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EVALUATION OF COMPRESSIVE STRENGTH, WATER ABSORPTION, AND THEIR INTERRELATIONSHIP IN GLASS WASTE POWDER-MODIFIED CONCRETE EXPOSED TO AN ACIDIC ENVIRONMENT

Adetomi Oluwabukunmi ABEGUNDE[1*], Kazeem Dele MUSBAU[2], Julianah Olawanle ADEOSUN[3], Kolapo Olubunmi OLUSOLA-ELEKA[4], Olayiwola Richard ALONGE[5], Samuel Adebayo AJIBOYE[6]

[1,2,3,4,5,6]*Department of Building, Osun State University, Osogbo, Nigeria*

[*]*Corresponding Author: adetomi.abegunde@uniosun.edu.ng*

Abstract
Acidic deterioration in sewage and industrial infrastructure poses a critical durability challenge for conventional concrete. Incorporating ultra-fine Glass Waste Powder (GWP) as a pozzolanic supplementary cementitious material consumes vulnerable calcium hydroxide and refines the pore structure to restrict fluid ingress. This study evaluated the compressive strength and water absorption of concrete with GWP replacing Portland limestone cement (Grade 42.5N) at 0% (control), 5%, 10%, and 20% by weight, with a water/cement ratio of 0.50. Compressive strength and water absorption tests were in accordance with BS EN 12390-3 and BS 1881-122:2011, respectively, and were correlated using linear regression. Standard 100 mm cubical specimens were cured in water for 28 days, then immersed in 3% sulfuric acid (H_2SO_4, ~0.55 M, pH of 0.85 ± 0.15) for 3, 7, 21, and 28 days. After 28 days of acid exposure, control concrete lost 17.4% compressive strength (24.2 to 20.0 MPa). The 5% GWP mix achieved the highest 28-day residual strength (22.1 MPa, 10.5% above control; 11.9% loss), while 20% GWP recorded the lowest fractional strength loss (9.7%). The 10% GWP mix minimized water absorption at all ages, reaching 4.55% at 28 days (35.9% lower than the control's 7.10%). Regression analysis showed a good negative linear correlation between compressive strength (S) and water absorption (W) ($S = 28.01 - 1.10W$, $R^2 = 0.862$). Pozzolanic reaction of fine glass particles generates secondary calcium-silicate-hydrate (C-S-H) gel, restricting aggressive ion ingress. Hence, GWP is a highly effective, sustainable alternative binder for enhancing concrete durability in aggressive acidic environments.

Keywords
Glass Waste Powder (GWP); Sulfuric Acid Resistance; Compressive Strength; Water Absorption; Microstructural Refinement

1. INTRODUCTION

Environmental degradation is one of the most serious problems of modern civil infrastructure, and chemical acid attack is one of the most severe forms of degradation affecting the durability and long-term structural integrity of concrete assets [1, 2]. Acidic environments are often found in agricultural processing plants, industrial wastewater networks, acid-sulphate soil conditions, and municipal sewage conveyance systems [2, 3]. For instance, in municipal sewerage pipes, biogenic sulfuric acid corrosion can lower the local surface pH to as low as 1.0–2.0 due to the metabolic oxidation of hydrogen sulphide (H_2S) gas by Thiobacillus bacteria [3]. Conventional Portland limestone cement (PLC) concrete is intrinsically highly susceptible to acid attack because its primary hydration products are highly alkaline [4], predominantly of calcium-silicate-hydrate (C-S-H) gel and crystalline calcium hydroxide ($Ca(OH)_2$, or portlandite) [3, 4].

When a mineral acid like sulfuric acid (H_2SO_4) contacts the concrete matrix, it initiates a series of destructive neutralization and decalcification reactions. The acid aggressively reacts with the soluble calcium hydroxide in the pore solution to form gypsum [3, 5] as presented in Equation 1. This gypsum formation is accompanied by substantial volumetric expansion, which induces high internal tensile stresses leading to micro-fracturing, physical cracking, and surface spalling [3, 6]. In the presence of aluminate phases within the binder, gypsum further reacts to form secondary ettringite ($3CaO{\cdot}Al_2O_3{\cdot}3CaSO_4{\cdot}31H_2O$), triggering subsequent swelling and expansive pressure [3, 6]. Simultaneously, the severe reduction in internal matrix pH destabilizes the core load-bearing C-S-H binder, stripping calcium ions and converting the dense crystalline structure into an amorphous, non-cohesive, and highly porous silica gel layer [3, 7]. This chemical cascade compromises compressive capacity and creates open capillary pathways for accelerated fluid ingress and deeper acid penetration [7, 8].

$$Ca(OH)_2 + H_2SO_4 + 2H_2O \rightarrow CaSO_4{\cdot}2H_2O \text{ (gypsum)} + 2H_2O \quad (1)$$

To counter these chemical vulnerabilities while addressing pressing global environmental mandates, the concrete manufacturing sector must transition toward sustainable, low-carbon binders [1, 2, 9]. Standard Portland cement clinker production is highly resource- and energy-intensive, and incorporating supplementary cementitious materials (SCMs) represents a primary pathway to reduce greenhouse gas emissions and conserve raw limestone resources [10], [1, 9, 10]. At the same time, municipal and industrial solid waste management presents a critical global challenge [1, 2, 10]. Although glass is highly recyclable, millions of tons of waste glass are landfilled annually because of mixed-colour contamination, breakage, or high remelting costs [1], [8]. Grinding this non-biodegradable waste glass into an ultra-fine powder provides a sustainable secondary resource that can partially replace cement, delivering dual benefits of waste diversion and clinker minimization [9 -11].

Finely ground glass waste powder (GWP) has high pozzolanic reactivity when ground below 45–75 µm [3, 11]. While coarser glass aggregates can sometimes trigger expansive and harmful alkali-silica reactions (ASR) [2, 11], ultra-fine GWP has a high silica content (often exceeding 70% SiO_2, though the specific glass waste utilized in this study measured 68.9% SiO_2 as shown in Table 1), which can reduce ASR risk while actively contributing to strength development [3, 11, 12]. Upon hydration, the reactive amorphous silica in GWP pozzolanically reacts with the free $Ca(OH)_2$ generated during cement hydration to form secondary, insoluble calcium-silicate-hydrate (C-S-H) gel [3, 9, 12] as chemically represented in Equation (2).

$$3Ca(OH)_2 + 2SiO_2 \rightarrow 3CaO{\cdot}2SiO_2{\cdot}3H_2O \quad (2)$$

As expressed in Equation (2), this pozzolanic reaction consumes the highly acid-sensitive $Ca(OH)_2$ portlandite phase and converts it into a stable, load-bearing binder phase [3, 12]. Replacing cement with GWP therefore improves the chemical durability through two coupled mechanisms: chemical pozzolanic consumption and physical pore-structure refinement [1, 12, 13]. First, chemically depleting the portlandite phase reduces the available substrate needed to form expansive gypsum and ettringite [3, 12, 13]. Second, the secondary C-S-H gel fills capillary voids and densifies the Interfacial Transition Zone (ITZ) between the paste and aggregate [4, 12, 13]. This microstructural modification replaces wide, continuous capillary channels with isolated, tortuous gel micropores [8, 13]. Consequently, fluid transport and permeability rates are significantly reduced [9, 13], retarding the ingress of aggressive hydronium and sulfate ions [3, 18].

Despite growing interest in waste glass utilization, existing literature [1, 2, 10, 11] has predominantly focused on the mechanical and microstructural performance of GWP concrete under standard water curing conditions. A critical research gap remains regarding how GWP-modified matrices concurrently evolve in terms of mechanical capacity and water absorption properties during sustained acid attack. Specifically, there is a lack of quantitative models that directly link moisture absorption kinetics to residual strength loss under acidic degradation. To address this gap, this study experimentally evaluated the compressive strength and water absorption of concrete incorporating 0%, 5%, 10%, and 20% GWP subjected to immersion in sustained 3% sulfuric acid at 3, 7, 21, and 28 days after 28 days of standard hydration. In addition, regression analysis was used to establish a statistical interrelationship between the properties.

2. MATERIALS AND METHOD

This section outlines the experimental framework used to systematically assess the performance of Glass Waste Powder (GWP)-modified concrete subjected to sustained acidic exposure. The methodology encompasses the physical and chemical characterization of raw constituent materials; concrete mix proportioning across replacement levels of 0%, 5%, 10%, and 20% GWP at a fixed water-to-cement ratio of 0.50; specimen preparation; and standardized testing procedures.

2.1 Raw Materials and Characterisation

The basic materials used for this research include cement, glass waste powder, fine and coarse aggregates, water, and a superplasticizer. Portland limestone cement of grade 42.5N and aggregates (sand and granite) were purchased from local suppliers in Osogbo. Glass bottles were collected, ground in a ball mill for 45 minutes at 300 rpm at Landmark University, Omu-Aran, Kwara State. The ground material was then sieved through a standard 75 µm sieve to obtain GWP. This particle fineness threshold (<75 µm) is critical because ultra-fine glass micro-particles possess a high specific surface area that significantly accelerates pozzolanic reactivity with calcium hydroxide, whereas coarser glass particles (>100 µm) can induce expansive and deleterious alkali-silica reactions (ASR). Superplasticizer was used to maintain a medium slump, Class S2 (50–90 mm), for all concrete mixes. To determine the elemental oxide composition of both the cement and GWP, high-resolution X-ray Fluorescence (XRF) spectrometry was conducted. To prepare the soil samples for XRF analysis, the material was dried at 110 °C, sieved to under 63 µm (200-mesh), and prepared as either pressed pellets using a binder at 2 t/cm² or fused glass disks. For fused disk preparation, 0.5 g of sample was mixed with 5 g of $Li_2B_4O_7$flux along with reference materials (GSS8 and BCS-CRM 354) and melted at 1100 °C for 15 minutes to form 30 mm glass disks. Calibration curves were established using these certified reference material mixtures to enable direct XRF measurement.

Natural river sand with a fineness modulus of 2.65 (conforming to medium-grade Zone 2 fine aggregate per BS 882 / ASTM C33) and a maximum aggregate size of 4.75 mm served as fine aggregate. Crushed granite with a maximum nominal size of 19 mm and specific gravity of 2.68 (determined per BS 812 / ASTM C127 for volume calculations was used as coarse aggregate. A maximum aggregate size of 19 mm was selected to satisfy standard mix proportioning rules, ensuring the nominal size did not exceed one-fourth of the minimum specimen dimension (100 mm cube mould), thereby preventing mould wall interference and edge effects during compaction. Potable water was used for mixing and control curing.

2.2 Concrete Mix Proportions and Sample Preparation

A constant water-to-cementitious-materials ratio (w/c) of 0.50 was maintained across all mixtures, following the Building Research Establishment (BRE) mix-design method [14], at a free water content of 210 kg/m³. Four concrete mixes were prepared: a control mix (GWP0) with 100% Portland cement, and three modified mixes incorporating GWP at 5% (GWP5), 10% (GWP10) and 20% (GWP20) replacement by mass of cementitious material. Table 1 summarises the mix proportions.

Table 1: Mix proportions (kg/m³) at w/c = 0.50

Mix	Cement (kg/m³)	GWP (kg/m³)	Sand (kg/m³)	Granite (kg/m³)	Free water (kg/m³)
GWP0	420	–	708	1062	210
GWP5	399	21	708	1062	210
GWP10	378	42	708	1062	210
GWP20	336	84	708	1062	210

2.3 Acid Exposure Conditioning

Standard 100 × 100 × 100 mm cubical specimens were cast, with three replicates prepared per mix per test age, and demoulded after 24 hours. Specimens were initially cured in water (Figure 1a) at ambient laboratory temperature for 28 days to establish a baseline of cement hydration and pozzolanic activation. Following water curing, specimens were transferred to an exposure bath containing a nominal 3% sulfuric acid **(**H_2SO_4**)** solution and continuously immersed for designated exposure durations of 3, 7, 21, and 28 days, as shown in Figure 1b. The acidic medium utilized in this exposure was nominal 3% sulfuric acid (H_2SO_4). The acidic medium was a nominal 3% volume-to-volume (v/v) aqueous sulfuric acid (H_2SO_4) solution, prepared by diluting analytical-grade concentrated sulfuric acid (98% purity, specific gravity 1.84) in deionized water. Chemically, this 3% v/v concentration corresponds to a molar concentration of approximately 0.55 M (normality of 1.10 N), yielding an initial measured solution pH of 0.85 ± 0.15 at 20 ± 2ºC. This concentration was selected to simulate severe industrial chemical effluent and biogenic sewer pipe corrosion (where bacterial oxidation reduces matrix surface pH to 1.0–2.0). The exposure medium and concentration were fixed across all mixes to isolate the effect of GWP replacement level; the specific acid species was recorded in the original laboratory protocol only as an "acidic medium" and was not independently verified by titration, and this is treated as a methodological limitation .



Figure 1a: GWP Concrete Cured in Water



Figure 1b: GWP Concrete Cured in Acid

2.4 Compressive Strength Test and Water Absorption Test Procedures

Compressive strength was determined at the 28-day water-cured baseline and after 3, 7, 21, and 28 days of acid exposure in accordance with BS EN 12390-3 (Testing hardened concrete — Part 3: Compressive

strength of test specimens). At each designated testing age, three replicate 100 X 100 X 100 mm cubical specimens per mix were removed from the water or acid curing baths. Specimens removed from the acid solution were immediately rinsed with clean water to neutralize surface residual acid and surface-dried with a damp cloth. Testing was performed using a calibrated digital compression testing machine with a capacity of 2000 kN. Each specimen was positioned centrally on the lower bearing platen with the smooth cast sides facing the bearing surfaces (perpendicular to the casting direction) to ensure uniform load distribution. A constant, continuous loading rate of 0.6 ± 0.2 MPa/s (corresponding to approximately 3.6 kN/s for 100 mm cubes) was applied without shock until specimen failure occurred. The maximum peak load at failure (P) was recorded, and the compressive strength (S) was computed using Equation (3):

$$S = \frac{P}{A} \tag{3}$$

where S is the compressive strength (MPa), P is the maximum applied load (N), and A is the loaded cross-sectional area of the cube (mm^2).

Water absorption was measured following the procedure stated in BS 1881-122:2011. The samples were oven-dried at 105 ± 5°C to a constant mass (approximately 72 hours), cooled in a desiccator, and weighed to determine the dry mass (M_1). The dried samples were placed in water at 20 ± 5°C and left for 30 minutes, surface-dried with a damp cloth, and weighed again to obtain the saturated mass (M_2). The percentage water absorption (W) representing capillary porosity was calculated using Equation (4):

$$W = \left[\frac{(M_2 - M_1)}{M_1}\right] \times 100 \tag{4}$$

where W is the water absorption (%) indicative of accessible pore structure/porosity, M1 is the oven-dry specimen mass (g) and M_2 is the saturated specimen mass after 30 minutes of water immersion (g).

3. RESULTS AND DISCUSSION

This section presents and critically evaluates the experimental findings obtained from the preliminary tests conducted on the cementitious materials used, and the results of the compressive strength and the water absorption tests. This section also presents the relationship between the compressive strength and water absorption of GWP concrete exposed to a sulphuric environment.

3.1 Chemical Composition and Characterisation of Raw Materials

Table 2 shows the chemical oxide compositions of PLC and GWP, determined via X-ray Fluorescence (XRF). The XRF analysis revealed that the Glass Waste Powder (GWP) is predominantly composed of silicon dioxide (SiO_2, 68.9%), with lower fractions of ferric oxide (Fe_2O_3, 5.4%), calcium oxide (CaO, 7.8%), sodium oxide (Na_2O, 15.2%), and aluminium oxide (Al_2O_3, 0.7%). The sum of the primary pozzolanic oxides (SiO_2 + Al_2O_3 + Fe_2O_3) for the GWP is 75.0%, exceeding the standard 70% minimum threshold established by ASTM C618 for pozzolanic materials [15]. This chemical composition confirms that the ultra-fine GWP possesses suitable pozzolanic potential to react with the Portlandite ($Ca(OH)_2$) generated during cement hydration, forming secondary calcium-silicate-hydrate (C-S-H) gel that refines matrix microstructure [1, 2, 12]

Table 2: Chemical Composition of Cementing Materials

Bulk oxide composition	Portland limestone cement (%)	Glass waste powder (%)
CaO	64.5	7.8
SiO_2	20.0	68.9
Al_2O_3	4.6	0.7
Fe_2O_3	3.7	5.4
MgO	2.5	1.3
MnO	0.1	0.1
TiO_2	0.3	0.1
K_2O	0.7	0.5
Na_2O	0.3	15.2
P_2O_5	0.1	0.1
Cl	0.1	-
SO_3	3.1	-

3.2 Compressive Strength Performance in the Acidic Medium

Table 3 presents the compressive strength of each mix at the 28-day baseline (water-cured) and after 3, 7, 21, and 28 days of acid exposure. At the 28-day water-cured baseline, incorporating GWP slightly improved starting strength up to 10% replacement, with GWP10 recording the highest starting strength (25.2 MPa, a 4.1% increase over the control). This is due to the pozzolanic activation of fine silica under standard hydration conditions [9, 11, 12].

Upon exposure to the acid medium, compressive strength progressively decreased for almost all mixes over exposure time due to acidic leaching, with the notable exception of the 20% replacement mix (GWP20). For GWP20, the compressive strength rose slightly from 23.7 MPa at the baseline to 23.9 MPa after 3 days of acid immersion, before gradually declining. This minor early-age strength gain suggests that the secondary pozzolanic reaction of GWP was highly active during early exposure, temporarily outpacing the rate of chemical surface decalcification. After 28 days of acid exposure, the control concrete (GWP0) dropped to 20.0 MPa, a 17.4% decrease, accompanied by visual softening of the outer surface.

Incorporating GWP substantially improved strength retention across all replacement levels. After 28 days of acid exposure, GWP5 performed best, reaching 22.1 MPa (10.5% above the control) with only 11.9% fractional strength loss relative to its baseline. GWP10 followed closely, reaching 21.6 MPa at 28 days (8.0% above the control) with a 14.3% loss. Interestingly, despite having the lowest absolute baseline strength of all mixtures (23.7 MPa), GWP20 recorded the smallest overall fractional strength loss of any mix (9.7%), reaching 21.4 MPa after 28 days of chemical attack. This outstanding chemical resilience is attributed to the high GWP content, which extensively consumes and depletes the vulnerable portlandite phase during hydration, chemically mitigating the rate of expansive gypsum formation [1, 2, 5, 8].

Table 3: Compressive Strength and Fractional Loss of Concrete

Mix	28 d (water) (Baseline) (MPa)	3 d (acid) (MPa)	7 d (acid) (MPa)	21 d (acid) (MPa)	28 d (acid) (MPa)	Loss at 28 d (acid) w.r.t. 28d (water) (%)
GWP0 (control)	24.2	23.5	22.4	20.8	20.0	17.4
GWP5	25.1	25.0	24.7	23.3	22.1	11.9
GWP10	25.2	25.0	24.5	23.3	21.6	14.3
GWP20	23.7	23.9	23.4	22.6	21.4	9.7

3.3 Water Absorption Dynamics in the Acidic Environment

Water absorption directly measures capillary porosity and pore interconnectivity, which reflect the concrete's physical permeability and durability potential. Table 4 presents the water absorption of control and GWP-modified concrete at different acid exposure durations.

Table 4: Water absorption of concrete

Mix	28 d (water) (%)	3 d (acid) (%)	7 d (acid) (%)	21 d (acid) (%)	28 d (acid) (%)	Reduction vs. control at 28 d (%)
GWP0	4.24	4.62	5.26	6.23	7.10	–
GWP5	2.90	3.25	3.78	4.64	5.40	23.9
GWP10	2.50	2.72	3.13	3.79	4.55	35.9
GWP20	3.00	3.48	3.94	5.08	6.12	13.8

For every mix, water absorption increased progressively with increasing acid-exposure duration, corresponding to gradual decalcification of hydration products and the development of coarser, interconnected capillary pores at the surface. At every exposure age, incorporating GWP significantly reduced water absorption relative to the control, with 10% replacement achieving the lowest value overall. Water absorption increased with exposure age to the sulfuric solution.

After 28 days of sustained acid immersion, the control concrete recorded a peak absorption of 7.10%, whereas the GWP-modified mixtures achieved lower values of 5.40% (GWP5), 4.55% (GWP10), and 6.12% (GWP20), corresponding to absorption reductions relative to the control of 23.9%, 35.9%, and 13.8%, respectively. The non-linear response observed in Table 4—where water absorption resistance is maximized at 10% replacement before declining at 20%—highlights a fundamental microstructural trade-off between pozzolanic pore refinement and binder dilution [1, 17]. At 5% and 10% GWP incorporation, the high specific surface area of ultra-fine amorphous silica facilitates rapid pozzolanic consumption of crystalline calcium hydroxide ($Ca(OH)_2$) [3, 12]. As expressed in Equation (2), this reaction generates secondary insoluble calcium-silicate-hydrate (C-S-H) gel, which precipitates directly within continuous capillary voids and refines the ITZ surrounding aggregate boundaries [4, 13]. This pore-blocking mechanism replaces wide capillary pores with discontinuous gel micropores, thereby restricting water ingress [9, 17]. At 10% replacement (GWP10), the stoichiometric ratio between pozzolanic silica and available portlandite reaches an

optimum, yielding the densest microstructure and achieving a maximum 35.9% reduction in absorption [17, 18].

Conversely, increasing GWP replacement to 20% (GWP20) reduced the total clinker content by 20%, which in turn decreased the baseline concentration of $Ca(OH)_2$ synthesized during primary cement hydration [12, 13]. Consequently, a fraction of the GWP in GWP20 remains unreacted, acting primarily as an inert physical micro-filler [10, 11]. While these micro-particles still provide physical void filling, the excess unreacted material and reduced volume of total C-S-H gel slightly coarsen the capillary network relative to GWP10, causing absorption to rise to 6.12% (though remaining 13.8% lower than the unmodified control) [17, 18]. This parabolic trend in water absorption aligns closely with observations by Alfaiad et al. [5], Baikerikar et al. [11], and Adesope and Ayanlola [18], who reported that pozzolanic glass powder achieves maximum fluid transport resistance at 10%–15% replacement levels. Beyond this threshold, clinker dilution and micro-particle agglomeration gradually increase fluid permeability [1, 2, 10].

3.4 Interrelationship Between Compressive Strength and Water Absorption

The compressive strength (S, MPa) and water absorption (W, %) were correlated for all 4 mixes and 5 ages (n = 20), and regression analysis was performed to establish a predictive relationship for GWP concrete in an acidic environment. Ordinary least-squares regression yielded a strong inverse linear relationship. The inverse linear interrelationship between compressive strength (S, MPa) and capillary water absorption (W, %) is formally expressed by Equation (5):

$$S = 28.01 - 1.10W \tag{5}$$

where S is the estimated compressive strength (MPa) and W is the measured capillary water absorption (%)

In concrete materials engineering and durability modelling, a coefficient of determination $R^2 > 0.80$ and a strong Pearson correlation coefficient ($r > 0.90$) are widely recognized as indicating a highly robust statistical fit for heterogeneous binder matrices. The linear model presented in Equation (5) shows an outstanding statistical fit, with a coefficient of determination ($R^2 = 0.8624$) and a strong Pearson correlation coefficient ($r = -0.9287$). $R^2 = 0.8624$ demonstrates that 86.2% of the variance in residual compressive strength is directly accounted for by water absorption. While an exponential fitting model was also evaluated, it yielded a virtually identical coefficient of determination ($R^2 = 0.8624$), confirming that the simpler linear equation is highly suitable and more parsimonious for predicting strength within the measured absorption range (2.5% to 7.1%). Figure 2 shows the fitted linear regression line.

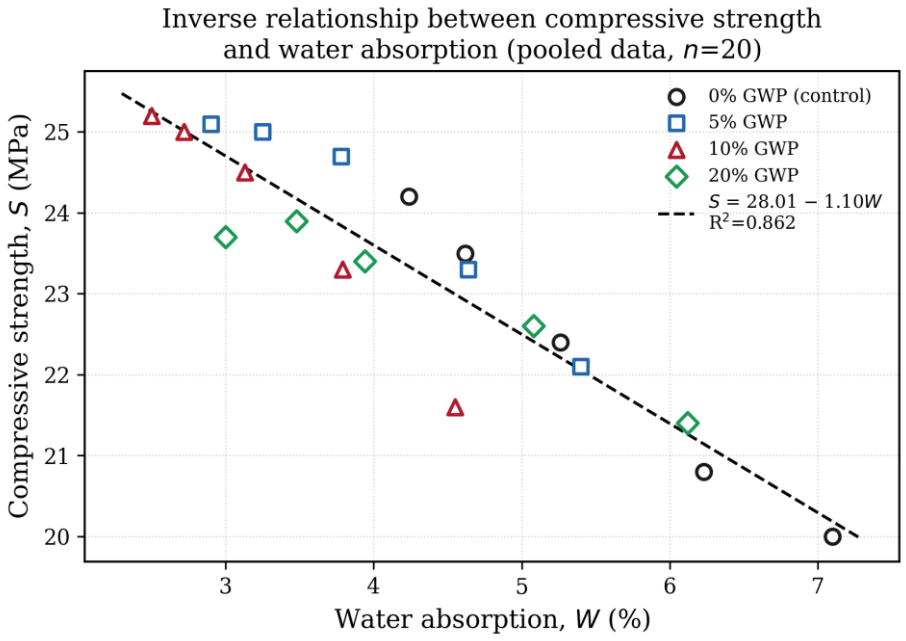


Figure 2. Inverse relationship between compressive strength and water absorption, pooled across all mixes and ages.

Physically, water absorption represents the volume of interconnected pore channels through which chemical species penetrate [17]. The strong regression alignment demonstrates that water absorption is a highly reliable proxy indicator. For critical concrete infrastructure like sewer pipes, taking core samples is destructive, expensive, and structurally undesirable [5]. By leveraging Equation (5), maintenance engineers can perform simple, non-destructive water absorption testing on small superficial concrete chips to quickly and reliably estimate residual compressive capacity without compromising structural integrity [19].

4. CONCLUSION

This study demonstrates that incorporating finely ground Glass Waste Powder (GWP) as a partial replacement for Portland limestone cement significantly enhances the compressive strength and water absorption properties of concrete subjected to sustained 3% sulfuric acid exposure. Overall, GWP-modified mixtures exhibited superior chemical durability compared with the unmodified control concrete, displaying lower absolute compressive strength loss and smaller fractional degradation across all testing ages. Incorporating 5% GWP (GWP5) achieved the highest absolute residual compressive strength of 22.1 MPa after 28 days of acid immersion (10.5% higher than the control concrete) with a fractional strength loss of 11.9%. Meanwhile, the 20% replacement mix (GWP20) minimized relative degradation, recording the lowest fractional strength loss of 9.7% from its baseline due to extensive pozzolanic consumption of vulnerable portlandite. For water absorption, GWP incorporation markedly restricted capillary water absorption, with 10% replacement (GWP10) proving optimal by recording a 28-day acid-exposed absorption of only 4.55% (a 35.9% reduction relative to the control). This reduction stems from pozzolanic C-S-H gel formation and interfacial transition zone refinement, which convert continuous capillary voids into tortuous gel micropores. Furthermore, ordinary least-squares regression yielded a calibrated inverse linear interrelationship ($S = 28.01 - 1.10W$, $R^2 = 0.8624$), establishing a practical, non-destructive monitoring proxy to estimate residual compressive strength based on simple moisture-absorption testing. Ultimately, replacing 5% to 10% of cement with ultra-fine GWP delivers a highly effective, sustainable binder strategy that extends the service life of civil infrastructure in aggressive sewer and industrial environments while advancing municipal landfill waste recycling goals. Despite these positive findings, specific methodological limitations bound the interpretation of these results. The investigation was restricted to a single water-to-cement ratio (0.50) and a single acid concentration (3% H_2SO_4) over a 28-day exposure timeframe. Additionally, the tests were conducted in a semi-static closed chemical bath representing localized, stagnant sewer or sump conditions. Future research should extend exposure durations beyond 28 days, evaluate dynamic fluid flow, and incorporate automated titration for continuous pH control to more closely replicate actual long-term service environments.

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