass powder on setting time

Compressive strength

It can be seen from Fig. 5 that the addition of glass powder leads to a decrease in compressive strength. With the increase of age, the decreasing trend of compressive strength of mortar slows down. This may be due to the fact that the volcanic ash of glass powder in the early stage of cement hydration is not strong, and only the filling effect of micro-aggregate is exerted. In the later stage of hydration, the volcanic ash effect of glass powder gradually increases, which shows that the decreasing trend of mortar strength slows down, and glass powder can be filled into the void of mortar to further improve the later strength of mortar. With the increase of glass powder content, the effective C-S-H hydration products are further reduced, and the compressive strength of glass powder decreases. However, with the appearance of volcanic ash effect of glass powder, the decrease gradually decreases. A formula can be obtained by fitting

$$y = y_0 + A_1 e^{-\frac{x}{t_1}} + A_2 e^{-\frac{x}{t_2}} \quad (1\text{-}2)$$

A_1 and A_2 may represent the influence of volcanic ash effect and filling effect on compressive strength.

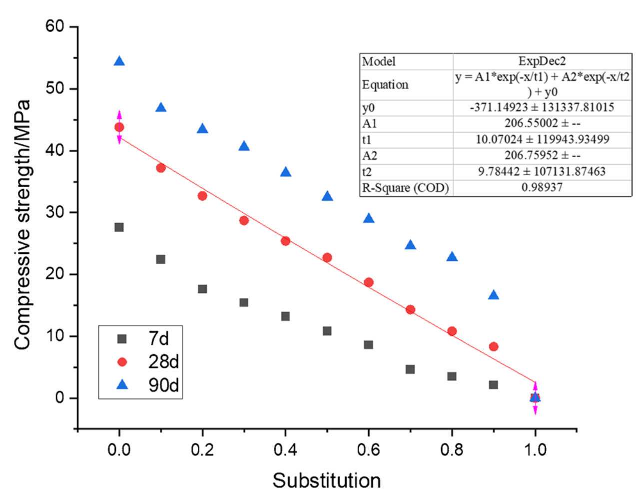

Fig. 5 Effect of glass powder substitution rate on compressive strength

Inductively coupled plasma mass spectrometry

From Fig. 6, it can be seen that with the increase of the substitution rate of glass powder, the concentration of sodium ions increases, which indicates that the glass powder is dissolved in water, but the early strength is low, which may be related to the slow volcanic ash effect, and also, the Al ion concentration decreases more obviously, on the one hand, it may be due to the reduction of cement, and on the other hand, it may be caused by the inhibition effect of glass powder on Al ions. Because of the low Ca content of glass powder, the early Ca ion concentration appears to decrease significantly with the increase of glass powder substitution rate, and also, the cement hydration and volcanic ash reaction cannot be separated from Ca ion, so this also explains the decrease of strength when the glass powder substitution rate is higher, which has no obvious effect on Si due to the low solubility of Si.

Scanning electron microscope-energy dispersive spectrometer analyses

From Fig. 7, the addition of glass powder does indeed have an impact on the Ca/Si ratio of the hydration products. As the substitution rate increases, both at 28 days and 90 days, the Ca/Si ratio tends to decrease. This is because glass powder contains less Ca but is rich in Si. Therefore, the addition of glass powder not only influences the quantity of hydration products but also affects their properties due to the change in the Ca/Si ratio.

Mercury intrusion porosimetry

Mercury intrusion porosimetry was used to evaluate the durability performance of mortar for 28 days and 90 days. The results of total porosity are shown in Fig. 8. The pores in the gelling material can be divided into gel pores (< 10 nm), medium pores (10–100 nm), capillary pores (100–1000 nm), and large pores (> 1000 nm), which are reported to be

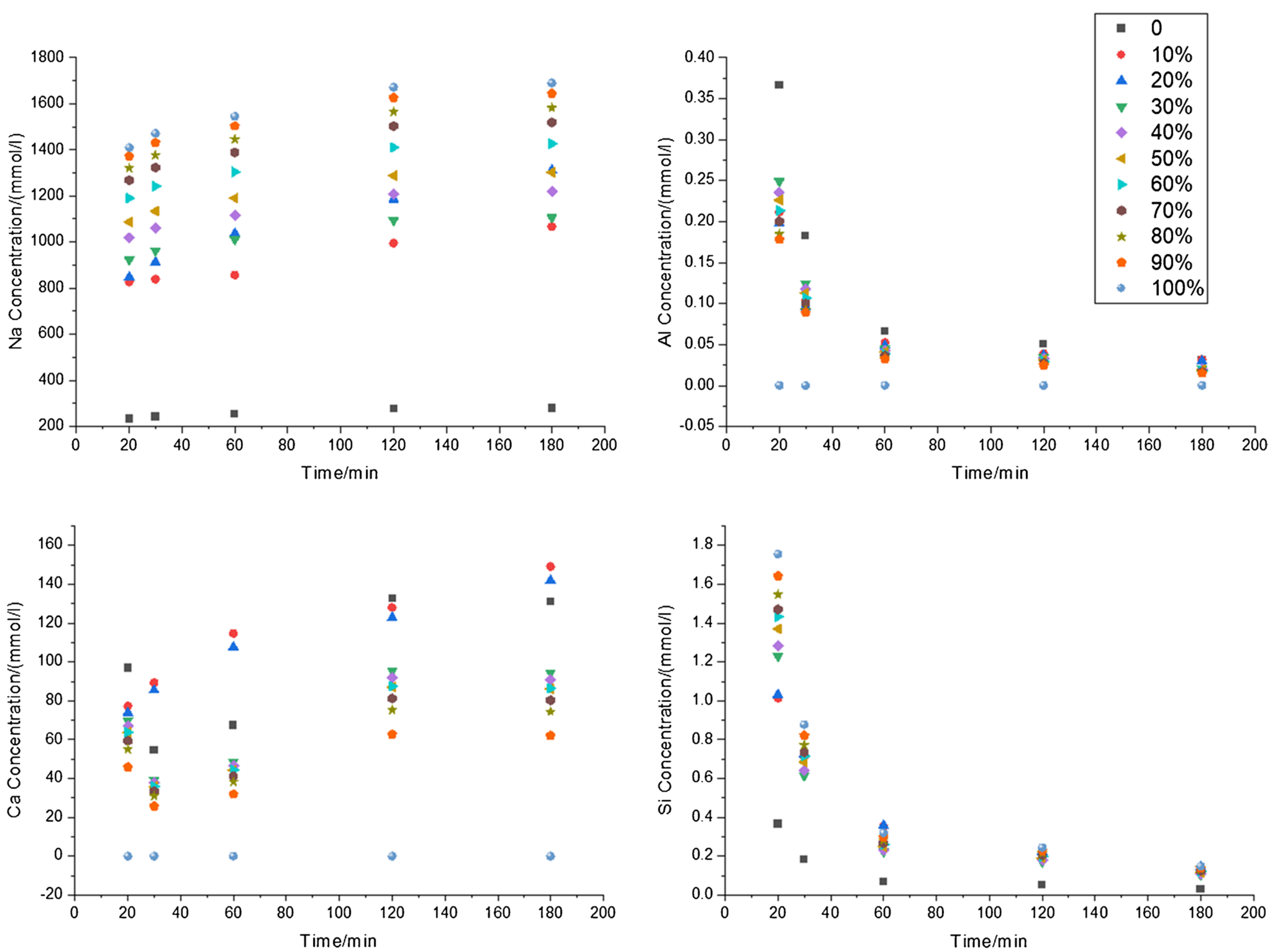

Fig. 6 Effect of glass powder on ion concentration

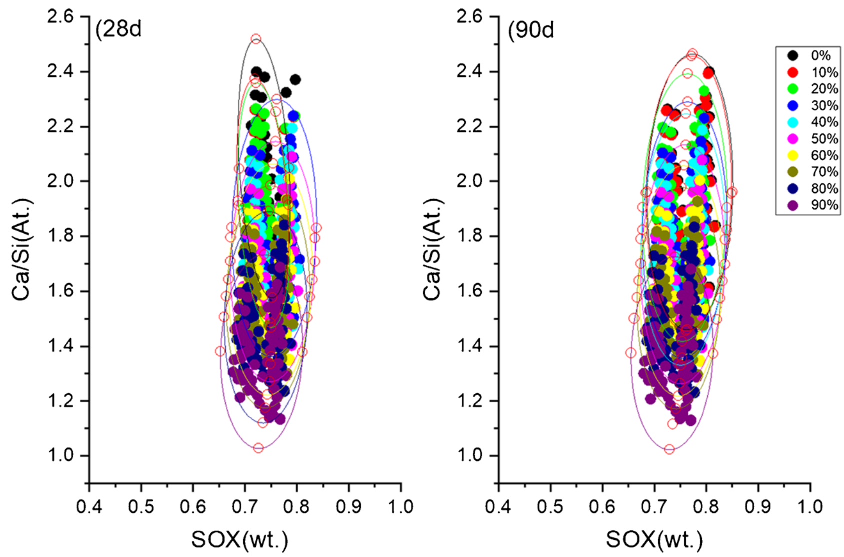

Fig. 7 Comparison of scanning electron microscope-QEDS data points for C-S-H after 28 days and 90 days of hydration

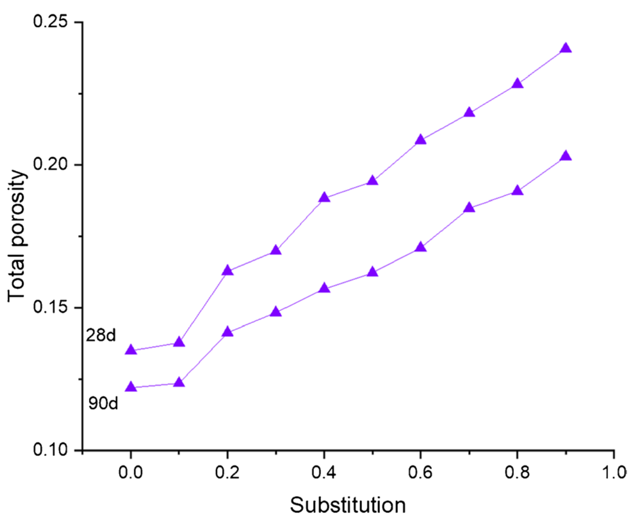

Fig. 8 Total porosity of mortar at different ages

harmless or less harmful to the gelling material below 100 nm. Figure 9 gives the volume percentage of each pore size for 28- and 90-day mortar. From Fig. 8, it can be seen that the total porosity becomes larger with the increase in glass powder substitution rate, and the total porosity at 28 days is larger than that at 90 days.

From Fig. 9, with the increase of substitution rate, < 10 nm, 10–100 nm pore structure decreases, indicating that the reduction of favorable pores and harmful pores increased. The pores of 100 nm–1 μm and 1 μm–10 μm increase, and the two account for the largest proportion in many pores, and the pores larger than 10 μm decrease. It may be due to the micro-aggregate filling pore effect of glass powder; the late pozzolanic reaction effectively fills the pores generated by the hydration reaction, reduces the evaporation of water, and weakens the drying shrinkage of mortar. The incorporation of glass powder can improve the durability of mortar and reduce the damage caused by glass to the environment.

Ultrasonic pulse velocity

The mercury intrusion porosimetry test results show the results of connected pores, in order to better measure the durability of cement-based materials, through the ultrasonic pulse velocity value in Fig. 10. Indeed, it is observed that the ultrasonic pulse velocity value tends to decrease as the substitution rate of glass powder increases. However, at 90 days, due to the complete hydration reaction of cement and the secondary hydration reaction of glass powder, the gap decreases. This phenomenon indicates that although the early stages may not be favorable for durability, with the occurrence of additional reactions such as the volcanic ash reaction, the durability of the material improves over time.

Life cycle assessment

Since glass powder can partially replace cement by just collecting and processing, it can be seen from Fig. 11 that the energy consumption and environmental pollution are much less than cement, and in addition, better economic benefits can be obtained. From the above, it can be seen that there is no significant effect on the performance with the right amount of admixture, and in addition, compared with the traditional recycling process, adding glass powder to concrete can obtain more excellent performance.

Thermodynamic modeling

The simulation was carried out for variable hydrocolloid ratio, and the results of hydration products are shown in

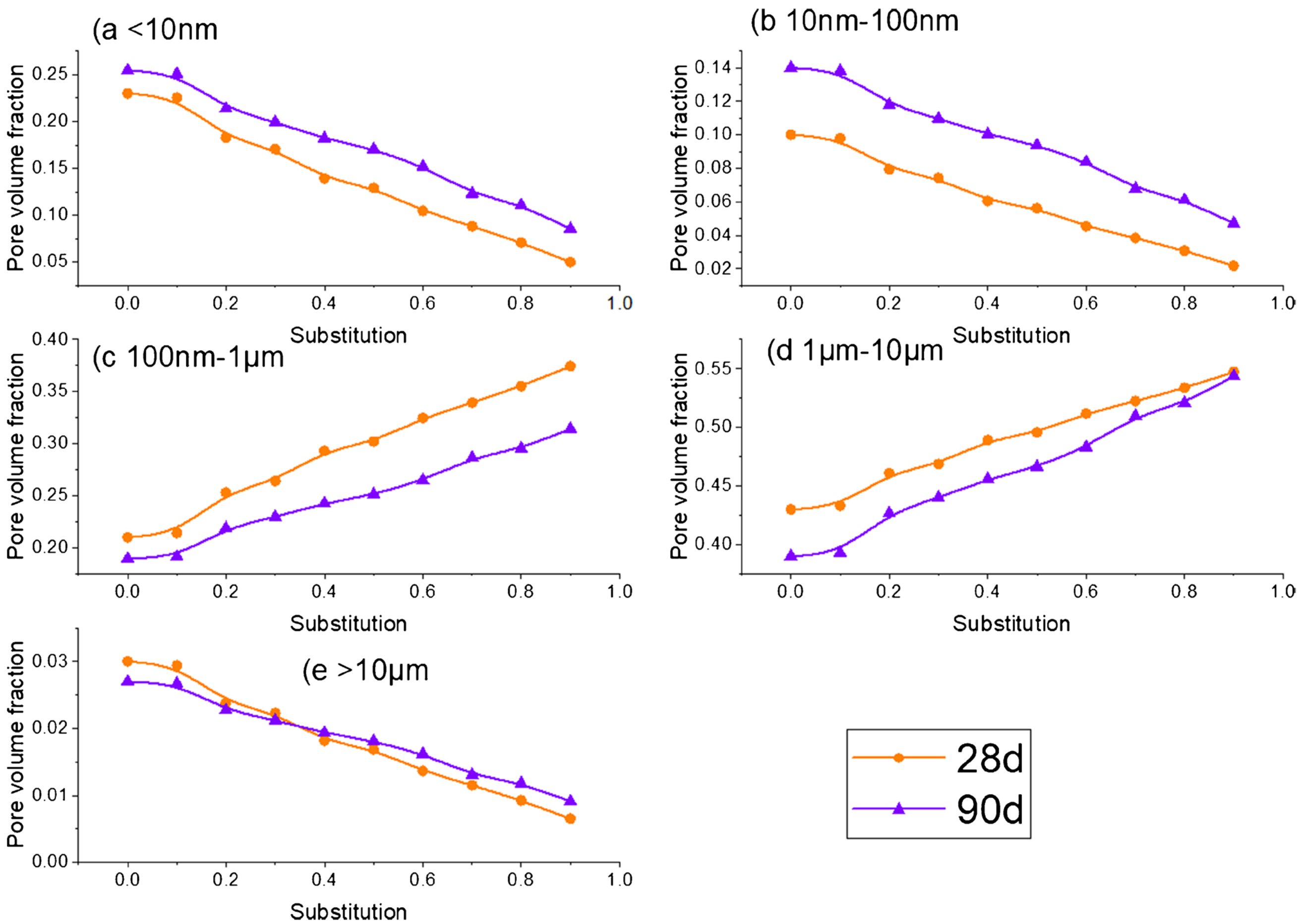

Fig. 9 **a–e** Volume ratio of mortar pore sizes for 28 and 90 days

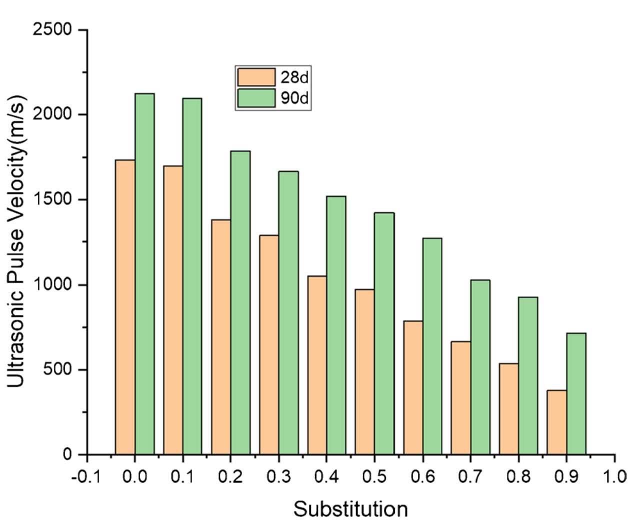

Fig. 10 Effect of glass powder on ultrasonic pulse velocity

Fig. 12. As the substitution rate of glass powder increases, the content of calcium hydroxide initially increases and then decreases, while the content of C-S-H gradually decreases. It is important to note that the simulation cannot accurately represent substitution rates above 40% due to the inability to achieve thermodynamic equilibrium. However, in experimental studies, some strength is still observed despite this limitation.

Conclusion

The incorporation of glass powder into concrete can indeed have an impact on its performance. However, when used in a reasonable amount, it can effectively address the issue of cement energy consumption and yield positive economic benefits. Here are some key observations regarding the effects of glass powder on concrete:

(1) Slump test and rheological performance: The replacement of cement with glass powder can enhance

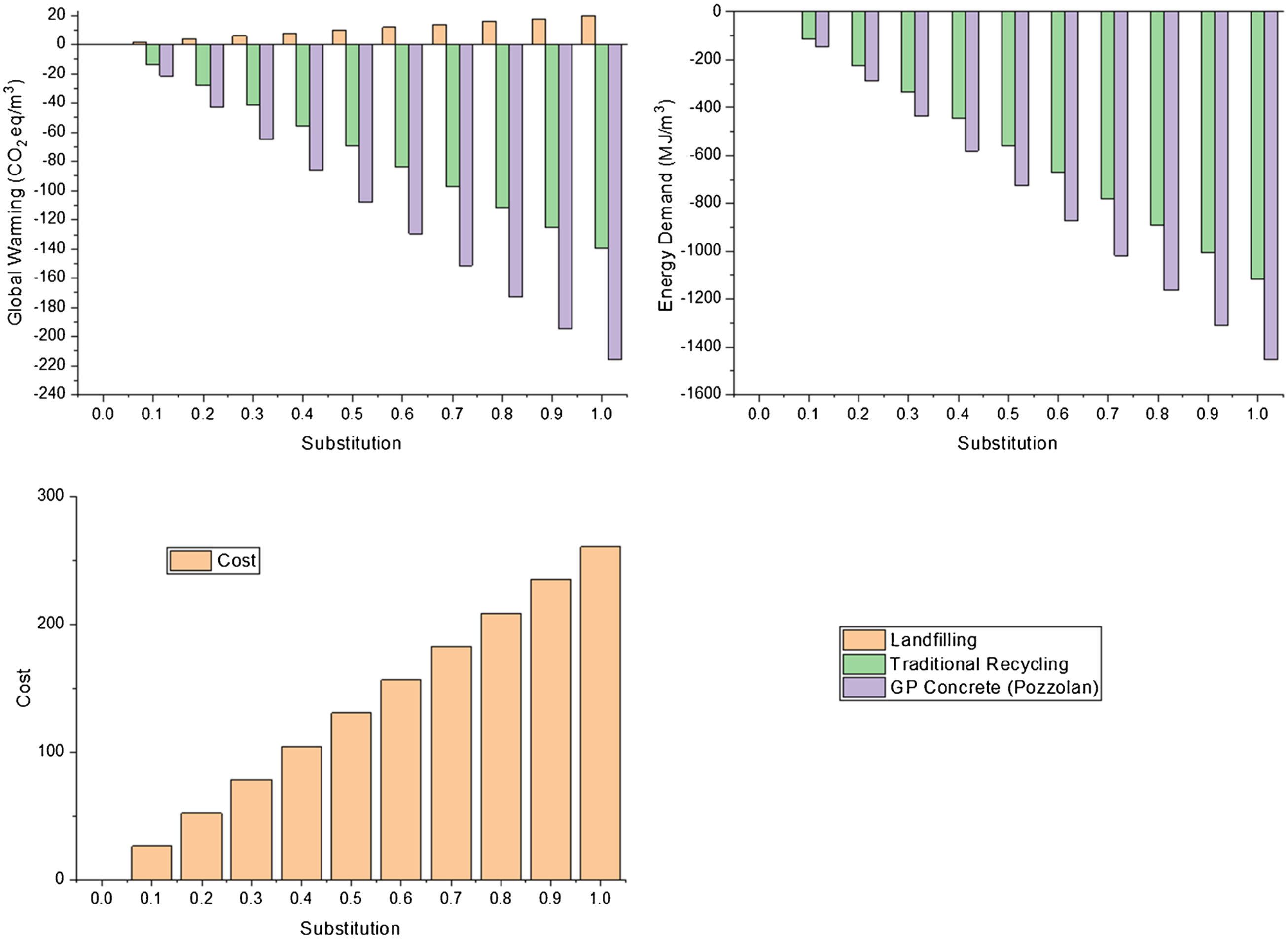

Fig. 11 Life cycle assessment

the workability of mortar by improving its mixing properties. The slump of mortar tends to increase as the amount of cement replaced by glass powder increases. This is due to the lower water absorption of glass powder, which results in increased slump while keeping the total water consumption unchanged.

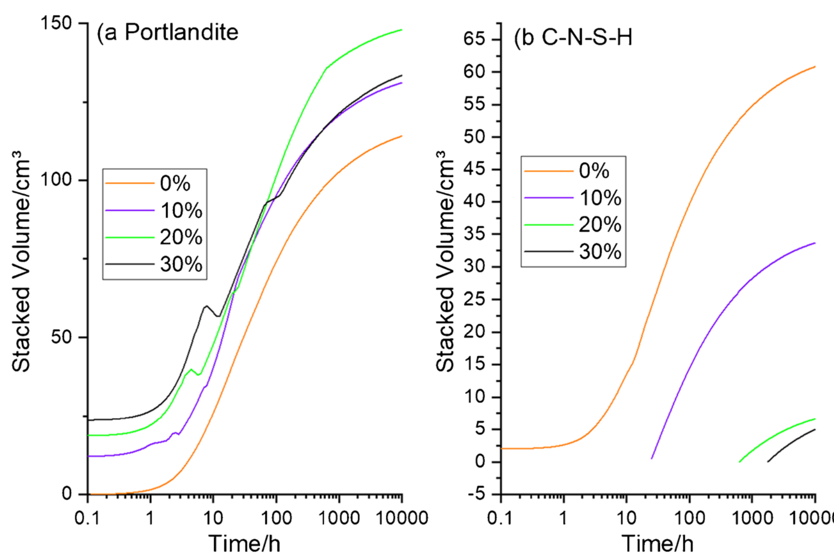

Fig. 12 Thermodynamic simulation results (**a** Effect of glass powder on Portlandite (**b** Effect of glass powder on C-N-S-H

(2) Early and late strength: The inclusion of glass powder affects both the early and late strength of mortar. Tests such as inductively coupled plasma mass spectrometry, nanoindentation, and scanning electron microscope-energy dispersive spectrometer (SEM-EDS) analysis reveal that glass powder dissolves in water, affecting the reaction and nature of hydration products. Thermodynamic simulations show that the content of calcium hydroxide initially increases and then decreases, while the hydration products C-S-H continuously decrease.
(3) Reduction of harmful voids: With the passage of time, the presence of harmful voids in mortar mixed with glass powder gradually decreases. A higher substitution rate of glass powder leads to greater total porosity. The decrease in hydrated cementitious material and the increase in porosity occur due to the replacement of glass powder. However, as the age of the concrete increases, the difference in total porosity diminishes. Full-cycle analysis demonstrates that the incorporation of glass powder can yield favorable economic and environmental benefits.

Overall, the addition of an appropriate amount of glass powder in concrete can enhance its workability, influence strength development, and contribute to the reduction of harmful voids, leading to positive economic and environmental outcomes.

Data availability Data available on request from the authors.

Declarations

Conflict of interest The authors declare no competing interests.

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