

Evaluating Concrete Strength Properties with Waste Glass as a Partial Replacement for Various Coarse Aggregate Gradings

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Abstract

The reuse of waste glass in concrete production is an attractive option for achieving waste reduction and preserving natural resources from further depletion, thereby protecting the environment and promoting sustainability. This present study examined the variation in the strength properties of concrete using waste glass aggregate (WGA) as a partial replacement for different coarse aggregate gradings. Three-quarter-inch (20 mm) and one-inch (25 mm) coarse aggregates were partially replaced with WGA of the respective sizes in different percentages: 0 %, 10 %, 20 % and 30 %. Physical properties such as specific gravity, bulk density, slump, and workability of fresh concrete and strength properties such as compressive strength and tensile strength of hardened concrete of grade M25, mix ratio 1:1:2 were tested after 7, 14, 28, 56 and 90 days. The results of the physical properties revealed that the WGA exhibited a lower specific gravity value of 2.70, bulk density of 1364 kg/m³, and moisture content of 0 % as compared to granite, with a specific gravity value of 2.74, bulk density of 1660 kg/m³, and moisture content of 0.01 %. The compressive strength results of both 20 mm and 25 mm WGA increase as the curing age of the concrete increases progressively from 7 days up to 90 days. At 7 and 90 days the compressive strength results of 20 mm aggregate of the control mix concrete were 30.05 N/mm² and 42.60 N/mm² respectively while that of 20 mm 30 % WGA partial replacement were 32.14 N/mm² and 45.70 N/mm² respectively, and for 25 mm aggregate control mix concrete were 29.74 N/mm² and 49.80 N/mm² respectively, while that of 25 mm, 30 % WGA partial replacement were 28.71 N/mm² and 45.50 N/mm² respectively. The tensile strength for all the ages reached the optimum value at 10 % partial replacement WGA for both 20 mm and 25 mm. At 28 days, the tensile strength result of 20 mm aggregate of the control mix concrete was 2.86 N/mm², while 20 mm 10 % WGA replacement was 2.90 N/mm², and for 25 mm aggregate control mix concrete, the tensile strength result was 3.11 N/mm², while that of 25 mm WGA was 2.55 N/mm². The results of the strength properties showed that the concrete grade M25 adopted was suitable for the WGA partial replacement, as the compressive strength results for all ages did not fall below 25 N/mm².

Keywords: Waste-glass, Strength properties, Partial replacement, Coarse aggregates, Grading.

INTRODUCTION

Concrete remains the most extensively used construction material worldwide, valued for its strength, versatility, and durability. However, its production demands significant quantities of natural aggregates, particularly coarse aggregates, raising concerns over resource depletion and environmental sustainability (Ibrahim *et al.*, 2024). Simultaneously, the disposal of non-biodegradable waste materials such as glass poses an escalating challenge (Berdnyk & Vyhovskiy, 2023). Appropriately processed waste glass offers potential as a partial replacement for natural aggregates, thereby reducing landfill waste, conserving natural resources, and supporting global sustainability objectives.

Concrete is a composite of cement, water, fine and coarse aggregates, and, in some cases, admixtures, each influencing fresh and hardened properties (Alhamad *et al.*, 2022). Aggregates constitute 70–80% of concrete volume, with their quality, grading, and shape critically affecting mechanical performance (Skocek *et al.*, 2024).

Grading, determined by sieve analysis, impacts void content, packing density, workability, and durability (Luo *et al.*, 2024; ASTM C125-07, 2007; Okonkwo *et al.*, 2023). Well-graded aggregates enhance density and durability (Onyechere *et al.*, 2024; Ali *et al.*, 2024), while particle shape, ranging from rounded to angular, affects paste demand and interparticle bonding (Konitufe *et al.*, 2023; Baghbani *et al.*, 2023).

Waste glass utilisation in concrete has been studied with varying outcomes. Qaidi *et al.* (2022) reported reduced workability and strength at higher replacement levels, though emerald green glass with SBR latex achieved satisfactory performance at up to 30% replacement. Proper processing is essential to meet aggregate specifications (Memon *et al.*, 2022). While some studies suggest improvements in strength (Firoozi *et al.*, 2023), others highlight potential drawbacks, such as weak paste bonding and risks of alkali-silica reactions (Gholampour *et al.*, 2024). Finely ground glass exhibits pozzolanic activity, enhancing microstructure and

strength (de Brito *et al.*, 2022). Mechanical performance generally remains stable up to 30% replacement (Ansari *et al.*, 2020), with pozzolanic admixtures recommended to mitigate durability concerns.

Calcium carbide residue (CCR), a high-calcium by-product of acetylene gas production, also offers potential as a supplementary cementitious material. Studies have shown that CCR can improve compressive strength, workability, and sulfate resistance when used alone or with other pozzolanic materials (El-Nadoury, 2022; Jabbar, 2023). The combined use of waste glass and CCR has been explored to synergistically enhance concrete properties, with glass acting as an inert filler and CCR contributing to hydration and strength through pozzolanic reactions.

Despite extensive research on waste glass and CCR, limited attention has been given to how aggregate gradation influences the performance of concrete containing waste glass. Given the pivotal role of gradation in determining workability, strength, and durability, this study investigates the compressive strength of concrete incorporating waste glass as a partial coarse aggregate replacement across different gradations, aiming to identify an optimal replacement strategy that balances sustainability and structural integrity.

METHODOLOGY

Theoretical Background

This experimental study was carried out to evaluate the effect of incorporating crushed waste glass as a partial replacement for coarse aggregate in fresh concrete. The waste glass was crushed into small fragments resembling the size of gravel and granite. These crushed fragments were mixed into fresh concrete, and their impact on the strength characteristics of the concrete was investigated.

Materials Design and Preparation

Waste Glass: The waste glass materials used for this study were sourced from dumpsites and restaurants in Ikole-Ekiti. These included primarily bottles from wine, soft drinks, and alcoholic beverages. The collected glass was manually crushed using a metallic rammer and basin and then sieved manually to achieve particle sizes comparable to conventional coarse aggregates. Safety measures such as gloves and protective goggles were strictly observed throughout the handling and processing of the waste glass to reduce the risk of injury.

Aggregates: Aggregates were obtained locally from the school premises and classified into fine and coarse aggregates.

Fine Aggregate: Natural River sand was employed as the fine aggregate. It was properly washed to remove any clay, silt, or organic impurities. The sand was visually inspected to confirm a variation in grain shape and gradation.

Coarse Aggregate: Granite was used as the conventional coarse aggregate in accordance with ASTM C33-03 specifications. The granite used had an angular shape and a nominal maximum size of 20 mm, making it suitable for use in reinforced concrete applications.

Cement: Ordinary Portland Cement (53 Grade – Elephant brand) conforming to IS 269:1976 was used as the binding material. The cement was stored in air-tight containers under controlled humidity conditions to prevent contamination from moisture.

Water: Clean potable water sourced from the school facility was used for both mixing and curing of the concrete. In cases where the primary water source was unavailable, rainwater and water from nearby streams were used as alternatives. A consistent water-cement ratio of 0.5 was maintained for all mixes, especially the control mix with 0% waste glass aggregate (WGA).

Moulds: Concrete specimens were cast using moulds prepared in two standard dimensions. Cube moulds measuring 150 mm × 150 mm × 150 mm were fabricated by a carpenter, while cylindrical moulds measuring 150 mm in diameter and 300 mm in height were purchased for compressive and split tensile strength testing.

Equipment: Various equipment and tools were utilised for the experimental procedures. These included a slump cone for workability tests, a compression testing machine for strength evaluation, moulds for casting specimens, metallic rammers for compacting the mix, a weighing balance for accurate measurement of materials, as well as shovels and head-pans for mixing and transportation of the concrete.

Preliminary Investigations

Preliminary laboratory tests were conducted at the Soil Mechanics Laboratory of Lagos State Polytechnic, Ikorodu, to evaluate the physical and mechanical properties of the waste glass aggregate (WGA), granite, and river sand.

Specific Gravity: The specific gravity of the materials was determined using the pycnometer method in accordance with IS 2770: Part 3: 1963. Samples were oven-dried at 115°C for 16 hours before testing. The specific gravity values were used to assess the density and weight characteristics of the aggregates.

Moisture Content: The moisture content was determined using the oven-drying method as described in BS 812: Part 109:1990. The samples were oven-dried at a constant temperature of 105 °C until a constant weight was achieved. This test ensured that water content in the aggregates did not interfere with the designed water-cement ratio.

Bulk Density: Bulk density was assessed in accordance with BS 812: Part 2:1995. The procedure involved placing the aggregates in a cylindrical container, compacting them with tamping rods, and recording the total weight. The result was then expressed in kg/m³, providing insight into the unit weight of the materials used.

Mixing and Proportioning of Concrete

The concrete mix used in this research followed a nominal mix ratio of 1:1:2 for cement, fine aggregate, and coarse aggregate, respectively. This ratio was selected to achieve a compressive strength of 25 N/mm² (Grade M25). A water-cement ratio of 0.5 was maintained throughout the experiment. The coarse aggregate was partially replaced with waste glass

aggregate (WGA) at four levels: 0 %, 10 %, 20 % and 30 %.

Preliminary Information: The mix design process adopted a ratio of 1:1:2 for Grade M25 concrete, with a water-cement ratio of 0.5. Curing was carried out in five sets for 7, 14, 28, 56, and 90 days. Waste glass aggregate (WGA) was incorporated at replacement levels of 0 %, 10 %, 20 %, and 30 %, producing a total of 40 cubes, 10 for the control mix and 30 for the WGA-modified mixes.

Mix Design Calculations: Each concrete cube had a volume of 0.003375 m³, calculated from the dimensions (0.15 m × 0.15 m × 0.15 m). Assuming a concrete density of 2400 kg/m³, the mass of concrete per cube was 8.1 kg. Therefore, the total mass required for 40 cubes was 324 kg.

RESULTS AND DISCUSSIONS

Chemical Analysis

Sample Digestion Procedure: One gram of the pulverised sample was weighed into a conical flask and moistened with distilled water. Subsequently, 100 ml of aqua regia was added and the mixture was boiled to near dryness. After cooling, 5 ml of 6M H₂SO₄ and 5 ml of distilled water were added, and the sample was boiled for 10 minutes. The resulting solution was filtered and made up to 100 ml for mineral analysis.

Table 1: Mix proportions for each replacement level.

Proportion	WGA (kg)	Granite (kg)	Fine Aggregate (kg)	Cement (kg)	Water (kg)	No. of Cubes
0%	0.000	4.05	2.05	2.05	1.025	10
10%	0.405	3.645	2.05	2.05	1.025	10
20%	0.810	3.240	2.05	2.05	1.025	10
30%	1.215	2.835	2.05	2.05	1.025	10

Mineral Analysis: The filtrate was analysed using an Atomic Absorption Spectrophotometer (Buck Scientific 210 VGP) and flame photometer (FP 902 PG). The oxides were calculated using standard conversion tables.

Sulfite Determination: One gram of the sample was dissolved in 50 ml of 0.05 mol/l iodine solution and allowed to stand for 5 minutes. Then, 2 ml of diluted hydrochloric acid was added. The excess iodine was titrated with 0.1 mol/l sodium thiosulfate using starch as an indicator.

Loss on Ignition (LOI): Loss on ignition was determined following ASTM D7348. The samples were sequentially heated at 100°C, 550°C, and 1000°C to remove water, organic matter, and carbonates, respectively. The final weight loss was recorded as the LOI.

Results:

The chemical compositions of Portland cement, glass, granite, and sand are summarised in Table 2 and illustrated in Figure 1.

Table 2: Chemical Composition of Constituent Elements

S/N	Chemical Composition	Portland Cement	Glass	Granite	Sand
1	Na ₂ O	0.51	9.609	5.194	0.356
2	CaO	62.60	21	7.114	0.223
3	K ₂ O	0.29	2.176	8.208	1.091
4	MgO	1.74	0.719	0.609	2.271
5	Al ₂ O ₃	5.09	3.017	9.670	12.104
6	Mn ₂ O ₃	0.007	0.072	0.275	0.030
7	Fe ₂ O ₃	3.20	0.746	4.817	0.497
8	SiO ₂	20.34	94.23	75.830	81.484
9	SO ₃	2.19	0.012	3.701	2.130
10	LOI	0	0.023	2.096	0.697



Figure 1: Chemical Composition of the Constituents

Specific Gravity: The specific gravity of granite, sand, and WGA aggregates was found to be 2.75, 2.64, and 2.70 respectively. These values fall within the range specified by BS 812: Part 2: 1995, which states that most natural aggregates possess specific gravity values between 2.60 and 2.70. Aggregates with values below 2.4 are classified as lightweight. The WGA sample, with a specific gravity of 2.70, qualifies as a normal-weight aggregate (Popovics, 1992).

Moisture Content: The moisture contents recorded for sand, WGA, and granite aggregates were 1.14%, 0.60%, and 0.01% respectively. Fine aggregates exhibited the highest moisture content, attributable to higher porosity. Proper control of moisture content is critical in concrete mix design as it directly influences the water-to-cement (w/c) ratio, and thus the workability and strength of the concrete. According to Abram's law, concrete compressive strength is inversely related to the w/c ratio. Therefore, both excess moisture and dry aggregates can negatively affect concrete quality.

Bulk Density: The bulk density of granite, sand, and WGA aggregates was 1660 kg/m³, 1786 kg/m³, and 1364 kg/m³, respectively. Bulk density reflects how compact an aggregate is under standard conditions.

Sand, having the highest bulk density, contains the fewest voids, which is ideal for an economical mix. The WGA, with the lowest bulk density, is comparatively lighter and may be classified as a lightweight aggregate.

Table 3: Physical Properties of Aggregates

Properties	WGA	Granite	Sand
Specific Gravity	2.70	2.75	2.64
Moisture Content (%)	0.60	0.01	1.14
Bulk Density (kg/m ³)	1364	1660	1786

Workability Test

Workability was assessed through slump tests for 20 mm and 25 mm WGA replacements at 0 %, 10 %, 20 %, and 30 %. The results are shown in Tables 4 and 5.

Table 4: Slump Value for 20 mm WGA Replacement

Proportion (%)	0 (Control)	10%	20%	30%
Slump (mm)	20	35	85	92

Table 5: Slump Value for 25 mm WGA Replacement

Proportion (%)	0 (Control)	10%	20%	30%
Slump (mm)	0	70	86	160

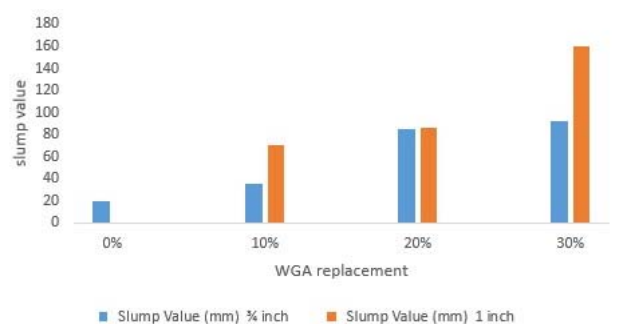


Figure 2: Variation in Workability of WGA Mix

Compressive Strength

The compressive strength was determined for concrete mixes with WGA replacements at various curing periods (7, 14, 28, 56, and 90 days). Results are shown in Tables 6 and 7.

Table 6: Compressive Strength for 20 mm WGA Replacement (N/mm²)

WGA (%)	7 Days	14 Days	28 Days	56 Days	90 Days
0%	30.05	28.94	35.05	40.10	42.60
10%	30.10	27.98	33.62	39.82	40.20
20%	31.60	32.05	38.85	43.70	43.99
30%	32.14	32.91	39.02	44.62	45.70

Table 7: Compressive Strength for 25 mm WGA Replacement (N/mm²)

WGA %	7 Days	14 Days	28 Days	56 Days	90 Days
0%	29.74	30.57	34.02	42.60	49.80
10%	38.12	31.06	32.51	43.80	49.70
20%	31.18	31.85	38.02	44.04	49.74
30%	28.71	30.16	32.83	42.26	45.50

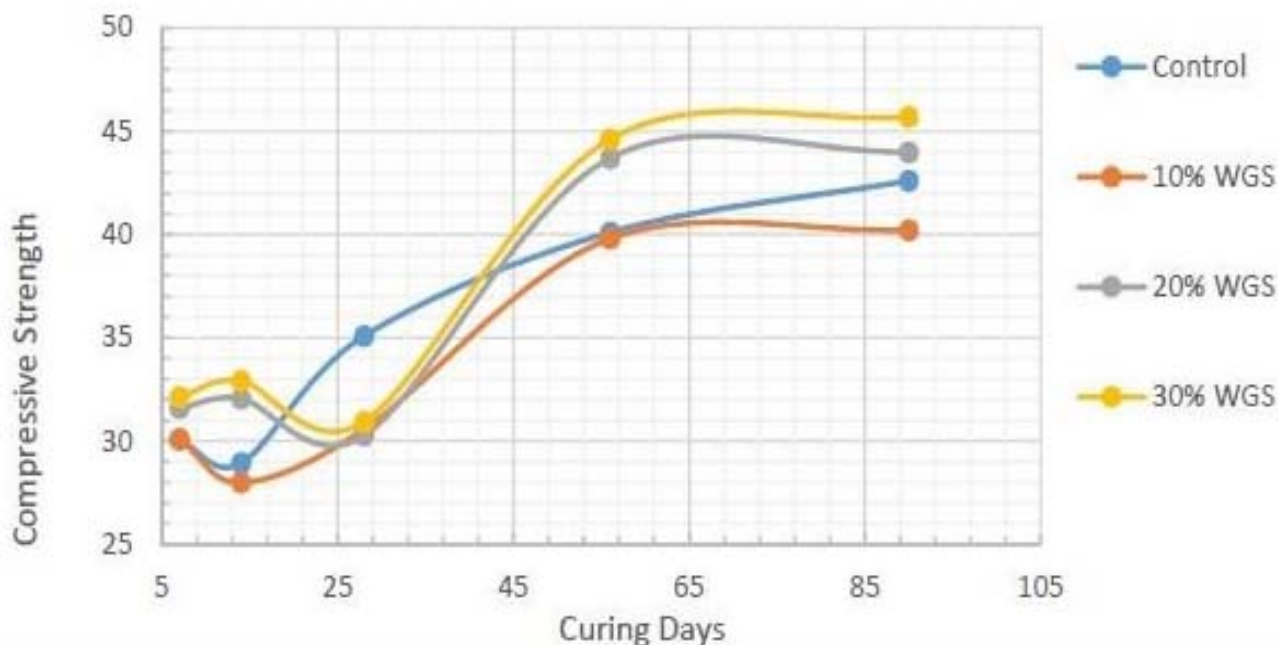


Figure 3: Compressive strength of concrete at 20mm WGA replacement at different proportion

CONCLUSION

This study established that waste glass aggregate (WGA) can be effectively used as a partial replacement for coarse aggregates in the production of M25 concrete, with results showing that compressive strength generally improved with increased WGA content and extended curing periods. Specifically, concrete with 25 mm WGA exhibited better workability than 20 mm WGA due to increased voids. The concrete mixes-maintained densities within the normal weight range (2240 kg/m³ to 2400 kg/m³), ensuring structural integrity. For 20 mm WGA, compressive strength increased from 20% to 30% replacement, peaking at 30%, while for 25 mm WGA, the highest strength occurred at 20% replacement. In all cases, compressive strength improved with longer curing up to 90 days. Tensile strength was highest at 10% WGA replacement for both sizes and declined with further increases. Overall, WGA is suitable for use in structural concrete up to 30% replacement without significantly compromising strength, making it a sustainable material for civil engineering applications.

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