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Statistical Optimization of Concrete Properties using Response Surface Methodology Incorporating Ground Waste Bottle Glass and Cow Bone Ash as Fine Aggregate Replacements

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ABSTRACT: Concrete is a globally dominant construction material. This study addresses natural sand depletion and waste disposal challenges, aiming to statistically optimize concrete properties using Response Surface Methodology with ground waste bottle glass and cow bone ash replacements. Ordinary Portland Cement (OPC) conforming to BS 12 (1996) was used with river sand partially replaced by ground waste bottle glass (GWBG) and cow bone ash (CBA) in a 1:3:6 mix at 0.50 w/c ratio. Chemical and mineralogical analyses were performed using XRF and XRD, respectively. Workability was evaluated through slump and compacting factor tests, while compressive and tensile strengths were determined per BS standards. Experimental data were statistically optimized using Response Surface Methodology (RSM) in Design-Expert software. The X-ray fluorescence (XRF) analysis of Cow Bone Ash (CBA) revealed CaO, P_2O_5, SiO_2, MgO, and Al_2O_3 contents of 55.3%, 24.7%, 1.52%, 0.48%, and 0.35%, respectively. The X-ray diffraction (XRD) analysis identified hydroxyapatite, calcite, quartz, portlandite, sylvite, magnesite, and hematite with relative intensities of 72.6%, 15.4%, 4.8%, 3.2%, 1.5%, 1.0%, and 0.5%, respectively. The slump height and compacting factor values from 0% to 20% replacements of GWBG with CBA ranges from 55.47 to 34.58 mm and 4.59 to 4.61%, respectively. The 28-day compressive strength and splitting tensile strengths values were 14.85 to 14.41 MPa and 5.59 to 5.47 MPa, respectively. The optimal mix combination of 12.5% GWBG and 7.5% CBA recorded a slump height of 37.22 mm, compacting factor of 0.82, water absorption of 3.84%, compressive strength of 17.94 MPa, and splitting tensile strength of 6.05 MPa. The optimal mix of 12.5% GWBG and 7.5% CBA achieved the best balance of strength, durability, and workability, demonstrating excellent performance for sustainable and eco-efficient concrete production.

KEYWORDS: Concrete optimization, Ground waste bottle glass (GWBG), Cow bone ash (CBA), Response surface methodology (RSM), Sustainable construction.

1.0 INTRODUCTION

Concrete remains the most widely utilized construction material globally, serving as a fundamental component in infrastructure and structural development. Its versatility, availability, and relatively low cost make it indispensable for both developing and industrialized nations (Diaferio and Varona, 2024). However, the heavy reliance on natural aggregates, particularly river sand, poses a severe threat to ecological balance and environmental sustainability. The excessive extraction of sand from riverbeds and other natural sources has resulted in environmental degradation, loss of biodiversity, and disruption of aquatic ecosystems (Damseth *et al.*, 2024). According to Mehta (2024), global concrete production has exceeded 4.83 billion tons annually, which underscores the immense strain placed on natural resources. The demand for sustainable alternatives has therefore become urgent, leading to a growing interest in the partial replacement of natural aggregates with waste-derived materials.

Furthermore, the rapid urbanization and industrialization observed in many developing nations have contributed to the escalating generation of solid wastes, including glass and animal bone residues, which often end up in landfills (Krishna, 2024). The disposal of waste glass poses a major environmental challenge due to its non-biodegradable nature and slow decomposition rate (Adekomaya and Majozi, 2021). Similarly, cow bone ash, a by-product of abattoirs, is typically discarded indiscriminately, creating sanitation and environmental problems in many urban and peri-urban regions (Oduntan and Ndidi, 2024). Incorporating such waste materials into concrete not only provides an effective recycling pathway but also contributes to cleaner environments and reduced landfill accumulation (Almusaed *et al.,* 2024). Previous studies have demonstrated that finely ground glass particles can serve as a partial substitute for fine aggregate, enhancing certain mechanical and durability properties when appropriately processed (Hakim *et al.,* 2024; Barbhuiya *et al.,* 2025).

Consequently, the statistical optimization of concrete properties through Response Surface Methodology (RSM) offers a modern and reliable approach for understanding the complex interaction between multiple mix variables (Hurtado-Alonso *et al.,* 2024). RSM enables the systematic analysis and optimization of input parameters—such as the proportion of waste glass and cow bone ash—to achieve desirable concrete performance outcomes with minimal experimental effort. This approach provides a predictive framework for evaluating the effects of material substitution on both fresh and hardened concrete properties. By employing this technique, it becomes possible to identify the optimal blend proportions that ensure strength, durability, and workability while minimizing costs and environmental impacts. Thus, RSM serves not only as a statistical optimization tool but also as a strategic instrument in advancing sustainable concrete technology.

In addition, adopting waste materials such as ground waste bottle glass and cow bone ash contributes significantly to the principles of circular economy and resource efficiency. The valorization of these wastes in concrete production exemplifies an eco-friendly solution to two pressing challenges—solid waste management and natural resource depletion (El-Emam, 2024). Several recent studies (Tamanna *et al.,* 2020; Steyn *et al.,* 2021) have established that the use of recycled waste glass can reduce the demand for sand while enhancing the impermeability and durability of concrete. Moreover, cow bone ash has been reported to improve cementitious reactions and microstructural densification, leading to better mechanical performance (Mitikie *et al.,* 2025). Therefore, this study situates itself within the framework of sustainable material engineering, aiming to develop a cost-effective and environmentally responsible concrete mixture through the synergy of waste glass and cow bone ash as fine aggregate replacements.

The major problem addressed by this study arises from the overexploitation of natural sand, the environmental menace of improper waste disposal, and the lack of optimized methods for integrating alternative fine aggregates into concrete. Sand mining contributes to environmental degradation, groundwater depletion, and the destruction of aquatic ecosystems (Pandey *et al.*, 2023). Meanwhile, glass and bone wastes remain underutilized, despite their potential as substitutes for natural aggregates. The challenge lies in understanding how these materials, when finely ground, influence the rheological, mechanical, and durability characteristics of concrete. Additionally, inconsistencies in the composition and particle size of waste glass have led to contradictory findings in previous studies, necessitating an optimized and statistically validated approach to determine the ideal replacement levels. Therefore, this study seeks to statistically optimize concrete mixes incorporating ground waste bottle glass and cow bone ash, thereby providing a reliable framework for material substitution that aligns with both performance and sustainability requirements.

The significance of this study lies in its dual contribution to sustainable construction and waste valorization. By converting abundant waste materials into useful concrete constituents, this research supports environmental conservation and the circular economy model promoted by the United Nations Sustainable Development Goals (Ogunmakinde *et al.,* 2022). The integration of ground waste bottle glass and cow bone ash into concrete production has the potential to reduce reliance on natural sand, mitigate waste accumulation, and minimize greenhouse gas emissions associated with sand mining and cement production (Farooq, 2022). Additionally, the application of RSM enhances the efficiency and scientific precision of material optimization, ensuring reproducibility and practical relevance of the results. Consequently, the outcomes of this study may serve as a benchmark for future research and policy formulation on sustainable material utilization in the construction industry.

2.0 MATERIALS AND METHOD

2.1 Sample Preparation and Mix Proportioning

Ordinary Portland Cement (OPC) conforming to BS 12 (1996) specifications was used as the principal binding agent in all concrete mixtures. The fine aggregate consisted of locally sourced river sand, partially replaced by ground waste bottle glass (GWBG) and cow bone ash (CBA), both serving as sustainable fine aggregate substitutes. Coarse aggregate of 20 mm nominal size and potable water were employed in accordance with BS EN 1008 (2002). The concrete was proportioned at a nominal 1:3:6 mix ratio (cement: fine aggregate: coarse aggregate), corresponding to a grade 15 concrete with an expected compressive strength of about 15 N/mm² at 28 days. This mix was adopted because it represents a conventional composition widely used for non-structural or low-load-bearing mass concrete works, offering an economical balance between strength, workability, and material efficiency for comparative evaluation. A constant water–cement ratio (w/c) of 0.50 was maintained across all mix categories to ensure consistency.

All materials were batched by weight for precision, and mixing was carried out using a Hobart A200 mechanical mixer (USA) to achieve homogeneity. The mixing sequence involved the dry blending of cement and fine aggregates (including sand, CBA, and GWBG) for two minutes, followed by the introduction of coarse aggregate and gradual addition of water. For CBA-only mixes, the river sand was replaced by 0%, 5%, 10%, 15%, and 20% CBA by weight. Similarly, the GWBG-only mixes followed the same replacement proportions. To evaluate the combined influence of both materials, five hybrid mixes were developed, maintaining a total fine aggregate replacement level of 20% distributed in different ratios of GWBG and CBA as depicted in Table 1. This arrangement was designed to provide adequate data points for the Response Surface Methodology (RSM) statistical modeling, enabling detailed analysis of both linear and interaction effects between the two waste materials.

Table 1: Mix Proportioning for Concrete Incorporating GWBG and CBA.

Mix ID	Ground Waste Bottle Glass (% by Sand)	Cow Bone Ash (% by Sand)	Total Fine Aggregate Replacement (%)
M0	0	0	0
M1	0	5	5
M2	0	10	10
M3	0	15	15
M4	0	20	20
M5	5	0	5
M6	10	0	10
M7	15	0	15
M8	20	0	20
M9	15	5	20
M10	10	10	20
M11	5	15	20
M12	12.5	7.5	20
M13	7.5	12.5	20

2.2 Material Characterization

The Particle Size Distribution of the GWBG was performed according to BS EN 933-1 (1997) as shown in Plate 1. While, the chemical composition of the cow bone ash was determined using X-Ray Fluorescence (XRF) spectroscopy with a Panalytical Axios FAST XRF Spectrometer (Malvern Panalytical, Netherlands). Mineralogical characterization was conducted using X-Ray Diffraction (XRD) on a Bruker D8 Advance diffractometer (Bruker AXS GmbH, Germany) equipped with Cu Kα radiation (λ = 1.5406 Å) at 40 kV and 40 mA, scanned from 5°–70° (2θ).

2.1 Workability Assessment

The workability of fresh concrete was assessed through slump and compacting factor tests in accordance with BS EN 12350-2 (2009) as illustrate in Plate 2, and BS 1881-103 (1983), respectively. The slump test was conducted using a standard Abrams cone (300 mm height, 200 mm base diameter, 100 mm top diameter) and a steel tamping rod of 16 mm diameter. The compacting factor test apparatus comprised two conical hoppers and a cylindrical mould fabricated according to standard dimensions. Each mix proportion was tested immediately after mixing to ensure consistent moisture and temperature conditions.

Plate 1: sieve analysis process of the of the GWBG

Plate 2: Slump test of the fresh concrete

2.2 Mechanical Strength Evaluation

Concrete cubes of 150 mm × 150 mm × 150 mm were prepared for compressive strength tests, while cylindrical specimens of 150 mm × 300 mm were cast for split tensile strength determination. All specimens were demolded after 24 h and cured in water at 25 ± 2 °C for 7, 14, 21, and 28 days. Compressive strength tests were conducted using a Controls MCC8 Digital Compression Testing Machine (Controls Group, Italy) with a capacity of 2000 kN, conforming to BS EN 12390-3 (2009). Split tensile strength was evaluated using the same machine in accordance with BS EN 12390-6 (2009). The average value of three samples per age was recorded for each test.

The compressive strength (fc) was determined using Equation (1):

$$f_c = \frac{P}{A} \qquad (1)$$

Where: P is the maximum applied load (N), and A is the cross-sectional area of the specimen (mm²).

The split tensile strength (ft) was calculated using Equation (2):

$$f_t = \frac{2P}{\pi DL} \qquad (2)$$

Where: P is the load at failure (N), D is the diameter (mm), and L is the length of the specimen (mm).

2.3 Statistical Optimization Analysis

Experimental data obtained from mechanical tests were analyzed using Response Surface Methodology (RSM) to model and optimize the interaction effects of waste bottle glass and cow bone ash on concrete properties. The statistical analysis was performed using Design-Expert Software (Version 13.0, Stat-Ease Inc., Minneapolis, USA). The Central Composite Design (CCD) approach was adopted to develop regression models, while Analysis of Variance (ANOVA) was employed to determine the statistical significance of each variable and their interactions at a 95% confidence level. Optimization plots and contour diagrams were used to identify the optimum substitution levels that produced the highest compressive and tensile strengths with acceptable workability.

The coded levels of factors presented in Table 2 were derived to statistically represent the variation in the substitution of sand with Ground Waste Bottle Glass (GWBG) and Cow Bone Ash (CBA).The selected range of 0–20% was based on preliminary experimental results. The midpoint value of 10% represents the optimum level expected to achieve balanced performance in strength and durability characteristics. The coded factors −1, 0, and +1 correspond to the low, medium, and high replacement levels respectively, aligning with the experimental design framework of the Response Surface Methodology (RSM) approach used in this study.

Table 2: Limit and Coded Levels of Factors for the Mix Design

Factors	Limit Range	Factor Levels		
		−1	0	+1
A: Ground Waste Bottle Glass (% by Sand)	0 – 20	0	10	20
B: Cow Bone Ash (% by Sand)	0 – 20	0	10	20

3.0 RESULTS AND DISCUSSION

The study evaluated material characteristics, workability, mechanical performance, and optimized concrete properties using Response Surface Methodology for improved performance.

3.1 Characterization of Material

The materials used were characterized to determine their physical, chemical, and structural properties for suitability in concrete production using XRD and XRF. The cow bone ash was characterized to identify its chemical composition and assess its potential as a cementitious material. The particle size distribution of GWBG was analyzed to evaluate its fineness and influence on the concrete’s packing density.

3.1.1 Characterization of Cow Bone Ash

The X-ray fluorescence (XRF) analysis of cow bone ash presented in Table 3 reveals that calcium oxide (CaO) and phosphorus pentoxide (P_2O_5) are the predominant oxides, constituting 55.3% and 24.7% respectively, indicating the calcined material’s strong resemblance to hydroxyapatite minerals. The high CaO concentration suggests a significant potential for pozzolanic or cementitious reactivity when used as a supplementary material in concrete, as calcium-rich ashes have been reported to improve early strength gain and matrix densification. This observation is consistent with the findings of Luka *et al.* (2022), who attributed enhanced strength properties of blended cement composites to the presence of reactive lime in animal bone ash.

In addition, the presence of minor oxides such as SiO_2 (1.52%), Al_2O_3 (0.35%), and Fe_2O_3 (0.25%) further indicates trace pozzolanic potential, although their relatively low proportions suggest that cow bone ash primarily acts as a filler and microstructural stabilizer rather than a highly reactive pozzolan. The limited silica and alumina content may also reduce the secondary formation of calcium silicate hydrate (C–S–H) gels, a trend similarly observed by Almulhim *et al.* (2022), who noted that the reactivity of bone ash depends more on its calcium-phosphate network than its silicate content.

Furthermore, the low quantities of MgO, SO_3, K_2O, and TiO_2 imply reduced risk of deleterious expansion or alkali-silica reaction in concrete mixtures containing the ash. This chemical stability supports the suitability of cow bone ash as a partial cement replacement material with minimal risk of durability impairment. Overall, the XRF characterization confirms that the ash possesses a highly alkaline, calcium-dominated composition capable of improving the mechanical and hydration properties of cementitious materials, aligning with reports by Putra *et al.* (2024) on the beneficial use of animal bone-derived powders in sustainable concrete development.

Table 3: X-Ray Fluorescence (XRF) Analysis of Cow Bone Ash

Oxide	Cow Bone Ash (%)
CaO	55.3
P_2O_5	24.7
SiO_2	1.52
MgO	0.48
Al_2O_3	0.35
Fe_2O_3	0.25
SO_3	0.18
K_2O	0.12
Cl	0.05
TiO_2	0.02
MnO	0.02
CuO	0.01
V_2O_5	0.01
ZnO	0.01

The X-ray diffraction (XRD) analysis of cow bone ash presented in Table 4 identifies hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$) as the dominant crystalline phase, with a relative intensity of 72.6%. This confirms that the ash is primarily composed of calcium-phosphate minerals derived from the calcination of bone matter, which enhances its potential for improving the hydration characteristics of cementitious materials. The prominence of hydroxyapatite aligns with findings by Patil *et al.* (2025), who reported that bone-derived ashes rich in hydroxyapatite contribute to microstructural refinement and improved bonding within concrete matrices.

The presence of calcite ($CaCO_3$) at 15.4% further indicates partial carbonation during or after the combustion process, contributing to additional filler effects that enhance particle packing and reduce porosity. Similarly, quartz (SiO_2) detected at 4.8% provides limited pozzolanic contribution but supports matrix densification through its inert filling properties, a trend consistent with observations by Adepoju and Fapohunda (2020) on low-silica supplementary materials. The minor peaks corresponding to portlandite ($Ca(OH)_2$), sylvite (KCl), magnesite ($MgCO_3$), and hematite (Fe_2O_3) in small proportions (below 4%) suggest the presence of accessory phases that can influence early hydration and durability performance.

Table 4: X-Ray Diffraction (XRD) Analysis of Cow Bone Ash

S/No	Dominant Minerals Identified	Chemical Formula	Relative Intensity (%)
1	Hydroxyapatite	($Ca_{10}(PO_4)_6(OH)_2$)	72.6
2	Calcite	($CaCO_3$)	15.4
3	Quartz	(SiO_2)	4.8
4	Portlandite	($Ca(OH)_2$)	3.2
5	Sylvite	(KCl)	1.5
6	Magnesite	($MgCO_3$)	1
7	Hematite	(Fe_2O_3)	0.5

3.1.2 The Particle Size Distribution of the GWBG

The particle size distribution analysis presented in Figure 1 shows that the ground waste bottle glass (GWBG) consists predominantly of well-graded fine aggregates with a significant portion passing through the 4 mm sieve (99.2%) and gradually decreasing to 9.2% at the 0.075 mm sieve size. The distribution indicates a continuous gradation, suggesting an appropriate blend of coarse and fine particles that can contribute to good packing density and reduced void ratio within the concrete matrix. The calculated particle size parameters—D_{60} = 0.72 mm, D_{30} = 0.30 mm, and D_{10} = 0.11 mm—further reveal a uniformity coefficient (Cu) of 6.55 and a coefficient of curvature (Cc) of 1.13, implying a well-graded material suitable for partial fine aggregate replacement.

This gradation enhances the internal particle arrangement, improving the mechanical interlock and reducing the risk of segregation and bleeding during concrete mixing. Similar findings were reported by Perera *et al.* (2021), who observed that finely ground glass particles with a broad size distribution enhanced the compaction and strength development of blended concrete mixes. Furthermore, the small percentage of particles below 0.075 mm indicates a limited presence of fines, which minimizes excessive water demand and maintains adequate workability.

3.2 Workability of Fresh Concrete

3.2.1 Slump value

The results of the slump test presented in Figure 2 show notable variations in the workability of concrete mixes incorporating different proportions of ground waste bottle glass (GWBG) and cow bone ash (CBA). The control mix, containing 0% GWBG and 0% CBA, recorded the highest slump value of 55.47 mm, indicating optimal workability under normal conditions. However, as the CBA content increased from 5% to 20% at a constant 0% GWBG, the slump values decreased progressively from 48.62 mm to 34.58 mm, demonstrating a reduction in workability due to the high lime and phosphate content of CBA, which tends to increase water demand and reduce fluidity.

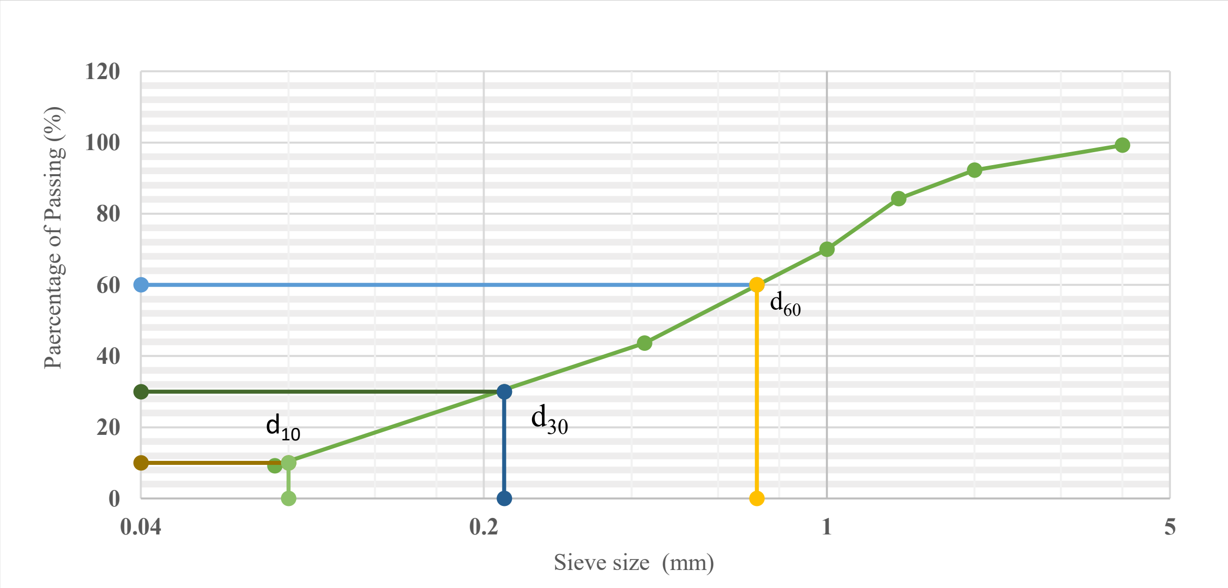


Figure 1: Particle Size Distribution of the GWBG

This behavior agrees with the findings of Win *et al*. (2022), who reported that ashes with high calcium oxide content reduce slump by enhancing particle cohesion and reducing free water in the mix.

Conversely, the mixes containing only GWBG showed irregular variations in slump. For instance, 10% GWBG achieved a relatively high slump value of 45.29 mm, while further increases to 15% and 20% drastically reduced workability to 15.36 mm and 10.42 mm, respectively. This fluctuation can be attributed to the angular and smooth surface texture of crushed glass particles, which at lower levels may enhance flow but, at higher dosages, restrict paste coating and aggregate lubrication. Similar findings were reported by Abdulmunem and Hasan (2022), who observed that fine glass particles initially improve flowability but lead to stiff mixes when used excessively due to particle interference effects.

For blended mixes of GWBG and CBA, moderate combinations such as 12.5% GWBG + 7.5% CBA and 10% GWBG + 10% CBA exhibited improved slump values of 37.22 mm and 33.56 mm, respectively, compared to other hybrid mixes. This suggests a synergistic interaction between the materials, where the fine glass particles help offset the water absorption tendency of CBA. These results are consistent with the observations of Chen *et al.* (2021), who reported that balanced combinations of pozzolanic and inert waste materials can enhance the flow behavior of concrete by optimizing particle packing and paste distribution.

The compacting factor values presented in Figure 3 demonstrate the influence of ground waste bottle glass (GWBG) and cow bone ash (CBA) on the consistency and workability of fresh concrete. The control mix (0% GWBG + 0% CBA) recorded a compacting factor of 0.90, indicating a relatively high degree of workability typical of a wellproportioned nominal mix. As the percentage of CBA increased from 5% to 20%, the compacting factor gradually declined from 0.86 to 0.77, suggesting that CBA reduced the ease of compaction due to its high lime and phosphate content, which increase the surface area and water absorption capacity of the mix.

Similarly, when GWBG was used independently, the compacting factor exhibited considerable variation. At 10% GWBG, the value peaked at 0.97, indicating improved flow and reduced internal resistance, likely due to the fine glass particles enhancing paste lubrication.

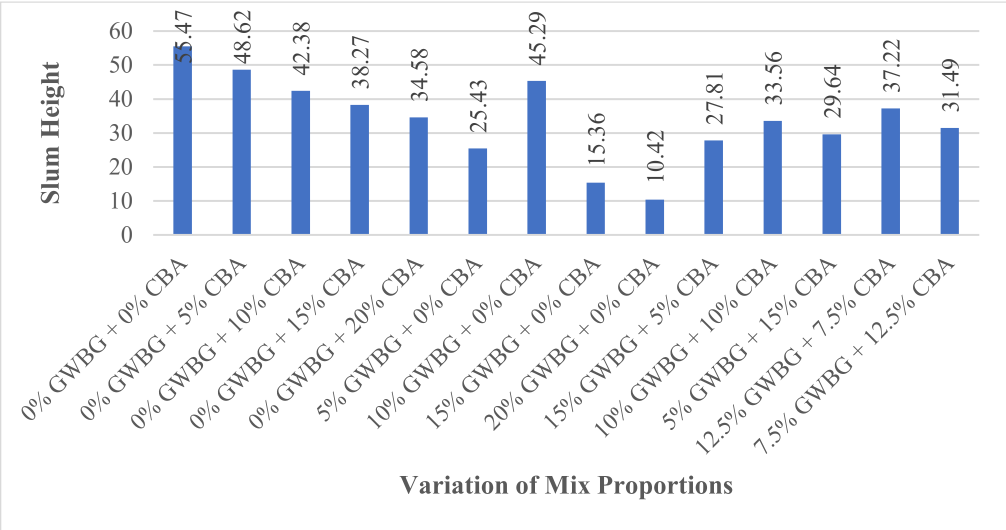


Figure 2: Slump Height (mm) of Fresh Concrete Incorporating CBA and GWBG.

However, higher replacements of 15% and 20% caused a sharp decline to 0.64 and 0.52, respectively, as excessive glass content reduced the paste volume available to coat aggregates, thereby hindering compaction. This trend aligns with the findings of Siddika *et al.* (2021), who noted that fine glass particles improve mix density only up to an optimal level, beyond which they cause particle segregation and stiffness.

For hybrid combinations of GWBG and CBA, moderate blends such as 12.5% GWBG + 7.5% CBA and 10% GWBG + 10% CBA recorded compacting factors of 0.82 and 0.78, respectively. These values indicate that balanced proportions of both materials can yield a workable mix with adequate cohesion and compaction efficiency. This synergistic performance is consistent with the findings of Adeboje et al. (2022), who highlighted that blending supplementary materials with complementary physical and chemical characteristics enhances mix uniformity and packing efficiency.

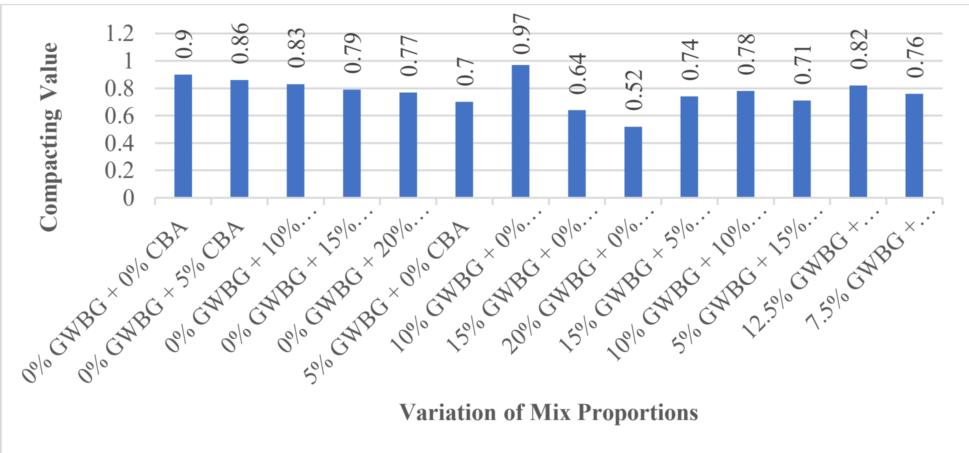


Figure 3: Compaction of Fresh Concrete Incorporating CBA and GWBG.

3.3 Mechanical Properties of Concrete

3.3.1 Water Absorption

The results of the water absorption test presented in Figure 4, illustrate the influence of ground waste bottle glass (GWBG) and cow bone ash (CBA) on the permeability characteristics of concrete at different curing ages. The control mix (0% GWBG + 0% CBA) exhibited water absorption values of 2.44%, 3.53%, 4.47%, and 4.59% at 7, 14, 21, and 28 days, respectively. This gradual increase with curing age indicates continuous hydration and capillary refinement, which is typical of conventional concrete.

For mixes containing only CBA, a reduction in water absorption was observed up to the 10% replacement level, where values dropped to 2.18% at 7 days and 3.88% at 28 days. This decline signifies that moderate CBA inclusion improves pore structure densification due to the pozzolanic reaction between bone ash-derived CaO and cementitious compounds. However, further increase beyond 15% led to higher absorption (up to 4.61% at 20% CBA), implying that excessive CBA introduces unreacted particles that increase void content. This pattern aligns with the findings of Wang *et al.* (2022), who reported that bone ash enhances concrete impermeability only up to an optimal dosage, beyond which the microstructure becomes more porous.

Conversely, the use of GWBG alone produced a continuous rise in water absorption across all curing ages, with the highest value of 7.65% recorded at 20% GWBG and 28 days. This trend suggests that glass powder, when used excessively, disrupts the cement matrix by creating microcracks and incomplete bonding zones. The observation agrees with the results of Nahi *et al.* (2020), who found that high glass powder content increases concrete permeability due to reduced paste cohesion and internal stress concentration.

Hybrid combinations of GWBG and CBA, however, showed improved performance compared to single replacements. The mix containing 12.5% GWBG + 7.5% CBA exhibited the lowest water absorption at 28 days (3.84%), indicating optimal synergistic interaction between both materials. Similarly, the 10% GWBG + 10% CBA and 15% GWBG + 5% CBA mixes recorded relatively low absorption values of 3.91% and 4.12%, respectively. These results suggest that the reactive silica in GWBG and the calcium-rich nature of CBA complement each other, leading to the formation of additional calcium silicate hydrate (C–S–H) gel that refines pore structure and limits water ingress.

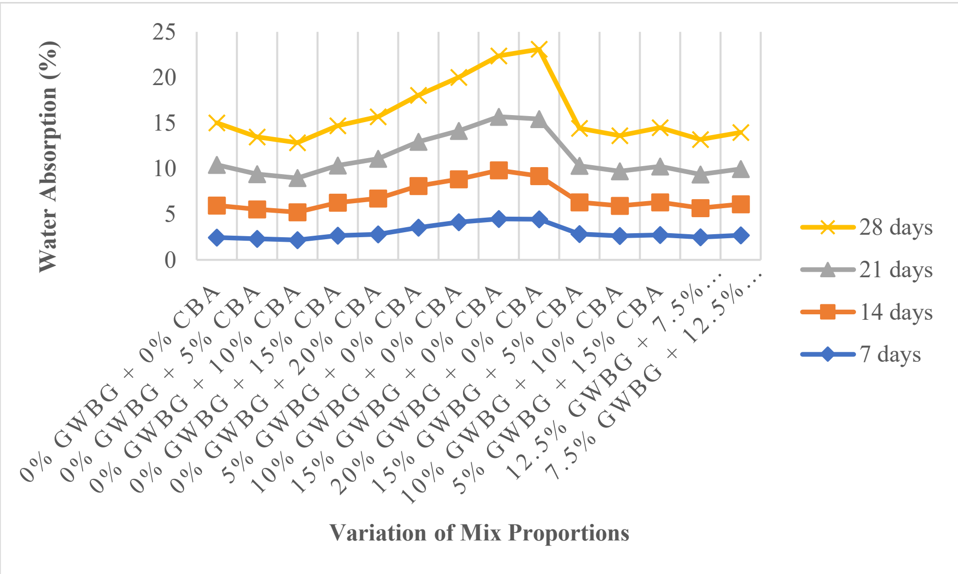


Figure 4: Water Absorption of Concrete Incorporating GWBG and CBA

3.3.2 Compressive Strength

The compressive strength results presented in Figure 5, reveal the influence of ground waste bottle glass (GWBG) and cow bone ash (CBA) on the strength development of concrete at different curing ages. The control mix (0% GWBG + 0% CBA) recorded compressive strengths of 13.87, 12.54, 12.38, and 14.85 N/mm² at 7, 14, 21, and 28 days, respectively, indicating a moderate strength gain with age. This trend reflects normal hydration progression, where the formation of calcium silicate hydrate (C–S–H) continues over time, enhancing the microstructural integrity of the concrete matrix.

Concrete mixes incorporating only CBA exhibited an initial improvement in strength up to the 10% replacement level, with the highest 28-day strength of 17.04 N/mm² achieved at 10% CBA. This increase signifies the effective pozzolanic reactivity of CBA, which provides additional calcium and silica for secondary hydration reactions that refine pore structure and improve bonding within the matrix. However, beyond the 10% level, a decline in strength was observed, as seen in the 20% CBA mix, which recorded a lower 28-day strength of 14.41 N/mm². This reduction may be attributed to the dilution effect, where excessive CBA reduces the available cementitious content. This behavior corresponds with the findings of Abdulwahab *et al.* (2025), who reported that bone ash enhances strength at optimal levels but reduces it when the replacement becomes excessive due to incomplete reaction of surplus ash particles.

Similarly, mixes containing only GWBG exhibited inconsistent performance, with strength generally decreasing as the GWBG content increased. The 10% GWBG mix attained a moderate 28-day strength of 11.93 N/mm², while the 20% GWBG mix declined significantly to 6.84 N/mm². This decline can be linked to the inert nature of glass particles at higher dosages, which may act as weak inclusions within the matrix, thereby increasing porosity and weakening interfacial bonding. The observed trend aligns with the findings of Sivasuriyan and Koda, (2025), who noted that high glass powder content tends to impair strength development due to poor cementitious reaction and increased brittleness of the matrix.

In contrast, hybrid combinations of GWBG and CBA demonstrated a significant enhancement in compressive strength compared to the single additive mixes. The blend containing 12.5% GWBG + 7.5% CBA recorded the highest 28-day compressive strength of 17.94 N/mm², followed closely by the 10% GWBG + 10% CBA mix with 17.28 N/mm². These results indicate a synergistic effect between GWBG and CBA, where the reactive silica in the glass powder combines with the calcium oxide content of CBA to form additional C–S–H gel, which densifies the microstructure and strengthens the interfacial transition zone. Similar findings were reported by Nawaz *et al.* (2025), who observed that combined pozzolanic materials containing silica and calcium-rich phases enhance concrete strength through complementary hydration and filler mechanisms.

3.3.3 Splitting Tensile Strength

The splitting tensile strength results presented in Figure 6, show the influence of ground waste bottle glass (GWBG) and cow bone ash (CBA) on the tensile performance of concrete over different curing ages. The control mix (0% GWBG + 0% CBA) achieved tensile strengths of 5.43, 5.51, 5.56, and 5.59 N/mm² at 7, 14, 21, and 28 days, respectively. This gradual improvement with curing age reflects the continued hydration of cement and densification of the concrete matrix. The relatively moderate strength of the control mix provides a reference for assessing the effects of CBA and GWBG on the tensile behavior of concrete.

Concrete containing only CBA exhibited a steady improvement in tensile strength up to a replacement level of 10%, which recorded a 28-day strength of 5.95 N/mm². This enhancement indicates that the fine CBA particles contributed to micro-filling and secondary pozzolanic reactions, promoting better interfacial bonding between the cement paste and aggregates. The increase in strength up to the optimum level can be attributed to the availability of reactive calcium and phosphate compounds that enhance matrix cohesion. However, a decline was observed beyond 10% CBA, with the 20% replacement mix showing a lower tensile strength of 5.47 N/mm², likely due to excessive dilution of the cementitious phase. This behavior corresponds with the observation of Becerra-Duitama and Rojas-Avellaneda, (2022), who reported that moderate inclusion of bone ash improves tensile strength through pozzolanic reactivity, while higher proportions tend to reduce performance due to incomplete hydration.

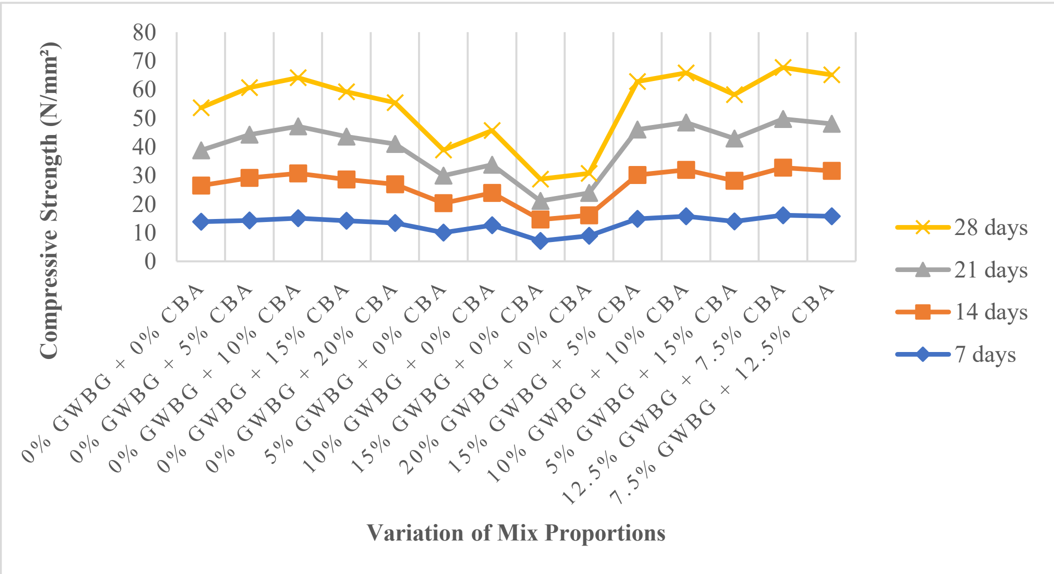


Figure 5: Compressive Strength of Concrete Incorporating GWBG and CBA (N/mm²).

On the other hand, concrete mixes incorporating only GWBG generally exhibited lower tensile strength values than the control. The 5% GWBG mix recorded the lowest 28-day tensile strength of 3.62 N/mm², whereas a slight improvement was noticed at 10% GWBG is 4.31 N/mm². The overall reduction in tensile capacity with increasing GWBG content can be linked to the brittle nature of glass and its relatively poor bond with the cement matrix when used alone. Moreover, the smooth surface texture of the glass particles limits mechanical interlocking, resulting in weaker tensile resistance. This observation is consistent with the findings of

Bao *et al.* (2024), who noted that high levels of glass powder substitution tend to compromise tensile strength due to weak interfacial bonding and microcracking tendencies.

Interestingly, the combined use of GWBG and CBA significantly enhanced the tensile performance of the concrete compared to the individual substitutions. The 12.5% GWBG + 7.5% CBA mix achieved the highest 28-day tensile strength of 6.05 N/mm², closely followed by the 10% GWBG + 10% CBA mix with 5.88 N/mm². This improvement demonstrates the synergistic interaction between the silica-rich GWBG and calcium-rich CBA, which promotes the formation of additional calcium silicate hydrate (C–S–H) and calcium phosphate compounds, thereby strengthening the interfacial transition zone and improving overall cohesion. Similar results were reported by Choi *et al.* (2022), who observed that hybrid supplementary cementitious materials with complementary chemical compositions enhance tensile strength by refining the microstructure and reducing crack propagation.

3.4 Statistical Analysis and RSM Models Development

The regression equations derived for the concrete responses provide valuable insight into the influence of ground waste bottle glass (GWBG) and cow bone ash (CBA) on both fresh and hardened properties.

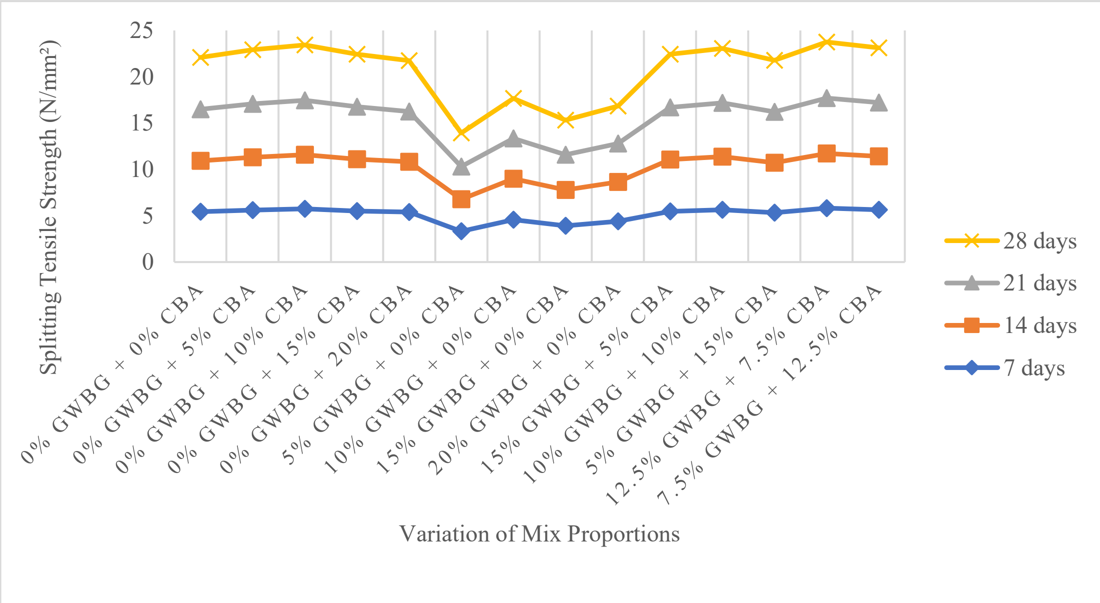


Figure 6: Splitting Tensile Strength of Concrete Incorporating GWBG and CBA (N/mm²)

As shown in Equation (1), the slump height decreases with increasing proportions of GWBG and CBA, signifying a decline in workability. This reduction can be attributed to the angular shape and rough surface texture of GWBG particles, which increase internal friction and reduce the lubricating effect of water. Equation (2) shows that the compacting factor also decreases with increasing levels of GWBG and CBA. This decline indicates that the mixes become stiffer and less workable as the replacement level rises, which may result from higher water demand caused by the irregular surface texture of the waste materials. The relationship between slump and compacting factor supports the conclusion that these materials modify the rheological behavior of the concrete mix.

Equation (3) reveals a nonlinear increase in water absorption with higher proportions of CBA, which suggests that CBA introduces more permeable voids within the concrete matrix due to its high porosity. The positive coefficient of B^2 in the model implies that excessive inclusion of CBA leads to higher absorption rates. Equations (4) and (5) demonstrate that compressive and splitting tensile strengths exhibit minor nonlinear variations, implying that an optimum combination of GWBG and CBA enhances the mechanical properties. This synergistic effect supports the observations of Adewumi and Alabi (2019), who noted that hybrid pozzolanic replacements can achieve improved strength performance when properly proportioned.

$$Slump\ Height = 34.16 - 6.35A - 3.43B \quad (1)$$

$$Compacting\ Factor = 0.7715 - 0.0440A - 0.0595B \quad (2)$$

$$Water\ Absorption = 4.30 + 0.2368A - 0.0618B - 0.6200AB - 0.2147A^2 + 1.08B^2 \quad (3)$$

$$Compressive\ Strength = 15.10 - 0.8277A + 0.4527B + 2.12AB + 0.6603A^2 - 2.58B^2 \quad (4)$$

$$Splitting\ Tensile\ Strength = 5.38 - 0.2365A + 0.2400B + 0.4775AB + 0.2186A^2 - 0.5414B^2 \quad (5)$$

The analysis of variance (ANOVA) presented in Table 5 evaluates the statistical significance of the effects of ground waste bottle glass (GWBG) and cow bone ash (CBA) on the selected concrete properties. The results for slump height and compacting factor revealed that the model F-values of 1.37 and 1.88, respectively, were not significant, as their corresponding p-values exceeded 0.05. This indicates that variations in GWBG and CBA had no statistically significant effect on the workability of the mixes. The lack of fit for both parameters was also non-significant, signifying that the models adequately represented the experimental data.

For water absorption, the quadratic model displayed an F-value of 2.61 with a p-value of 0.1216, suggesting a weak fit; however, the term B^2 (CBA^2) was found to be significant with a p-value of 0.0173. This implies that the higher dosage of CBA exerted a pronounced effect on water permeability, likely due to its porous microstructure and unreacted residue. This agrees with the findings of Okafor et al. (2021), who demonstrated that excessive ash inclusion leads to higher capillary absorption in blended concrete. The models for compressive and splitting tensile strengths, with F-values of 1.14 and 1.18, respectively, also showed no significant effects from either GWBG or CBA, although slight variations indicated possible synergistic interactions between the two materials. The non-significant lack of fit across all strength parameters further confirms model adequacy.

Table 5: Analysis of Variance (ANOVA) for the Effect of Ground Waste Bottle Glass (GWBG) and Cow Bone Ash (CBA) on Concrete Properties

Response Parameter	Source	Sum of Squares	df	Mean Square	F-value	p-value
Slump Height	Model	416.23	2	208.11	1.37	0.2980
	A – GWBG	322.22	1	322.22	2.12	0.1760
	B – CBA	94.01	1	94.01	0.62	0.4497
	Residual	1519.21	10	151.92		
	Lack of Fit	932.95	6	155.49	1.06	0.5003
Compacting Factor	Model	0.0439	2	0.0219	1.88	0.2023
	A – GWBG	0.0155	1	0.0155	1.33	0.2756
	B – CBA	0.0284	1	0.0284	2.44	0.1497
	Residual	0.1165	10	0.0117		
	Lack of Fit	0.0916	6	0.0153	2.45	0.2020
Water Absorption	Model	11.03	5	2.21	2.61	0.1216
	A – GWBG	0.4487	1	0.4487	0.53	0.4898
	B – CBA	0.0306	1	0.0306	0.04	0.8546
	AB	1.54	1	1.54	1.82	0.2193
	A^2	0.3208	1	0.3208	0.38	0.5572
	B^2	8.12	1	8.12	9.61	0.0173
	Residual	5.91	7	0.8448		
	Lack of Fit	4.80	3	1.60	5.75	0.0621
Compressive Strength (28 days)	Model	78.61	5	15.72	1.14	0.4221
	A – GWBG	5.48	1	5.48	0.40	0.5489
	B – CBA	1.64	1	1.64	0.12	0.7407
	AB	17.98	1	17.98	1.30	0.2916
	A^2	3.03	1	3.03	0.22	0.6537
	B^2	46.48	1	46.48	3.36	0.1094
	Residual	96.76	7	13.82		
	Lack of Fit	44.55	3	14.85	1.14	0.4348
Splitting Tensile Strength (28 days)	Model	4.45	5	0.8902	1.18	0.4045
	A – GWBG	0.4474	1	0.4474	0.59	0.4660
	B – CBA	0.4607	1	0.4607	0.61	0.4597
	AB	0.9120	1	0.9120	1.21	0.3075
	A^2	0.3325	1	0.3325	0.44	0.5276
	B^2	2.04	1	2.04	2.71	0.1438
	Residual	5.27	7	0.7529		
	Lack of Fit	1.25	3	0.4154	0.41	0.7534

The validation statistics presented in Table 6 provide an overall assessment of the adequacy and predictive reliability of the developed response surface models for the evaluated concrete properties. The coefficient of determination (R^2) values ranged between 0.2151 and 0.6510, indicating that the models moderately explain the variability in the responses. The water absorption model exhibited the highest R^2 of 0.6510, signifying a better correlation between experimental and predicted values compared to other responses. However, the negative predicted R^2 values for all models suggest limited predictive capability beyond the experimental design range, which may be attributed to experimental noise or inadequate representation of interaction effects.

The coefficients of variation (C.V.) ranged from 13.99% to 36.08%, with the compacting factor and splitting tensile strength showing lower variability, thus implying acceptable experimental precision. Adequate precision values between 3.29 and 4.82 were all above the threshold of 3.0, indicating sufficient signal-to-noise ratios and confirming the models' reliability in navigating the design space. Despite the moderate R^2 and negative predicted R^2 values, the models remain useful for explaining the relative influence of ground waste bottle glass and cow bone ash on the observed properties. The results, therefore, suggest that while the models can adequately describe the experimental data within the design limits, refinement through additional data points or higher-order interactions could enhance their predictive accuracy.

Table 6: Validation properties of response model.

Response	Std. Dev.	Mean	C.V. (%)	R^2	Adj. R^2	Pred. R^2	Adeq. Precision
Slump Height	12.33	34.16	36.08	0.2151	0.0581	-0.3867	3.30
Compacting Factor	0.108	0.772	13.99	0.2735	0.1283	-0.4206	3.99
Water Absorption	0.919	4.83	19.01	0.6510	0.4017	-1.1176	4.82
Compressive Strength	3.718	13.92	26.71	0.4483	0.0542	-1.2715	3.29
Splitting Tensile Strength	0.868	5.19	16.73	0.4579	0.0706	-0.5583	3.72

The comparison between the actual and predicted values of the experimental responses provides an essential measure of the predictive efficiency and accuracy of the developed response surface models. For slump height, the predicted values closely followed the experimental trend, with residuals mostly within acceptable limits except for Runs 8 and 9, where the differences between actual and predicted values (–15.88 and –18.89) exceeded statistical limits. This indicates potential variability in concrete consistency due to heterogeneity in mix proportions or minor measurement inconsistencies. Despite these deviations, most data points, such as Runs 4, 6, and 13, exhibited good conformity, suggesting that the model reasonably captured the slump behavior.

The compacting factor results demonstrated a relatively strong correlation between actual and predicted values, with minimal residuals observed in most runs, indicating a stable model fit. The highest deviation occurred at Run 9 (–0.1673), exceeding statistical limits, while other runs showed residuals below ±0.13, reflecting that the predicted compacting factors are consistent with experimental data. The low Cook's distance values further confirmed that no single observation significantly influenced the fitted model,

Similarly, the water absorption data exhibited close agreement between actual and predicted values, though some points, notably Runs 4 and 9, showed larger deviations exceeding model limits. These discrepancies suggest nonlinearity or unmodeled interaction effects between the mix variables. Nonetheless, the residual distribution was generally balanced, implying a satisfactory predictive ability.

For both compressive strength and splitting tensile strength, the predicted values accurately reflected experimental outcomes, with residuals symmetrically distributed around zero. A few higher residuals, such as in Runs 6 and 9, were within tolerable limits and did not distort the overall model fit.

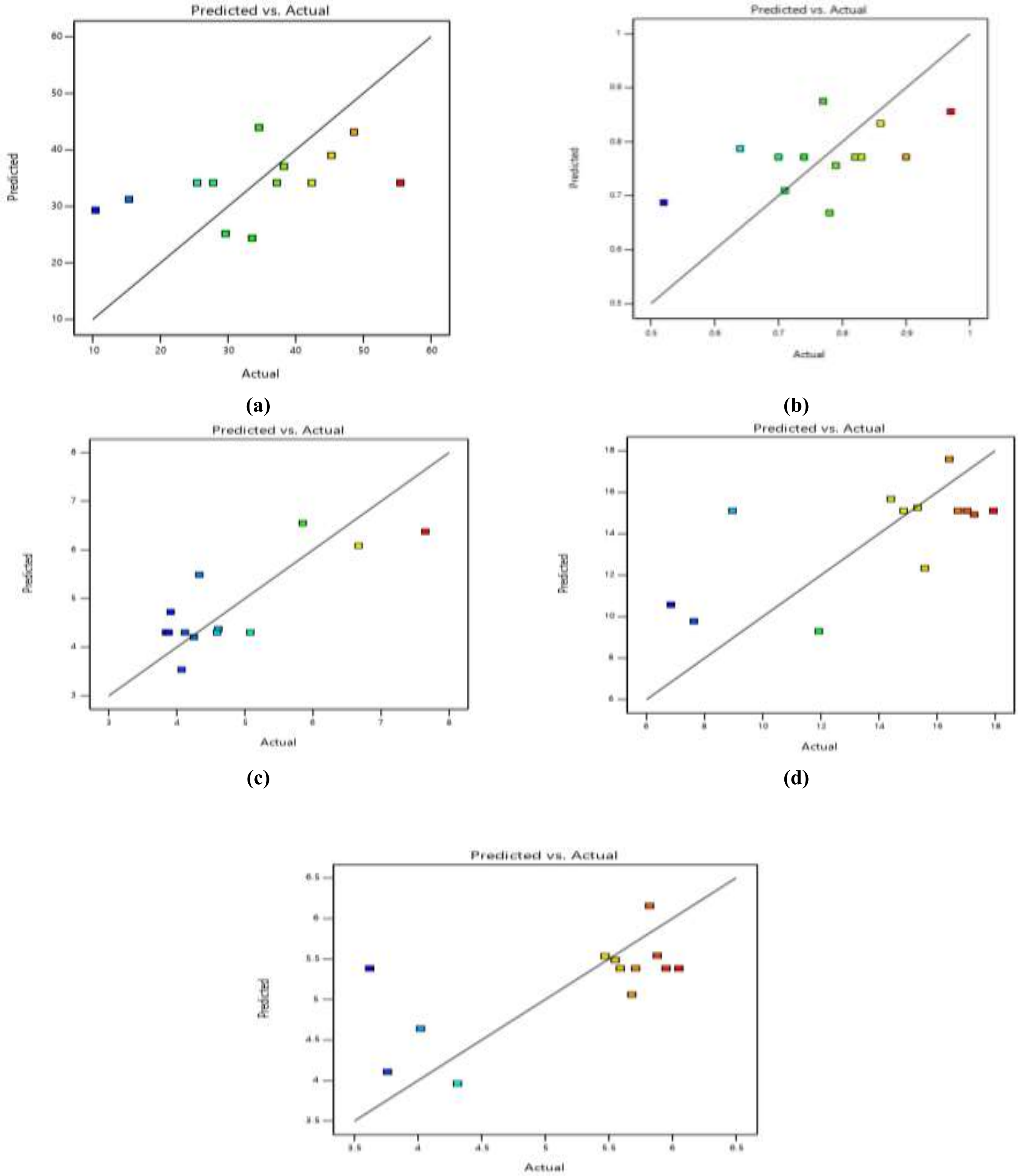


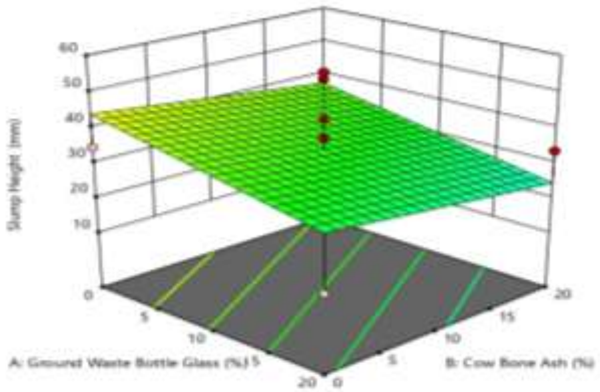
Figure 6: Actual versus predicted plot for (a) slump (b) compacting factor (c) 28-day water absorption (d) 28-day compressive strength (e) 28-day split tensile strength.

The 3D response surface plots reveal how the interaction between Cow Bone Ash (CBA) and Ground Waste Bottle Glass (GWBG) affected the workability and mechanical characteristics of the concrete mixtures. For the slump height, the surface displayed a clear nonlinear trend where the slump decreased progressively with increasing proportions of CBA and GWBG. The highest slump of 55.47 mm was obtained at the lowest replacement levels (0% CBA and 5% GWBG), while the lowest slump of 10.42 mm occurred when both materials were used at higher levels. This reduction in slump suggests that increasing these materials reduces workability due to higher water absorption and the angular nature of GWBG particles.

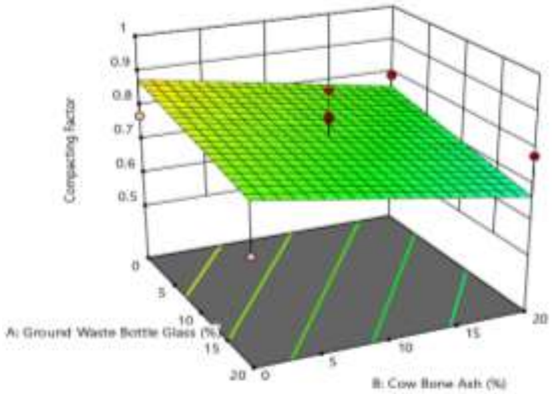
Similarly, the compacting factor followed a related pattern, with the mix exhibiting the highest compacting factor value of 0.97 at moderate CBA and GWBG levels, indicating improved workability at these proportions. The lowest compacting factor of 0.52 was recorded at high replacement levels, confirming that excessive incorporation of both materials results in stiffer and less workable mixes. In contrast, the 28-day water absorption results exhibited an increasing trend with higher replacement levels. The lowest water absorption value of 3.84% was recorded for mixes with low CBA and GWBG contents, while the highest absorption value of 7.65% occurred at higher replacement levels. This rise in absorption suggests that the porosity of the concrete matrix increased with more CBA and GWBG additions, likely due to incomplete hydration and less dense particle packing.

For the 28-day compressive strength, the response surface plot revealed a parabolic relationship between CBA and GWBG. The strength improved initially and then declined at higher levels of replacement. The maximum compressive strength of 17.94 MPa occurred at moderate replacement levels, whereas the lowest strength of 6.84 MPa was observed at higher substitutions. The initial increase in strength could be attributed to the pozzolanic activity of CBA and the filler effect of fine GWBG particles, which enhance the microstructure of the concrete. However, excessive replacement reduces available cementitious material, leading to strength loss.

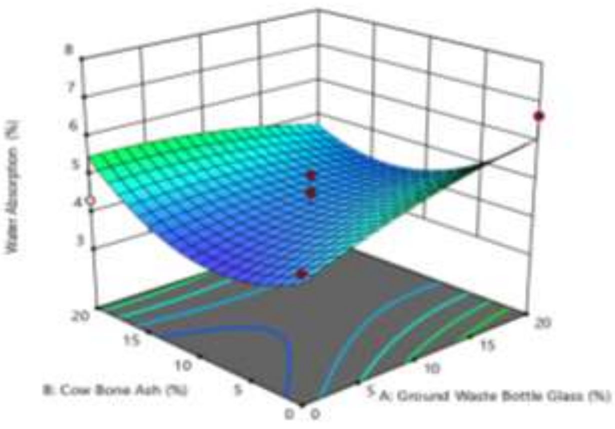
A similar pattern was observed in the 28-day splitting tensile strength, where the strength increased at moderate levels of CBA and GWBG but decreased beyond the optimum. The highest tensile strength value of 6.05 MPa was recorded at intermediate combinations, while the lowest value of 3.62 MPa occurred at the highest replacement levels. The improved tensile strength at moderate substitutions may be linked to better interfacial bonding and microstructural refinement, while higher replacements introduced microvoids and weak interfacial zones.



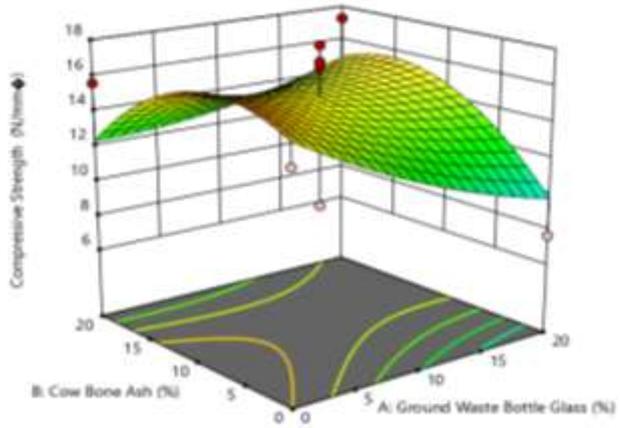
(a)



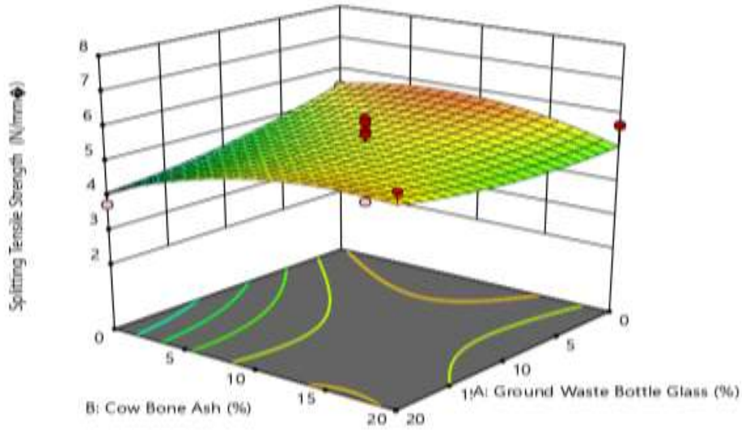
(b)



(c)



(d)



(e)

Figure 7: 3D response surface plot for the interaction effect of CBA and GWBG on (a) slump (b) compacting factor (c) 28-day water absorption (d) 28-day compressive strength (e) 28-day split tensile strength.

4.0 CONCLUSION

The study investigated the combined effect of Cow Bone Ash (CBA) and Ground Waste Bottle Glass (GWBG) on the workability and strength of concrete. Chemical analysis showed that CBA contained high CaO (55.3%) and P_2O_5 (24.7%) with dominant hydroxyapatite (72.6%) and calcite (15.4%) phases, indicating strong pozzolanic potential. Workability decreased with increasing replacements, as the slump reduced from 55.47 mm at the control mix to 10.42 mm at 20% GWBG, while the compacting factor peaked at 0.97 for 10% GWBG before dropping to 0.52 at higher levels. Water absorption increased with replacement, with the lowest value (3.84%) at 12.5% GWBG and 7.5% CBA, suggesting denser microstructure at moderate proportions. Compressive and tensile strengths exhibited a similar parabolic trend, attaining maximum values of 17.94 MPa and 6.05 MPa, respectively, at 12.5% GWBG and 7.5% CBA, before decreasing at higher substitutions. The optimal performance observed at moderate replacement levels was attributed to the synergistic effects of CBA's pozzolanic reaction and GWBG's filler property, which enhanced matrix densification and interfacial bonding, demonstrating that controlled use of these materials can improve both strength and sustainability in concrete production.

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