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Performance of Concrete Incorporating Waste Glass Cullet and Snail Shell Powder: Workability and Strength Characteristics

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Abstract

This study investigates the combined use of waste glass cullet (WGC) and snail shell powder (SSP) as a sustainable binary cementitious system to enhance the mechanical performance and durability of concrete, particularly for rigid pavement applications. Nine concrete mixes were formulated: a control mix, four mixes with 5%, 10%, 15%, and 20% WGC as partial cement replacement, and four corresponding mixes with 1% SSP addition. Slump, compressive strength, and flexural strength were evaluated at various curing ages. Results showed that while WGC reduced workability due to its angular morphology (slump decreased from 30 mm to 20 mm at 20% WGC), the inclusion of SSP slightly mitigated this reduction (21 mm at 20% WGC + 1% SSP). At 28 days, compressive strength increased from 40.0 MPa (control) to 45.0 MPa with 20% WGC and further to 48.0 MPa with the addition of SSP. Flexural strength also improved from 7.0 MPa (control) to 7.8 MPa with both WGC and SSP. These improvements were statistically significant ($p < 0.05$) and supported by correlation analysis, which revealed a strong inverse relationship between WGC content and slump ($r = -0.97$) and strong positive correlations between early and later-age strength. Microstructural analyses (SEM/EDX) confirmed enhanced matrix densification and pozzolanic activity. The findings demonstrate that up to 20% WGC with 1% SSP not only enhances strength development but also provides a viable, low-cost, and eco-friendly alternative for producing durable, load-bearing, and sustainable concrete for rigid pavements and infrastructure applications. This approach supports circular economic principles by valorizing industrial and biogenic waste streams in civil construction.

Keywords: compressive strength; flexural strength; snail shell powder; waste glass cullet; cement concrete; supplementary cementitious material

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1. Introduction

Concrete is one of the world's most important and widely used construction materials because of its strength, durability, affordability, and adaptability [1]. Due to its intrinsic resistance to adverse environmental conditions and its long-term reliability, it is suitable for a wide range of applications, from residential buildings to large infrastructure projects such as highways, bridges, and power plants [2–12]. The versatility of concrete extends to both structural and aesthetic applications, enabling innovation in architectural and civil engineering designs. The global consumption of concrete exceeds 10 billion tons annually, particularly in industrialized nations [13–18], and demand is projected to reach 18 billion tons by 2030. However, its production relies heavily on cement, water, and

aggregate resources that are becoming increasingly scarce. The concrete industry consumes approximately 1.5 billion tons of cement and 20 billion tons of aggregates annually [19–22], causing major environmental strain. Notably, excessive sand extraction has led to ecological degradation in many regions, prompting regulatory restrictions [19,21,23,24]. To address these concerns, researchers have turned to integrating waste materials and by-products into concrete [25,26], reducing the demand for virgin resources and mitigating environmental damage.

Concrete remains the backbone of global infrastructure; however, its production demands large quantities of raw materials and has a significant environmental impact, forming the foundation of buildings, bridges, and roadways worldwide. In spite of its vital role, concrete production is resource-intensive and environmentally damaging. Traditional concrete relies largely on cement, water, and natural aggregates, which not only strain natural resources but also contribute significantly to greenhouse gas emissions. Cement production is a major environmental concern, accounting for approximately 7% of global carbon dioxide (CO_2) emissions. This alarming trend has prompted researchers, engineers, and environmentalists to explore alternative solutions in pursuit of sustainability—one of the most pressing aspirations of our time—not only across various fields of civil engineering [27,28] but also in other disciplines [29,30]. One promising solution is the integration of industrial by-products and agricultural wastes, such as fly ash, slag, rice husk ash, and sugarcane bagasse, into concrete mixtures [21,31–36]. By replacing a portion of traditional cement with these alternative materials, it is possible to reduce the environmental footprint of concrete while maintaining or even enhancing its performance. This shift not only conserves natural resources but also provides productive use for materials that would otherwise contribute to waste. Because the construction industry seeks to align itself with global sustainability goals, the development and adoption of eco-friendly concrete alternatives represents a critical step forward [37–40].

Waste glass cullet (WGC), derived from post-consumer glass, is a major industrial waste stream, with global production exceeding 100 million tons annually. Despite its high silica content and pozzolanic potential when finely ground, only a fraction of this glass is recycled effectively [41]. Similarly, snail shells, a biogenic by-product of aquaculture and food processing, contribute to organic waste accumulation, particularly in countries with high mollusk consumption. Recycling WGC reduces landfill burden, conserves natural sand and silica sources, and offsets energy-intensive cement production [42]. Similarly, valorizing SSP mitigates biogenic waste accumulation, which otherwise leads to localized water and soil pollution due to its slow decomposition and high calcium content [43,44]. Both materials contribute to lowering carbon emissions and promote circular waste management systems. WGC has shown promise in concrete as a partial cement replacement. Its amorphous silica structure reacts during cement hydration to form calcium silicate hydrate (C-S-H), a key compound contributing to strength [45,46]. Previous studies show that replacing 10–20% of cement with WGC can enhance compressive strength and reduce permeability [42,47,48]. However, its angular shape can reduce workability due to increased internal friction. These incremental steps allow for the evaluation of both marginal and progressive substitution effects and reflect practical limits suitable for field application and regulatory compliance. Beyond 20%, studies have reported diminished workability and potential durability issues, which justified setting this as the upper bound in this study.

Snail shell powder (SSP) is a newly formed calcium-rich additive that can be used as a filler or even as a light pozzolan activity if calcium is crushed from discarded shells [43,49]. It contributes to early strength through filler effects and nucleation and helps densify the concrete matrix [50,51]. SSP also offers environmental benefits by providing productive use for an otherwise problematic biowaste. While both WGC and SSP have been stud-

ied independently, and dual-waste systems are increasingly common, few studies have systematically investigated the combined use of WGC and SSP in concrete as uncalcined, readily available Supplementary Cementitious Material. Most prior research focuses on high-reactivity pozzolans or thermally treated biogenic fillers, often involving complex or energy-intensive processing.

Despite the growing body of research on Supplementary Cementitious Material and dual-waste systems, few studies focus on low-reactivity, unprocessed binary combinations in structural-grade concrete. Most research favors calcined or chemically treated additives, which are energy-intensive and less practical for widespread use. This study fills a critical gap by systematically exploring the mechanical and rheological behavior of concrete made with raw WGC and SSP, suitable for both industrialized and resource-constrained settings. The central purpose of this study is to explore whether a synergistic interaction occurs between the high-silica content of WGC and the calcium-rich composition of SSP and how this interaction affects the fresh and hardened properties of concrete.

Unlike previous works, this study emphasizes simple material preparation and realistic substitution levels (10–20%) and focuses on mechanical performance and flowability without relying on advanced chemical or thermal processing. By addressing this scientific and practical gap, the research contributes to the development of cost-effective, scalable, and environmentally sustainable concrete suitable for deployment in both developed and resource-constrained settings. It also advances the global agenda of circular economy by valorizing post-consumer and organic waste streams into high-performance construction materials. The primary purpose of this study is to evaluate the combined use of WGC and SSP as a binary, low-energy Supplementary Cementitious Material system in concrete and assess their synergistic effects on key fresh and hardened properties such as workability, compressive strength, and flexural strength. This combination aims to reduce reliance on virgin cement and aggregates, provide a practical application for underutilized waste streams, and support the development of sustainable materials for load-bearing infrastructure.

2. Materials and Methods

2.1. Material Properties and Chemical Composition

The chemical compositions of the three key cementitious materials used in this study (OPC, WGC, and SSP) are listed in Table 1 and illustrated in Figure 1. The results reveal distinctive oxide profiles that directly influence the performance of concrete.

Table 1. Chemical composition determined via X-ray fluorescence (XRF) analysis.

Oxide	Typical Percentage (%)		
	OPC (%)	WGC (%)	SSP (%)
Calcium Oxide (CaO)	64.80	10.40	67.50
Silicon Dioxide (SiO_2)	23.40	71.00	0.50
Aluminum Oxide (Al_2O_3)	5.50	1.85	0.32
Iron Oxide (Fe_2O_3)	3.20	0.40	1.95
Magnesium Oxide (MgO)	2.20	0.62	2.12
Sodium Oxide (Na_2O)	0.20	13.00	2.27
Potassium Oxide (K_2O)	0.70	0.85	1.24
Sulfate (SO_3)	2.62	0.21	1.30
Phosphorus Pentoxide (P_2O_5)	–	–	1.45
Titanium Dioxide (TiO_2)	–	–	1.22
Carbon Dioxide (CO_2)	–	–	25.00
Chloride (Cl^-)	–	–	0.02
Loss on Ignition (LOI)	2.02	0.48	14.50

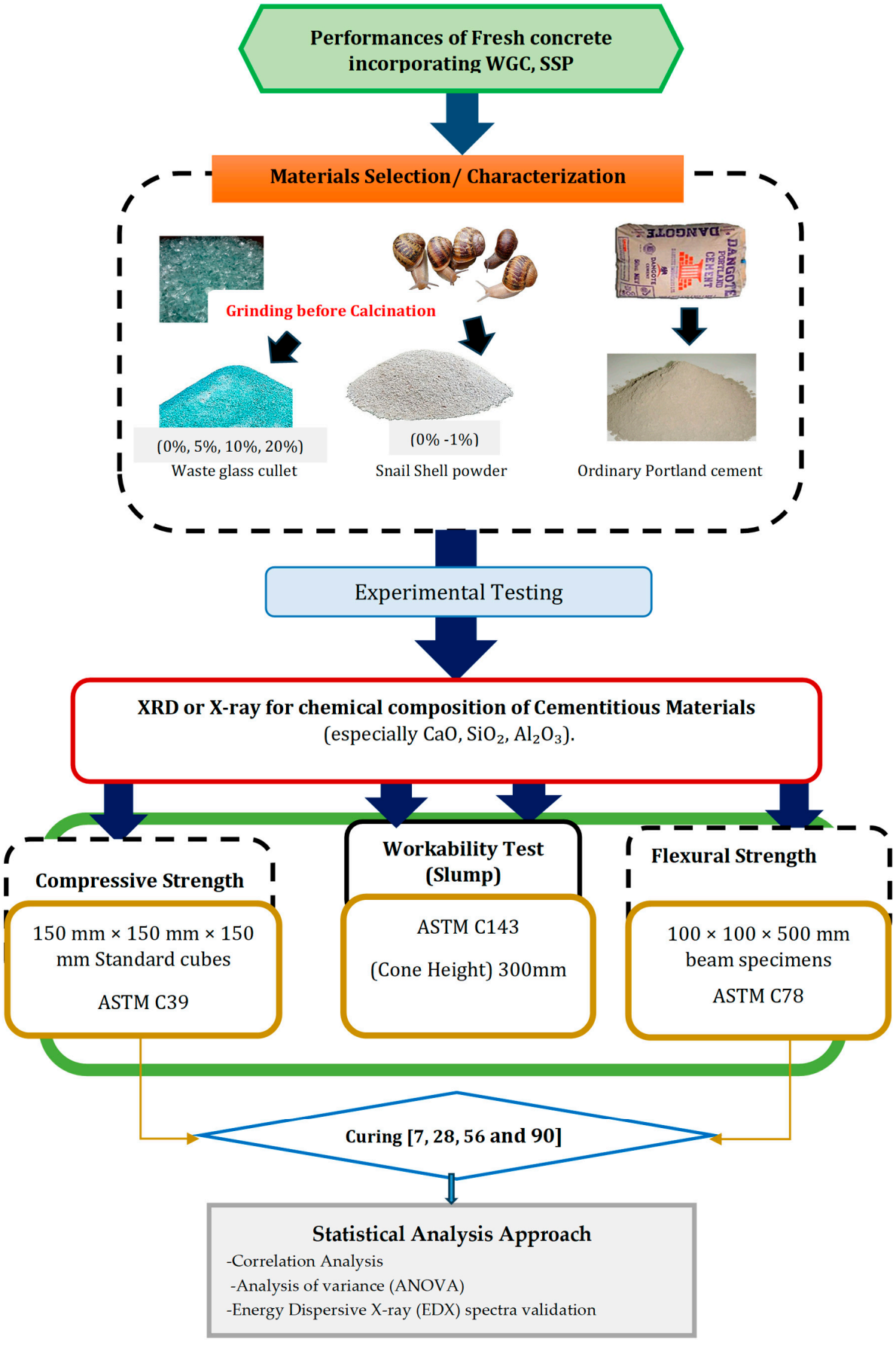


Figure 1. Schematic flowchart of experimental procedure testing.

2.1.1. Ordinary Portland Cement (OPC)

Ordinary Portland Cement exhibits a typical composition dominated by calcium oxide (CaO) at 64.80%, followed by significant quantities of silicon dioxide (SiO_2, 23.40%), aluminum oxide (Al_2O_3, 5.50%), and iron oxide (Fe_2O_3, 3.20%). These oxides contribute to the formation of primary clinker phases (C_3S, C_2S, C_3A, and C_4AF), which are responsible for strength development through hydration. A moderate loss on ignition (LOI) value of 2.02% reflects the presence of moisture and carbonates.

2.1.2. Waste Glass Cullet (WGC)

Waste glass cullet was notably high in silica (71.00%), indicating a strong pozzolanic potential when finely ground. The presence of alkali oxides, particularly Na_2O (13.00%) and K_2O (0.85%), is characteristic of soda-lime glass. While this alkali content raises concerns about the alkali–silica reaction (ASR), the amorphous nature of WGC and its fine particle size allow it to react with calcium hydroxide to form additional calcium silicate hydrate (C-S-H), which can enhance strength and reduce permeability. The low CaO content (10.50%) of WGC differentiates it from OPC, thereby highlighting its role as a reactive filler, as shown in Figure 2.

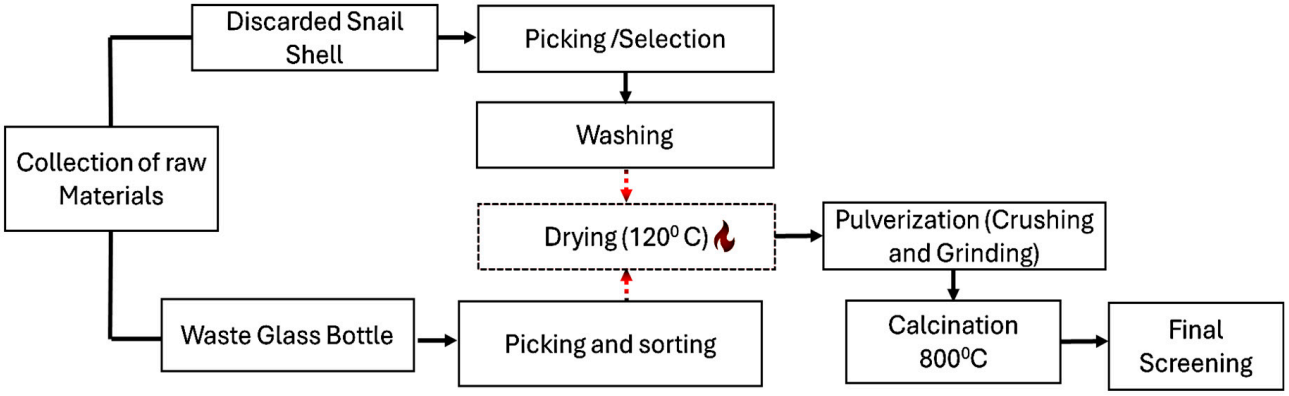


Figure 2. Production process of all recycled raw materials (waste glass cullet (WGC) and snail shell powder (SSP)).

2.1.3. Snail Shell Powder (SSP)

Snail shell powder is heavily dominated by calcium oxide (67.50%) and carbon dioxide (28.00%), resulting from carbonate-rich shells. This high CaO content suggests that SSP can contribute to early hydration reactions and may act as a stabilizing agent for alkalis in the mix. The presence of minor oxides such as MgO, Fe_2O_3, and P_2O_3 may contribute to additional reactivity or filler effects, while the LOI value of 14.50% confirms the substantial release of CO_2 during calcination, indicating the effective decomposition of $CaCO_3$ into reactive lime (CaO), as shown in Figure 3.

2.2. Properties of Aggregates

The natural river sand (fine aggregate) and crushed granite (coarse aggregate) used in this study were tested in accordance with ASTM C33 [52]. Key physical properties are summarized in Table 2.

These properties confirm that the aggregates conform to conventional specifications for structural concrete and contributed to consistent workability and strength outcomes.

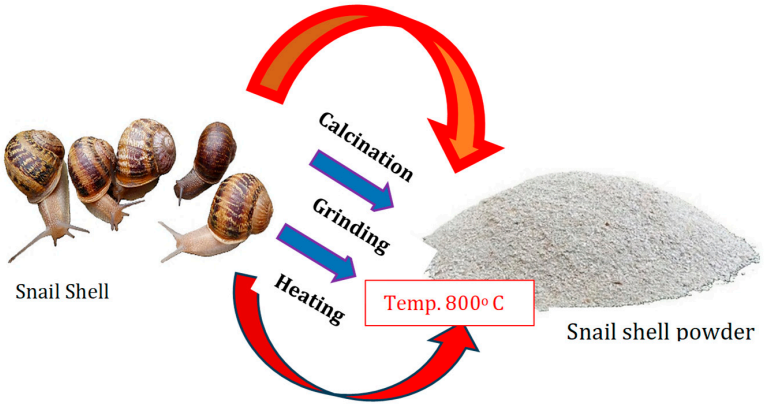


Figure 3. Pictorial view of snail shell and calcinated snail shell powder.

Table 2. Properties of aggregates used in the production of concrete.

Property	Fine Aggregate	Coarse Aggregate
Specific Gravity	2.62	2.70
Bulk Density (kg/m^3)	1590	1540
Water Absorption (%)	1.05	0.76
Fineness Modulus	2.85	6.50
Maximum Particle Size (mm)	4.75	19.0
Aggregate Crushing Value (%)	–	23.5
Aggregate Impact Value (%)	–	18.4

2.3. Materials Mix Proportion

The primary materials used in this study were OPC, fine and coarse aggregates, WGC, and SSP. The OPC conformed to the ASTM C150 [53] standards. Natural river sand was used as the fine aggregate, and crushed granite was used as the coarse aggregate. The waste glass cullet was collected from post-consumer sources, cleaned, dried, and ground to pass through a 150 µm sieve. The snail shells were sourced locally, calcined at 800 °C, and ground to a powder with particles smaller than 75 µm. Table 3 details the formulation of the nine concrete mixes, including a control, four binary mixes with 5–20% WGC, and four ternary mixes incorporating 1% SSP at each WGC level. The total cementitious content was maintained at 400 kg/m^3 in all the mixes to ensure consistency. Accordingly, the 1% SSP dosage was calculated based on the total cementitious mass, resulting in 4 kg/m^3 SSP for each ternary mix. The proportion of OPC was adjusted to accommodate the WGC and SSP contents, while the quantities of fine and coarse aggregates and water remained constant. This standardization allowed for a focused assessment of the impact of WGC and SSP on the fresh and hardened properties of concrete.

Table 3. Concrete mix proportions (kg/m^3) with varying waste glass cullet and fixed snail shell powder dosage.

Mix.NO.	Mix ID	OPC (kg/m^3)	WGC *		SSP **		Fine Agg. (kg/m^3)	Coarse Agg. (kg/m^3)	Water (kg/m^3)	w/cm ***
			(%)	(kg/m^3)	(%)	(kg/m^3)				
1.	Control	400	0	0	0	0	650	1200	200	0.50
2.	5WGC	380	5	20	0	0	650	1200	200	0.50
3.	10WGC	360	10	40	0	0	650	1200	200	0.50
4.	15WGC	340	15	60	0	0	650	1200	200	0.50
5.	20WGC	320	20	80	0	0	650	1200	200	0.50
6.	5WGC+1SSP	376	5	20	1	4	650	1200	200	0.50
7.	10WGC+1SSP	356	10	40	1	4	650	1200	200	0.50
8.	15WGC+1SSP	336	15	60	1	4	650	1200	200	0.50
9.	20WGC+1SSP	316	20	80	1	4	650	1200	200	0.50

(waste glass cullet *, snail shell powder **, water-to-cementitious material ***).

2.4. Testing Methods and Procedures

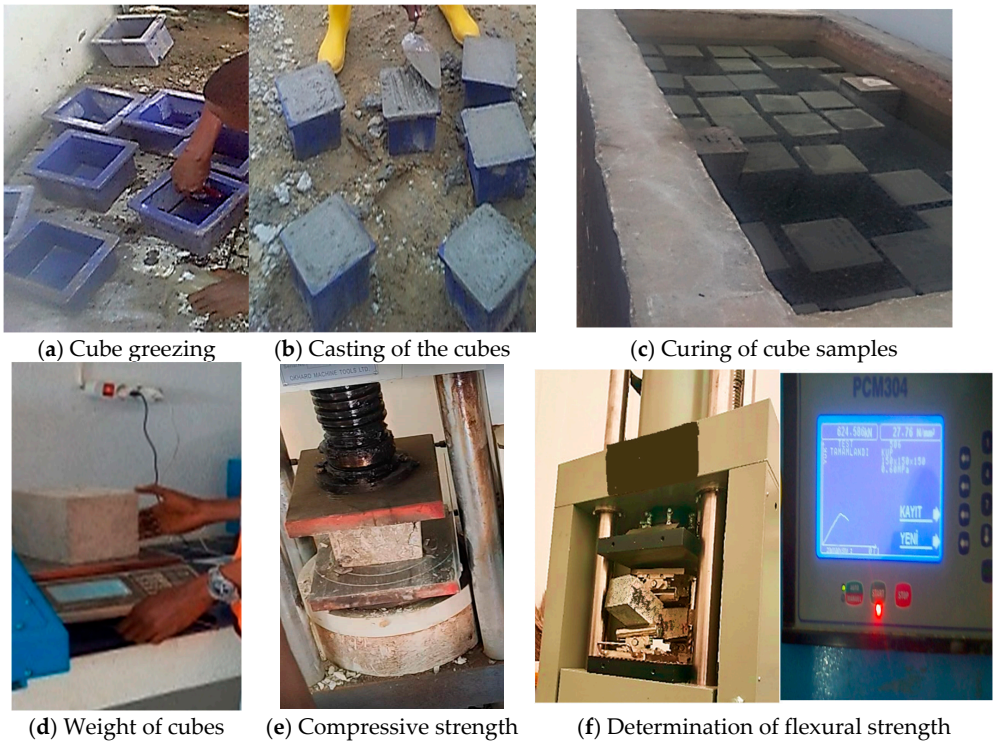
2.4.1. Chemical Composition

The chemical compositions of the cementitious materials, including OPC, WGC, and SSP, were determined using X-ray fluorescence. The analysis focused on quantifying the oxide content, particularly SiO_2, CaO, and Al_2O_3, to assess the pozzolanic reactivity of WGC and the ASR-mitigation potential of SSP.

2.4.2. Compressive and Flexural Strength Testing

The compressive strength was measured on 150 mm cube specimens after 7, 28, 56, and 90 days of curing, following ASTM C39 [54]. This test was used to determine the load-bearing capacity and overall strength performance of the concrete mixtures. The flexural strength of 100 × 100 × 500 mm beam specimens was evaluated using the third-point loading method in accordance with ASTM C78 [55]. This test assesses the resistance of concrete to bending, which is an important property of pavements and structural elements.

The mixture design and proportions of concrete mixtures were prepared by varying the replacement levels of OPC with GC and SSP. Six mixtures were designed, including a control mixture containing 100% OPC. Other mixes replaced OPC with 10%, 15%, and 20% WGC and binary and ternary blends incorporating both WGC and SSP in combined proportions of 15% and 20%, respectively. The water–cement ratio was maintained at 0.5 for all mixtures to ensure consistency in workability. The mix design followed the ACI 211.1-91 [56] guidelines. Concrete was prepared by machine mixing in a pan mixer. Standard 150 × 150 × 150 mm cubes were cast for the compressive strength tests, as shown in Figure 4, whereas 100 × 100 × 500 mm beams were cast for the flexural strength tests. Fresh concrete was placed in molds in two layers and compacted using a vibration table. After 24 h, the specimens were demolded and cured in a water tank at 23 ± 2 °C until the testing day.



(**a**) Cube greezing (**b**) Casting of the cubes (**c**) Curing of cube samples

(**d**) Weight of cubes (**e**) Compressive strength (**f**) Determination of flexural strength

Figure 4. Experimental set-up of compressive and flexural strength.

2.4.3. Slump Testing

The consistency and flowability of the fresh concrete were assessed using the slump cone test conducted according to ASTM C143 [57]. Slump values were used to evaluate the impact of the WGC and SSP on the workability of each mix. The workability test was performed using a slump test in accordance with ASTM C143 [57]. The slump value was recorded immediately after mixing to evaluate the consistency and flowability of fresh concrete.

3. Results and Discussion

This section presents the results obtained from the particle size distribution of WGC and SSP and experimental tests conducted on various concrete mixtures. The analysis included data on the workability measured by slump tests, compressive strength at different curing ages, and flexural strength assessed at 7, 28, 56, and 90 days.

3.1. The Particle Size Distribution of WGC and SSP

The particle size distribution analysis revealed that snail shell powder (SSP) exhibits a significantly finer profile than waste glass cullet (WGC), with D_{50} values of 14.2 µm and 21.0 µm, respectively as shown in Figure 5. SSP's narrower grading (D_{90}–D_{10} = 25.1 µm) enhances its microfiller effectiveness, promoting better particle packing and slight improvements in workability. In contrast, WGC's broader size distribution (D_{90}–D_{10} = 36.5 µm) increases internal friction in fresh concrete, contributing to reduced slump.

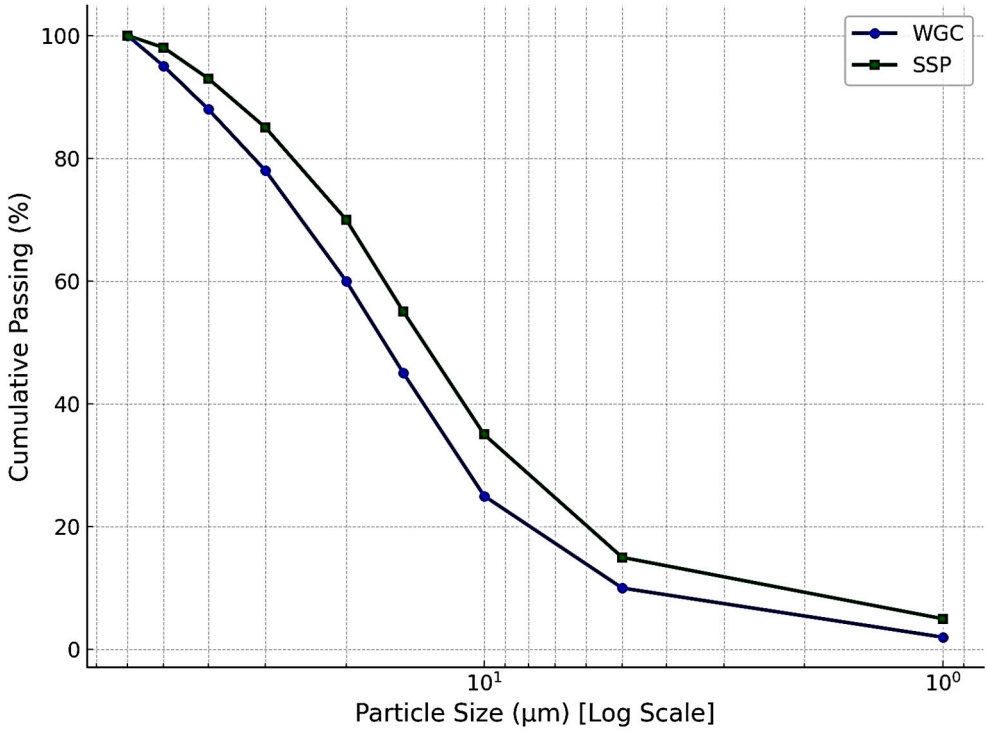


Figure 5. Particle size distribution curves for WGC and SSP.

The finer SSP particles help mitigate this drawback by occupying voids between larger particles and providing additional nucleation sites. Together, the WGC/SSP combination supports improved matrix densification and long-term strength development, validating their synergistic use as a low-energy Supplementary Cementitious Material system in sustainable concrete production.

3.2. Workability of Fresh Concrete Mixtures

The workability of the concrete mixtures was evaluated using slump tests, and the results are summarized in Table 4. The results demonstrated a trend correlated with the percentage of waste glass cullet used in the concrete mix.

Table 4. Slump test result for different mixtures.

Mix ID	Slump (mm)
Control	30
5WGC	28
10WGC	25
15WGC	22
20WGC	20
5WGC+1SSP	30
10WGC+1SSP	27
15WGC+1SSP	23
20WGC+1SSP	21

The workability of fresh concrete, as evaluated by slump tests, was significantly influenced by the incorporation of the WGC and SSP. A consistent decline in the slump was observed with increasing WGC content, indicating reduced workability. The control mix exhibited a slump of 30 mm, which decreased progressively to 20 mm with a 20% WGC substitution. This trend can be attributed to the angular and irregular morphology of the WGC particles, which increases the internal friction and disrupts the ease of movement within the concrete matrix. These characteristics hinder the cohesive flow of the mix and reduce its slump [58]. Despite the low water absorption capacity of glass, which might suggest a greater amount of free water, the dominant frictional effects and poor particle interlocking are likely to outweigh any other benefits. This phenomenon aligns with previous findings, where angular aggregates, including recycled glass, negatively affected the plasticity of concrete.

The addition of 1% SSP to the WGC-containing mixes slightly improved the slump values compared to their WGC-only counterparts. Notably, the slump for the 5% of the WGC mix increased from 28 mm to 30 mm upon SSP inclusion, whereas that for the 15% of the WGC mix improved from 22 mm to 23 mm. These modest gains suggest that SSP may function as a microfiller, enhancing particle packing and potentially reducing internal friction. Moreover, the calcium-rich composition of the snail shell powder, primarily in the form of calcium carbonate, may impart a mild lubricating effect within the mixture, thereby improving the flowability. Nonetheless, the improvement imparted by SSP was not sufficient to counteract the adverse effects of the high WGC content. Mixtures with 15% and 20% WGC, even when combined with SSP, remained within the "low" workability category. This indicates a limitation in the effectiveness of SSP at a 1% dosage level. To achieve acceptable fresh properties at higher levels of WGC substitution, alternative approaches, such as chemical admixtures or optimized gradation of fine aggregates, may be required. These findings suggested that up to 10% of WGC can be incorporated without significantly impairing workability, particularly when used in conjunction with 1% SSP. Beyond this threshold, the mix becomes increasingly stiff and less workable, which may hinder compaction and uniformity in field applications.

3.3. Statistical Analysis of Slump-Influencing Variables

Descriptive statistical analysis was conducted to further explore the relationships among WGC content, SSP dosage, and concrete slump (Table 5). The dataset included nine mix designs, each with recorded levels of WGC and SSP and corresponding slump

measurements. The mean WGC content was 11.11% (standard deviation [SD] = 6.97%), ranging from 0% to 20%. The SSP content varied between 0% and 1% with a mean of 0.44% (SD = 0.53%), reflecting its binary inclusion across the mixes. The mean slump was 25.11 mm, with a standard deviation of 3.82 mm, indicating moderate variability in workability.

Table 5. Statistical description between waste glass cullet, snail shell powder, and slump.

Statistic	Waste Glass Culet	Snail Shell Powder	Slump
Count (samples)	9	9	9
Mean value	11.11	0.44	25.11
Std dev.	6.97	0.53	3.82
Minimum value (%)	0	0	20
25%	5	0	22
50%	10	0	25
75%	15	1	28
Maximum value (%)	20	1	30

The interquartile range (IQR) for the slump ranged from 22 mm (25th percentile) to 28 mm (75th percentile), with a median value of 25 mm. These values reinforce the fact that most mixes achieve moderate workability and cluster around a fair range. The lowest slump value of 20 mm occurred in the mix with the highest WGC content (20%), confirming the negative correlation between WGC proportion and workability. Conversely, a maximum slump of 30 mm was recorded in both the control and 5% WGC + 1% SSP mixtures, indicating that a low WGC content and SSP inclusion favorably influenced workability. These statistical insights support the earlier interpretation that increasing WGC content reduces the slump, whereas SSP inclusion slightly offsets this reduction. However, the narrow range and relatively low variation in SSP suggest that its influence may not be fully captured in this dataset and warrant further investigation with broader SSP dosages or in combination with plasticizing admixtures.

3.4. Analysis of Variance (ANOVA)

One-way ANOVA was conducted to statistically evaluate whether the differences in the slump and mechanical properties across the various concrete mixtures were significant. The analysis compared the means of the slump, compressive strength (at 28 days), and flexural strength (at 28 days) among all groups. For slump, the ANOVA results indicated a statistically significant difference between the means of the different mixes ($p < 0.05$), confirming that the variations observed in slump were not due to random variation but rather the effect of WGC and SSP contents. Similarly, the ANOVA for compressive strength at 28 days revealed a significant difference among the mixture groups ($p < 0.05$), suggesting that the levels of WGC and SSP had a substantial influence on compressive performance. This supports earlier conclusions regarding the positive impact of these additives on the development of strength. In the case of flexural strength at 28 days, ANOVA also showed significant differences ($p < 0.05$), particularly highlighting the enhanced performance of the WGC+SSP mixes compared to the control and WGC-only samples. The ANOVA results validated the findings from the approximate mean strength data shown in Figure 6 and the correlation analyses, statistically confirming that the incorporation of WGC and SSP significantly affected the workability and strength outcomes in concrete mixtures as shown in Figure 6.

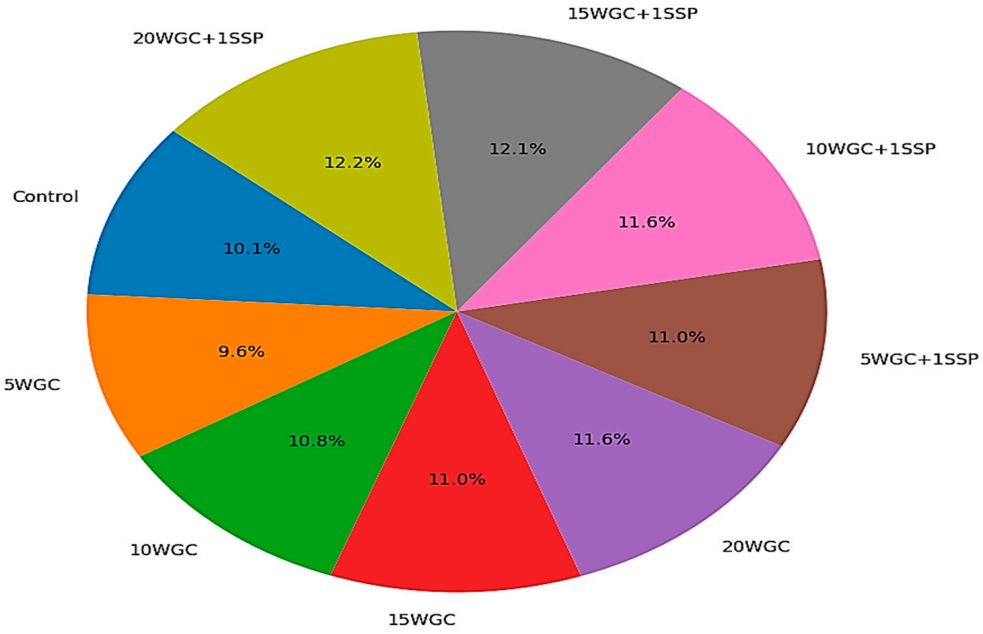
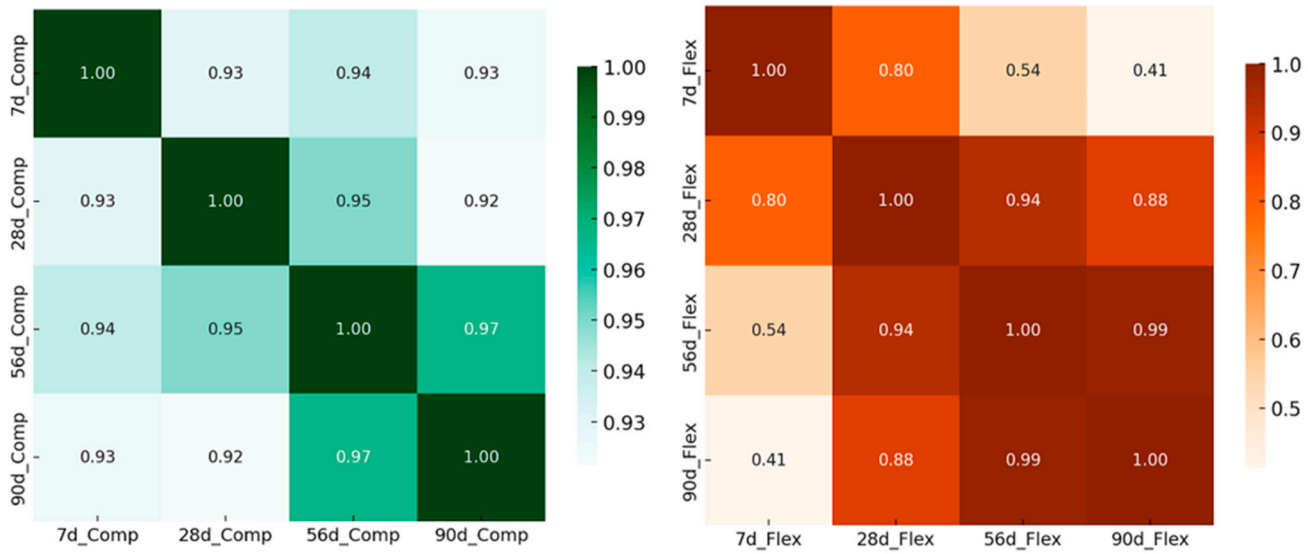


Figure 6. Approximate mean strength (compressive and flexural strength) contribution for each mix.

3.5. Correlation Analysis of Strength Properties

To evaluate the interdependence of strength development over time, Pearson correlation matrices were generated for both the compressive and flexural strength values at 7, 28, 56, and 90 days. The matrices provide insights into the consistency and predictability of strength gain across various mix compositions incorporating waste glass cullet (WGC) and snail shell powder (SSP), as shown in Figure 7.



(**a**) Compressive Strength matrix (**b**) Flexural strength matrix

Figure 7. The correlation matrix analysis on compressive and flexural strength performance.

3.5.1. Compressive Strength Correlation

The correlation matrix revealed strong positive correlations among all curing periods for compressive strength, with coefficients exceeding 0.97. The 28-day compressive strength exhibited near-perfect correlation with both the 56-day and 90-day strengths ($r = 0.998$ and $r = 0.997$, respectively), indicating highly predictable strength development across all

mix compositions. This confirms that the early-age compressive strength, particularly at 28 days, is a robust indicator of long-term performance.

3.5.2. Flexural Strength Correlations

The flexural strength correlations were also strong, with coefficients ranging from 0.93–0.99. Lower correlation values at 7 days suggest greater variability in early-age flexural behavior, likely due to microstructural sensitivity or initial curing conditions. However, the strength values from 28 days onward showed improved alignment, reflecting a more stable and predictable flexural development.

The correlation analysis affirms that concrete mixes containing WGC and SSP exhibit a systematic and reliable strength progression over time. The high correlation coefficients between the early and later curing periods support the practical use of 28-day strength tests to forecast long-term mechanical performance. These findings highlight the viability of using waste-derived materials for sustainable concrete production without compromising structural reliability.

3.5.3. Slump (Workability) Correlations

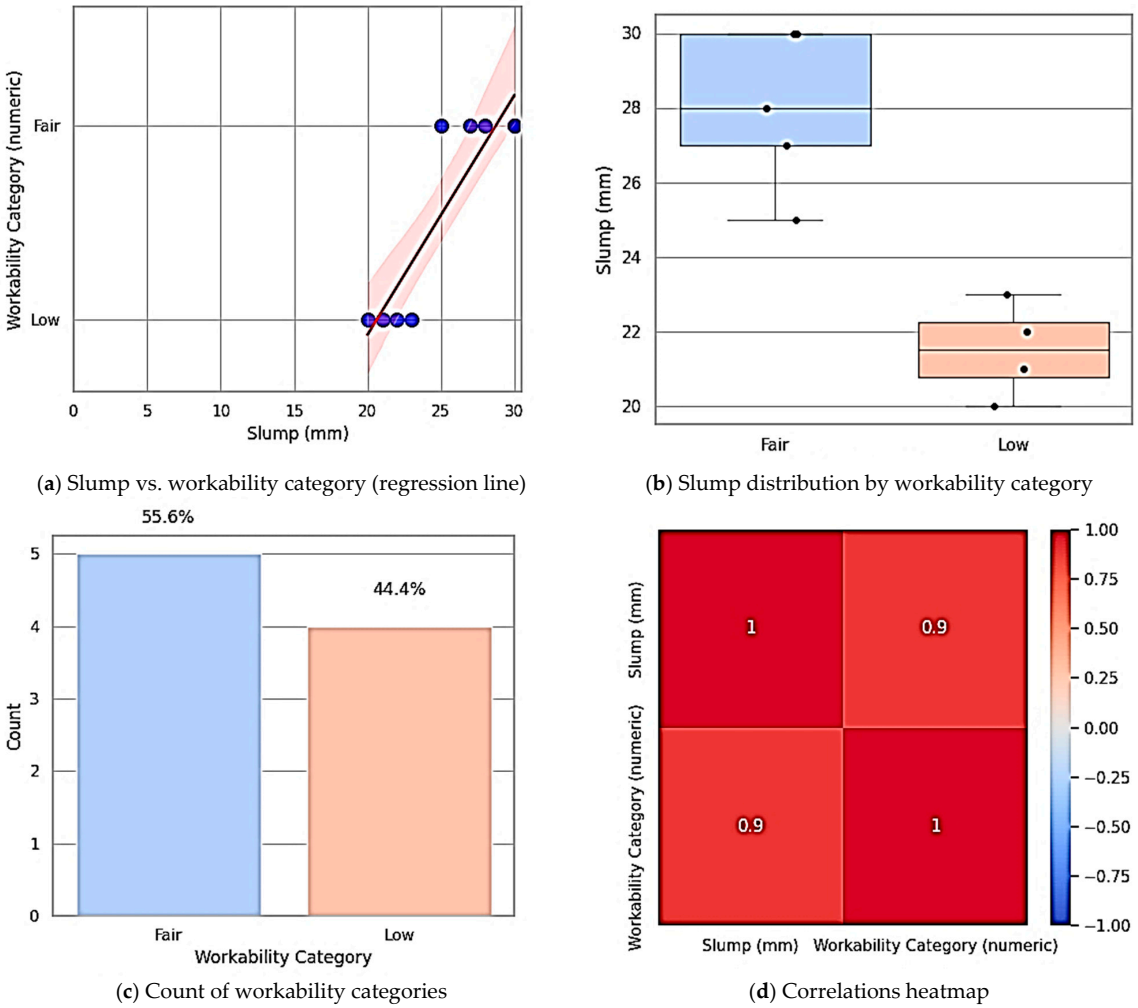
Notably, a strong negative correlation was observed between the WGC content and slump (r = –0.97), indicating that as the WGC percentage increased, the slump values consistently decreased (Figure 8). This statistically confirms earlier observations and reinforces the assertion that increasing WGC replacements lead to a significant loss in workability. Such a strong inverse relationship suggests that WGC is a dominant factor in determining the fresh properties of the concrete mix. In contrast, the correlation between the SSP and slump was very weak (r = 0.03), indicating no significant linear relationship. This outcome aligns with the marginal improvement in slump values observed in the WGC/SSP mixes and suggests that at a 1% dosage, SSP has a stabilizing but not strongly influential effect on workability. However, this did not preclude potential nonlinear effects or improvements at higher SSP replacement levels, which were not considered in this study. A low positive correlation between WGC and SSP (r = 0.19) was expected, as these variables were independently controlled and only paired in specific combinations (i.e., mixes with 0–20% WGC had either 0% or 1% SSP). Therefore, the correlation was weak and likely not to be statistically significant. These correlation results support the conclusion that the WGC content is the primary variable affecting the slump, whereas SSP plays a minimal compensatory role within the tested range. This strong negative relationship highlights the need for careful mix optimization or additional admixtures when incorporating higher percentages of recycled glass aggregate.

3.6. Compressive Strength Development

Figures 9 and 10 and Table 6 present the compressive strengths of the concrete samples incorporating WGC and SSP at curing ages of 7, 28, 56, and 90 days. The results show a consistent trend of increasing strength with both curing age and WGC/SSP content, indicating that the materials contribute positively to long-term mechanical performance.

At all ages, mixtures containing WGC alone exhibited equal or higher strength than that of the control. For example, at 28 days, the control mix achieved 40.0 MPa, whereas the 20% WGC mix (20WGC) reached 45.0 MPa, a 12.5% increase. This improvement may be attributed to the pozzolanic activity of the finely ground WGC, which contributes to the formation of secondary calcium silicate hydrate (C-S-H), densifying the microstructure over time. Additionally, the angular shape of the glass particles may contribute to improved interfacial bonding within the cement matrix. The inclusion of 1% SSP further enhanced the compressive strength during all curing periods. For instance, the 28-day strength of the 20WGC+1SSP mix was 48.0 MPa, compared to 45.0 MPa for 20WGC without SSP,

an increase of approximately 6.7%. The combination of WGC and SSP appears to have a synergistic effect owing to the improved particle packing, filler effects, and potential nucleation sites provided by the fine SSP particles. The high calcium carbonate content of the SSP may also play a role in early-age strength development by promoting additional hydration reactions.



(**a**) Slump vs. workability category (regression line)

(**b**) Slump distribution by workability category

(**c**) Count of workability categories

(**d**) Correlations heatmap

Figure 8. Distribution of slump based on workability and correlation.

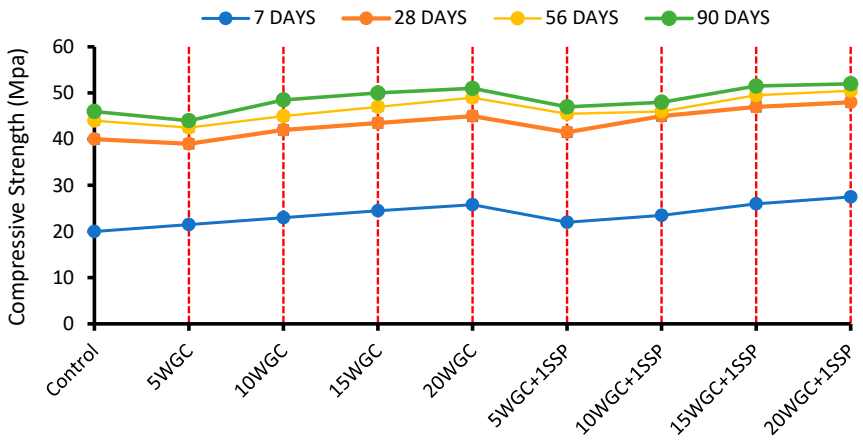


Figure 9. The compressive strength of samples on different curing days.

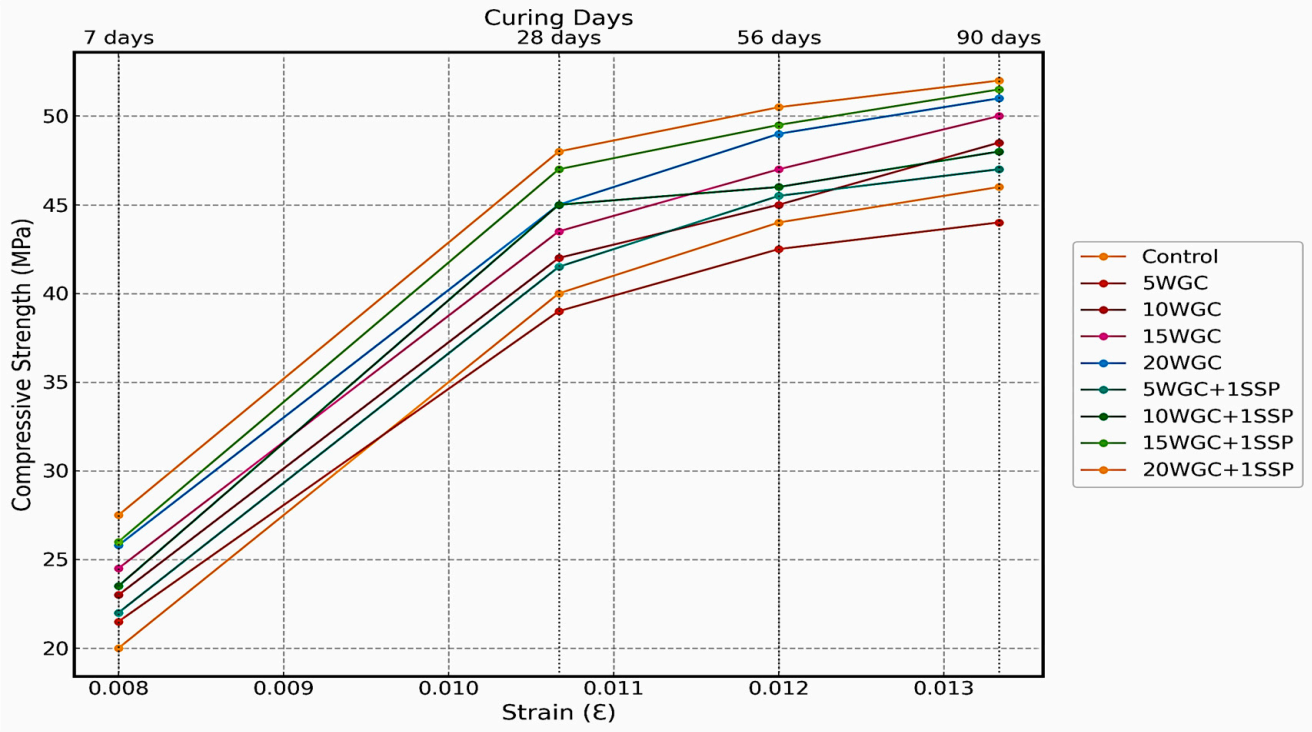


Figure 10. Chart showing the compressive stress and strain at different curing days.

Table 6. Compressive strength of samples at different curing ages (MPa).

Days	Strain (ε)	Control	5WGC	10WGC	15WGC	20WGC	5WGC+1SSP	10WGC+1SSP	15WGC+1SSP	20WGC+1SSP
7	0.008000	20.00	21.50	23.00	24.50	25.80	22.00	23.50	26.00	27.50
28	0.010667	40.00	39.00	42.00	43.50	45.00	41.50	45.00	47.00	48.00
56	0.012000	44.00	42.50	45.00	47.00	49.00	45.50	46.00	49.50	50.50
90	0.013333	46.00	44.00	48.50	50.00	51.00	47.00	48.00	51.50	52.00

Over time, all mixes showed significant strength gains between days 7 and 90. The rate of gain was particularly pronounced in the WGC and WGC + SSP mixes. 15WGC+1SSP increased from 26.0 MPa in 7 days to 51.5 MPa in 90 days, a 98% increase. This long-term strength development is indicative of the ongoing pozzolanic activity and microstructural refinement, particularly in mixes incorporating supplementary materials. These findings suggest that WGC up to 20%, especially when combined with 1% SSP, can not only offset potential drawbacks in fresh properties but also significantly improve compressive strength, especially at later curing ages. This makes such combinations attractive for sustainable construction applications in which long-term performance is prioritized.

3.7. Flexural Strength Performance

The flexural strength values of the concrete samples with varying proportions of WGC and SSP after 7, 28, 56, and 90 d of curing are presented in Table 7. Flexural strength is critical in assessing the tensile behavior and crack resistance of concrete, particularly in structural and pavement applications.

Table 7. Flexural strength of samples at different curing ages (MPa).

Days	Control	5WGC	W10GC	15WGC	20WGC	5WGC+1SSP	10WGC+1SSP	15WGC+1SSP	20WGC+1SSP
7	5.50	5.80	6.00	6.20	6.10	5.90	6.10	6.30	6.20
28	7.00	6.80	7.10	7.50	7.60	7.10	7.20	7.70	7.80
56	9.00	8.13	8.56	9.23	9.60	8.70	8.67	9.57	9.93
90	11.40	9.75	10.35	11.34	12.03	10.64	10.45	11.83	12.52

At 7 days, all mixes incorporating WGC exhibited a higher flexural strength than the control (5.50 MPa). The strength increased progressively with the WGC content, peaking at 6.20 MPa for the 15WGC mix in Figure 11. However, a slight decline was noted at 20% WGC (6.10 MPa) because of the reduced matrix cohesion or increased porosity at higher glass content. This suggests an optimal threshold of approximately 15% WGC for early-age flexural performance. The inclusion of 1% SSP further enhanced the early-age flexural strength across all WGC levels. For example, 15WGC+1SSP reached 6.30 MPa in 7 days, the highest among all mixes compared to 6.20 MPa of 15WGC without SSP. These improvements may stem from better particle packing, improved hydration kinetics, or crack-bridging potential contributed by fine-grained and calcium-rich SSP. After 28 days, a more pronounced improvement was observed. The control mix reached 7.00 MPa, whereas all modified mixes surpassed this benchmark. 20WGC+1SSP achieved the highest flexural strength (7.80 MPa), followed closely by 15WGC+1SSP (7.70 MPa) and 20WGC (7.60 MPa). These values represent an 11–12% improvement over the control. Notably, mixtures with both WGC and SSP consistently outperformed their WGC-only counterparts, highlighting the synergistic effect between the two materials on the flexural performance. The continuous strength gain from 7 to 28 days in all mixes suggests that both WGC and SSP contribute to long-term improvements in the tensile microstructure integrity. The angular shape and potential pozzolanic behavior of WGC may improve aggregate-paste bonding, while the fine SSP particles likely act as nucleation sites for additional C-S-H formation, enhancing matrix continuity and crack resistance. In summary, the incorporation of up to 20% WGC, particularly in combination with 1% SSP, significantly improved the flexural strength of concrete at both the early and later ages. These findings support the potential use of waste materials in structural- and flexural-demanding concrete applications.

3.8. Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) was employed to examine the morphological features of Ordinary Portland Cement (OPC), waste glass cullet (WGC), and snail shell powder (SSP), as shown in Figure 12. The micrographs revealed distinct differences in particle shape, texture, and surface characteristics across the materials, which are critical indicators of their behavior in cementitious systems. OPC particles exhibited irregular, angular geometries with compact, dense surfaces, typical of cement clinker phases such as tricalcium silicate (C_3S) and dicalcium silicate (C_2S). The absence of porosity and the relatively smooth texture suggest a limited surface area for hydration but promote strength development over time due to the crystalline structure. WGC particles were observed to have angular yet smooth surfaces, indicative of a vitreous and amorphous morphology. The glassy appearance and lack of crystalline boundaries confirm the amorphous silica nature of WGC, aligning with its high SiO_2 content. However, the smooth, non-porous texture may limit early-stage reactivity unless finely ground, as pozzolanic activity is closely linked to surface accessibility. SSP displayed a markedly different morphology, characterized by rough, porous, and flaky particles. This porous structure increases the specific surface area, facilitating better water absorption and interaction with cement hydration products. The observed microstructure reflects a biogenic calcium-rich source material that has undergone thermal treatment, though not necessarily complete calcination, as evidenced by residual organic textures.

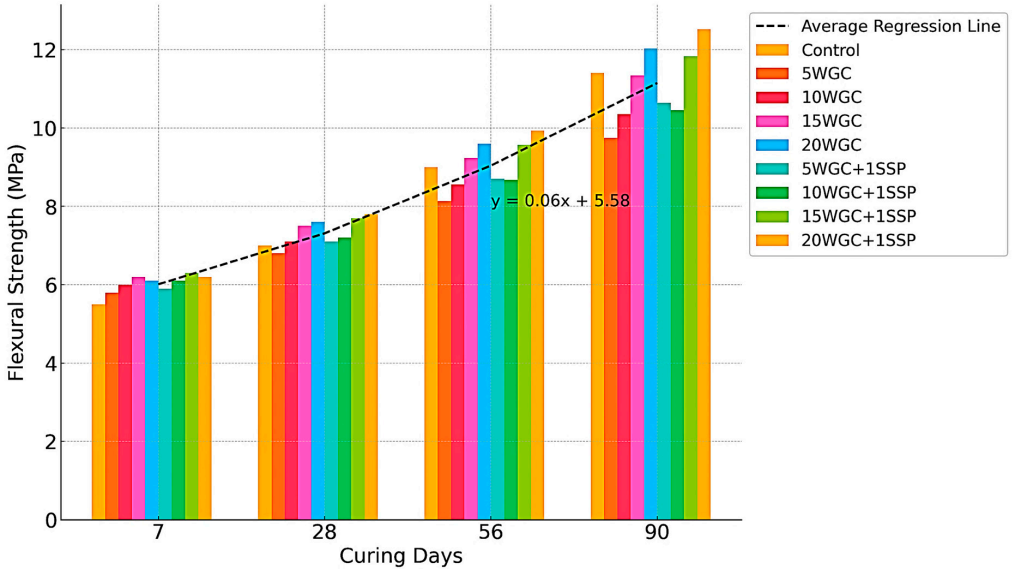


Figure 11. The flexural strength of samples on different curing days.

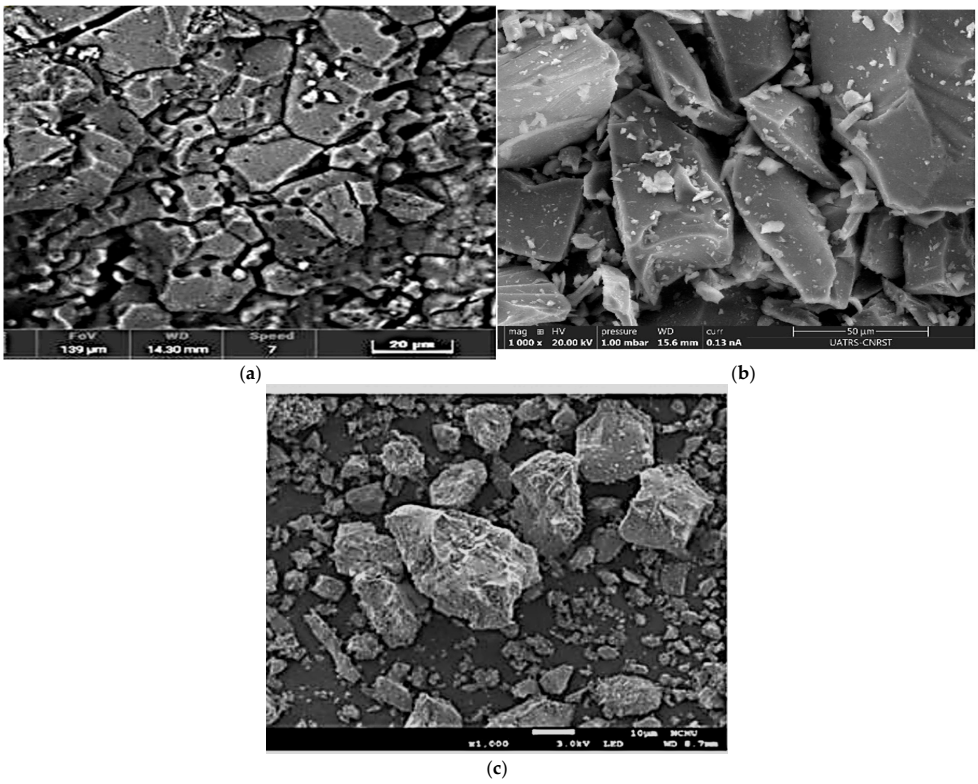


Figure 12. Scanning Electron Microscopy (SEM): (**a**) snail shell powder; (**b**) waste glass cullet; (**c**) Ordinary Portland Cement.

3.9. Energy Dispersive X-Ray (EDX) Spectra on Cementitious Materials

Energy Dispersive X-ray (EDX) spectroscopy was conducted in conjunction with SEM to qualitatively assess the elemental composition of the materials, supporting the oxide composition data obtained through XRF, as shown in Figure 13. OPC showed dominant peaks for calcium (Ca) and silicon (Si), confirming its high CaO (64.80%) and SiO_2 (23.40%) content. Additional signals from aluminum (Al) and iron (Fe) are consistent with minor phases such as aluminate and ferrite compounds. The elemental profile aligns well with expectations for a hydraulic cement system.WGC revealed strong signals for silicon (Si) and sodium (Na), which correspond to its high contents of SiO_2 (71.00%) and Na_2O (13.00%).

These elements are characteristic of soda-lime silicate glass. The amorphous nature of the material, inferred from both its morphology and chemistry, supports its potential as a reactive pozzolanic component, particularly when particle fineness is optimized. SSP exhibited prominent calcium (Ca) peaks, reflecting its high CaO (67.50%) content. The presence of carbon (C), phosphorus (P), and magnesium (Mg) suggests partial calcination and residual organic matter, in agreement with the high loss on ignition (LOI) value of 14.50%. Trace elements such as P_2O_5 and TiO_2 were also detected, likely originating from biological and soil-based impurities.

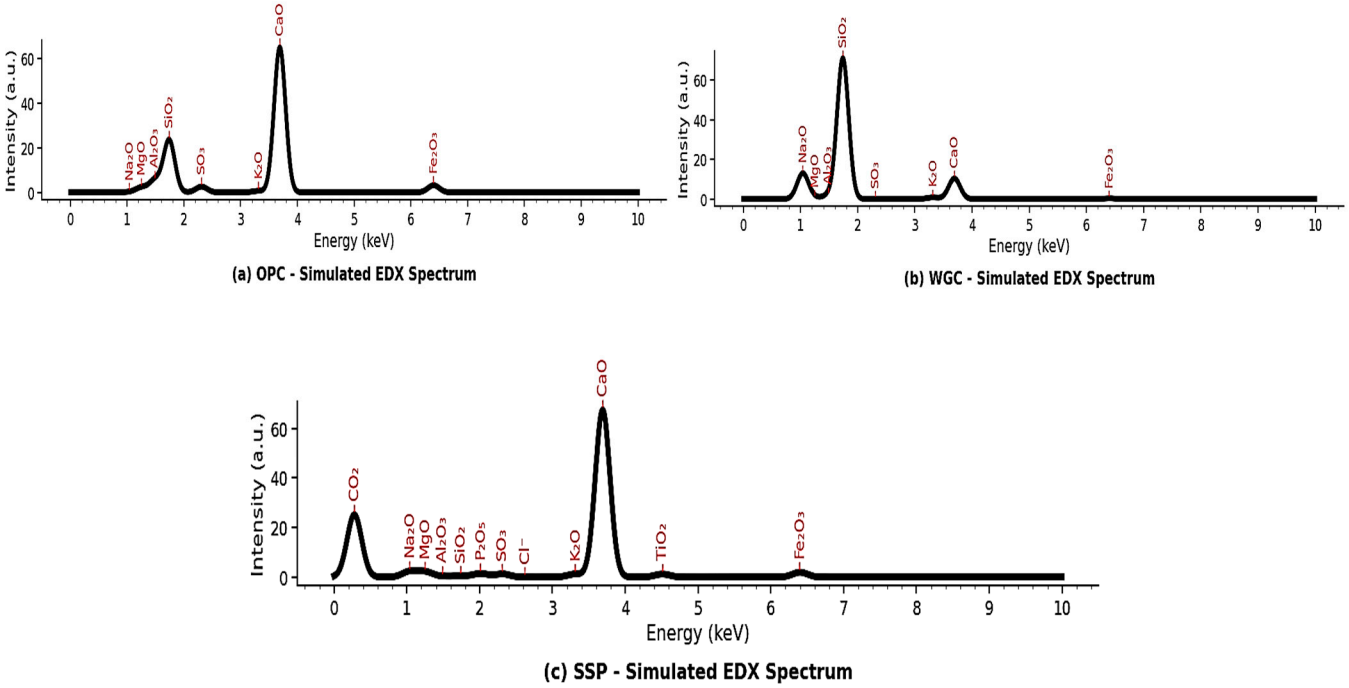


Figure 13. Simulated EDX for (**a**) Ordinary Portland Cement; (**b**) waste glass cullet; (**c**) snail shell powder.

Overall, the elemental composition, as revealed by the EDX analysis, supports the mechanical performance trends associated with each material. OPC remains the most reliable binder in terms of compressive and flexural strengths, whereas WGC shows promise as a Supplementary Cementitious Material with good potential for workability and long-term strength development. SSP, which is rich in calcium, requires processing or a combination of reactive components to yield significant mechanical benefits.

4. Conclusions

This study evaluated the combined effects of waste glass cullet (WGC) and snail shell powder (SSP) on the workability, compressive strength, and flexural strength of concrete, with a specific focus on applications in rigid pavements and infrastructure requiring high durability and strength. The experimental results and statistical analyses led to the following key conclusions:

1. Workability: Increased WGC content reduced slump values due to the angular shape and poor water absorption of glass particles. However, adding 1% SSP marginally improved slump, acting as a microfiller and improving paste flowability.
2. Compressive Strength: Strength increased with higher WGC levels. The highest 28-day strength (48.0 MPa) was recorded in the mix containing 20% WGC + 1% SSP, compared to 40.0 MPa in the control. At 90 days, the strength reached 52.0 MPa.

3. Flexural Strength: Similarly, flexural strength increased from 7.0 MPa (control) to 7.8 MPa in the optimized WGC/SSP mix, demonstrating improved tensile resistance and microstructural integrity.
4. Statistical analysis confirmed significant relationships: a strong negative correlation between WGC content and slump (r = –0.97) and strong positive correlations between WGC/SSP addition and strength parameters.
5. Microstructural and chemical analyses (SEM/EDX) confirmed that WGC contributes to pozzolanic silica, while SSP enhances calcium content and matrix compaction, leading to improved long-term strength.

The optimized mix design of 20% WGC and 1% SSP are ideal for the following:

- Rigid pavements and road slabs, where high compressive and flexural strength are critical.
- Load-bearing infrastructure, including beams, columns, and industrial flooring.
- Sustainable construction projects, particularly those targeting reduced cement usage and circular economy practices.
- Developing regions where waste glass and shell waste are locally available and processing capacity is limited.

This study confirms that a dual-waste approach using WGC and SSP offers a technically viable and environmentally responsible solution for producing durable, structurally sound, and low-carbon concrete, especially suitable for pavement-grade and infrastructure-level applications. Future work should focus on evaluating long-term durability parameters, including resistance to alkali–silica reaction, chloride penetration, and freeze–thaw cycles, and explore the durability performance under aggressive environmental conditions and the mitigation of alkali–silica reaction (ASR) through expansion tests.

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Abbreviations

OPC	Ordinary Portland Cement
WGC	Waste Glass Cullet
SSP	Snail Shell Powder
MPa	Megapascal (Unit of Pressure/Strength)
ANOVA	Analysis of Variance
SD	Standard Deviation
IQR	Interquartile Range
C–S–H	Calcium Silicate Hydrate

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