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Research Article

Evaluation of the effectiveness of glass waste powder in improving the durability of sand concretes

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ABSTRACT

The accumulation of municipal solid waste, including glass, poses significant environmental challenges worldwide. This study aims to evaluate the effect of waste glass powder (GP), used as a partial cement replacement in sand concrete, on its durability properties. Sand concrete mixtures were prepared by substituting cement with GP at mass proportions of 0%, 10%, 20%, 30%, and 40%. The durability performance was assessed through accelerated carbonation, total water immersion absorption, capillary water absorption, freeze-thaw cycling, wetting-drying cycling, and resistance to hydrochloric acid attack (5% HCl). Scanning electron microscopy (SEM) analysis was also conducted on specimens exposed to the acid solution. The results showed that increasing GP content generally increased the carbonation depth; however, the mixture containing 10% GP (SC-GP10%) exhibited the best resistance to accelerated carbonation, with a reduction in carbonation depth of approximately 15.41% compared to the control mix (SC-WGP). Similarly, the 10% GP mix exhibited superior resistance to freeze-thaw and wetting-drying cycles, with reductions in compressive strength loss reaching approximately 9.40% and 40.70%, respectively, relative to the control mix. Nevertheless, the incorporation of waste glass powder in sand concrete increased both total immersion absorption and capillary absorption. SEM observations on acid-exposed specimens revealed progressive surface degradation at the microstructural level, including the formation of micro-cracks and the presence of fine voids across the specimen surfaces, indicating a gradual deterioration of the cementitious matrix under hydrochloric acid attack. These findings indicate that, among the studied proportions, the incorporation of 10% waste glass powder as a partial cement replacement represents the optimal dosage for enhancing the overall durability of sand concrete. This approach not only offers a viable and sustainable solution for improving concrete performance but also contributes to the reduction of solid waste accumulation and the promotion of eco-friendly construction practices.

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1. Introduction

In recent years, the demand for raw materials in construction has increased significantly. Given the high costs associated with transporting conventional aggregates from one region to another, the exploitation of locally available materials, such as dune sand, river sand, and large deposits of natural and artificial fines, has become an economically viable solution, either to partially or totally replace a main constituent of ordinary concrete (aggregates or cement), or to formulate alternative concrete types, such as sand concrete (Chauvin and Grimaldi 1988). Although sand concrete and cement mortar are both produced without coarse aggregates, they differ in their mix design, performance, and intended applications. Cement mortar is generally composed of cement, fine sand, and water and is mainly used for masonry, plastering, and repair works, where high structural strength is not the primary objective. In contrast, sand concrete is specifically proportioned using optimized grading of one or more sand fractions, often combined with mineral additions and chemical admixtures, to obtain a dense granular skeleton with enhanced mechanical strength and durability. Consequently, sand concrete is regarded as a structural cement-based material, whereas cement mortar is primarily intended for non-structural applications (Bederina et al. 2005; Chauvin and Grimaldi 1988).

On the other hand, environmental pollution resulting from the extraction of raw materials, such as cement, and the increasing volume of waste, particularly industrial waste, has led researchers to explore the recovery and integration of waste materials into concrete compositions. Several studies have demonstrated that the incorporation of waste, in various forms, into concrete can improve its properties (Chen et al. 2002; Shi and Zheng 2007; Zeghichi et al. 2012). Incorporating waste into concrete, therefore, represents a technical, environmental, and economic solution for reducing raw material consumption and landfill accumulation (Mathur 2006; Schwarz et al. 2008; Idir et al. 2010; Nassar and Soroushian 2012; Aly et al. 2012; Mahmud et al. 2025; Ünal and Canbaz 2025).

Among the various types of waste, glass has attracted considerable attention from researchers due to its wide availability, low recycling cost, and its ability to be recycled without loss of quality (Sobolev et al. 2007). Glass powder is generally considered a pozzolanic material owing to its relatively high amorphous silica content (Idir et al. 2011; Shi et al. 2005). The potential of waste glass powder to support resource-efficient construction and circular-economy practices has also been demonstrated (Ünal and Canbaz 2026). Several studies have explored the use of waste glass as either an aggregate substitute or a partial cement replacement in concrete (Meyer et al. 2001; Park et al. 2004; Topcu and Canbaz 2004; Sangha et al. 2004; Shao et al. 2000; Chen et al. 2002; Shayan and Xu 2006; Taha and Nounu 2008). Moreover, replacing 20% of cement with glass powder has been reported to reduce CO₂ emissions by approximately 18% (Islam et al. 2017).

Regarding durability performance, several investigations have been conducted on the effect of glass powder

on the durability of ordinary concrete and mortar. Schwarz et al. (2008) reported that fine glass powder improved the resistance of concrete to chloride ion penetration, showing performance comparable to that of fly ash. Jain and Neithalath (2010) confirmed that glass-powder-modified concretes exhibited lower chloride diffusion coefficients. Matos and Sousa-Coutinho (2012) found that mortar containing waste glass powder as a cement replacement showed enhanced resistance to chloride ingress and acceptable carbonation performance. Jain et al. (2020) demonstrated improved durability of concrete incorporating waste glass powder, particularly in terms of water absorption and acid resistance. Bulut (2024) evaluated capillary water absorption and acid resistance in waste-modified concrete as key indicators of durability performance. Siad et al. (2016) investigated the effect of glass powder on sulfuric acid resistance and reported improved performance of glass-powder-containing cementitious materials. Adesina and Das (2020) showed that glass powder enhanced the durability properties of engineered cementitious composites. Furthermore, Salim and Mosaberpanah (2021) reported improved durability of high-performance mortar containing waste glass powder under different curing regimes. Ramakrishnan et al. (2017) also observed enhanced durability when glass powder was used as a supplementary cementitious material combined with ground granulated blast furnace slag.

However, a critical review of the existing literature reveals that the majority of durability studies on glass powder have been conducted on ordinary concrete and mortar, while very limited research has addressed the durability behavior of sand concrete incorporating glass powder as a partial cement replacement. Sand concrete differs fundamentally from ordinary concrete in its composition, as it lacks coarse aggregates and relies on fine sand as the primary aggregate, resulting in a distinct pore structure and transport properties that may significantly influence durability performance. This gap in the literature is particularly important given the growing interest in sand concrete as a sustainable construction material in regions with abundant sand resources and limited gravel availability.

In a previous study, Ammari et al. (2023) investigated the effect of glass powder incorporation on the physical and mechanical properties of sand concrete, considering different dosages of glass powder from 0 to 40%. The results showed that glass powder effectively enhanced the physical and mechanical properties of sand concrete, with 10% identified as the optimal replacement level for mechanical performance. Nevertheless, the durability behavior of these glass-powder-based sand concrete mixtures remained unexplored, which is essential for validating the practical applicability of this material in real construction environments.

Therefore, the present study aims to fill this gap by comprehensively evaluating the durability performance of sand concrete containing waste glass powder as a partial cement replacement at dosages ranging from 0 to 40%. The durability assessment includes accelerated carbonation, total water immersion absorption, capillary water absorption, freeze-thaw cycling, wetting-drying cycling, resistance to hydrochloric acid attack, and scan-

ning electron microscopy (SEM) analysis. This comprehensive investigation provides new insights into the long-term performance of glass-powder-based sand concrete and establishes a complete characterization framework complementing the previously reported mechanical properties.

2. Materials Description and Testing Procedures

2.1. Materials description

The fine aggregates employed in this investigation consist of two locally sourced sands: a dune sand (DS), extracted from the southern area of El Oued city (Algeria), and a river sand (RS), obtained from the southeastern zone of El M'Ghair city (Algeria). The particle size of DS does not exceed 0.63 mm, whereas RS has a maximum grain diameter of 5 mm. To achieve an adequate

particle size distribution, both sands were blended to produce a mixed sand (RDS) following a grain size correction approach, in which the fine fraction of RS was adjusted by the addition of DS. The sands were blended at an RS-to-DS mass ratio of 1.7:1. This ratio was selected based on previous studies, which demonstrated that it provides an appropriate particle size distribution by combining the coarse fraction of river sand with the fine fraction of dune sand. This optimized grading contributes to a denser granular skeleton, which is considered advantageous for sand concrete production (Bederina et al. 2005; Ammari et al. 2021). The mineralogical characterization of the sands, carried out by X-ray diffraction (XRD) analysis (Figs. 1 and 2), confirmed their predominantly siliceous nature, with minor traces of calcium carbonate (CaCO_3) also detected. Moreover, the physical characterization results, summarized in Table 1, indicate that the mixed sand RDS meets the cleanliness requirements specified by standard NF P18-598 (1991).

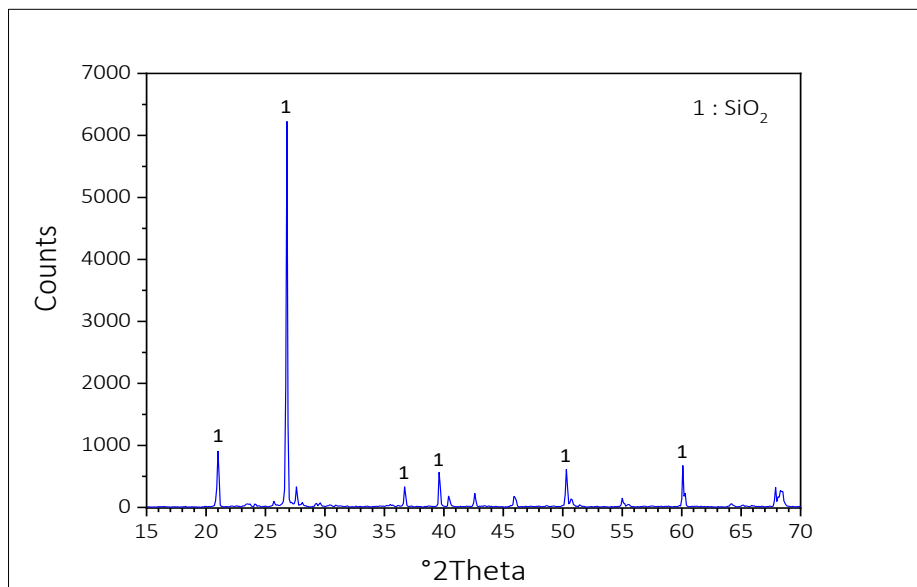


Fig. 1. X-ray diffraction (XRD) pattern of the utilized dune sand (DS).

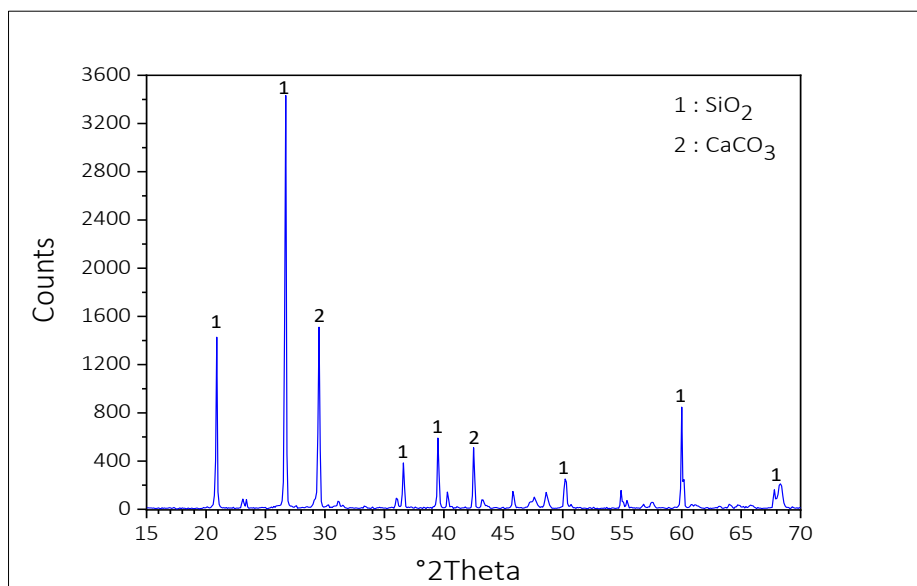


Fig. 2. X-ray diffraction (XRD) pattern of the utilized river sand (RS).

Table 1. Physical characteristics of the used sand (RDS).

Maximum diameter (mm)	5
Apparent density (kg/m ³)	1577
Absolute density (kg/m ³)	2570
Fineness modulus	2.2
Compactness (%)	61.36
Porosity (%)	38.64
Visual sand equivalent (%)	92.02
Piston sand equivalent (%)	77.13

The binding material adopted in this study is a Portland composite cement, designated as CEM II/B-L 42.5N, conforming to the Algerian standard NA 442 (2013). This cement type incorporates limestone as a secondary constituent and belongs to the normal early strength class (42.5N). The measured absolute density and Blaine specific surface area of the cement are 3080 kg/m³ and

449 m²/kg, respectively, and its detailed chemical composition is provided in Table 2. Given the inherently high porosity of sand concrete resulting from the absence of coarse aggregates, it is essential to optimize the particle packing density by filling the intergranular voids within the fine fraction of the sand. For this purpose, a limestone filler was incorporated as a fine mineral addition. This filler plays a fundamental role in the formulation of sand concrete by completing the grain size distribution curve and reducing the overall porosity of the mixture, as highlighted by Chauvin and Grimaldi (1988).

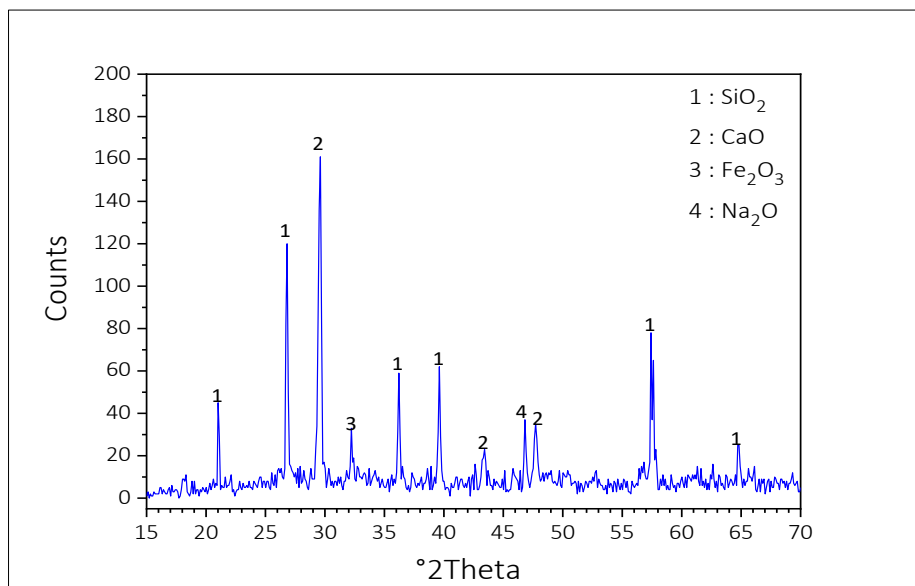
The limestone filler utilized in this research was obtained from crushing waste sourced from a quarry situated in the northern vicinity of Hassi Messaoud city (Algeria). The filler was produced by sieving the fine fraction of this crushing waste through an 80 µm mesh sieve. The physical characterization of this filler revealed absolute and apparent density values of 2500 kg/m³ and 981 kg/m³, respectively. The mineralogical analysis confirmed that the filler is entirely calcareous in nature, composed predominantly of calcium carbonate (CaCO₃), as reported by Ammari et al. (2023).

Table 2. Chemical composition of the cement used in this study.

Element	SiO ₂	CaO	MgO	Al ₂ O ₃	Fe ₂ O ₃	SO ₃	K ₂ O	Cl-	Na ₂ O	Free CaO	LOI	Insoluble Residues
Quantity (%)	18.84	60.03	1.81	4.90	3.21	2.65	0.68	0.017	0.09	0.67	8.49	1.13

The supplementary cementitious material investigated in this study is a glass powder derived from white industrial glass waste. The preparation process involved crushing the collected glass fragments into fine particles, followed by sieving through an 80 µm mesh to obtain a uniform powder with a controlled fineness. This powder was incorporated into the sand concrete mixtures as a partial mass substitute for cement at varying replacement levels. The measured physical properties of the glass powder include an absolute density

of 2570 kg/m³ and a Blaine specific surface area of 288 m²/kg. The mineralogical composition, determined through XRD analysis (Fig. 3), revealed the presence of silica (SiO₂) as the dominant constituent, along with calcium oxide (CaO), iron oxide (Fe₂O₃), and sodium oxide (Na₂O). The high silica content (SiO₂ ≥ 70%) confirms the siliceous nature of the glass powder, which is a key prerequisite for potential pozzolanic reactivity when used as a cement replacement in cementitious materials.

**Fig. 3.** X-ray diffraction (XRD) pattern of the utilized glass powder.

Due to the specific granular composition of sand concrete, the incorporation of a chemical admixture is considered indispensable to ensure adequate workability of the fresh mix, as emphasized by Chauvin and Grimaldi (1988). In this regard, a high-range water-reducing superplasticizer, commercially known as MEDAPLAST-SP 40, was selected for all concrete mixtures. This admixture is supplied in liquid form, allowing for easy dispersion in the mixing water, and its properties comply with the requirements of the European standard EN 934-2 (2012).

2.2. Testing procedures

2.2.1. Preparation of the investigated concrete

The various sand concrete mixture compositions investigated in this study are summarized in Table 3. Glass powder was incorporated as a partial replacement of cement at mass percentages ranging from 10% to 40%, with increments of 10%. For ease of identification throughout this study, the different sand concrete mixtures were designated as follows:

- SC-WGP: Reference sand concrete without glass powder (control mix);
- SC-GP10%: Sand concrete incorporating 10% glass powder;
- SC-GP20%: Sand concrete incorporating 20% glass powder;
- SC-GP30%: Sand concrete incorporating 30% glass powder;
- SC-GP40%: Sand concrete incorporating 40% glass powder.

2.2.2. Mixing process and storage of specimens

To ensure thorough homogeneity of the mixture and thereby enhance the overall quality of the concrete, the mixing process was performed at a low speed following a specific sequential procedure:

- Step 1: Cement and glass powder were first dry-mixed together for 2.5 minutes to ensure uniform blending of the binding materials;
- Step 2: Limestone filler and sand were then introduced in a dry state, and mixing was continued for an additional 2.5 minutes;
- Step 3: Once a homogeneous dry blend was achieved, 70% of the total mixing water was gradually incorporated into the mixture over a period of 1.5 minutes without interruption;
- Step 4: The remaining 30% of the mixing water, pre-mixed with the chemical admixture, was finally added and mixed for 1 minute without interruption.

This mixing protocol was adopted based on several previous studies conducted on sand concrete (Bederina et al. 2016; Ammari et al. 2020a; Ammari et al. 2020b). After mixing, the fresh concrete was cast into molds, with each mold filled in two equal layers. Each layer was vibrated and compacted using 30 manual strokes to ensure adequate compaction and to minimize entrapped air voids. The molded specimens were then kept in their molds for 24 hours before being demolded. Subsequently, the specimens were stored under controlled laboratory conditions (temperature: $25 \pm 3 \text{ }^{\circ}\text{C}$; relative humidity: $50\% \pm 8\%$) until the designated testing date.

Table 3. Concrete mix designs considered in this study.

Composition	Cement (kg/m ³)	Glass powder (kg/m ³)	Total binder (kg/m ³)	Sand (RDS) (kg/m ³)	Limestone filler (kg/m ³)	Mixing water (l/m ³)	Water-to- binder ratio	Super-plasticizer *	
								(%)	(kg/m ³)
SC-WGP	400	0	400	1296	150	235	0.59	1.5	6
SC-GP10%	360	40	400	1296	150	235	0.59	1.5	6
SC-GP20%	320	80	400	1296	150	235	0.59	1.5	6
SC-GP30%	280	120	400	1296	150	235	0.59	1.5	6
SC-GP40%	240	160	400	1296	150	235	0.59	1.5	6

* The super-plasticizer dosage is expressed as a mass percentage of the total binder content (cement + GP).

2.2.3. Experimental techniques

a. Accelerated carbonation

The resistance of sand concrete to carbonation was assessed through an accelerated carbonation protocol conducted in accordance with the AFPC-AFREM procedure described in XP P18-458 (2008). The principle of this test involves exposing concrete specimens to a controlled gaseous environment composed of 50% CO₂ and 50% air inside a dedicated carbonation chamber (Fig. 4(a,b)), while maintaining the relative humidity within the range of 40% to 80%, which is considered the most favorable range for carbonation progression. For each mixture composition, four cubic specimens measuring

10 × 10 × 10 cm were prepared: three designated for carbonation depth measurements, and one dedicated to tracking the mass evolution throughout the testing period. Two additional reference specimens per mix were stored under ambient laboratory conditions (temperature of $20 \pm 5 \text{ }^{\circ}\text{C}$ and relative humidity of $65\% \pm 7\%$) to monitor the natural carbonation progression for comparative purposes.

The specimen pre-conditioning protocol comprised the following sequential steps. Initially, all specimens underwent a 28-day curing period in a humid environment with a relative humidity exceeding 95%, or alternatively were submerged in water. Upon completion of the curing phase, each specimen was weighed to establish its reference mass. Subsequently, the specimens

were transferred to an oven maintained at $40 \pm 2^\circ\text{C}$ for 48 hours, after which they were weighed again to record their conditioned mass. Prior to placement in the carbonation chamber, the two square faces of each specimen were sealed with adhesive aluminum foil to ensure

unidirectional CO_2 diffusion through the four exposed lateral faces (Fig. 4(c)). The specimens were then positioned inside the chamber with a minimum spacing of 2 cm between adjacent samples to guarantee uniform gas exposure on all unsealed surfaces

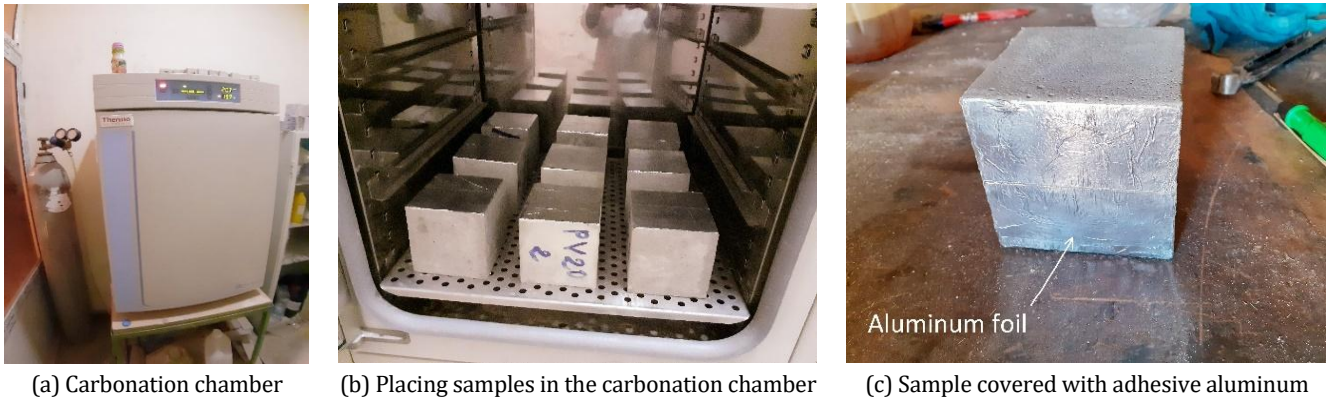


Fig. 4. Accelerated carbonation test.

The carbonation depth was evaluated at three exposure ages: 7, 14, and 28 days. At each designated age, the specimens were removed from the chamber and weighed to record any mass change. To determine the carbonation front, each specimen was split into two halves, and the freshly fractured surfaces were immediately sprayed with a phenolphthalein indicator solution (1% concentration dissolved in alcohol). This colorimetric technique relies on the pH sensitivity of phenolphthalein: the non-carbonated zone, characterized by a high pH close to 13, turns pink upon contact with the indicator, whereas the carbonated zone, where the pH has dropped to approximately 8.5 due to the consumption of calcium hydroxide by CO_2 , remains colorless. The carbonation depth on each exposed face was measured using a graduated ruler, with five readings recorded per face, comprising the minimum distance, the maximum distance, and three intermediate distances. The final reported carbonation depth for each specimen corresponds to the arithmetic mean of all measured values across the exposed faces.

b. Water absorption by total immersion

The water absorption by total immersion was evaluated on cubic specimens with dimensions of $5 \times 5 \times 5$ cm, in accordance with the Belgian standard NBN B 15-215 (1989). For each mixture composition, three specimens were prepared and tested to ensure the reproducibility of results. Prior to testing, the specimens were oven-dried at $105 \pm 5^\circ\text{C}$ until a constant mass was achieved, and then fully immersed in water at $20 \pm 2^\circ\text{C}$ until saturation, as prescribed by the standard. The reported values represent the arithmetic mean of three measurements for each mix.

c. Capillary water absorption

Capillary water absorption was evaluated on prismatic specimens with dimensions of $4 \times 4 \times 16$ cm. For each mixture composition, three specimens were pre-

pared and tested to ensure the reproducibility of results. Before the capillary absorption measurements, the test specimens were pre-conditioned according to the recommendations of the AFPC-AFREM procedure. The test consisted of placing each specimen vertically with its lower face in contact with a thin layer of water (approximately 5 mm deep), while the lateral surfaces were sealed to ensure unidirectional water uptake. The mass gain due to capillary absorption was recorded at predetermined time intervals. The capillary absorption coefficient (C_A) was calculated as the cumulative mass of absorbed water per unit exposed surface area according to Eq. (1):

$$C_A = \frac{M_t - M_0}{A} \quad (1)$$

where (M_t) is the mass of the specimen at time (t) (kg), (M_0) is the initial dry mass of the specimen (kg), and (A) is the exposed cross-sectional area in contact with water (m^2). In this study, the exposed surface area was 4×4 cm (0.0016 m^2). The reported values represent the arithmetic mean of three measurements for each mixture.

d. Freeze-thaw and wetting-drying

In the present study, the durability of sand concrete was evaluated through wetting-drying and freeze-thaw cyclic tests following ASTM D559 (2015) and ASTM D560 (2016), respectively. Although these standards were originally developed for compacted soil-cement mixtures, their use for sand concrete is well justified. Unlike ordinary concrete, sand concrete contains no coarse aggregates and relies exclusively on fine sand as the primary aggregate combined with cement and filler (Bederina et al. 2005; Chauvin and Grimaldi 1988), making its granular composition and matrix structure significantly closer to those of soil-cement mixtures than to that of conventional concrete. Moreover, the standard freeze-thaw test for ordinary concrete, as described in ASTM C666/C666M (2015), involves rapid cycles under water-saturated conditions with temperatures down to -18°C , a protocol specifically designed for concrete containing

coarse aggregates and therefore not directly applicable to sand concrete given its distinct pore structure and transport properties. Furthermore, several previous studies on sand concrete and similar fine-aggregate cementitious composites have successfully adopted ASTM D559 (2015) and ASTM D560 (2016) as appropriate durability testing protocols (Bederina et al. 2016; Aoual-Benslafa et al. 2011), confirming their suitability for this type of material. Finally, in the absence of a dedicated international standard for evaluating the cyclic durability of sand concrete, the selection of ASTM D559 and ASTM D560 is deemed technically appropriate, given the compositional analogy between sand concrete and soil-cement mixtures, and is consistent with the established testing methodology reported in the literature for similar fine-aggregate cementitious systems.

The freeze-thaw test was performed on cubic specimens measuring $10 \times 10 \times 10$ cm, in accordance with the testing protocol adopted in this study. For each mixture composition, three specimens were prepared to ensure the reproducibility of results. A total of twelve accelerated aging cycles were applied, starting at a curing age of 28 days. Each cycle consisted of freezing in air at -5°C for four hours, followed by complete immersion in water at 23°C until full thawing was achieved (approximately four hours). A temperature-controlled chamber was used to regulate the thermal cycles. The mass and compressive strength of each specimen were measured before and after the completion of all freeze-thaw cycles to evaluate both the weight loss and the strength degradation induced by the cyclic exposure. The reported values represent the arithmetic mean of three measurements obtained for each mix.

To assess the durability of sand concrete under alternating moisture conditions, the wetting-drying test was performed on cubic specimens measuring $10 \times 10 \times 10$ cm, in accordance with the testing protocol adopted in this study. Specimens were cast for all mixture compositions (0%, 10%, 20%, 30%, and 40% GP), with three replicates per mix to guarantee the reliability of the experimental data. At the age of 28 days, the specimens were subjected to twelve accelerated aging cycles. Each cycle involved immersion in water for five hours, followed by oven drying at 70°C for 42 hours. The mass and compressive strength of each specimen were determined both prior to and after the completion of the wetting-drying program, allowing the quantification of weight loss and strength degradation as indicators of durability performance. All reported results correspond to the mean value of three tested specimens per mixture.

e. Resistance to acid attack

The resistance of sand concrete to acid attack was evaluated by monitoring the mass variation and conducting chemical analyses on specimens immersed in a hydrochloric acid (HCl) solution, following the general guidelines of ASTM C267 (2020). Prismatic sand concrete specimens with dimensions of $4 \times 4 \times 16$ cm were used for this test. For each mixture composition (0%, 10%, 20%, 30%, and 40% GP), three specimens were prepared and tested to ensure reliable and reproducible measurements. After 28 days of water curing, the speci-

mens were removed from water and exposed to ambient conditions at a temperature of 23°C for 30 minutes to remove excess surface water. The initial dry mass of each specimen was then recorded before immersion in the acid solution (Bassuoni and Nehdi 2007). A hydrochloric acid solution with a concentration of 5% was prepared in acid-resistant containers and maintained at an ambient temperature of 23°C . The specimens were positioned with a spacing of 2 cm apart, ensuring that all surfaces were covered with approximately 2 cm of acid solution. The pH level of the solution was monitored every two days using pH indicator strips, and the recorded pH remained below 4 throughout the testing period. The durability performance was evaluated macroscopically through mass variation measurements, and microstructurally through X-ray diffraction (XRD) and scanning electron microscopy (SEM) analyses. The reported mass variation values represent the average of three specimens per mixture.

f. Microstructural analysis

The microstructural characteristics of sand concrete specimens were investigated using scanning electron microscopy (SEM) and X-ray diffraction (XRD) to gain a deeper understanding of the effect of glass powder incorporation on the cementitious matrix. For each mixture composition, representative samples were carefully selected and examined to ensure that the observations reflected the overall microstructural behavior of the material. SEM analysis was performed using a Phenom ProX scanning electron microscope to examine the surface morphology, identify micro-cracks, and detect any microstructural changes induced by the different testing conditions. Multiple micrographs were captured at various magnifications and from different locations on each specimen to ensure representative imaging of the microstructure. For XRD analysis, the cement matrices of the studied sand concrete mixtures were first crushed and sieved through an $80\ \mu\text{m}$ mesh to obtain a fine powder suitable for diffraction measurements. The prepared samples were then analyzed using a PROTO AXRD diffractometer to identify the crystalline phases and assess the mineralogical changes resulting from glass powder addition and exposure to aggressive environments.

3. Results and Analysis

3.1. Accelerated carbonation

3.1.1. Carbonation depth

The visual examination of the specimens after exposure to accelerated carbonation is illustrated in Fig. 5. A clear distinction between two zones can be observed on the fractured surfaces: the outer carbonated region, which retains the natural grey color of concrete due to the consumption of calcium hydroxide and the associated pH reduction to approximately 8.5, and the inner non-carbonated core, which turns pink upon spraying with the phenolphthalein indicator, confirming that the alkalinity of the pore solution remains intact in this zone ($\text{pH} \approx 13$).

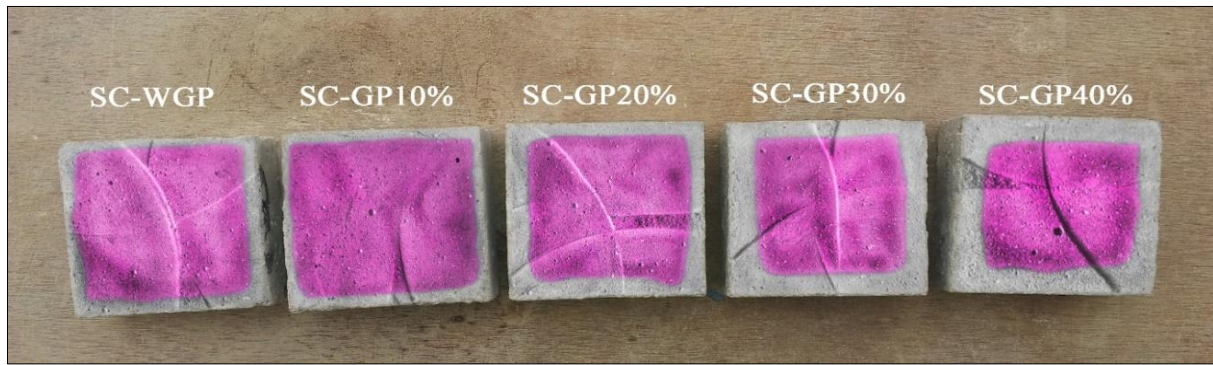


Fig. 5. Carbonation front detection using phenolphthalein indicator on the studied concretes at 28 days.

The carbonation front separating these two regions appears well-defined and regular across all tested sand concrete compositions, indicating a relatively uniform CO_2 diffusion pattern through the matrix. Regarding the influence of glass powder content, the results reveal that the incorporation of 10% GP produced the most favorable performance, exhibiting a reduced carbonation depth compared to the reference mix (SC-WGP). This improvement can be attributed to the pozzolanic reaction of the glass powder at this dosage, which generates ad-

ditional C-S-H gel that refines the pore structure and hinders CO_2 penetration into the matrix. However, at replacement levels exceeding 10%, a progressive increase in carbonation depth was observed, suggesting that the dilution of the cementitious matrix at higher GP dosages creates a more porous and permeable microstructure that facilitates the inward diffusion of carbon dioxide.

The evolution of carbonation depth as a function of exposure time at 7, 14, and 28 days for all sand concrete compositions is presented in Fig. 6.

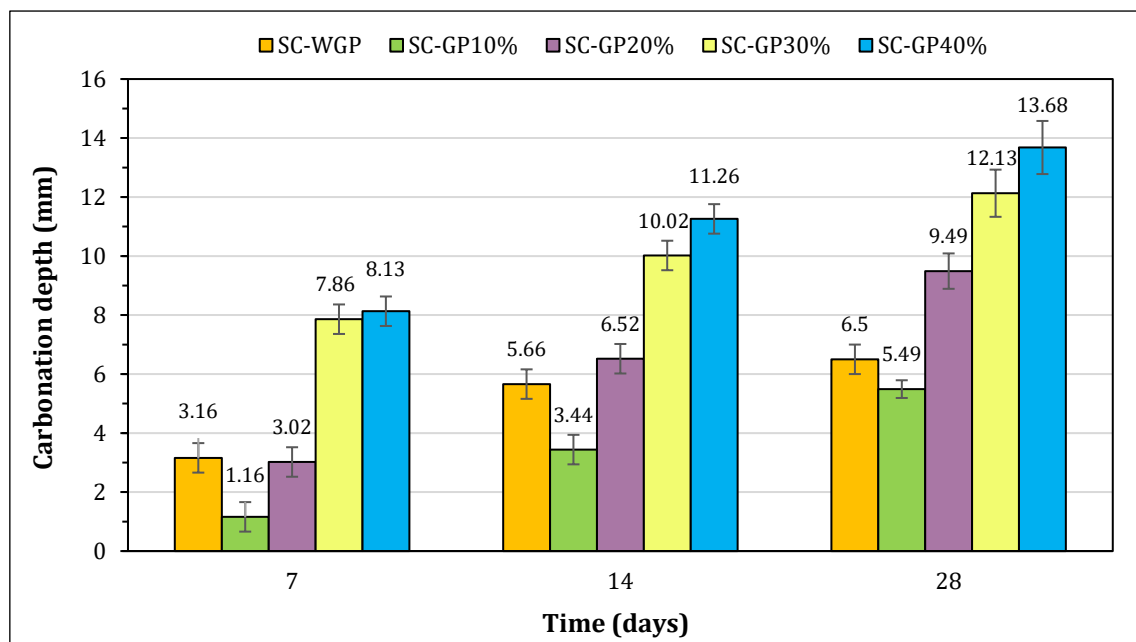


Fig. 6. Evolution of carbonation depth over time.

The results reveal a clear dependence of carbonation depth on the glass powder replacement level, with distinctly different behaviors observed below and above the 10% GP threshold. At 28 days of accelerated carbonation exposure, the reference mix (SC-WGP) recorded a carbonation depth of 6.49 mm, while the SC-GP10% mix exhibited the shallowest carbonation front among all tested compositions, reaching only 5.49 mm, which corresponds to a reduction of approximately 15.41% in carbonation depth compared to the reference mix. This enhanced resistance to carbonation penetration at 10% GP can be attributed to the effective pozzolanic reaction at this dosage, which consumes a portion of the available calcium

hydroxide ($\text{Ca}(\text{OH})_2$) to form additional C-S-H gel. While this reaction theoretically reduces the amount of $\text{Ca}(\text{OH})_2$ available for carbonation, the resulting densification of the pore structure at 10% GP appears to outweigh this effect by significantly hindering the inward diffusion of CO_2 through the matrix. Schwarz et al. (2008) reported a comparable pore-refining effect at moderate glass powder replacement levels, which effectively reduced the transport properties of the cementitious matrix. Similarly, Matos and Sousa-Coutinho (2012) observed that glass powder at low replacement dosages contributed to an acceptable carbonation performance due to the balance between pore refinement and $\text{Ca}(\text{OH})_2$ consumption.

In contrast, replacement levels exceeding 10% GP led to a progressive and substantial increase in carbonation depth. At 28 days, the carbonation depth rose sharply to 9.49 mm, 12.13 mm, and 13.68 mm for SC-GP20%, SC-GP30%, and SC-GP40%, respectively, corresponding to increases of 46.22%, 86.90%, and 110.79% in carbonation depth relative to the reference mix. Notably, the most pronounced increase in carbonation depth occurred between SC-GP10% and SC-GP20%, where it nearly doubled from 5.49 mm to 9.49 mm (a difference of 4.00 mm), indicating the existence of a critical threshold between 10% and 20% GP beyond which the carbonation resistance deteriorates rapidly. This pronounced increase in carbonation depth can be explained by two concurrent mechanisms. First, the excessive replacement of cement by glass powder significantly reduces the total quantity of $\text{Ca}(\text{OH})_2$ produced during hydration, thereby lowering the carbonation buffering capacity of the matrix, as the carbonation process fundamentally relies on the reaction between atmospheric CO_2 and $\text{Ca}(\text{OH})_2$ to form calcium carbonate (CaCO_3). Second, the dilution effect at higher dosages results in an insufficiently densified microstructure with greater pore connectivity, which facilitates the penetration of CO_2 into deeper layers of the concrete. Islam et al. (2017) emphasized that beyond an optimal glass powder threshold, the beneficial pozzolanic contribution is outweighed by the detrimental reduction in cement content, leading to a decline in overall performance. These findings are also consistent with those of Salim and Mosaberpanah (2021), who reported that carbonation resistance of glass-powder-modified cementitious materials deteriorated significantly at high replacement levels due to the combined effect of reduced portlandite availability and increased porosity. Consequently, the SC-GP10% composition exhibited the lowest measured carbonation depth among all tested compositions.

In addition to the accelerated carbonation test, an attempt was made to evaluate the natural carbonation be-

havior of the studied sand concrete compositions. It is widely recognized that natural carbonation provides more realistic results compared to accelerated testing, as it reflects the actual service conditions of the material under atmospheric CO_2 concentrations of approximately 0.04%. However, the practical implementation of natural carbonation tests presents significant challenges, primarily due to the difficulty of maintaining constant ambient conditions over extended periods and the inherently slow rate of CO_2 diffusion at such low concentrations. In the present study, companion specimens for each mix were stored under ambient laboratory conditions (temperature of $20 \pm 5^\circ\text{C}$ and relative humidity of $65\% \pm 7\%$) throughout the experimental program. The results indicated that none of the tested sand concrete compositions exhibited any measurable carbonation depth under natural exposure conditions during the monitoring period. This absence of detectable carbonation depth can be attributed to the relatively short exposure duration, which was insufficient for atmospheric CO_2 at low concentrations to penetrate to a measurable depth within the concrete matrix. Siad et al. (2016) noted that the carbonation process under natural conditions is extremely slow, particularly for well-cured concrete specimens, and that measurable carbonation depths typically require exposure periods of several months to years, depending on the environmental conditions and concrete permeability. This observation further confirms that accelerated carbonation testing remains the most practical and reliable method for evaluating the carbonation resistance of sand concrete within a reasonable experimental timeframe.

3.1.2. Variation of mass gain

Alongside the carbonation depth measurements, the mass evolution of all sand concrete specimens was monitored at 7, 14, and 28 days of accelerated carbonation exposure, and the results are presented in Fig. 7.

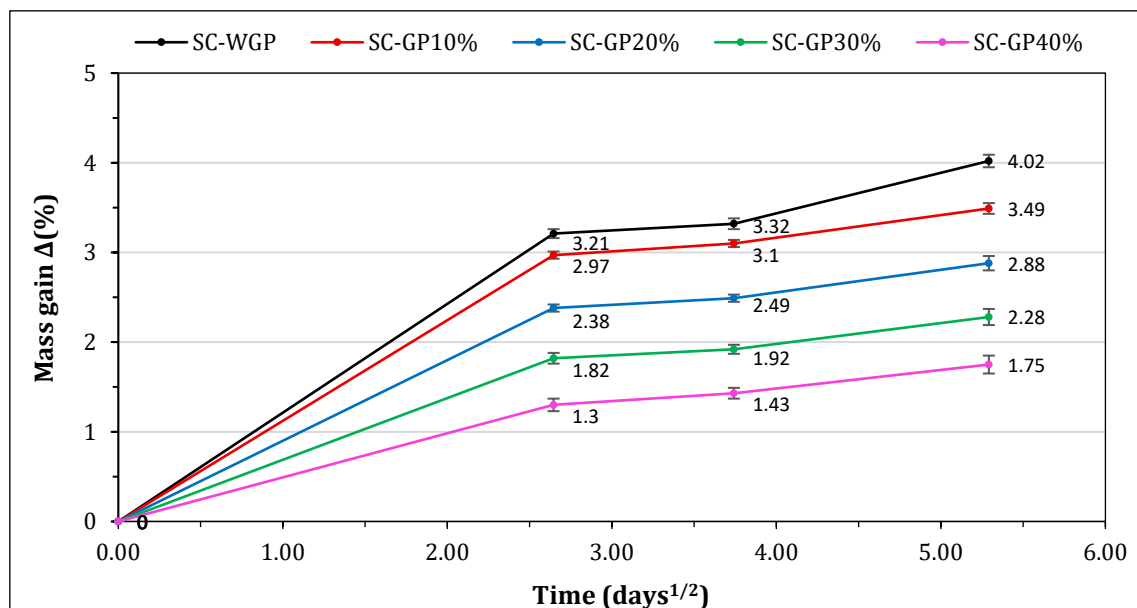


Fig. 7. Evolution of mass gain over time for the studied concretes.

During the carbonation process, the reaction between the diffused CO_2 and the calcium hydroxide ($\text{Ca}(\text{OH})_2$) present in the pore solution produces calcium carbonate (CaCO_3), which has a higher molar mass than the original portlandite, resulting in a net mass gain of the specimens. Therefore, the magnitude of mass gain serves as an indirect indicator of the extent of the carbonation reaction within the cementitious matrix.

The results demonstrate that the incorporation of glass powder into sand concrete progressively reduced the mass gain across all replacement levels compared to the reference mix (SC-WGP). At 28 days, the reference mix recorded the highest mass gain of 4.02%, which decreased to 3.49%, 2.88%, 2.28%, and 1.75% for SC-GP10%, SC-GP20%, SC-GP30%, and SC-GP40%, respectively. These values correspond to reductions of approximately 13.18%, 28.36%, 43.28%, and 56.47% in mass gain relative to the reference mix, with the SC-GP40% composition exhibiting the lowest mass gain among all tested compositions. Regarding the temporal evolution, a rapid increase in mass gain was observed during the first 7 days for all compositions, reflecting the initial stage of carbonation where the CO_2 reacts readily with the $\text{Ca}(\text{OH})_2$ accessible in the surface-connected pores. Beyond this period and up to 28 days, the mass gain evolved at a considerably slower rate, with all compositions following a nearly parallel trend, indicating that the carbonation front had progressed into deeper and less accessible pore regions where the CO_2 diffusion rate is considerably reduced.

The progressive reduction in mass gain with increasing glass powder content is directly related to the decreasing availability of $\text{Ca}(\text{OH})_2$ within the matrix. As the cement content is reduced through glass powder substitution, the total amount of $\text{Ca}(\text{OH})_2$ generated during hydration diminishes proportionally, leaving less portlandite available to react with the diffused CO_2 and consequently producing less CaCO_3 . This mechanism explains why the SC-GP40% mix, having the lowest cement content among all compositions, recorded the lowest mass gain. Shi et al. (2005) confirmed that the pozzolanic reaction of glass powder further consumes the available $\text{Ca}(\text{OH})_2$ to

produce C-S-H gel, thereby additionally reducing the portlandite reservoir available for carbonation. Matos and Sousa-Coutinho (2012) reported analogous observations in mortar containing glass powder, where the mass gain during carbonation decreased with increasing glass powder dosage due to the reduced $\text{Ca}(\text{OH})_2$ content.

It is essential, however, to interpret these mass gain results in conjunction with the carbonation depth measurements discussed above, as the two indicators convey complementary but distinct information about the carbonation process. While a lower mass gain may appear to indicate better carbonation resistance, it actually reflects a reduced $\text{Ca}(\text{OH})_2$ content rather than an inherently superior resistance to CO_2 penetration. This is clearly evidenced by comparing the SC-GP10% and SC-GP40% compositions: although SC-GP40% exhibited the lowest mass gain (1.75% vs. 3.49% for SC-GP10%), it recorded the deepest carbonation front (13.68 mm vs. 5.49 mm for SC-GP10%). This apparent contradiction confirms that the lower mass gain at higher GP dosages is not an indicator of improved durability, but rather a consequence of the depleted $\text{Ca}(\text{OH})_2$ reserve, which consequently allows CO_2 to penetrate more rapidly through the poorly buffered matrix. In contrast, the SC-GP10% composition achieved both a moderate reduction in mass gain (13.18%) and the shallowest carbonation depth (5.49 mm), confirming that at this dosage, the pozzolanic reaction refines the pore structure sufficiently to impede CO_2 diffusion while maintaining an adequate $\text{Ca}(\text{OH})_2$ buffering capacity to resist carbonation progression.

3.2. Water absorption by total immersion

This property provides a direct indication of the behavior of glass powder-based concrete when exposed to water. Water absorption capacity is a key indicator of the porosity of concrete, as it directly reflects the presence and volume of internal pores. The water absorption coefficients obtained by total immersion for the various concrete mixtures investigated in this study are presented in Fig. 8.

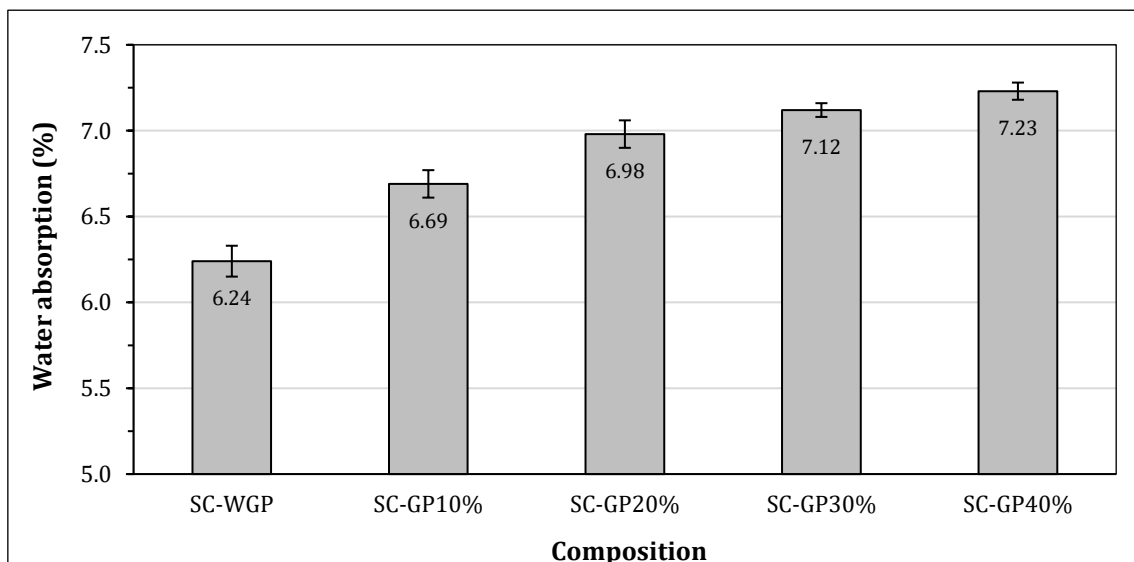


Fig. 8. Influence of glass powder proportion on water absorption by immersion.

The total water absorption results reveal an unfavorable effect of glass powder incorporation on the porosity-related properties of sand concrete. The water absorption coefficient increased progressively with increasing GP content across all replacement levels. The reference mix (SC-WGP) recorded a water absorption value of 6.24%, which increased to 6.69%, 6.98%, 7.12%, and 7.23% for SC-GP10%, SC-GP20%, SC-GP30%, and SC-GP40%, respectively. These values correspond to increases of approximately 7.21%, 11.86%, 14.10%, and 15.87% relative to the reference mix. This systematic increase suggests that glass powder incorporation adversely affects the pore structure of sand concrete, a trend that requires further analysis in light of the underlying microstructural mechanisms.

The primary explanation for this behavior lies in the modification of the pore network within the cementitious matrix. At higher glass powder replacement levels, the reduction in cement content leads to a decrease in the volume of hydration products, particularly C-S-H gel, which is primarily responsible for filling the capillary pores and densifying the microstructure. This creates additional interconnected voids within the matrix, facilitating greater water ingress and retention. Furthermore, the smooth and non-reactive surface of unreacted glass particles, especially at dosages above 20%, may weaken the bond at the particle-paste interface, generating micro-gaps that contribute to increased porosity and water accessibility. Adesina and Das (2020) observed a similar increase in water absorption with increasing glass powder content in cementitious composites, attributing it to the reduced hydration activity at higher replacement levels that leaves more unfilled pore space within the matrix. Letelier et al. (2019) also reported comparable findings in mortars containing waste glass, noting that the absorption increase was directly related to the higher porosity resulting from cement dilution. Moreover, Jain et al. (2020) demonstrated that incorporating 25% glass powder into concrete increased the water absorption coefficient by approximately 8% compared to the control concrete, which closely aligns with the 7.21% increase observed in the present study at 10% GP. Ramakrishnan et al. (2017) further confirmed this trend, showing that increasing the glass powder replacement level to 20% resulted in a measurable rise in the water absorption coefficient.

It is worth noting, however, that the rate of absorption increase is not uniform across all replacement levels, exhibiting a clear decelerating pattern. The most notable increment occurred between the reference mix and SC-GP10%, with the absorption rising from 6.24% to 6.69% (a difference of 0.45%). This increment progressively diminished to 0.29% between SC-GP10% and SC-GP20%, then to 0.14% between SC-GP20% and SC-GP30%, and finally to only 0.11% between SC-GP30% and SC-GP40%. This plateau-like behavior at higher dosages suggests that beyond a certain replacement threshold, the pore network reaches a near-saturation state where additional glass powder no longer substantially alters the overall porosity. At low replacement levels such as 10%, the pozzolanic activity of the glass powder partially compensates for the porosity increase by producing secondary C-S-H gel that fills a portion of the newly formed

voids. Schwarz et al. (2008) reported a similar observation, noting that fine glass powder at moderate replacement levels provided a degree of pore refinement that partially mitigated the negative effects of cement reduction. At higher dosages, however, the limited availability of calcium hydroxide restricts the extent of the pozzolanic reaction, leaving a greater volume of unreacted glass particles that do not contribute to pore filling, thereby amplifying the absorption increase. Matos and Sousa-Coutinho (2012) confirmed this mechanism, showing that excessive glass powder replacement led to a dilution effect that progressively increased the porosity of cementitious materials.

This finding highlights the importance of carefully selecting the glass powder replacement level to minimize the adverse impact on water absorption. While the absorption increase at 10% GP remains within an acceptable range (7.21% increase, from 6.24% to 6.69%), the progressive deterioration at higher dosages raises concerns about the long-term performance of sand concrete in water-saturated environments, where elevated absorption can accelerate the ingress of aggressive agents and compromise the overall durability of the material. The implications of this porosity increase on other durability indicators, such as resistance to cyclic environmental exposure and chemical attack, will be examined in the subsequent sections.

3.3. Capillary water absorption

In addition to total water absorption, the capillary water absorption test provides further insight into the pore connectivity and transport properties of sand concrete, as it specifically reflects the ability of the material to absorb water through its capillary pore network under the effect of surface tension. Fig. 9 presents the average values of the capillary absorption coefficients over 24 hours for all studied compositions.

The results indicate that the capillary absorption of sand concrete is considerably and adversely affected by the incorporation of glass powder at all replacement levels. The reference mix (SC-WGP) recorded a capillary absorption value of 7.68 kg/m², which increased progressively to 8.85, 10.02, 10.94, and 12.76 kg/m² for SC-GP10%, SC-GP20%, SC-GP30%, and SC-GP40%, respectively. These values correspond to increases of approximately 15.23%, 30.47%, 42.45%, and 66.14% relative to the reference mix. Notably, the capillary absorption increase is considerably more pronounced than the total immersion absorption increase discussed previously (which ranged from 7.21% to 15.87%), suggesting that glass powder incorporation predominantly affects the capillary pore structure rather than the overall porosity of the matrix.

This amplified capillary absorption can be attributed to several microstructural factors. First, the progressive replacement of cement by glass powder reduces the quantity of hydration products available to fill and segment the capillary pore network, resulting in a more interconnected and continuous capillary system that facilitates faster water transport. Second, at higher replacement levels (30–40%), the excess of unreacted glass particles may create preferential pathways at the particle-paste interface, acting as channels that enhance capillary

suction. Matos and Sousa-Coutinho (2012) investigated the capillary absorption of mortar containing 10% and 20% glass powder as cement replacement and reported a measurable increase in the capillary absorption coefficient at both dosages, attributing this to the coarsening of the pore structure caused by the reduced cement hydration. Adesina and Das (2020) observed a similar trend in cementitious composites incorporating glass powder, confirming that the capillary pore connectivity

increases with higher glass powder content due to the insufficient formation of pore-blocking hydration products. Furthermore, Schwarz et al. (2008) compared the microstructural effects of glass powder and fly ash in concrete and noted that while both materials exhibited pozzolanic activity, glass powder at higher dosages was less effective in refining the capillary pore structure, which is consistent with the progressive capillary absorption increase observed in the present study.

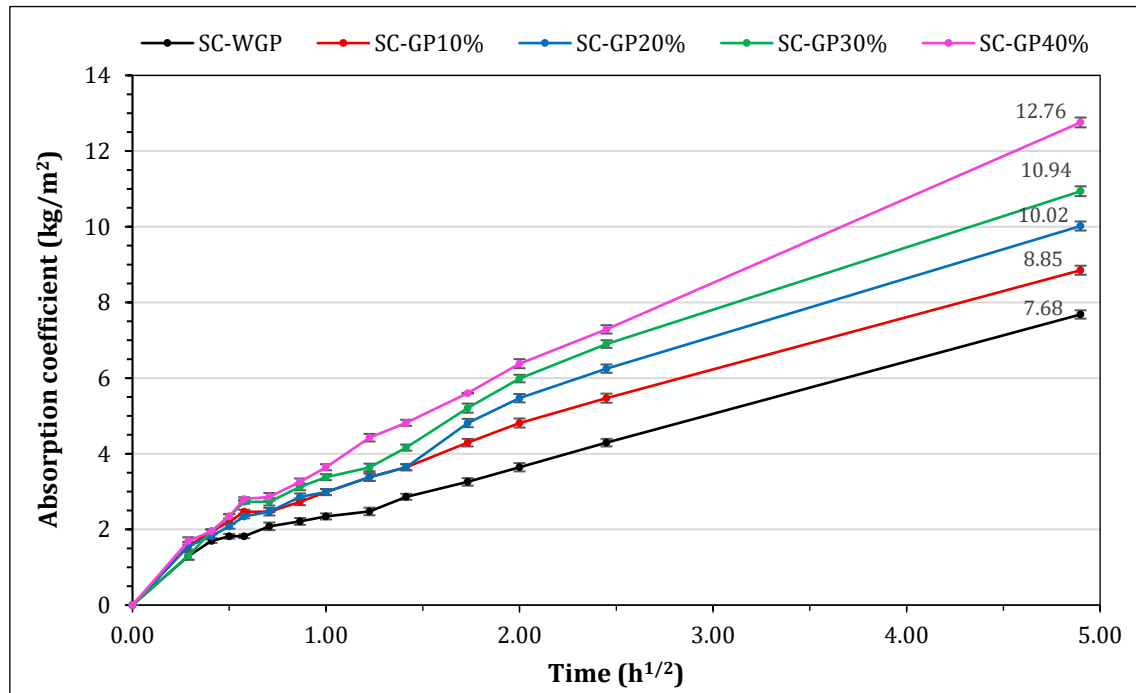


Fig. 9. Evolution of capillary absorption of the studied concretes as a function of time.

An examination of the differences between successive mixtures shows that the cumulative capillary water absorption increased by 1.17 kg/m² between SC-WGP and SC-GP10%, by 1.17 kg/m² between SC-GP10% and SC-GP20%, by 0.92 kg/m² between SC-GP20% and SC-GP30%, and by 1.82 kg/m² between SC-GP30% and SC-GP40%. Therefore, the increase was not uniform across the investigated replacement levels, and the largest increment occurred between 30% and 40% GP. However, without additional statistical or microstructural evidence, this change should not be interpreted as proof of a critical threshold or a transition in the capillary pore network. Islam et al. (2017) emphasized the existence of such threshold effects in glass powder modified concrete, where the benefits of glass powder diminish beyond an optimal level, giving way to accelerated deterioration of the microstructural properties.

When compared to the total immersion absorption results, the capillary absorption data reveal a more severe impact of glass powder on sand concrete properties. While total immersion absorption showed a decelerating increase that plateaued at higher GP dosages, capillary absorption exhibited an accelerating trend, particularly at 40% GP. This discrepancy can be explained by the different mechanisms governing each test: total immersion absorption captures the overall accessible pore volume, whereas capillary absorption is governed by the connec-

tivity and diameter distribution of the capillary pores. The glass powder incorporation, while not dramatically increasing the total pore volume at higher dosages, appears to significantly enhance the continuity and connectivity of the capillary network, thereby amplifying the capillary suction forces. This adverse effect on capillary absorption represents an important consideration for the practical application of glass-powder-based sand concrete, particularly in environments where capillary rise may facilitate the transport of aggressive agents such as chlorides and sulfates into the concrete matrix. However, at 10% GP, the capillary absorption increase remains the most moderate among all replacement levels (15.23%), reinforcing the importance of limiting the glass powder dosage to preserve the transport properties of sand concrete.

3.4. Freeze-thaw test

The resistance of concrete to freeze-thaw cycles is a fundamental durability characteristic for construction elements exposed to cold climates. This resistance is closely related to several material properties, including porosity, permeability, pore structure, and aggregate characteristics. To quantify the strength and mass loss induced by the freeze-thaw cycles for all studied compositions, the variations were recorded and the results are presented in Fig. 10.

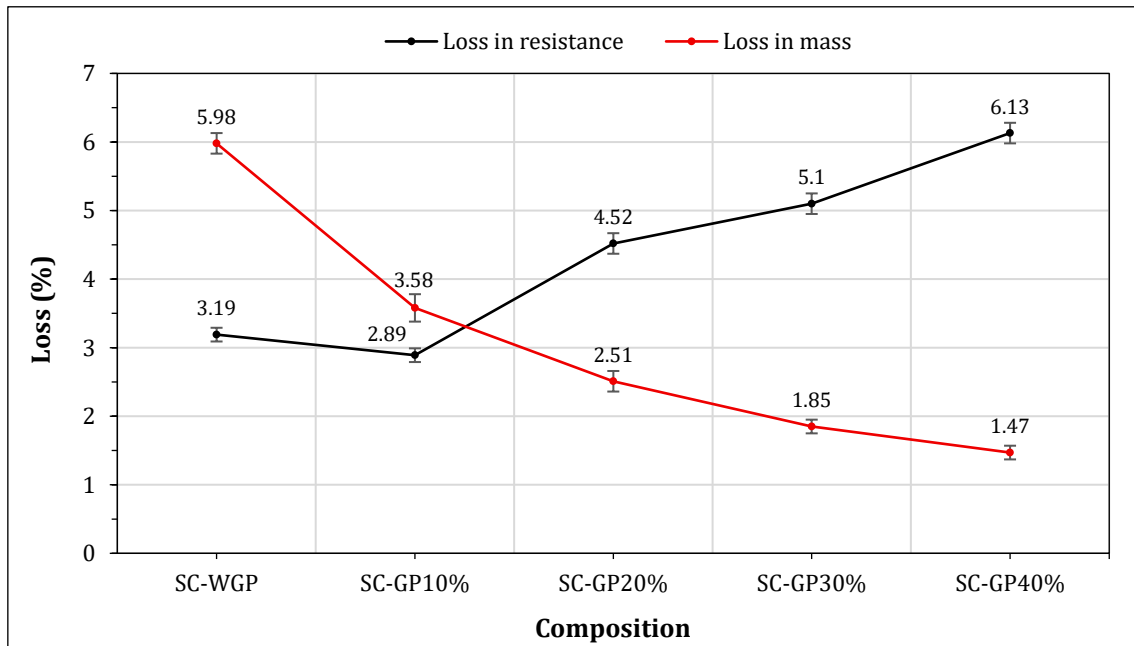


Fig. 10. Impact of freeze–thaw cycles on the durability of the studied concretes.

The freeze-thaw test results reveal that the impact of glass powder incorporation on the durability of sand concrete varies depending on the performance indicator considered. In terms of compressive strength loss, a reduction in compressive strength was observed for all compositions after twelve freeze-thaw cycles, which is consistent with the well-established phenomenon of internal micro-crack propagation induced by repeated freezing and thawing of pore water within the cementitious matrix. Ammari et al. (2020a) reported a similar trend when studying the durability of sand concrete containing barley straw fibers, where freeze-thaw cycles caused measurable strength degradation across all tested compositions. Among all tested mixtures in the present study, the 10% GP mix (SC-GP10%) exhibited the lowest compressive strength loss of 2.89%, compared to 3.19% for the reference mix (SC-WGP). However, beyond this dosage, the compressive strength loss increased progressively, reaching 4.52%, 5.10%, and 6.13% for SC-GP20%, SC-GP30%, and SC-GP40%, respectively. This superior strength retention at 10% GP can be attributed to the pozzolanic reaction of the fine glass powder with calcium hydroxide ($\text{Ca}(\text{OH})_2$). Supporting this observation, Shi et al. (2005) demonstrated that glass powder possesses significant pozzolanic reactivity due to its high amorphous silica content, which reacts with $\text{Ca}(\text{OH})_2$ to produce additional calcium silicate hydrate (C-S-H) gel. Shayan and Xu (2006) confirmed this pozzolanic behavior through field trials on concrete slabs, showing that glass powder effectively contributed to pore structure refinement and matrix densification. Similarly, Idir et al. (2011) investigated the pozzolanicity of glass cullet fines and reported that finely ground glass powder exhibited a clear pozzolanic potential comparable to conventional supplementary cementitious materials. This denser microstructure limits the penetration and accumulation of water within the pores, thus reducing the internal stresses generated during ice formation and consequently minimizing the strength degradation.

At higher replacement levels (20–40%), the dilution effect of excessive glass powder replacement progressively weakens the binding capacity of the cementitious matrix, resulting in increased internal damage under cyclic freezing and thawing stresses.

This finding is in agreement with the observations of Schwarz et al. (2008), who observed that while fine glass powder improved the durability characteristics of concrete at low replacement levels, the beneficial effect diminished at higher dosages. Matos and Sousa-Coutinho (2012) also reported that excessive cement replacement by glass powder led to a dilution effect that negatively impacted the overall performance of cementitious materials. Furthermore, Islam et al. (2017) emphasized the existence of an optimal replacement level, beyond which the mechanical and durability properties begin to decline. However, when mass loss is considered as the performance criterion, a distinctly opposite trend emerges. The results show that increasing the glass powder content progressively reduced the mass loss rates across all compositions. The reference mix (SC-WGP) recorded the highest mass loss of 5.98%, while the incorporation of glass powder reduced this value to 3.58%, 2.51%, 1.85%, and 1.47% for SC-GP10%, SC-GP20%, SC-GP30%, and SC-GP40%, respectively. Notably, the 40% GP mix exhibited the lowest mass loss, representing a reduction of approximately 75.42% compared to the reference mix. This behavior can be explained by the presence of unreacted glass particles within the matrix at higher replacement levels. Sobolev et al. (2007) highlighted that glass is a material that can be recycled without loss of quality, indicating its inherent chemical stability and resistance to degradation. Shi et al. (2005) further confirmed the high chemical durability of glass particles, noting that their low solubility and inert nature allow them to act as physically stable inclusions that resist surface erosion and scaling during aggressive exposure conditions. Furthermore, the smooth and non-porous surface of glass particles may contribute to reducing water absorption at

the surface level, which limits the physical deterioration caused by ice crystallization at the outer layers.

This apparent divergence between the two performance indicators highlights the necessity of adopting a multi-criteria evaluation approach when assessing the freeze-thaw durability of sand concrete. Jain et al. (2020) adopted a similar multi-criteria approach when evaluating the durability of concrete containing waste glass powder, assessing both water absorption and acid resistance to obtain a comprehensive durability characterization. Likewise, Ramakrishnan et al. (2017) conducted multiple durability tests on concrete incorporating glass powder as a supplementary cementitious material and emphasized that no single test can fully capture the overall durability behavior. Mass loss predominantly reflects surface deterioration and physical erosion of the outer layers, whereas compressive strength loss captures the extent of internal microstructural damage, including the propagation of micro-cracks and the degradation of the interfacial transition zone between the cement paste and aggregate. In the case of higher GP contents (30% and 40%), although the surface integrity was better preserved as evidenced by lower mass loss values of 1.85% and 1.47% respectively, the excessive cement replacement led to a dilution effect that weakened the overall cementitious matrix, making it more susceptible to internal damage. This explains why the 40% GP mix, despite exhibiting the lowest mass loss (1.47%), showed the

highest compressive strength loss (6.13%) among all tested compositions.

Therefore, considering the overall balance between both durability indicators, the 10% GP mix offers the most favorable compromise under freeze-thaw conditions. While it does not achieve the absolute lowest mass loss (3.58% vs. 1.47% for SC-GP40%), it provides the best compressive strength retention (2.89%), which is considered the more critical parameter for structural performance, as internal microstructural integrity directly governs the load-bearing capacity and long-term serviceability of sand concrete in real construction applications. This observation is consistent with the findings of Ammari et al. (2023), who identified 10% GP as the optimal replacement level for mechanical properties of sand concrete in their previous study.

3.5. Wetting-drying test

The wetting-drying test is commonly employed to evaluate the long-term durability of concrete exposed to cyclic moisture conditions, such as those encountered in humid or coastal environments. This test allows the assessment of both strength and mass variations after repeated wetting-drying cycles, providing a comprehensive indication of the material's resistance to moisture-induced degradation. The results obtained for all studied compositions are presented in Fig. 11.

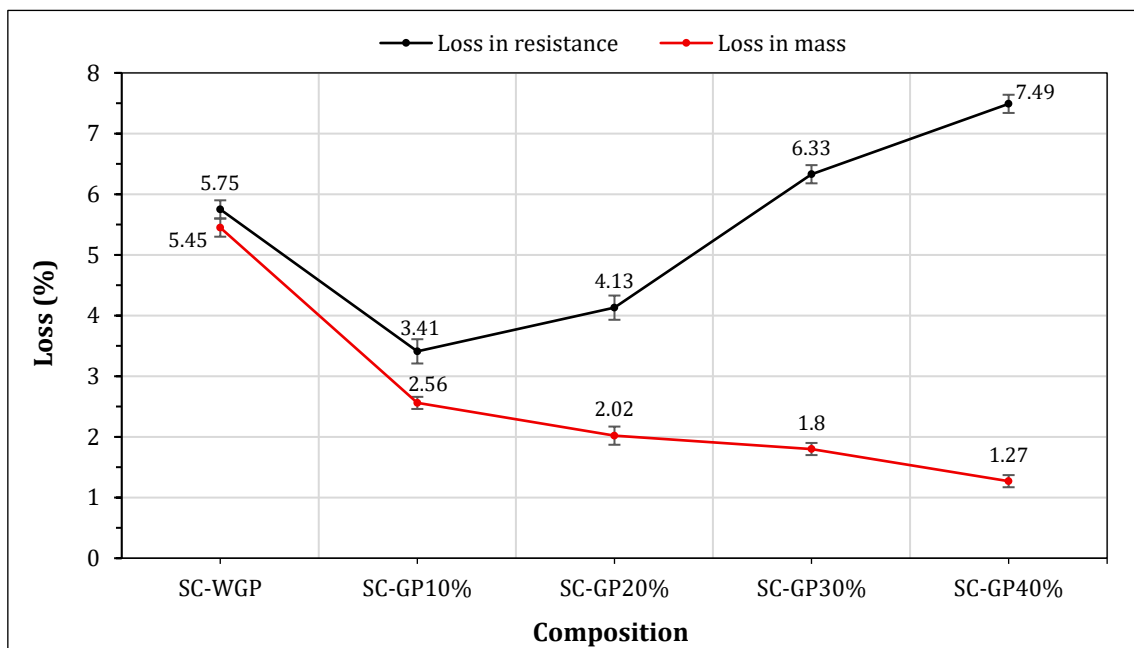


Fig. 11. Impact of wetting-drying cycles on the durability of the studied concretes.

An analysis of the compressive strength loss and mass loss results presented in Fig. 11 reveals two contrasting trends that merit careful discussion. Regarding compressive strength, the incorporation of 10% GP (SC-GP10%) led to the lowest strength loss of 3.41%, representing a substantial reduction of approximately 40.70% compared to the reference mix (SC-WGP), which recorded a loss of 5.75%. The 20% GP mix also showed a moderate improvement with a strength loss of 4.13%. In contrast,

higher dosages of glass powder proved detrimental to strength retention, with SC-GP30% and SC-GP40% recording strength losses of 6.33% and 7.49%, respectively, both exceeding the reference mix. This non-linear behavior suggests that at a low replacement level of 10%, the glass powder effectively participates in the pozzolanic reaction, generating secondary C-S-H gel that strengthens the interfacial transition zone (ITZ) between the paste and sand grains. Schwarz et al. (2008)

reported comparable findings, demonstrating that fine glass powder at moderate replacement levels improved the microstructure of concrete and enhanced its resistance to aggressive environments. Adesina and Das (2020) further confirmed that glass powder incorporation enhanced the durability properties of cementitious composites by densifying the matrix and reducing porosity, which corroborates the improved wetting-drying resistance observed at 10% GP in the present study. Beyond 20% replacement, however, the insufficient availability of calcium hydroxide to react with the excess glass powder results in a progressively weaker and more porous matrix that becomes increasingly vulnerable to moisture-induced internal damage. This is consistent with the observations of Matos and Sousa-Coutinho (2012), who found that high dosages of glass powder as cement replacement compromised the durability performance of mortar, and with Islam et al. (2017), who reported that the benefits of glass powder incorporation diminish beyond an optimal threshold.

Conversely, the mass loss results exhibit a consistent and monotonic decreasing trend with increasing glass powder content, irrespective of the observed strength behavior. The reference mix (SC-WGP) showed the highest mass loss of 5.45%, which was progressively reduced to 2.56%, 2.02%, 1.80%, and 1.27% for SC-GP10%, SC-GP20%, SC-GP30%, and SC-GP40%, respectively. The 40% GP mix thus achieved a considerable reduction of approximately 76.70% in mass loss compared to the reference mix. Unlike the strength loss trend, the continuous improvement in mass stability with increasing GP content can be attributed to the progressive filling of surface-accessible pores by unreacted glass particles. Jain and Neithalath (2010) demonstrated that glass-powder-modified concretes exhibited lower diffusion coefficients, attributing this improvement to the physical pore-blocking effect of fine glass particles, which is consistent with the reduced mass loss observed in the present study. Similarly, Letelier et al. (2019) found that waste glass incorporation in mortars contributed to reducing permeability, supporting the hypothesis that the impermeable and smooth surface texture of glass particles creates a barrier effect that limits water ingress and egress during wetting-drying cycles, thereby preserving the surface integrity and reducing material detachment from the outer layers.

This divergence between compressive strength loss and mass loss trends under wetting-drying conditions confirms that a single performance indicator is insufficient to fully characterize the durability of sand concrete, as previously observed in the freeze-thaw results. However, a notable distinction exists between the two tests: while the freeze-thaw results showed relatively modest differences in strength loss across compositions (ranging from 2.89% to 6.13%), the wetting-drying test produced a wider dispersion (from 3.41% to 7.49%), indicating that sand concrete is more sensitive to wetting-drying cycles than to freeze-thaw cycles, particularly at higher glass powder dosages. Ammari et al. (2020a) and Bederina et al. (2016) reported similar observations regarding the sensitivity of sand concrete to cyclic moisture exposure, attributing it to the inherently porous microstructure of this type of concrete. This heightened

sensitivity can be explained by the fact that the alternating shrinkage and swelling stresses generated during drying and wetting phases create differential moisture gradients between the surface and the core of the specimens, which are more damaging to the weakened matrix at high GP replacement levels than the volumetric expansion caused by ice crystallization during freeze-thaw cycling.

In light of these findings, the 10% GP mix once again demonstrates the best overall durability performance under wetting-drying conditions. It is the only composition that simultaneously improved both performance indicators relative to the reference mix, achieving the lowest strength loss (3.41%) and a substantial reduction in mass loss (2.56%, representing a 53.03% decrease compared to the reference mix). Although higher GP dosages provided superior mass stability, this benefit was offset by a considerable deterioration in mechanical performance. This conclusion is in agreement with the findings of Ammari et al. (2023), who identified 10% GP as the optimal dosage for mechanical performance of sand concrete. Salim and Mosaberpanah (2021) also reported that low glass powder replacement levels yielded the best durability performance in high-performance mortar, while Ghrici et al. (2007) demonstrated that low replacement levels of pozzolanic materials achieved the best balance between durability and mechanical strength, further reinforcing the conclusion that 10% GP represents the optimal compromise for sand concrete.

3.6. Resistance to acidic environments

This section focuses on evaluating the resistance of sand concrete incorporating glass powder to chemical degradation induced by hydrochloric acid (HCl) exposure. The assessment was conducted on specimens immersed in a 5% HCl solution, and the durability performance was characterized through two complementary approaches: a physical evaluation based on monitoring the mass variation over the immersion period, and a microstructural investigation employing X-ray diffraction (XRD) analysis and scanning electron microscopy (SEM) observations to identify the mineralogical and morphological changes occurring within the cementitious matrix as a result of acid-induced deterioration.

3.6.1. Mass variation

The mass variation results of all sand concrete compositions after 90 days of immersion in the HCl acid solution are presented in Fig. 12.

The temporal evolution of mass loss reveals a continuous and progressive degradation pattern for all tested compositions throughout the entire immersion period, from the first week up to 90 days, with no stabilization observed, indicating that the acid attack is an ongoing and persistent process that progressively deteriorates the cementitious matrix over time. This observation is consistent with findings reported in the literature, where prolonged HCl exposure was shown to cause continuous mass loss in cementitious materials due to the sustained dissolution of hydration products (Huang et al. 2005).

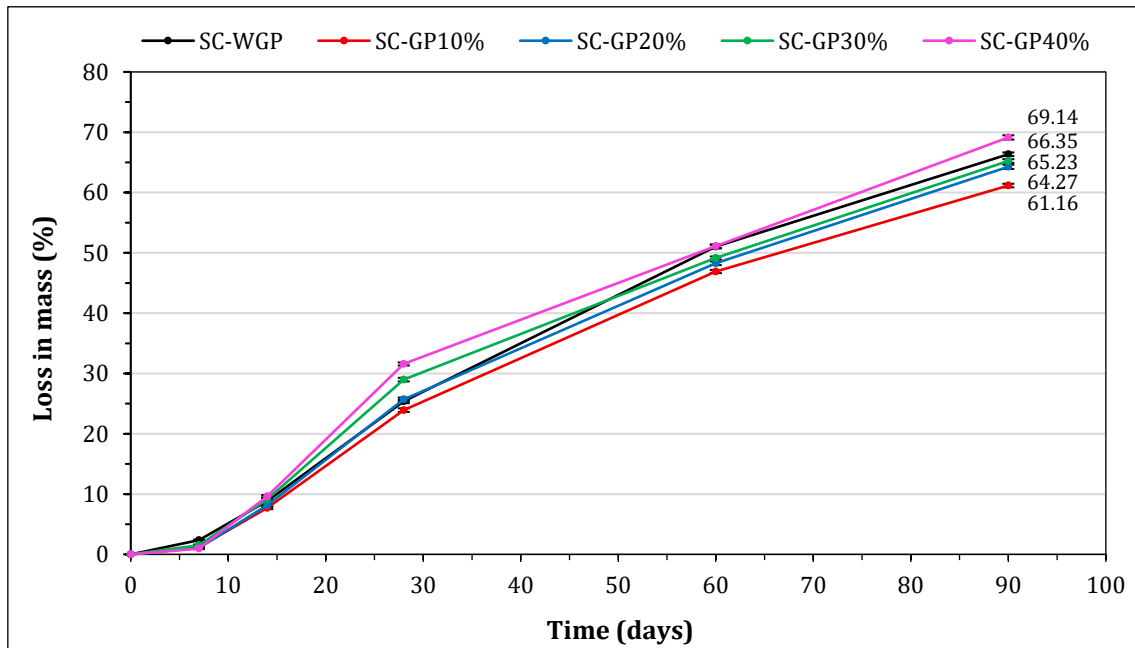


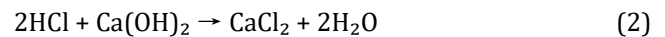
Fig. 12. Evolution of mass changes of the studied concretes with immersion time in acid solution.

At 90 days, the mass loss values for all compositions were notably high, ranging from 61.16% to 69.14%, reflecting the severe aggressiveness of the 5% HCl solution on the sand concrete matrix. The reference mix (SC-WGP) recorded a mass loss of 66.35%, while the incorporation of glass powder at 10%, 20%, and 30% reduced this value to 61.16%, 64.27%, and 65.23%, respectively, corresponding to reductions of approximately 7.82%, 3.13%, and 1.69% relative to the reference mix. Among all tested compositions, the SC-GP10% mix demonstrated the highest resistance to acid-induced mass loss, achieving the lowest value of 61.16%. This improved performance can be attributed to the effective pozzolanic reaction at this dosage, which produces additional C-S-H gel that densifies the microstructure and reduces the permeability of the matrix, thereby decelerating the rate of acid penetration into the inner layers of the concrete. Salim and Mosaberpanah (2021) reported a comparable improvement in acid resistance at low glass powder replacement levels, attributing it to the enhanced pore refinement that limits the ingress of aggressive agents into the cementitious matrix. The SC-GP20% and SC-GP30% compositions also exhibited improved acid resistance compared to the reference, although the beneficial effect diminished progressively with increasing GP content, suggesting that the pore-refining capacity of the pozzolanic reaction weakens as the cement content decreases.

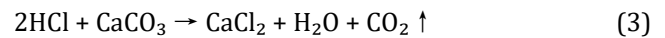
However, a critical reversal in this trend was observed at 40% GP, where the mass loss increased to 69.14%, exceeding the reference mix by 4.21%. This finding is particularly noteworthy as it demonstrates that the SC-GP40% composition is the only mix that performed worse than the reference concrete under acid exposure. At this high replacement level, the severe dilution of the cementitious matrix results in a substantially reduced $\text{Ca}(\text{OH})_2$ content and an insufficiently densified microstructure with elevated porosity and enhanced pore connectivity, which accelerates the penetration of

the HCl solution into deeper regions of the concrete. Jain et al. (2020) observed a similar behavior, reporting that while glass powder incorporation at moderate levels improved the chemical resistance of concrete, excessive dosages compromised the matrix density and consequently reduced the overall acid resistance.

The deterioration mechanism governing the mass loss under HCl exposure involves two principal chemical reactions. The first reaction occurs between the hydrochloric acid and the calcium hydroxide ($\text{Ca}(\text{OH})_2$) present in the pore solution, as expressed in Eq. (2):



The second reaction involves the attack of HCl on the calcium carbonate (CaCO_3) present in the matrix, as expressed in Eq. (3):



Both reactions generate calcium chloride (CaCl_2), a highly soluble salt that crystallizes within the pore network of the concrete. The continuous formation and accumulation of this salt induces expansive internal stresses within the matrix, leading to the initiation and propagation of micro-cracks that progressively disintegrate the composite structure and cause material detachment (Barbhuiya and Kumala 2017). As the exposure duration increases, these cracks create preferential pathways that further facilitate the penetration and propagation of the acid solution into deeper regions of the cementitious matrix, creating a self-accelerating degradation cycle that amplifies the mass loss over time (Huang et al. 2005).

Therefore, the acid resistance results confirm that the glass powder effect on sand concrete durability is dosage-dependent and not uniformly beneficial. The incorporation of GP at 10%, 20%, and 30% improved acid resistance compared to the reference mix, with the best performance observed at 10% replacement. However, at

40% GP, the excessive cement replacement led to a net deterioration in acid resistance, with a mass loss exceeding even that of the reference concrete. This dual behavior reinforces the importance of limiting the glass powder replacement level to preserve both the matrix density and the chemical buffering capacity, and further confirms that 10% GP offers the most favorable balance between microstructural enhancement and acid durability for sand concrete.

3.6.2. Visual examination

The physical state of all sand concrete specimens after 90 days of exposure to the 5% HCl solution is documented in Fig. 13. A visual comparison between the acid-exposed specimens and the unexposed reference speci-

mens revealed several characteristic signs of deterioration common to all tested compositions. The most prominent feature observed was the formation of a brownish layer deposited on the external surfaces of all exposed specimens. This discoloration is attributed to the precipitation of calcium chloride (CaCl_2) crystals on the concrete surface, generated by the chemical reactions between HCl and the calcium-bearing phases (Ca(OH)_2 and CaCO_3) within the cementitious matrix, as previously reported by Ghrici et al. (2007) and Aoual-Benslafa et al. (2011) for cementitious materials exposed to similar acidic environments. Additionally, a noticeable deterioration was observed at the corners and edges of the specimens, which represent the most vulnerable zones due to their higher surface-to-volume ratio that exposes them to multi-directional acid penetration.



Fig. 13. Visual examination of concretes exposed to acid solution at 90 days.

Despite this visible degradation, the specimens generally retained their overall geometric integrity and surface texture, although a measurable dimensional reduction was observed. The reported dimensions represent the average values obtained from three specimens for each mixture after acid exposure, with the average final dimensions of approximately $30 \times 30 \times 145$ mm compared to the original $40 \times 40 \times 160$ mm. This dimensional reduction corresponds to an approximately 43.75% decrease in the cross-sectional area and an approximately 49% reduction in specimen volume, quantitatively confirming the severity of the acid-induced material dissolution over the 90-day exposure period. Siad et al. (2016) documented comparable physical deterioration patterns on the surfaces of concrete specimens containing glass powder after prolonged immersion in aggressive acid

solutions, confirming that surface erosion and material loss are inevitable consequences of acid exposure for all concrete compositions, although the extent of damage varies with the matrix density and pore structure.

3.6.3. X-ray diffraction (XRD) analysis

The XRD diffractograms of the surface samples collected from the sand concrete specimens after 90 days of exposure to a 5% HCl solution are presented in Figs. 14 and 15 for the reference concrete (SC-WGP) and the SC-GP40% mixture, respectively. The SC-GP40% specimen was selected as a representative glass-powder-modified concrete because all glass-powder mixtures exhibited essentially the same crystalline phases after acid exposure, with only slight variations in peak intensities.

Therefore, presenting a single representative diffractogram is sufficient to illustrate the mineralogical characteristics of the glass-powder-modified concretes and to

facilitate comparison with the reference concrete in order to evaluate the influence of glass powder on the mineralogical evolution under hydrochloric acid attack.

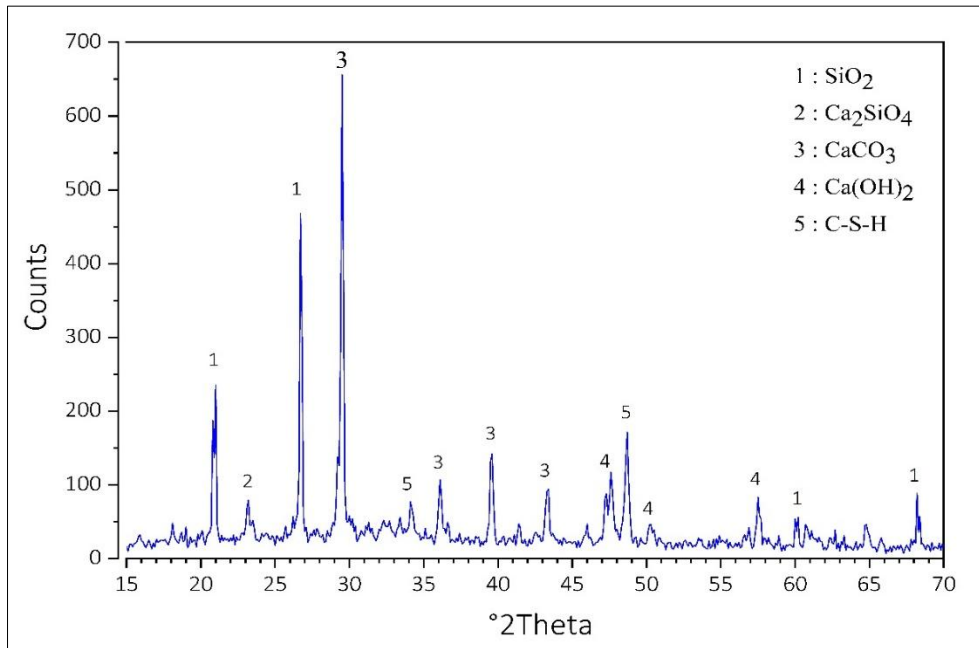


Fig. 14. X-ray diffraction analysis of the control concrete (SC-WGP) after hydrochloric acid attack.

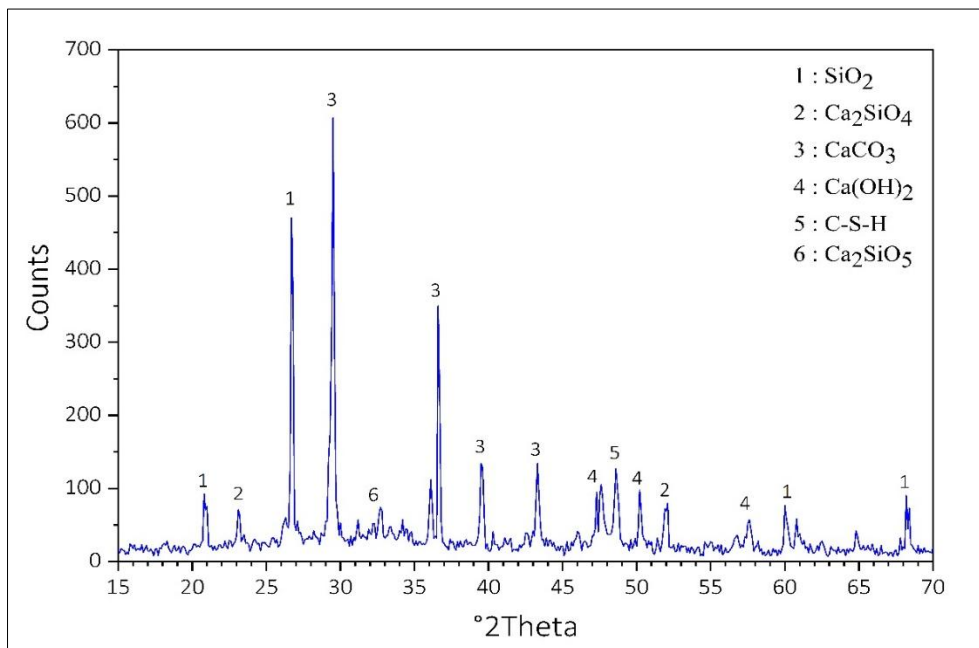


Fig. 15. X-ray diffraction analysis of concrete containing glass powder (SC-GP40%) after hydrochloric acid attack.

The mineralogical analysis of the reference mix (Fig. 14) identified the following crystalline phases: quartz (SiO_2), originating from the siliceous sand aggregate; dicalcium silicate (Ca_2SiO_4), corresponding to residual unhydrated cement; calcium carbonate (CaCO_3), associated with the limestone filler and its reaction products; portlandite ($\text{Ca}(\text{OH})_2$), the principal hydration product of cement; and calcium silicate hydrate (C-S-H), the main binding phase of the cementitious matrix.

The diffractogram of the SC-GP40% specimen (Fig.

15) revealed the same crystalline phases identified in the reference mix, with the notable detection of an additional calcium silicate phase (Ca_2SiO_5). The exclusive presence of this supplementary phase in the glass-powder-modified specimen provides direct mineralogical evidence of the pozzolanic reaction between the amorphous silica content of the glass powder and the available calcium hydroxide, leading to the formation of additional calcium silicate compounds that contribute to densifying the cementitious matrix and refining the pore structure.

Furthermore, the detection of CaCO_3 and Ca(OH)_2 peaks in both diffractograms, despite the prolonged acid exposure, indicates that the acid attack did not completely consume these calcium-bearing phases, suggesting that remnants of these compounds persisted within the inner regions of the specimens where the acid penetration was limited. Nevertheless, the partial dissolution of Ca(OH)_2 and CaCO_3 through their reaction with HCl, as described in Eqs. (2) and (3), remains the primary mechanism responsible for the mass loss and structural degradation observed across all tested compositions.

3.6.4. Scanning electron microscopy (SEM) analysis

The microstructural characteristics of the SC-GP10% sand concrete specimens before and after 90 days of exposure to a 5% HCl solution were examined using scanning electron microscopy (SEM), and the representative micrographs are presented in Figs. 16 and 17, respectively. The analyzed samples were extracted from the surface region of the specimens, which was directly exposed to the acid solution and therefore represented the most severely deteriorated zone.

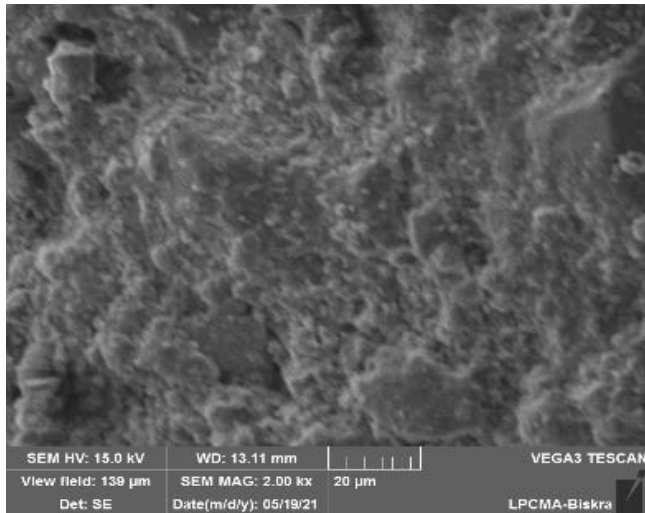


Fig. 16. SEM micrograph of the SC-GP10% specimen before exposure to the 5% HCl solution (after 28 days of curing), showing the surface region (magnification $\times 2000$).

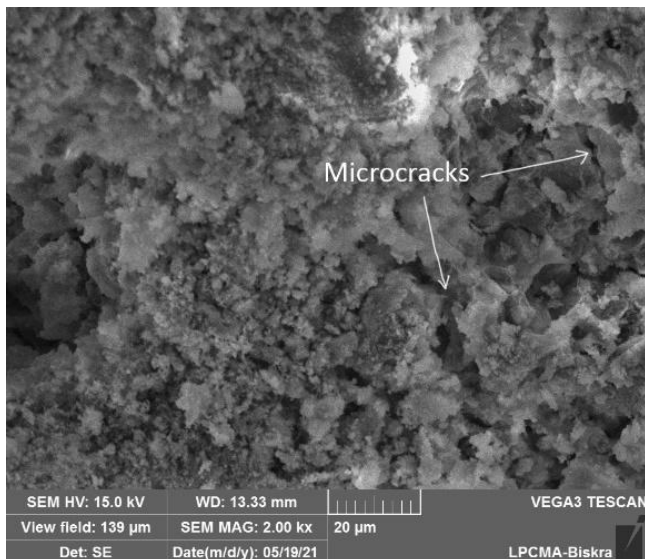
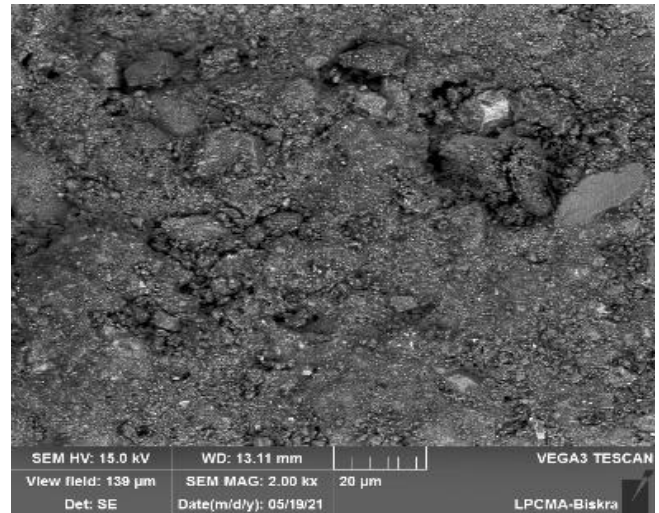
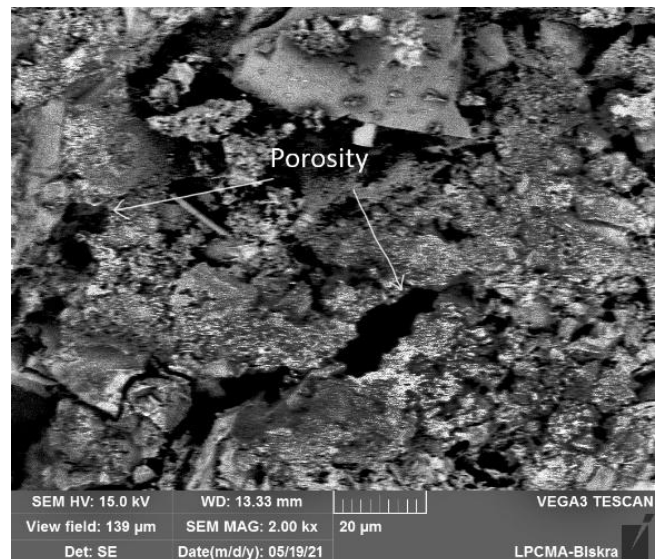


Fig. 17. SEM micrograph of the SC-GP10% specimen after 90 days of exposure to the 5% HCl solution, showing the surface region (magnification $\times 2000$).



The SC-GP10% mixture was selected as a representative glass-powder-modified concrete because all mixtures containing glass powder exhibited similar surface deterioration and comparable microstructural features after acid exposure, with only minor differences in the extent of damage. Therefore, the selected SEM micrographs are representative of the microstructural re-

sponse of the glass-powder-modified concretes under hydrochloric acid attack. The SEM micrograph of the SC-GP10% specimen before acid exposure (Fig. 16) reveals a relatively dense and compact cementitious matrix, characterized by a well-developed microstructure with identifiable C-S-H gel phases and a coherent interfacial transition zone (ITZ) between the cement paste and the

sand grains. The overall morphology indicates adequate hydration and satisfactory pore filling under normal curing conditions.

In contrast, the SEM micrograph of the same SC-GP10% specimen after 90 days of immersion in the 5% HCl solution (Fig. 17) reveals pronounced microstructural degradation. The exposed surface exhibits a considerably more porous and disrupted matrix, with the formation of numerous micro-cracks and an increase in the volume and size of voids compared with the specimen before acid exposure. This deterioration is attributed to the progressive dissolution of the calcium-bearing hydration products, primarily $\text{Ca}(\text{OH})_2$ and CaCO_3 , through their chemical reaction with HCl, as described in Eqs. (2) and (3). The dissolution of these phases creates additional void spaces within the matrix, while the crystallization of the reaction product CaCl_2 within the existing pores generates expansive internal stresses that initiate and propagate micro-cracks, further weakening the structural integrity of the cementitious matrix.

4. Conclusions

This study investigated the influence of glass powder incorporation at varying replacement levels (0%, 10%, 20%, 30%, and 40%) on the durability properties of sand concrete, including water absorption, capillary absorption, accelerated carbonation, freeze-thaw resistance, wetting-drying resistance, and resistance to hydrochloric acid attack. The experimental findings revealed that the effect of glass powder on sand concrete durability is dosage-dependent and not uniformly beneficial, with both favorable and unfavorable trends observed depending on the property considered and the replacement level adopted. The principal conclusions drawn from this investigation are summarized as follows:

- The incorporation of glass powder adversely affected both the total water absorption and capillary absorption of sand concrete at all replacement levels. The total immersion absorption increased from 6.24% for the reference mix to 7.23% for the 40% GP mix (an increase of 15.87%). The cumulative capillary water absorption after 24 hours increased from 7.68 kg/m² for the reference mixture to 12.76 kg/m² for the SC-GP40% mixture, corresponding to an increase of approximately 66.1%. This progressive deterioration in transport properties represents a notable limitation of glass powder incorporation, particularly at dosages exceeding 20%, and should be carefully considered in the design of sand concrete intended for water-exposed environments.
- Regarding accelerated carbonation resistance, the 10% GP mix achieved the shallowest carbonation depth of 5.49 mm at 28 days, representing a reduction of 15.41% compared to the reference mix (6.49 mm). However, higher replacement levels led to a pronounced increase in carbonation depth, reaching 13.68 mm at 40% GP (an increase of 110.79%), due to the combined effect of reduced $\text{Ca}(\text{OH})_2$ availability and increased matrix porosity.
- Under freeze-thaw cycling, the 10% GP mix exhibited the lowest compressive strength loss of 2.89%, while higher GP dosages led to progressively greater strength deterioration, reaching 6.13% at 40% GP. Conversely, mass loss decreased consistently with increasing GP content, with the 40% GP mix recording the lowest mass loss of 1.47%. A similar divergence between strength loss and mass loss indicators was observed under wetting-drying conditions, where the 10% GP mix achieved the lowest strength loss of 3.41% and was the only composition that simultaneously improved both performance indicators relative to the reference mix.
- The acid resistance results demonstrated that glass powder incorporation at 10%, 20%, and 30% improved the resistance of sand concrete to HCl attack, with the 10% GP mix recording the lowest mass loss of 61.16% after 90 days. However, the 40% GP mix exhibited a mass loss of 69.14%, exceeding even the reference mix (66.35%), confirming that excessive glass powder replacement compromises the chemical resistance of the matrix.
- SEM analyses revealed that the acid-exposed specimens exhibited pronounced microstructural degradation, characterized by increased porosity and micro-crack propagation resulting from the dissolution of calcium-bearing phases and the crystallization of CaCl_2 within the pore network. XRD analysis confirmed these observations and further identified an additional calcium silicate phase (Ca_2SiO_5) exclusively in the glass-powder-containing specimens, suggesting that the observed phase assemblage may be associated with reactions involving the glass powder; however, further verification is required to confirm the occurrence and extent of the pozzolanic reaction. This additional phase formation may contribute to matrix densification and could partly explain the enhanced acid resistance observed at low GP replacement levels.

Overall, this study demonstrates that 10% glass powder represents the optimal replacement level for sand concrete durability, not because it is uniformly superior under every criterion, but because it offers the most favorable compromise between mechanical integrity, carbonation resistance, cyclic durability, and acid resistance, with only a moderate and acceptable increase in absorption properties. This behavior can be attributed to the balance between the beneficial pozzolanic contribution of glass powder at moderate replacement levels and the adverse dilution effect occurring at higher dosages. At 10% GP, the pozzolanic reaction promotes the formation of additional calcium silicate hydrate (C-S-H) phases, contributing to matrix refinement and reducing the penetration of aggressive agents. In contrast, excessive glass powder incorporation reduces the available cementitious phase and calcium hydroxide content, limiting hydration and pozzolanic reactions and resulting in a less compact microstructure with increased pore connectivity. Consequently, the durability performance of sand concrete progressively declines at higher GP replacement levels, confirming the existence of an optimum glass powder content beyond which the negative

effects outweigh the beneficial contributions. These findings provide practical guidelines for the valorization of glass waste in sand concrete production. Future research should investigate the long-term natural carbonation behavior over extended exposure periods, evaluate the performance under combined aggressive environments, and explore the potential use of glass powder in conjunction with other supplementary cementitious materials to mitigate the observed increase in absorption properties.

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Conflict of Interest

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Data Availability

The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

AI Assistance

No AI-based tools were used in the preparation of this manuscript.

Author Contributions

All authors made substantial contributions to the conception and design of the study, acquisition of data, analysis and interpretation of data; drafted or critically revised the manuscript for important intellectual content; and approved the final version to be published.

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