

Effect of ternary blended guinea corn husk ash, waste glass powder and cement on concrete compressive Strength

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Abstract

The growing demand for cement has intensified environmental concerns associated with high energy consumption, carbon dioxide emissions, and the disposal of agricultural and industrial wastes. This study evaluates the potential of Guinea Corn Husk Ash (GCHA) and Waste Glass Powder (WGP) as supplementary cementitious materials in ternary blended concrete. The objective was to assess their suitability as partial cement replacements and optimize the workability and compressive strength of concrete. Ordinary Portland cement, GCHA, WGP, fine aggregates, and coarse aggregates were used in the study. Material characterization was carried out through physical, chemical, and microstructural analyses using ASTM-standard tests, X-ray Fluorescence (XRF), X-ray Diffraction (XRD), and Scanning Electron Microscopy (SEM). Concrete mixes containing combined GCHA and WGP replacement levels ranging from 0% to 20% were produced. Workability was evaluated using the slump test, while compressive strength was determined at curing ages of 7, 28, and 56 days. Response Surface Methodology (RSM) implemented in Design-Expert software was employed to optimize the mix proportions. The XRF results revealed silica contents of 86.40% and 92.95% for GCHA and WGP, respectively, satisfying the requirements for Class F pozzolanic materials. Slump values decreased with increasing replacement levels, indicating reduced workability. Although higher replacement levels reduced early-age compressive strength, continuous strength development was observed up to 56 days due to ongoing pozzolanic activity. RSM optimization identified an optimum blend of 10% GCHA and 10% WGP and compressive strength of 32.2 MPa. The findings demonstrate that GCHA and WGP can serve as sustainable partial cement replacements, reducing cement consumption while promoting environmentally friendly concrete production.

Keywords: Guinea Corn Husk Ash (GCHA), Waste Glass Powder (WGP), Supplementary Cementitious Materials, Ternary Blended Concrete, Compressive Strength

Introduction

The construction industry remains one of the largest consumers of natural resources globally, accounting for roughly 40-50% of raw material extraction and half of all non-renewable resources consumed, with cement production alone responsible for approximately 7% of global anthropogenic CO₂ emissions (Adisa *et al.*, 2025, 2026). In 2023-2024, the global cement industry emitted around 1.47-2.4 billion metric tons of CO₂ (with figures varying by inclusion of full lifecycle or direct process emissions), and cement manufacturing continues to rank among the top industrial emitters (Barbhuiya *et al.*, 2024). As pressure mounts to decarbonize the built environment (which overall accounts for 34% of global GHG emissions), researchers have increasingly turned to alternative binder systems that reduce reliance on Ordinary Portland Cement (OPC) without compromising structural performance (Sbahieh *et al.*, 2023). Ternary blended cement, in which two supplementary cementitious materials (SCMs) partially replace OPC, has emerged as a particularly effective strategy. These blends often outperform binary systems (single SCM) in both mechanical properties (e.g., compressive strength development) and durability

aspects such as reduced permeability, improved resistance to chemical attack (sulfate, acid, chloride), lower shrinkage, and enhanced long-term performance (Odeyemi *et al.*, 2024). A 2025 study on ternary blended concrete incorporating shea nutshell ash and ground oyster seashell found that strength gains became more pronounced at later curing ages, with roughly a 3% improvement at 10% combined substitution after 90 days compared to the control mix, alongside marked improvements in resistance to acid and sulfate attack (Oyebisi and Alquraish, 2025). Such findings reinforce the case for combining two complementary waste-derived materials rather than relying on a single supplementary cementitious material (SCM).

Guinea Corn Husk Ash (GCHA) and waste glass powder are two such materials with strong potential in ternary blended systems. GCHA is an agricultural by-product generated in large volumes during the post-harvest processing of guinea corn, particularly across Northern Nigeria, where it is routinely heaped and burned as waste rather than put to productive use (Aburime *et al.*, 2020). Beyond its disposal burden, GCHA has been shown to contain a high combined proportion of silica, alumina, and iron oxide, exceeding the 70% threshold that classifies a material as pozzolanic under ASTM C618. Recent investigations have reported combined $\text{SiO}_2\text{--Al}_2\text{O}_3\text{--Fe}_2\text{O}_3$ contents as high as 86% in GCHA, alongside compressive strengths reaching 49.3 N/mm² at 5% cement replacement after 28 days, confirming its viability as a partial OPC substitute (Aburime *et al.*, 2020; Ndububa and Yakubu, 2015). A more recent 2025 comparative study by Olorunfemi *et al.*, (2025) examined GCHA alongside rice husk ash (RHA) as substitutes for silica fume in high-performance concrete, finding that while RHA's higher amorphous silica content and reactive surface improved compressive, tensile, and flexural strength, GCHA's relatively lower reactivity and higher water demand led to a gradual decline in strength at higher replacement levels, underscoring the importance of optimizing GCHA dosage and identifying complementary materials that offset this limitation.

Waste glass offers exactly this kind of complementary behavior. When finely ground into powder, waste glass exhibits pozzolanic reactivity, reacting with calcium hydroxide released during cement hydration to form additional calcium-silicate-hydrate (C-S-H) gel, which densifies the microstructure and improves long-term durability (Akinpelu, Amao, *et al.*, 2025; Khan *et al.*, 2025). Recent systematic reviews note that while early-age strength can be modestly reduced by glass powder addition, its pozzolanic activity compensates over time, and replacement levels of 10–20% are generally identified as the optimal balance between mechanical performance, durability, and cost-effectiveness (Semmana *et al.*, 2025; Shukla *et al.*, 2025). Other recent ternary systems pairing waste glass powder with a second recycled material, such as thermally treated autoclaved aerated concrete waste, which have demonstrated that glass powder additions of around 15% can reduce compressive strength by only marginal amounts while substantially increasing flexural strength, illustrating the kind of performance trade-offs that careful ternary mix design can exploit (Muhedin and Ibrahim, 2023). Particle-size effects matter too: Tong *et al.*, (2024) using compound blends of glass sand and glass powder at optimized particle sizes achieved increases in compressive, tensile, and flexural strength of up to 35.6%, 21.7%, and 13.8% respectively, alongside substantial reductions in water absorption and chloride permeability, when compared to conventional concrete.

The broader rationale for using waste-derived materials such as GCHA and glass powder in concrete extends well beyond mechanical performance. Researchers have long explored substituting one or more concrete constituents with discarded materials, like crumb rubber from tyres, rice husk ash, copper slag, steel slag, waste plastic, and waste glass among them, to partially

or fully replace aggregates and cement (Adisa *et al.*, 2026; Islam *et al.*, 2022; Nandiyanto *et al.*, 2022). This practice lowers construction costs, conserves increasingly scarce natural resources, and reduces the CO₂ emissions associated with clinker production. It also diverts solid waste from landfills, addressing two environmental problems simultaneously: resource depletion in construction and the growing burden of unmanaged waste streams (Asonibare *et al.*, 2025). Crushed recycled glass, in particular, has been the subject of extensive research into its effects on the fresh and hardened properties of concrete.

Glass remains an indispensable material in modern infrastructure, yet its recycling rate lags far behind its recyclability. Glass can, in principle, be recycled indefinitely without any loss in quality, but global recovery still falls well short of this potential: recent industry analysts estimate that global glass recycling rates remain below 35%, even though regions with strong deposit-return and extended-producer-responsibility schemes such as the European Union, where average glass packaging collection reached 80.8% in 2023, which demonstrate that far higher recovery is achievable with the right policy infrastructure (Baek *et al.*, 2025; Roy, 2020). In Nigeria, however, recovery of waste glass and other recyclables remains low, constrained by inadequate collection infrastructure, the absence of formal recycling policy, and limited manufacturer participation in take-back schemes. This persistent gap between glass's recyclability and its actual recovery rate means that large volumes of waste glass continue to accumulate, particularly in regions without mature recycling systems. Compounding the problem, reusing recovered glass in new glass manufacturing is often impractical because its chemical composition can vary significantly depending on source and color, limiting closed-loop recycling options (Akinpelu, Olayiwola, *et al.*, 2025).

Unrecovered glass is typically disposed of in landfills, where it persists for exceptionally long periods. Unlike most conventional solid waste, glass is chemically inert and effectively non-biodegradable, meaning it can occupy landfill space that might otherwise accommodate genuinely biodegradable waste streams for centuries to come. This slow decomposition, combined with the steadily rising volume of glass entering the waste stream worldwide, makes the case for diverting waste glass into productive applications such as a pozzolanic component in ternary blended cement, which is increasingly urgent. Combining GCHA and waste glass powder as dual SCMs in a ternary blend therefore offers a route to addressing two distinct waste streams at once, while drawing on the demonstrated, complementary pozzolanic behavior each material brings to cement hydration and long-term concrete performance.

The aim of this study is to investigate the effect of a ternary blend composition of Guinea Corn Husk Ash (GCHA), waste glass powder (WGP), and cement on the compressive strength of concrete. To achieve this aim, the study prepares and characterizes GCHA and WGP, assesses the workability of concrete incorporating these materials, evaluates the influence of the ternary blended binder on the strength properties of concrete, and investigates the microstructural changes that occur when GCHA and WGP are introduced into the mix.

Materials and Methods

2.1 Materials

Portland Limestone Cement (PLC) conforming to BS EN 197-1 (2011) was obtained from Mohadis Construction Limited, Ilorin, Nigeria. Crushed granite coarse aggregate (4.75–12.5 mm) and natural river sand fine aggregate, both conforming to BS EN 12620:2013, were sourced locally in Ilorin. Guinea Corn Husk Ash (GCHA) was produced by calcining cleaned, air-dried guinea corn husk (Malete, Ilorin) at 600 °C, after which the ash was ground and sieved to pass a 75 µm

sieve (Figure 1a). Waste glass powder (WGP), soda-lime silicate glass sourced from discarded window and container glass, which was crushed and milled to pass a 0.125 mm sieve in accordance with BS 8591:2013 (Figure 1b). Potable water conforming to BS EN 1008:2002 was used throughout.

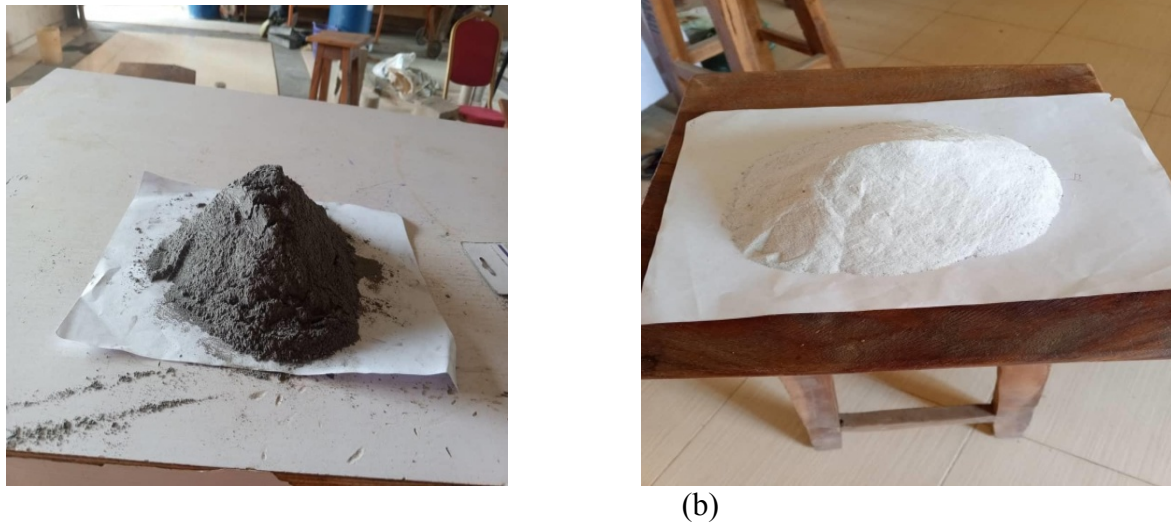


Figure 1: (a) Guinea corn husk ash; (b) Waste glass powder

Material Characterization

Physical properties of the cement (specific gravity, fineness, standard consistency, initial and final setting times) were determined per BS EN 197-1 (2011), while aggregate properties (specific gravity, bulk density, particle size distribution, fineness modulus, water absorption) were determined per BS EN 1097-6:2020. The oxide composition of GCHA and WGP was determined by X-ray fluorescence (ASTM E1621, 2013). Phase composition and crystallinity were assessed by X-ray diffraction (ASTM E3294, 2022), and particle morphology was examined by scanning electron microscopy (ASTM E986, 1997). All characterization tests were performed at the Integrated Research Laboratories, Ibadan, Nigeria.

Mix Proportioning, Casting, and Curing

Ten concrete mixes (Figure 2) were designed using Design-Expert software, a response surface methodology (RSM) tool that has previously been applied to optimize concrete mixtures incorporating supplementary cementitious materials such as fly ash, silica fume, and metakaolin (Hamada and Abed, 2024; Olorunfemi *et al.*, 2025), incorporating varying proportions of GCHA and WGP as partial cement replacement. Dry constituents (cement, GCHA, WGP, and aggregates) were mixed for 1 min before water was added in two stages, with mixing continuing for a further 2 min to ensure homogeneity (with water cement ratio of 0.5). Slump was measured immediately after mixing, after which the concrete was cast into lubricated $100 \times 100 \times 100$ mm cube moulds, compacted, and left to set for 24 h. A total of 90 cubes were produced, demoulded after 24 h, and water-cured at room temperature until testing at 7, 28, and 56 days. The mix proportion is shown in Table 1.

	Std	Run	Component 1 A:WGP %	Component 2 B:GCHA %	Component 3 C:Cement %	Response 1 Slump mm	Response 2 Compressive St... N/mm2
	8	1	3	13	84		
	11	2	20	0	80		
	13	3	0	0	100		
	2	4	0	20	80		
	9	5	3	3	94		
	4	6	10	10	80		
	12	7	0	20	80		
	7	8	13	3	84		
	5	9	10	0	90		
	10	10	7	6	87		
	1	11	20	0	80		
	3	12	0	0	100		
	6	13	0	10	90		
	14	14	10	10	80		

Figure 2: Concrete mix proportions from Design Expert

Table 1: Concrete mix proportions

Run	Cement (kg/m ³)	WGP (kg/m ³)	GCHA (kg/m ³)	Water (kg/m ³)	Fine (kg/m ³)	Aggregate	Coarse (kg/m ³)	Aggregate
1	336	12	52	200	600		1200	
2	320	80	0	200	600		1200	
3	400	0	0	200	600		1200	
4	320	0	80	200	600		1200	
5	376	12	12	200	600		1200	
6	320	40	40	200	600		1200	
7	320	0	80	200	600		1200	
8	336	52	12	200	600		1200	
9	360	40	0	200	600		1200	
10	348	28	24	200	600		1200	
11	320	80	0	200	600		1200	
12	400	0	0	200	600		1200	
13	360	0	40	200	600		1200	
14	320	40	40	200	600		1200	

Testing Procedures

Workability

Slump was determined immediately after mixing in accordance with BS EN 12350-2 (2019). A standard slump cone was filled in three layers, each tamped 25 times with a rounded tamping rod, after which the cone was lifted vertically and the subsidence of the concrete measured as the slump value. This test was performed on all ten mixes to evaluate the effect of GCHA and WGP content

on fresh-state consistency and to ensure adequate workability for placement and compaction. The test was conducted at Department of civil Engineering in University of Ilorin, Kwara state.

Compressive Strength

Compressive strength was determined in accordance with BS EN 12390-3 (2019). Cubes were removed from the curing tank at 7, 28, and 56 days, surface-dried, and tested to failure under a compression testing machine at a constant loading rate until failure. Three cubes were tested per mix at each curing age, and the average of the three values was reported as the compressive strength for that mix and age. Results were used to evaluate strength development trends and to identify the optimum GCHA/WGP replacement levels relative to the control mix. The test was conducted at Department of civil Engineering in University of Ilorin, Kwara state.

Microstructural Analysis

Microstructural analysis was conducted on fragments retrieved from crushed compressive strength specimens at 28 days to assess the influence of GCHA and WGP on hydration product formation and matrix densification. This analysis was carried out at the Integrated Research Laboratories, Ibadan.

Scanning Electron Microscopy (SEM)

Specimens were gold-coated and examined under SEM (ASTM E986-97) to observe surface morphology, particle distribution, and the nature of the interfacial transition zone between the paste and aggregate, providing visual evidence of pore structure and bonding quality.

X-ray Diffraction (XRD)

Powdered samples from the crushed specimens were analysed by XRD (ASTM E3294-22) to identify the crystalline and amorphous phases present after hydration, including calcium silicate hydrate (C-S-H), calcium hydroxide ($\text{Ca}(\text{OH})_2$), and any secondary pozzolanic reaction products, allowing the hydration behaviour of the GCHA–WGP ternary blend to be compared with that of the control mix.

Results and Discussions

Physical Properties of materials

The properties of materials are presented in Table 2.

Table 2: Physical properties of the materials

Physical property	Cement	GCHA	WGP	Fine aggregates	Coarse aggregates
Specific Gravity	3.05	1.26	2.31	2.64	2.56
Consistency (%)	30				
Initial Setting time (mins)	115				
Final setting time(mins)	365				
Fineness Test(%)	4.25	8.5	12.64		
Fineness modulus				2.32	
Water absorption capacity				2.15	0.64
Bulk density(kg/m^3)				1590	1675

The particle size distribution (PSD) curve, shown in Figure 3, illustrates the relationship between the sieve size (mm) and the percentage passing (%) for the fine aggregate. The test results were plotted on a semi-logarithmic graph with the sieve size on the logarithmic x-axis and the percentage passing on the y-axis. As observed from the curve, the gradation shows a smooth and

continuous shape, indicating a well-graded fine aggregate suitable for concrete production. The distribution curve passes through key characteristic particle diameters: $D_{10}=0.16$ mm (Effective size), $D_{30}=0.35$ mm, and $D_{60}=0.65$ mm.

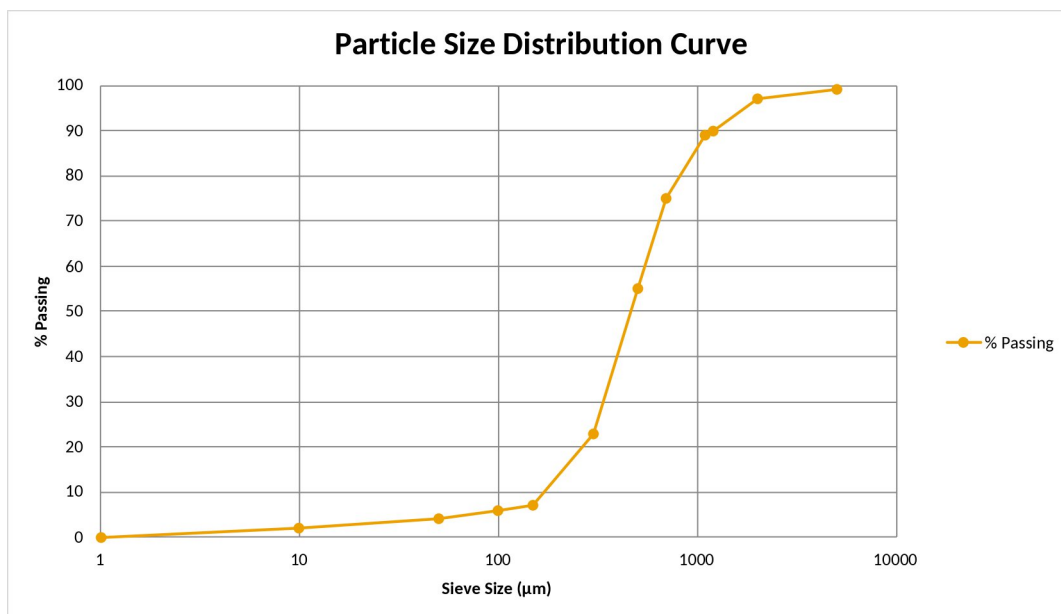


Figure 3: Particle size distribution (PSD) curve

Chemical and Mineralogical Characterization Oxide Composition (XRF)

The XRF results (Table 3) show that GCHA is a high-silica, low-alkali, low-calcium agro-ash, with $\text{SiO}_2 = 86.4\%$ and $\text{Al}_2\text{O}_3 = 5.32\%$. With CaO and alkali contents both below 1%, the combined $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ content (94.2%) and low loss-on-ignition satisfy ASTM C618 Class F pozzolan requirements, confirming GCHA's suitability as a supplementary cementitious material (SCM).

Table 3: XRF results of GCHA

Oxide Compound	Composition (%)
SiO_2	86.4
V_2O_5	0.03
Cr_2O_3	1.3
MnO	0.29
Fe_2O_3	2.43
Co_3O_4	0.21
NiO	0.04
CuO	0.45
Nb_2O_3	0.02
MoO_3	0.01
W_2O_5	0
P_2O_5	0
Sc_2O_3	0
CaO	0.87

MgO	1.69
K ₂ O	0.48
Al ₂ O ₃	5.32
TiO ₂	0.01
Ta ₂ O ₅	0

WGP exhibited an even higher combined oxide content ($\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 = 95.75\%$; Table 4), well above the 70% ASTM C618 threshold, with low alkalis and low loss-on-ignition (0.34%). Although individual Al_2O_3 content is minimal (0.02%), this does not affect classification, as ASTM C618 specifies only a combined minimum. Both materials therefore meet the chemical requirements for use as SCMs, with reactivity expected to depend primarily on fineness and amorphous phase content.

Table 4: XRF results of WGP

Oxide Compound	Composition (%)
SiO ₂	92.95
CaO	2.65
Al ₂ O ₃	0.02
Fe ₂ O ₃	2.78
MgO	0.32
Na ₂ O	0.02
K ₂ O	0.23
TiO ₂	0.48
MnO	0.24
L.O. I	0.34

Phase Composition (XRD)

XRD patterns of GCHA (Figure 4) and WGP (Figure 5) both showed a broad amorphous halo, between 15–35° 2θ for GCHA and superimposed with discrete quartz, orthoclase, albite, and muscovite peaks for WGP, indicating predominantly amorphous, reactive microstructures with only minor crystalline inclusions. This amorphous-dominant character is favourable for pozzolanic reactivity, as it reacts more readily with calcium hydroxide (portlandite) during hydration.

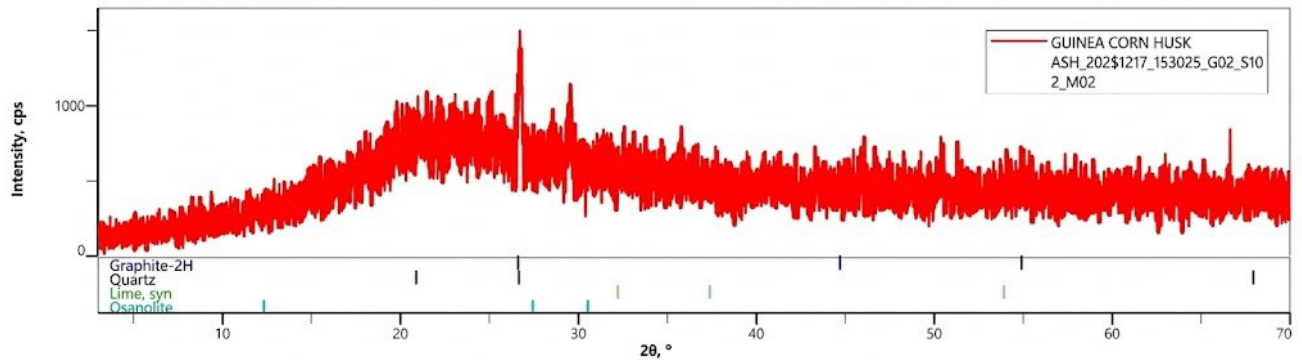


Figure 4: XRD patterns of GCHA

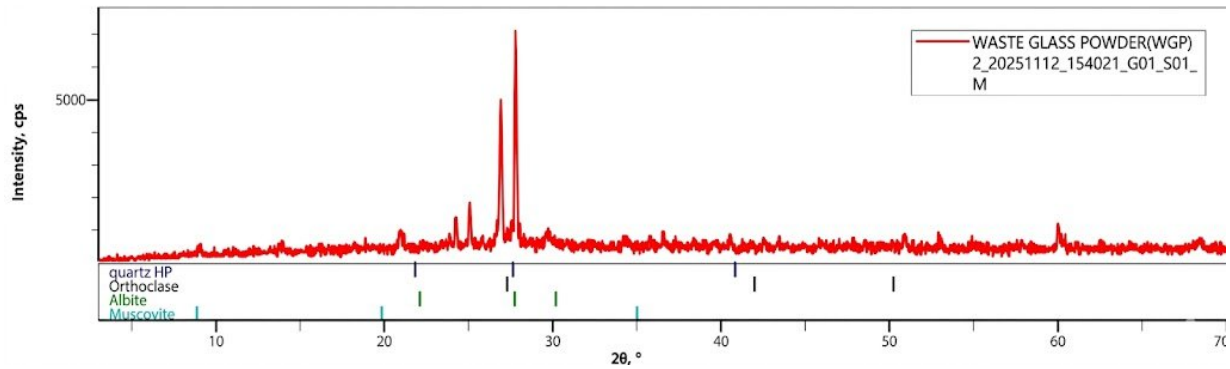


Figure 5: XRD pattern of the waste glass powder

The control concrete (Figure 6) showed a markedly different, crystalline-dominated pattern, with prominent quartz ($\sim 26.6^\circ$ 2θ) and feldspar reflections from the aggregate, a distinct portlandite peak ($\sim 18.0^\circ$ 2θ), and only a modest amorphous hump, which is consistent with unconsumed $\text{Ca}(\text{OH})_2$ typical of plain OPC hydration. In contrast, the ternary blend (10% GCHA + 10% WGP; Figure 7) displayed a more pronounced amorphous halo ($20\text{--}35^\circ$ 2θ) alongside an attenuated portlandite peak, indicating active pozzolanic consumption of $\text{Ca}(\text{OH})_2$ and the formation of secondary, poorly crystalline C-S-H/C-A-S-H gel. This mineralogical shift supports improved long-term densification and durability in the blended mixes relative to the control.

Multiple Profile

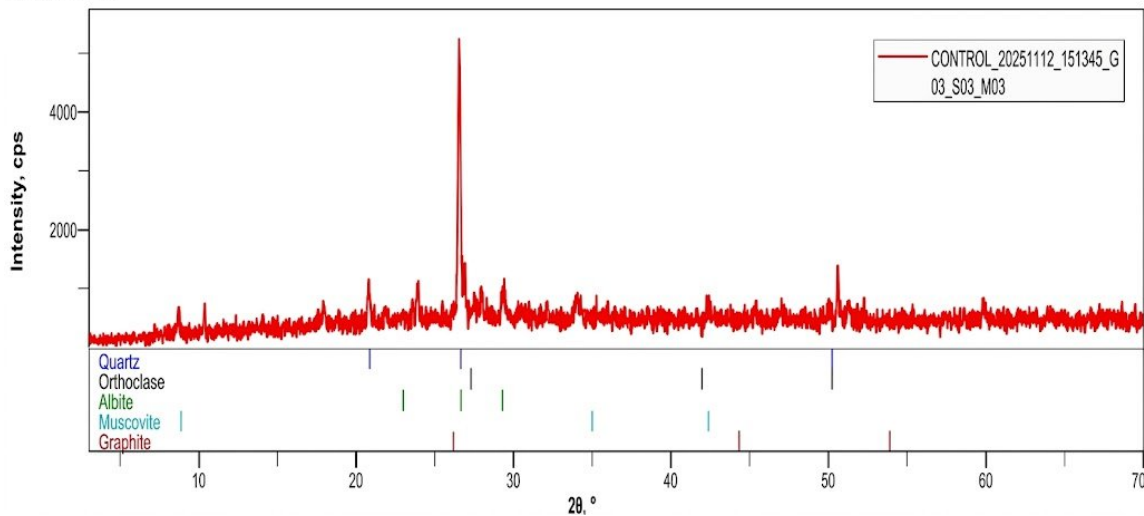


Figure 6: XRD pattern of control concrete

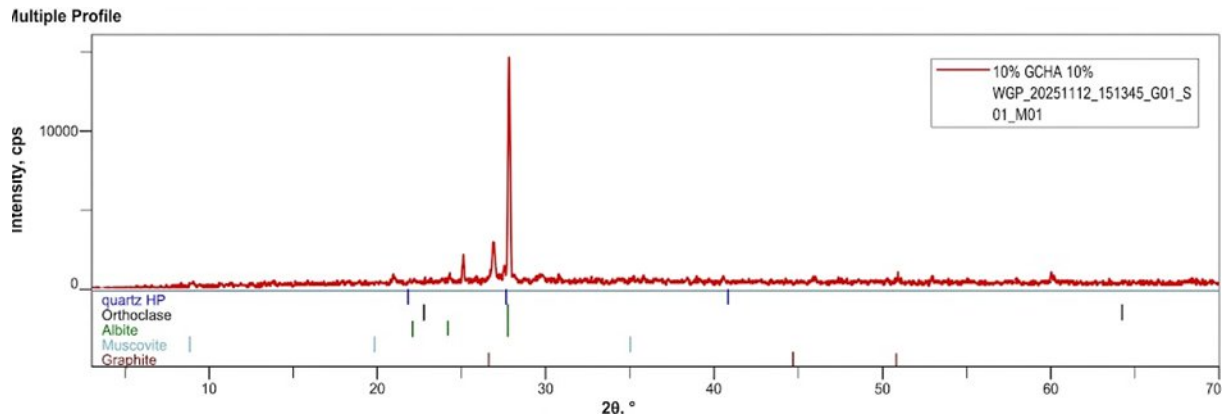


Figure 7: XRD pattern of concrete with 10% GCHA + 10% WGP

Particle Morphology (SEM)

SEM micrographs revealed contrasting morphologies for the two SCMs (Figure 8). GCHA particles (2–60 μm) were irregular, porous, and cenosphere-like, with a rough, high-surface-area texture favourable for pozzolanic reactivity but associated with increased water demand. WGP particles, by contrast, showed a dense, angular, fractured morphology typical of mechanically ground glass, with many particles exceeding 75 μm , suggesting that finer milling would further enhance its reactivity.

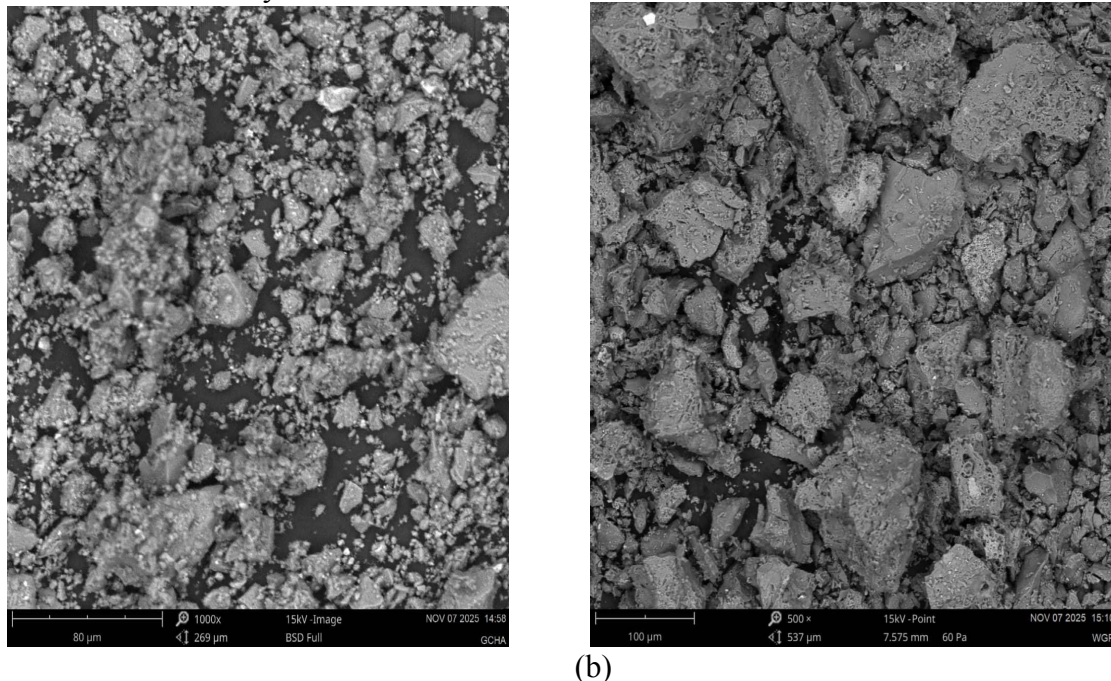


Figure 8: SEM images of (a) GCHA and (b) WGP

The control concrete (Figure 9a) displayed a dense, well-hydrated matrix with limited porosity and tightly bonded aggregate-paste interfaces, typical of plain OPC concrete without pozzolanic refinement. The ternary blend (10% GCHA + 10% WGP; Figure 9b) showed a more heterogeneous matrix, combining denser, well-hydrated regions with porous zones containing partially reacted pozzolanic particles and microvoids at the interfacial transition zone, which is consistent with the

moderate strength reduction observed at higher replacement levels, while still indicating progressive pozzolanic bonding.

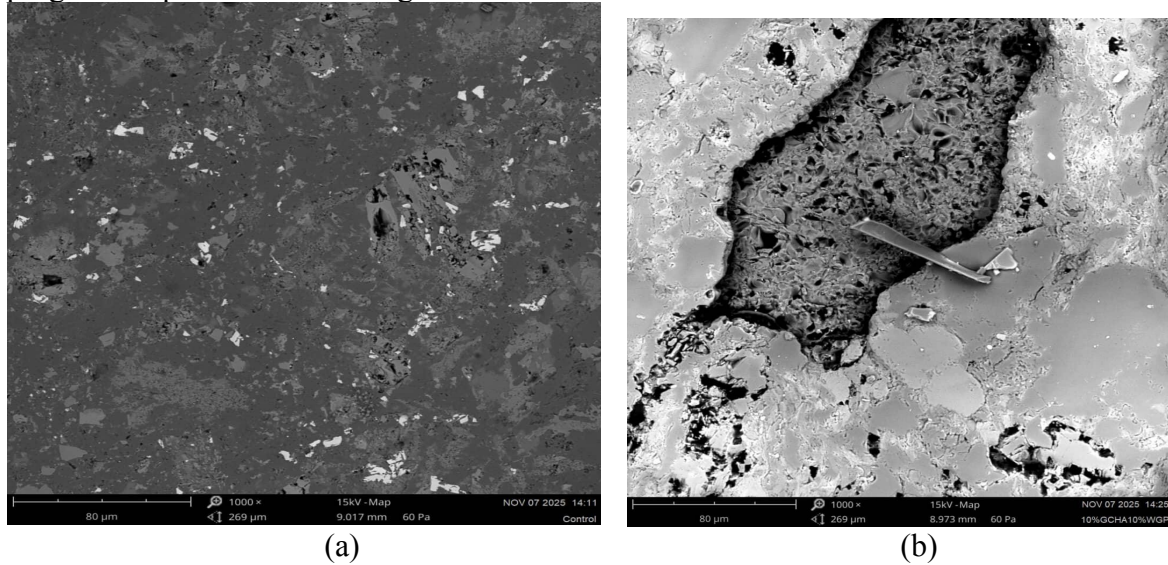


Figure 9: SEM image of (a) control concrete (b) 10% GCHA + 10% WGP

Fresh Concrete Properties

Slump

Slump generally decreased with increasing GCHA and WGP content (Table 5), from 50 mm in the control to as low as 32 mm at 20% GCHA. GCHA exerted a stronger influence on workability loss than WGP, attributable to the higher water demand of its porous, high-surface-area particles, whereas WGP's denser, smoother particles produced a comparatively gentler reduction in slump.

Table 5: Slump results

GCHA (%)	WGP (%)	Slump (mm)
0	0	50
3	3	47
3	13	44
6	7	45
0	10	48
10	10	40
10	0	42
13	3	38
0	20	47
20	0	32

Hardened Concrete Properties

Compressive Strength

Compressive strength generally decreased with increasing GCHA and WGP content, particularly at early ages (Table 6). The control mix achieved the highest strength at all curing ages (30.6, 35.6, and 36.2 MPa at 7, 28, and 56 days, respectively). Strength reduction was most pronounced at high single-material substitution (e.g., 20% WGP alone: 14.9 MPa at 7 days) and moderated where

GCHA and WGP were combined in balanced proportions (e.g., 10% GCHA + 10% WGP: 26.7 MPa at 7 days), suggesting a degree of synergy between the two materials at moderate replacement levels. All mixes gained strength with curing age, though the rate of gain was lower in mixes with higher total replacement, with 20% GCHA mixes stabilizing around 27–30 MPa by 28–56 days. These results indicate that while GCHA and WGP support sustainability goals, replacement level must be optimized to balance environmental benefit against strength performance.

Table 6: Compressive strength results at 7, 28, and 56 days

GCHA %	WGP %	7 days	28 days	56 days
0	0	30.6	35.6	36.2
3	3	25	31	31.6
3	13	19.6	26.3	27.8
6	7	17.6	29.1	29.6
0	10	20.3	31.3	31.5
10	10	26.7	32	32.2
10	0	18.1	28.5	30.7
13	3	17.4	27.5	28.4
0	20	14.9	24.3	27.8
20	0	20.6	27	30.6

Response Surface Analysis

Effect of GCHA and WGP on Slump

The 3D response surface (Figure 10) confirmed a near-linear decline in slump with increasing GCHA and WGP content, with GCHA producing a steeper reduction than WGP, consistent with its higher water absorption. The combined increase of both materials produced the lowest slump values, reflecting reduced free water availability and a stiffer mix.

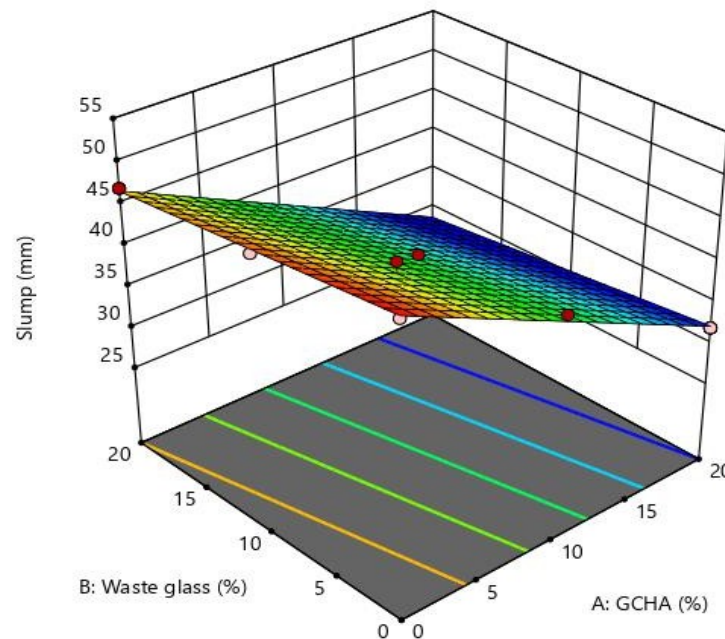


Figure 10: 3D response surface for slump vs. GCHA and WGP content

Effect of GCHA and WGP on Compressive Strength

The 56-day compressive strength response surface (Figure 11) showed a curved, upward trend, with strength increasing as GCHA and WGP were incorporated together at moderate levels, peaking above either material acting alone. This indicates a synergistic, rather than purely additive, interaction between the two SCMs, consistent with combined pore refinement and secondary gel formation from dual pozzolanic activity.

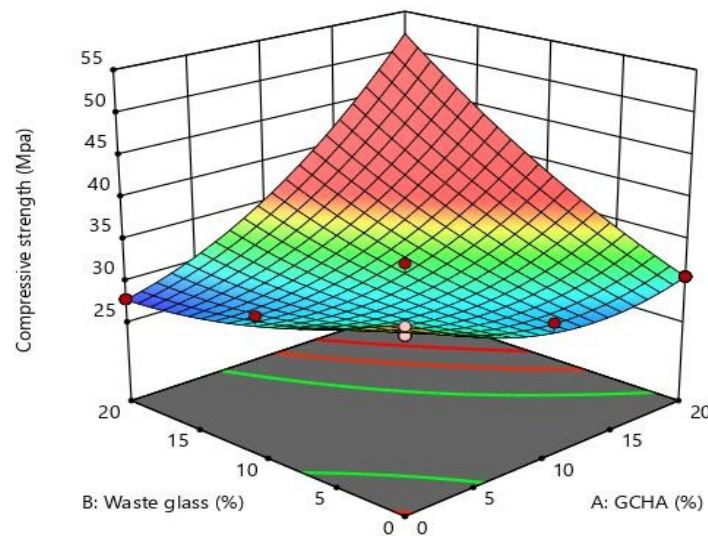


Figure 11: 3D response surface for 56-day compressive strength vs. GCHA and WGP content

Optimization

Numerical optimization was performed to identify the GCHA–WGP combination offering the most favourable balance between compressive strength retention and cementitious material replacement, using a composite desirability function constrained to the tested design space (total replacement $\leq 20\%$), shown in Figure 12. The analysis identified 10% GCHA + 10% WGP as the optimum blend, achieving a measured 56-day compressive strength of 32.2 MPa — the highest strength recorded among all mixes at the maximum tested replacement level of 20%, outperforming both single-material 20% replacement blends (20% WGP: 30.6 MPa; 20% GCHA: 27.8 MPa). This result corresponds to a composite desirability of 0.724, reflecting a strong trade-off between sustainability gains and mechanical performance. This outcome is consistent with the broader trend observed across the study: compressive strength generally declines with increasing combined GCHA–WGP replacement relative to the control mix. The 10% GCHA + 10% WGP blend therefore represents the most effective proportion for maximizing cement replacement while minimizing strength loss, and is recommended as the optimal ternary blend within the scope of this investigation.

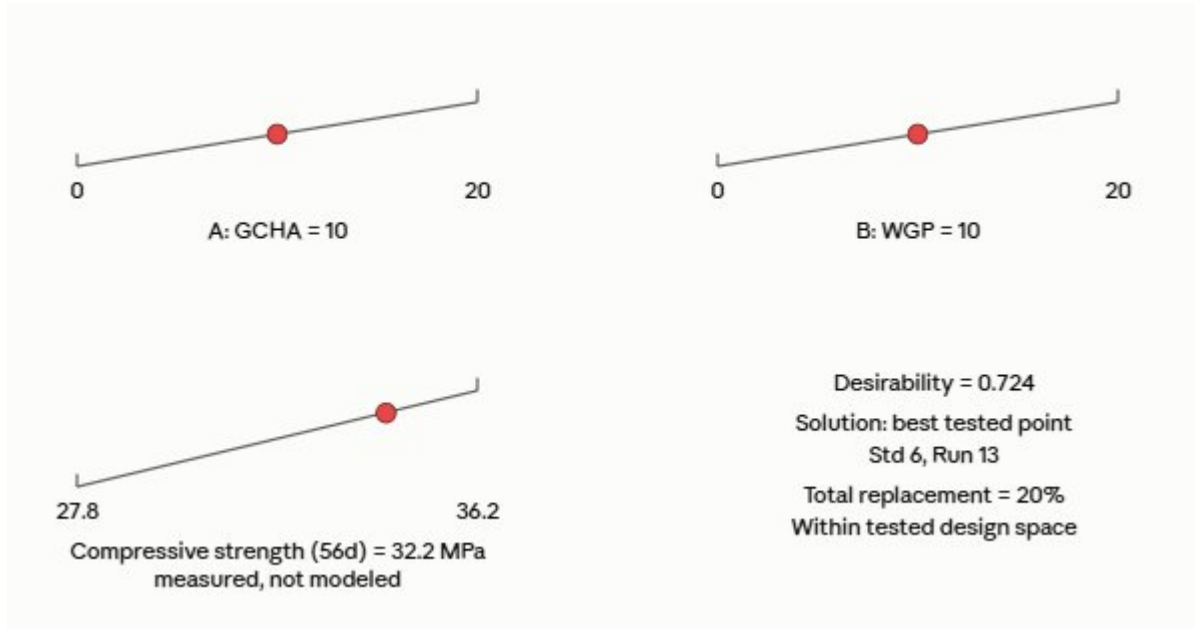


Figure 12: Optimization plot

Model Validation

Slump Model

The slump model was statistically significant ($F = 86.26$, $p < 0.0001$), with GCHA and WGP both significant contributors (Table 7). The model showed a strong fit ($R^2 = 0.977$; adjusted $R^2 = 0.915$; predicted $R^2 = 0.837$), with the small gap between adjusted and predicted R^2 confirming good generalizability. The final regression equation (Eq. 1) was:

$$\text{Slump (mm)} = 50.3 - 0.9(\text{GCHA}\%) - 0.2(\text{WGP}\%) \quad (1)$$

Table 7: ANOVA for slump model

Source	Sum of Squares	df	Mean Square	F Value	P-value
Model	562.86	3	187.62	86.26	< 0.0001
Lack of Fit	13.05	3	4.35		
Pure Error	1.9	3	0		
Total	575.91	9			

Compressive Strength Model

The compressive strength model was also statistically significant ($F = 8.16$, $p = 0.0078$; Table 8), with $R^2 = 0.854$ and adequate precision of 11.71 (well above the threshold of 4), confirming a strong signal-to-noise ratio. The predicted R^2 was 0.512. Although positive, the gap between the adjusted R^2 (0.7488) and the predicted R^2 indicates that the model has only moderate predictive ability outside the experimental design points. This is a recognised limitation of response surface models when the number of experimental runs is modest relative to the number of terms retained (particularly the interaction and quadratic terms). The final regression equation (Eq. 2) was:

$$\text{Compressive strength (MPa)} = 36 - 1.1(\text{GCHA}\%) - 0.79(\text{WGP}) + 0.076(\text{GCHA} \times \text{WGP}) + 0.040(\text{GCHA}^2) + 0.018(\text{WGP}^2) \quad (2)$$

Table 8: ANOVA and fit statistics for compressive strength model

Statistic	Value
F-value	8.16
P-value	0.0078
R ²	0.8535
Adjusted R ²	0.7488
Predicted R ²	0.512
Adequate Precision	11.71

Conclusions and recommendations

GCHA and WGP satisfy ASTM C618 Class F pozzolan requirements, with high silica contents of 86.4% and 92.95%, respectively, confirming their suitability as supplementary cementitious materials. Increasing their replacement levels reduced workability and compressive strength, with GCHA having a greater effect on slump due to its porous, water-absorptive nature, although all mixes gained strength up to 56 days. Numerical optimisation identified 10% GCHA + 10% WGP as the optimum blend, achieving a 56-day compressive strength of 32.2 MPa and a desirability of 0.724, outperforming the corresponding 20% single-material replacements. XRD and SEM results further confirmed active pozzolanic reactions, increased C–S–H formation, and matrix densification. Thus, 10% GCHA + 10% WGP is recommended as the optimal ternary blend within the investigated design space.

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