Research on Engineering Structures & Materials
www.jresm.org
Research Group

Research Article

Enhancing the external sulfate attack resistance of high-volume fly ash concrete containing waste glass powder

Mahmood Fawzi Ahmed [*,a]

Department Education of Hit, General Directorate of Education in Anbar, Ministry of Education, 31007 Hit, Iraq

Article Info

Article History:

Received 15 Oct 2025

Accepted 15 Nov 2025

Keywords:

Fly ash;
HVFA concrete;
External sulfate attack;
Waste glass powder;
Concrete durability

Abstract

The urgent need to reduce the environmental footprint of concrete production has intensified research into sustainable alternatives to ordinary Portland cement (OPC) and ways to utilize industrial waste. This study is motivated by the need to enhance both the mechanical properties and durability of high volume fly ash (HVFA) concrete, by incorporating waste glass powder (GP) as a partial replacement for fly ash, with a particular focus on improving resistance to external sulfate attack. The cementitious binder of the reference mixture was a blend of 50% (OPC) and 50% fly ash by weight. Another two mixes were prepared by substituting 10% and 20% of fly ash weight with glass powder (GP). Key properties evaluated included compressive strength, water absorption, ultrasonic pulse velocity (UPV), and external sulfate resistance. Compressive strength was assessed for each mixture after 150 days of curing in both a 5% sodium sulfate (Na_2SO_4) solution and in normal water. The durability index was calculated as the difference in compressive strength between the sulfate-exposed and water-cured specimens. The results demonstrated that the inclusion of 10% and 20% glass powder in HVFA concrete present higher strength (43.6, 38.6 MPa) at both curing method in compare with reference mix (34.9 MPa). Therefore, the durability index of mixes with GP was improved, whereas 10% of GP is the optimum replacement level. The results of water absorption will decline from 3.15% to 2.33% and 2.65%, while (UPV) will increase from 4.683 Km/sec to 5.292 and 5.023 Km/sec of 10%GP and 20%GP mixtures, respectively. Significantly, UPV measurements increased by 13% and 7.2% for concrete mixes containing 10% and 20% GP, respectively, compared to the control mix, further confirming enhanced concrete uniformity and quality.

1. Introduction

Climate change and global warming become vital issues that require urgent solving pathways. The manufacturing of ordinary Portland cement, a key binder of concrete, is one of the majority carbon emissions, accounting for about 8% of the total emission around the world [1-2]. Due to the global continuation of the construction industry and the development of infrastructures, there is an imperative to decarbonization of conventional concrete and its constituents. One of the encouraging solutions of shifting conventional concrete to more sustainable building material is using supplementary cementitious materials (SCMs) together with ordinary Portland cement. There are different types of SCMs that can be used in concrete mixtures, including industrial by-products such as fly ash, silica fume, blast furnace slag, etc., and some sources from end-of-life materials as recycled waste glass [3]. Fly ash can be used as a blended or mineral admixture at a level of 50% by the total mass of cementitious materials. This allows for the development of a high concrete (HVFAC) system as defined by Mehta [4-5]. Several researchers have been attracted to

*Corresponding author: mahmodmfa81@gmail.com
[a]orcid.org/0000-0003-1342-6898
DOI: http://dx.doi.org/10.17515/resm2025-1267ic1015rs

high-volume fly ash concrete and have conducted studies on its production and characteristics. Kumar et al., evaluated the mechanical and durability properties of HVFAC prepared by replacing OPC by 20%, 40%, 50%, 60%, and 70% with FA. The authors found that the compressive strength and ultrasonic pulse velocity results have decreased with the increase of FA content, while the volume of permeable voids has declined by 15.65% at the 50% fly ash level, and then the permeable voids increase for mixes with 60% and 70% FA content [6]. Similarly, Babalu et al. [7] investigated the compressive and flexural strengths and some durability properties of HVFAC mixtures that included 30%, 40%, 50%, 60%, and 70% of FA as a cement substitute. The main results show that the mix with 30% FA content presented the highest compressive and flexural strength and best resistance in acidic environment. Moreover, some studies investigated the durability of HVFAC against the external and internal sulfate attack. Al-Attar and Taha [8] evaluated the effect of internal sulfate attack by adding natural gypsum ($CaSO_4$) to the fine aggregate of high-volume fly ash self-compacting concrete. The strength degradation of all mixes including 50% and 60% FA was neglectful at the early age, followed by a more reduction in the strength for the 60% FA and 50% FA mixes, respectively. In the same context, Liu et al., [9] determined the variation of physical and mechanical properties of high-volume fly ash self-compacting concrete exposure to dry - wet cyclic sulfate attack with 5% Na2SO4. Other research represented by Das et al. [10] examined the durability of ternary blended high volume fly ash—ground granulated blast furnace slag concrete exposed to aggressive environments. The binder of the tested mixes was blended as: (50% OPC + 25% FA + 25% GGBFS), (50% OPC + 20% FA + 30% GGBFS), and (50% OPC + 30% FA + 20% GGBFS). On the other hand, the excessive use of glass products in different fields has generated a significant amount of end-life waste. This waste of glass is usually disposed of as damping and landfilling, consequently hazardous, and adverse effects will accrue on the environment and ecological balance. Recycling and reuse waste glass as fine glass powder in concrete production will provide a sustainable approach to overcome this challenge [11]. Numerous researchers would encourage for introducing (GP) into concrete as a partial replacement of cement because of its pozzolanic activity and amorphous phase [12-13]. The work of Paul et al. [14] lies in replacing the cement with waste glass powder at levels from 0 to 40%, then measuring the shrinkage, durability, and mechanical properties of two concrete grades, M30 and M40. In additional experimental research, Muhedin and Ibrahim [15] described the physical, mechanical, and microstructure properties of concrete that containing 0%, 10%, 15%, and 20% of waste glass powder as partial replacement of cement and fine aggregate separately. Furthermore, some researchers have used waste glass powder as a blend with other pozzolanic additives. Abed et al. [16] utilized waste glass powder and silica fume as pozzolanic materials to partially substitute cement in mortar manufacture. The study of Chengjin Li [17] discovered the compressive strength and sulfate corrosion resistance of concrete mixture made of blended limestone powder and glass powder with cement. The author found that combination of 10% limestone powder and 5% glass powder was the best mixed to improve the corrosion resistance and strength. Also, Akinpelu et al. [18] examined the impact of waste glass powder and metakaolin as partial substitutes for cement in self-compacting concrete. Their research indicated that a ternary mixture including 5% metakaolin and 10% waste glass powder significantly enhanced both workability and mechanical qualities, exceeding the control mix in strength and microstructural performance. Furthermore, fly ash availability is diminishing in many regions due to the closure of coal power plants, and because of its slower pozzolanic reaction, it mainly contributes to long-term strength gains. Glass powder, with its high amorphous silica content and fine particle size, exhibits faster reactivity and can enhance early-age strength when blended with fly ash. [19]. Hence, there is a gap in research on the durability performance of concrete made with high volumes of blended fly ash and waste glass powder in aggressive external sulfate attacks. The primary aim of this study is to systematically investigate the durability performance and mechanical properties—specifically, compressive strength, water absorption, and ultrasonic pulse velocity—of high-volume fly ash (HVFA) concrete incorporating varying proportions of waste glass powder (GP) as a partial replacement for fly ash. This study concentrates on evaluating the performance of HVFA concrete at higher replacement rates, which is essential for optimizing waste glass utilization and produce more durable and sustainable concrete that can be applicable in a wide range of civil engineering fields.

2. Experimental Work

2.1 Materials

The ordinary Portland cement used was (CEM I 32.5 R), which meets Iraqi specification (IQ.S No.5:2019) [20]. The cementitious materials consisted of blended Fly ash (FA) and waste glass powder (GP) as per ASTM C618 [21]. The process of producing glass powder (GP) involved the collection of the broken pieces of waste window glass, then crushing and grinding these wastes to produce the final product of GP as shown in (Fig. 1). The Fly ash was brought from an electrical power station in Turkey and it is available in local markets. The chemical oxides and properties of (FA) and (GP) are presented in Table 1. The crushed gravel of size (5-14) mm was used as coarse aggregate, while the fine aggregate was natural sand of maximum size 5 mm and grading in zone 2. All aggregates are complying with Iraqi specification (IQ.S No.45:1984) [22]. For adjusting the workability, high range water reducing admixture (superplasticizer – Glenium 51) was utilize. The tap water (free from contaminates) was used for mixing and curing.

Fig. 1. Waste glass powder used in HVFA concrete mixture

Table 1. Chemical analysis and physical properties of fly ash, and waste glass powder

Chemical oxides	FA	GP	OPC
SiO_2	56.5	78.2	20.73
Al_2O_3	23.7	1.53	5.18
Fe_2O_3	6.3	0.71	3.48
CaO	5.8	8.1	62.87
MgO	1.2	0.56	2.16
SO_3	1.5	0.1	1.92
L.O.I	1.2	0.32	2.16
Blain fineness (m^2/kg)	420	290	320
Strength activity index, %	83	90.5	/

2.2 Mixture Design and Preparation of the Specimens

A total of three concrete mixtures were prepared and tested to evaluate some durability aspects related to external sulfate attack. The mix design of control mixture based on using blended of (50% FA with 50% OPC) to produce high volume fly ash concrete with a target compressive strength up to 30 MPa at 28 days. For the other two mixtures, the FA was replaced with waste GP by 10% and 20% of weight. These substitution level (10% and 20% GP) has selected for evaluating the performance of HVFA concrete at higher replacement rates, which is essential for optimizing waste glass utilization and enhancing sustainability advantages. The denotation and the proportion of materials of all mixes are presented in Table 2. The mixing process started by blending the OPC, FA, and GP manually. Then, the binder was mixed with the coarse and fine aggregate inside the drum of an electrical mixer. The water and superplasticizer were added gradually into the mixer, and the mixing process was done in about 8 minutes until achieved a homogenous mixture. The fresh concrete was cast into cubic molds of (15×15×15) cm, compacted with steel rod, covered with plastic sheet and left to set for 24 hours before being demolded.

Table 2. Mix proportion of HVFA concrete (kg/m[3])

Materials	Batch name		
	M1(50FA:0GP)	M2(40FA:10GP)	M3(30FA:20GP)
Cement	250	250	250
Fly ash	250	200	150
Glass powder	0	50	100
Coarse aggregate	1080	1080	1080
Fine aggregate	722	722	722
(w/cm), %	0.35	0.35	0.35
Superplasticizer, %*	3	3	3

** The dosage of superplasticizer is (%) by weight of cement*

2.3 Curing, Exposing Regime and Testing Methods

Immediately after demolding the specimens of each mix, the total of (108) samples were divided into two groups according to the specified curing regime. For the first group, the samples were cured normally by immersion in water (taken as the reference of compressive strength). The samples of the second group have immersed directly (after demolding) in a chemical solution of 5% sodium sulfate (Na_2SO_4) prepared as per ASTM C1012 [23]. Figure 2 shows the specimens immersed inside the sodium sulfate solution. As an indication of the uniformity and quality of the concrete matrix, the samples of normal curing (first group) were tested to measure the water absorption and transmit velocity of ultrasonic pulse (UPV) at 7 and 28 days according to ASTM C642 [24] and ASTM C597 [25], respectively. To evaluate the long-term durability performance, the strength development of all mixes in each curing regime was determined by testing the compressive strength as per BS 1881:116 [26] at ages of 7, 28, 90, 120, and 150 days. The test of specimens at a later age (150 days) will provide more reliable results about the concrete's performance over its service lifecycle.

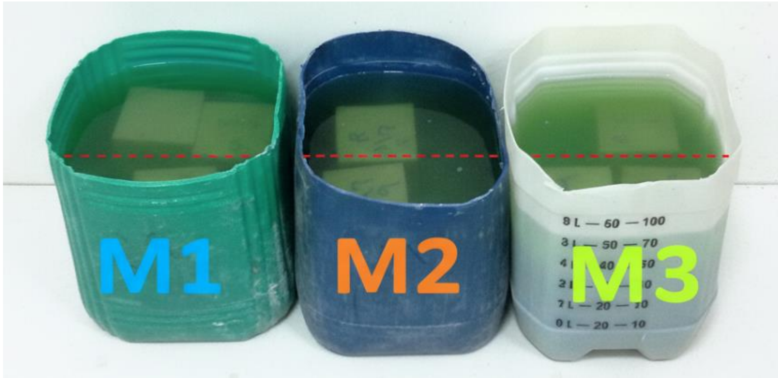
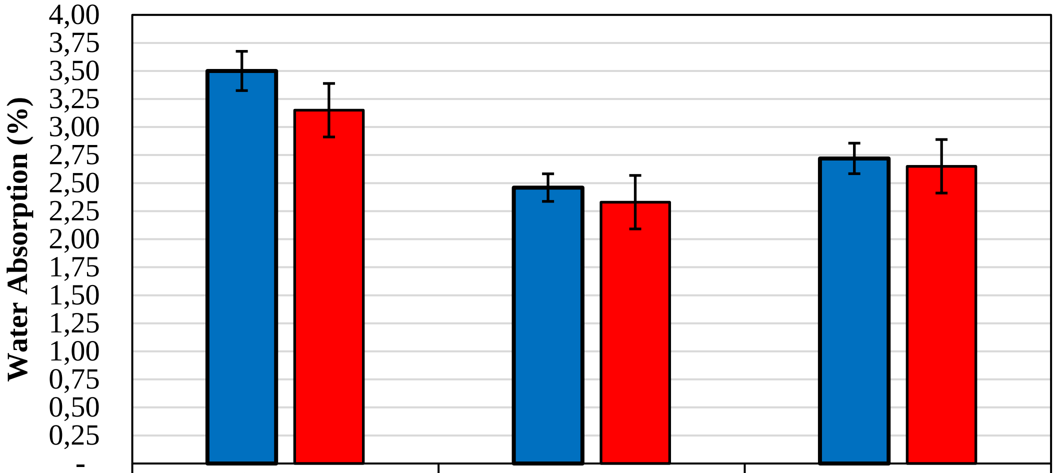


Fig. 2. Some specimens of HVFA concrete mixtures submersed in Na_2SO_4 solution

3. Results and Discussion

3.1 Water Absorption

As shown in (Fig. 3), the water absorption of HVFA concrete lies in 3.5% and 3.15% at 7 and 28 days, respectively. Notably, the replacement of FA with 10% and 20% GP will decrease the water absorption by 29.7% and 22.3% at 7 days, respectively. This decrement will be 26.0% for mix M2 (40FA:10GP), and 15.8% for mix M3 (30FAP:20GP) at age of 28 days. From Figure 3 it can be seen that the mixture M2 (40FA:10GP) have the lowest water absorption. The reduction in water absorption is due to the pozzolanic activity and the filling effect of glass powder within gel pores and concrete matrix. Glass powder is rich in amorphous silica, which reacts pozzolanically with calcium hydroxide ($Ca(OH)_2$) released during cement hydration. This secondary reaction results in the formation of additional calcium silicate hydrate (C-S-H) gel, which fills the capillary pores and reduces overall porosity [12], [27-28]. On the other hand, the fine particle size of glass powder improves the particle packing density within the cementitious matrix. The glass powder particles act as fillers that occupy voids between the larger cement and fly ash particles. This leads to a more compact and refined microstructure, further decreasing the volume of permeable pores available for water absorption [1], [29]. Furthermore, the synergistic effect of glass powder with fly ash will complement the slower pozzolanic activity of fly ash, accelerating the densification process and contributing to a more impermeable matrix at earlier ages [14]. These findings are consistent with previous studies that reported enhanced durability and reduced permeability when glass powder was used as a partial replacement of cementitious materials [11], [27].



	M1 (50FA:0GP)	M2 (40FA:10GP)	M3 (30FA:20GP)
7 day	3,50	2,46	2,72
28 day	3,15	2,33	2,65

Fig. 3. Water absorption of HVFA concrete mixtures

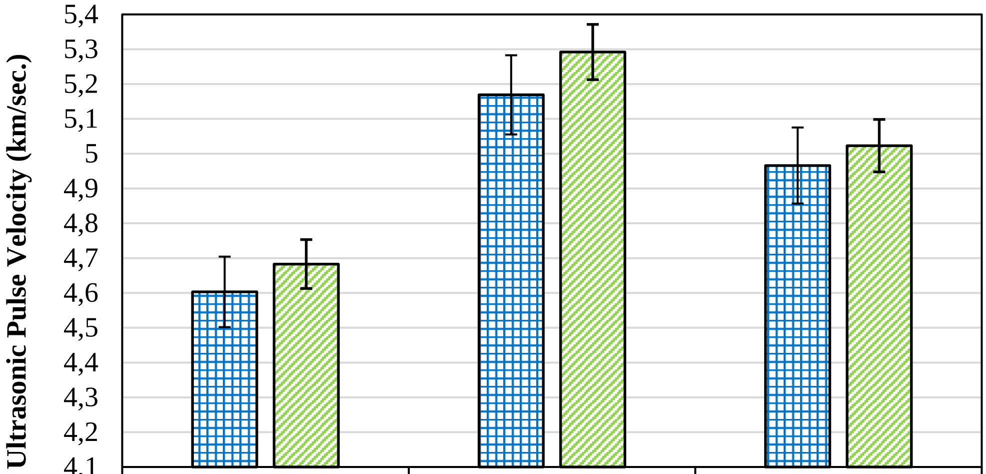
3.2 Ultrasonic Pulse Velocity

The values of ultrasonic pulse velocity measured for all mixes at 7 and 28 days are presented in (Fig. 4). The results of all concrete mixes indicate increasing of UPV with curing age as a consequence of improving the concrete structure due to the continuous of cement hydration. The inclusion of 10% and 20% GP has increased the UPV of reference mix (M1) up to 13.0% and 7.2% respectively. As expected, the substitute of FA with fine particles and high pozzolanic activity of GP will enhance the hydration process, refinement the pores size and backing of the interfacial transition zone (ITZ), as mention previously. Therefore, the transmitted time of the pulse within concrete matrix will decline significantly, so its velocity increase, similarly to the previous study of Safiy et al. [29].

3.3 Development of Compressive Strength

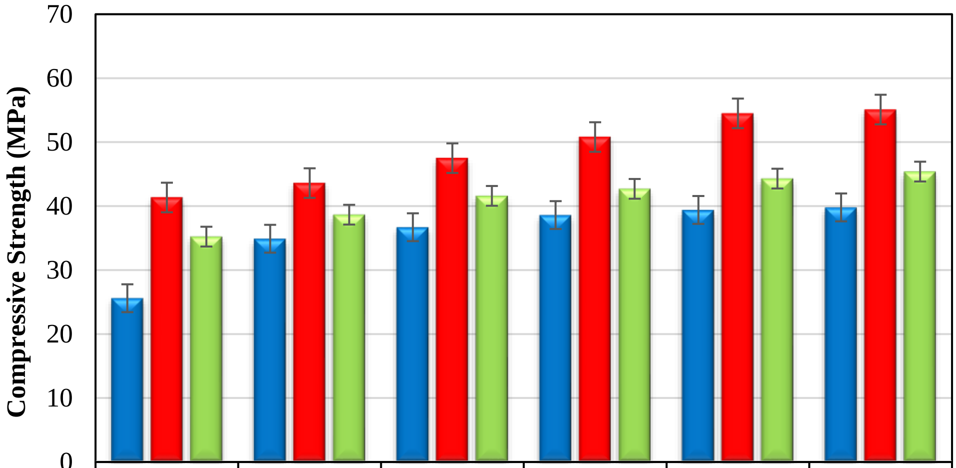
Two types of solutions used in the curing of concrete specimens.

Specimens cured in water: The results of compressive strength of HVFA concrete mixtures (M1), (M2), and (M3) are graphically presented in (Fig. 5). All the specimens under water curing demonstrated a continuous increasing of compressive strength with time. The outcomes show that the strength of M1, M2, and M3 at age of 7 days developed by 56.0%, 33.7%, and 28.6% after 120 days, respectively. The results of Figure 5 indicate the addition of GP significantly enhanced the compressive strength. The pozzolanic activity and fineness of GP will densified ITZ and refine the size of pores. Consequently, the strength of concrete has been improved [26-29]. Although fly ash has a slow pozzolanic activity, a corresponding the strength gain at early ages is also slow.



	M1 (50FA:0GP)	M2 (40FA:10GP)	M3 (30FA:20GP)
7 day	4,603	5,169	4,966
28 day	4,683	5,292	5,023

Fig. 4. Ultrasonic Pulse Velocity of HVFA concrete mixtures

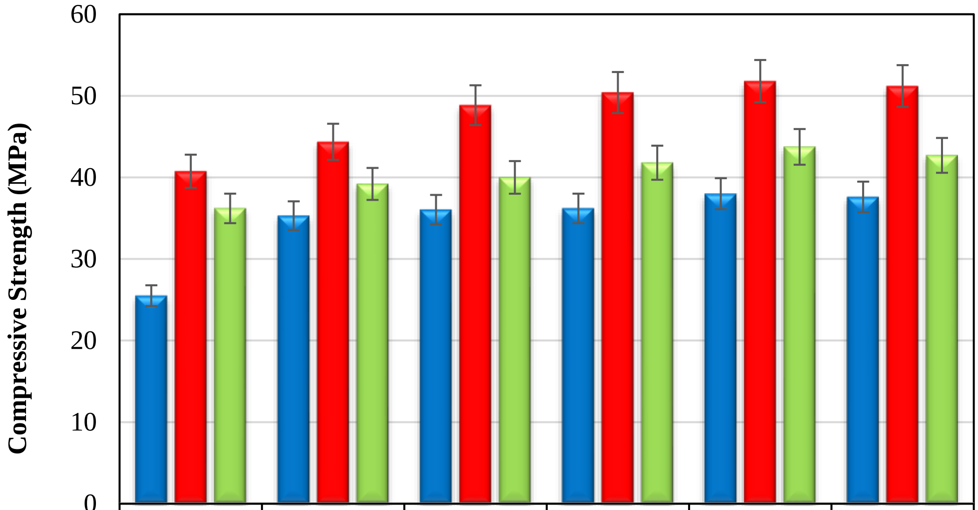


	7 days	28 days	60 days	90 days	120 days	150 days
M1 (50FA:0GP)	25,60	34,90	36,70	38,60	39,4	39,8
M2 (40FA:10GP)	41,35	43,60	47,50	50,80	54,5	55,1
M3 (30FA:20GP)	35,23	38,66	41,60	42,70	44,3	45,4

Fig. 5. Compressive strength of HVFA concrete mixtures curing in water

Nevertheless, the reference mix (M1) exhibited a retarding of the strength development in compare with M2 and M3 mixes till the later ages. While the addition of glass powder (GP) accelerates early-age strength gain, fly ash (FA) plays a crucial role in strength development of the mixes (M2 and M3) at later ages through the continuous pozzolanic activity that consumption the weak calcium hydroxide and formation additional stronger and durable gel [19]. The blend of 10% GP and 40% FA yielded in the highest strength at all test ages. This may be attributed to optimizing the synergistic effects of both supplementary cementitious materials in relation to the highest pozzolanic activity, optimized particle packing and filler effect, and balancing of replacement level and hydration products. This finding matches with the results of UPV and water absorption test and in same trend as the previous studies [11], [29-30].

Specimens submersing in Na_2SO_4 solution: The strength development of HVFA concrete specimens immersed in 5% Na_2SO_4 sulfate solution are shown in (Fig. 6.) It was observed that all concrete mixtures exhibited continuous strength gain with time up to 120 days. The 7th day's compressive strength of M1, M2, and M3 increased by 49%, 27.11%, and 20.83% at age of 120 days, respectively.



	7 days	28 days	60 days	90 days	120 days	150 days
M1 (50FA:0GP)	25,50	35,30	36,05	36,20	38	37,6
M2 (40FA:10GP)	40,75	44,36	48,85	50,40	51,8	51,2
M3 (30FA:20GP)	36,20	39,20	40,00	41,80	43,74	42,7

Fig. 6. Compressive strength of HVFA concrete mixtures submersing in Na_2SO_4 solution

The compressive strength of all mixes has steadily increased at ages 28, 60, and 90 days to reach the maximum strength at 120 days. The compressive strength at 28 days for M1, M2, and M3 was 35.30, 44.36, and 39.20 MPa, respectively. The values have increased by 2.12%, 10.12%, and 2.04% at 60 days, and by 2.55%, 13.61%, and 6.63% at 90 days, respectively. This behavior can be attributed to the formation of more cementitious hydration products and densification of the microstructure. After 150 days of immersing, all specimens will begin to face the adverse effects of sulfate solution. The compressive strength of mixes M1, M2, and M3 at 150 days has slightly decreased by 1.06%, 1.17%, and 2.43% compared to the results of 120 days, respectively. The reduction in strength of HVFA mixes related to the mechanism of sulfate attack on cement paste components, mainly the reaction between calcium hydroxide and sulfate ions. Consequently, high volume products (gypsum and ettringite) will take place within hardened cementitious matrix, leading to more cracking and degradation.

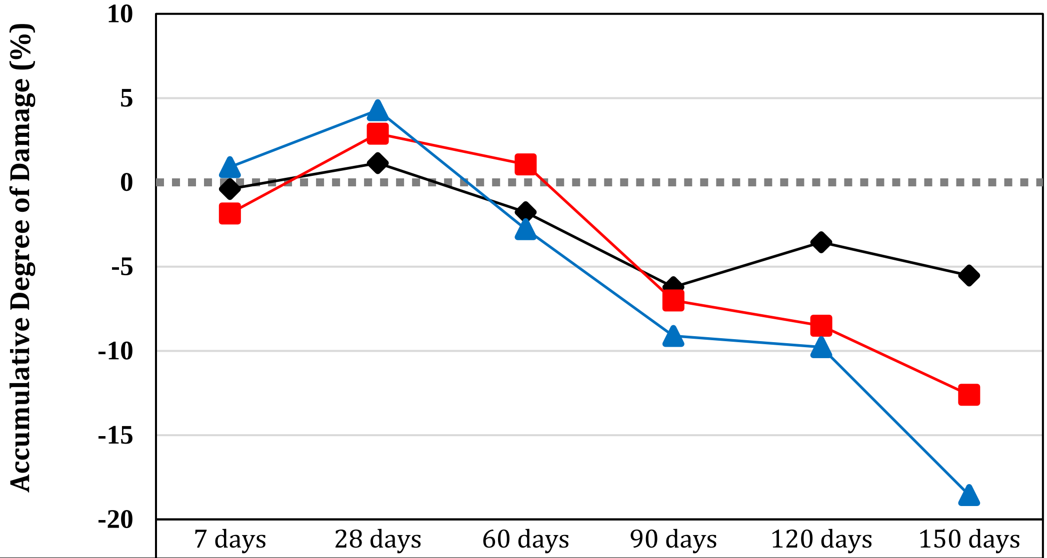
3.4 Durability Index (Degree of Damage)

The durability index, represented as the degree of damage (Di), is a crucial measure in this study for quantitatively evaluating the resistance of high-volume fly ash (HVFA) concrete to external sulfate attack. The index reflects the variation in compressive strength of concrete specimens subjected to a sulfate-rich environment against those cured under normal water conditions. The (Di) measured according to the following equation [31]:

$$Di = 1 - \frac{Cs}{Cw} \tag{1}$$

Where; Di is a degree of damage (durability index), Cs: compressive strength of samples exposed to sulfate attack after a given period, Cw: compressive strength of samples cured normally in water at the same period.

A higher (Di) value indicates greater deterioration, while a lower value signifies better durability and resistance to sulfate-induced degradation. The results of concrete damage degree are graphically presented in Figure 7. It can be seen that the degree of damage of each mix was increased with time, and it reached to the maximum at end time of test – 150 days due to prolonged sulfate exposure. The reference mix (M1) exhibited the lowest degree of damage. This phenomenon is attributed to the slower strength gain of M1 under water curing, resulting in a smaller variation between the strengths in sulfate and water curing. While M2 (40% FA, 10% GP) and M3 (30% FA, 20% GP) mixes showed higher strength increments under normal curing, which led to a larger differential when compared to sulfate-exposed specimens. Consequently, their degree of damage was higher. This observation does not suggest inferior performance; instead, it indicates that the rapid strength gain achieved through the addition of glass powder is not entirely sustained under aggressive sulfate conditions. Despite this, all mixes containing glass powder (M2 and M3) retained significantly higher absolute compressive strengths than the reference mix after sulfate exposure, underscoring the beneficial role of GP in enhancing sulfate resistance and overall durability.



	7 days	28 days	60 days	90 days	120 days	150 days
M3 (30:20)	2,75	1,40	-3,85	-2,11	-1,26	-5,95
M2 (40:10)	-1,45	1,74	2,84	-0,79	-4,95	-7,08
M1 (50:0)	-0,39	1,15	-1,77	-6,22	-3,55	-5,53

Fig. 7. Degree of damage of HVFA concrete mixtures after exposure to Na_2SO_4 solution

4. Conclusions

This study investigated high-volume fly ash concrete (HVFA) with 10% and 20% waste glass powder (GP) additions for evaluating its resistance to external sulfate attack. Experimental methods included physical and mechanical tests and durability examinations over 150 days. The following conclusions can be drawn from the key finding of this paper as below:

- The study confirms that structural concrete with a significant fly ash content—up to 50% of the binder—can attain a target compressive strength of 30 MPa within 28 days. This illustrates the feasibility of replacing a significant amount of ordinary Portland cement (OPC) with fly ash, which is necessary for mitigating the environmental impact of concrete production.
- The use of waste glass powder as a partial replacement for fly ash, at 10% and 20% content, significantly enhances the compressive strength of high-volume fly ash concrete (HVFA). The incorporation of 10% and 20% GP increases strength relative to the reference mix from 34.9 MPa to (43.6 and 38.6) MPa at 28 days, and improves strength development at both early and later stages to reach (55.1 and 45.4) MPa, respectively.
- The pozzolanic activity and filling of glass powder have improved the microstructure of HVFA concrete. The water absorption test indicated a notable reduction in the absorption rate of mixtures incorporating glass powder relative to the reference mixture; absorption decreased from 3.15% in the reference mixture (M1: 50% FA, 0% GP) to 2.33% in M2 (40% FA, 10% GP) and 2.65% in M3 (30% FA, 20% GP) at 28 days, indicating enhanced density along with lower pore volume caused by the pozzolanic reaction of the glass powder.
- The ultrasonic pulse velocity (UPV) test findings indicated an increased in ultrasonic wave speed from 4.683 km/s in the reference mix to 5.292 km/s in M2 and 5.023 km/s in M3 at 28 days. This enhancement signifies an improvement in the homogeneity and consistency of the

concrete's matrix, associated with a decrease in micro-cracks and a strengthening in the concrete's durability.

- Results indicate that HVFA concrete with glass powder displays superior resistance to sulfate-induced deterioration relative to the control mix. The durability index, determined by the variation in compressive strength between water-cured and sulfate-exposed samples, indicates that mixtures with glass powder (notably at a 10% substitution) have less strength degradation and exhibit enhanced durability over time.
- Of the studied mixtures, a mix including 50% Ordinary Portland Cement, 40% fly ash, and 10% glass powder (referred to as M2) exhibited superior performance regarding strength and durability. This mixture achieved the highest compressive strength, minimal water absorption, superior UPV, and optimal resistance to sulfate attack, establishing it as the optimum mixture for mechanical and durability properties.
- This type of concrete is highly encouraged for civil engineering applications since it is innovative and sustainable. It contributes to sustainable development goals by lowering the environmental impact of concrete production and using industrial waste.
- Recommendations for further studies of high-volume fly ash–glass powder concrete are required to investigate the effects of lower GP content (e.g., 5% or less) and the combined use of GP with other supplementary cementitious materials, as well as the impact on other concrete properties such as shrinkage, creep, and fire resistance, which will help further advance the field.

References

[1] Ahmed MF. High volume brick powder concrete synergistic with metakaolin: physicomechanical properties and drying shrinkage. Kufa Journal of Engineering. 2025 Feb 4;16(1):214–32. https://doi.org/10.30572/2018/kje/160113

[2] Berkouche A, Belkadi A, Aggoun S, Hammouche R, Benaniba S. Predictive modeling of glass powder and activator effects on slag-based geopolymers via central composite design. Research on Engineering Structures and Materials [Internet]. 2024 Jan 1. https://doi.org/10.17515/resm2024.337st0703rs

[3] United Nations Environment Programme. Building Materials and the Climate: Constructing a New Future. Nairobi. 2023. https://doi.org/10.59117/20.500.11822/43293

[4] Mehta, P. Kumar. High-performance, high-volume fly ash concrete for sustainable development. In: Proceedings of the international workshop on sustainable development and concrete technology. Ames, IA, USA: Iowa State University, 2004. p. 3-14.

[5] Runganga D, Okonta F, Musonda I. Strength and Durability Properties of High-Volume Fly Ash (HVFA) Binders: A Systematic review. CivilEng. 2024 May 9;5(2):435–60. https://doi.org/10.3390/civileng5020022

[6] Kumar M, Sinha AK, Kujur J. Mechanical and durability studies on high-volume fly-ash concrete. Structural Concrete. 2020 Sep 16;22(S1). https://doi.org/10.1002/suco.202000020

[7] Babalu R, Anil A, Sudarshan K, Amol P. Compressive strength, flexural strength, and durability of high-volume fly ash concrete. Innovative Infrastructure Solutions. 2023 Apr 24;8(5). https://doi.org/10.1007/s41062-023-01120-x

[8] Al-Attar T, Taha A. Resistance of High-Volume fly Ash Self-Compacting concrete to internal sulfate attack. Engineering and Technology Journal. 2018 Dec 1;36(12A):1260–6. https://doi.org/10.30684/etj.36.12a.7

[9] Liu J, Li A, Yang Y, Wang X, Yang F. Dry–Wet cyclic sulfate attack mechanism of High-Volume fly ash Self-Compacting concrete. Sustainability. 2022 Oct 12;14(20):13052. https://doi.org/10.3390/su142013052

[10] Das BB, Black L, Barbhuiya S, Snehal K, Sumukh EP. Resistance to acid, alkali, chloride, and carbonation in ternary blended high-volume mineral admixed concrete. Journal of Sustainable Cement-Based Materials. 2024 Sep 25;1–22. https://doi.org/10.1080/21650373.2024.2405979

[11] Zhou C, Li M, Nguyen QD, Lin X, Castel A, Pang Y, et al. Application of waste glass powder for sustainable concrete: Design, performance, perspective. Materials. 2025 Feb 7;18(4):734. https://doi.org/10.3390/ma18040734

[12] Dobiszewska M, Pichór W, Tracz T, Petrella A, Notarnicola M. Effect of glass powder on the cement hydration, microstructure and mechanical properties of mortar. Mater Proc. 2023 Feb 22;40. https://doi.org/10.3390/materproc2023013040

[13] Bhavanaa R, Reddy KRC. Predicting the mechanical properties of concrete from waste glass through the use of boost and random forest. Research on Engineering Structures and Materials [Internet]. 2025 Jan 1. https://doi.org/10.17515/resm2025-891me0510rs

[14] Paul D, Bindhu KR, Matos AM, Delgado J. Eco-friendly concrete with waste glass powder: A sustainable and circular solution. Construction and Building Materials. 2022 Sep 24; 355:129217. https://doi.org/10.1016/j.conbuildmat.2022.129217
[15] Muhedin DA, Ibrahim RK. Effect of waste glass powder as partial replacement of cement & sand in concrete. Case Studies in Construction Materials. 2023 Sep 26;19: e02512. https://doi.org/10.1016/j.cscm.2023.e02512
[16] Abed, Huda Saad; Al-Saffar, Zaid Hazim; Hamad, Ali Jihad. Synergistic effect of the silica fume and glass powder as pozzolanic materials in cement mortar. International Journal of Sustainable Building Technology and Urban Development, 2024, 15.1: 43-56.
[17] Li C. Study on compressive strength and sulfate corrosion resistance of limestone powder and waste glass powder mixed concrete. Materials Research Express. 2024 Jan 16;11(2):025502. https://doi.org/10.1088/2053-1591/ad1ef6
[18] Akinpelu MA, Amao AO, Salman ASM, Gabriel DS. Sustainable self-compacting concrete: A study on the combined effects of waste glass powder and metakaolin as cement replacements. Research on Engineering Structures and Materials [Internet]. 2025 Jan 1. https://doi.org/10.17515/resm2025-610ma0105rs
[19] Fernando V, Lokuge W, Seligmann H, Wang H, Gunasekara C. Sustainable Mortar with Waste Glass and Fly Ash: Impact of Glass Aggregate Size and Life-Cycle Assessment. Recycling [Internet]. 2025a Jul 4;10(4):133. https://doi.org/10.3390/recycling10040133
[20] Iraqi Standard Specification No.5, Portland cement, 2019.
[21] ASTM International. ASTM C618-22, Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete. 2022.
[22] Iraqi Standard Specification No. 45. The aggregates of the natural resources used in concrete construction, 1984.
[23] ASTM International, ASTM C1012/C1012M-18b. Standard test method for length change of hydraulic-cement mortars exposed to a sulfate solution, 2018.
[24] ASTM International, ASTM C642-21. Standard test method for density, absorption, and voids in hardened concrete, 2021.
[25] ASTM International, ASTM C597-22. Standard test method for ultrasonic pulse velocity through concrete. 2022.
[26] British Standards BS 1881-116:1983. Testing concrete - Method for determination of compressive strength of concrete cubes. 1983.
[27] Dahamm, E.K., Hama, S.M. and Al-Jumaily, I.A. Effect of nano-sized clay and waste glass powder on rheological and hardened properties of self-compacting concrete. Research on Engineering Structures and Materials, 2023. https://doi.org/10.17515/resm2022.563ma1026
[28] Zeybek, Ö., Özkılıç, Y. O., Karalar, M., Çelik, A. İ., Qaidi, S., Ahmad, J., ... & Burduhos-Nergis, D. P. Influence of replacing cement with waste glass on mechanical properties of concrete. 2022. Materials, 15(21), 7513. https://doi.org/10.3390/ma15217513
[29] Saify, S., Radhi, M. S., Al-Mashhadi, S. A., Mareai, B., Jabr, S. F., Mohammed, Z. A., ... & Al-Husseinawi, F. Impact of waste materials (glass powder and silica fume) on features of high-strength concrete. 2023. Open Engineering, 13(1), 20220479. https://doi.org/10.1515/eng-2022-0479
[30] Abo El-Kassem, Mohamed Hamdy; MOHAMED, Osama Mahmoud; ABD EL-HAMID, Mohamed Zakaria. Effect of using glass powder as a partial replacement of cement on concrete properties. journal of al-azhar university engineering sector, 2022, 17.62: 219-236.
[31] Mangi, Sajjad Ali, et al. Short-term effects of sulphate and chloride on the concrete containing coal bottom ash as supplementary cementitious material. Engineering Science and Technology, an International Journal, 2019, 22.2: 515-522. https://doi.org/10.1016/j.jestch.2018.09.001