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Pozzolanic Effect of Ashes Recovered from Gasified Guinea Corn Husk on the Mechanical Properties of High-Performance Concrete

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Abstract

The environmental challenges and rising cost of cement production have stimulated interest in sustainable alternatives for high-performance concrete (HPC). Agricultural residues offer potential as supplementary cementitious materials due to their pozzolanic properties. This study aimed to evaluate HPC incorporating gasified guinea corn husk ash (GCHA) and natural fibres as partial cement replacements. GCHA was produced via a top-lit updraft gasifier, milled, sieved, and characterised using Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDS), and Fourier Transform Infrared Spectroscopy (FTIR) to assess morphology and chemical composition. Twelve concrete mixes were prepared based on a mixture experimental design, varying GCHA (0–10%) and fibre contents (0–1%). Workability, compressive strength, and split tensile strength were measured at 7, 28, and 56 days of curing, and results were analysed using regression modelling and optimisation techniques. Findings revealed that GCHA exhibited high silica and alumina content (~50%), conducive to pozzolanic reactions, while fibres improved crack resistance. The optimal mix, comprising 94% cement, 5% GCHA, and 1% fibre, achieved compressive strength of 54.45 MPa and tensile strength of 6.54 MPa at 56 days, surpassing the target grade 50 concrete. The study concludes that GCHA is a viable additive for HPC.

Keywords: Gasification, Agricultural waste material, supplementary cementitious materials, mechanical properties, Pozzolan.

1. Introduction

Concrete is a mix of cement, coarse and fine aggregates, and water. Cement makes up a small portion of this mixture, typically 10-15% of the total mass (Sinngu et al., 2022). Though very strong when compressed, concrete is weak in tension and needs reinforcement to keep it from swaying or cracking (Aburime et al., 2020). High-performance concrete (HPC) is a tailored mix designed to deliver exceptional performance, durability, and service life balancing cost considerations, for specific materials, applications, and environmental conditions (Odeyemi et al., 2020). unlike conventional concrete, high-performance concrete heavily relies on chemical admixtures to enable reduced water content, resulting in a more compact and less porous hydrated cement paste (Tran & Ghosh, 2020). It combines cement with supplementary cementitious material like ground blast furnace slag, flay ash, or silica fume in varying proportions to achieve desired properties (Tuleun, 2024).

The rising cost and scarcity of cement, particularly in Nigeria, pose significant challenges to affordable housing and infrastructure projects. With cement accounting for 10-15% of concrete's total mass, exploring alternatives like guinea corn husk could help mitigate these issues and make construction more affordable (Odeyemi et al., 2020; Soomro and Kalinowska, 2023). Efforts have been made to reduce raw materials consumption, ensure environmentally friendly operations and improve the quality of cement. To achieve this, consideration is being given for partial replacement for cement using waste materials such as maize straw and rice husk (Odeyemi et al., 2020).

Agricultural wastes such as rice husk ash, sugarcane bagasse ash, and palm oil fuel ash-are rich in reactive silica that can chemically react with calcium hydroxide in concrete to form additional calcium silicate hydrate (C-S-H) gel, resulting in a more compact and stronger concrete microstructure. Research has shown that these agricultural wastes contain highly reactive silica which reacts with calcium hydroxide in concrete, resulting in compact concrete microstructure (Warati et al., 2026)

Additionally, guinea corn husk is one of the agro-wastes generated after the guinea corn seed has been removed. These husks often become solid wastes in landfills thereby polluting the environment (Adetola et al., 2024)(; Atoyebi et al., 2019a, b). Finding new uses for waste can reduce environmental pollution and its potential hazards. Therefore, this study explores the potential of pozzolanic ash obtained from gasifying guinea corn husk in an updraft (top-lit) gasifier as an SCM, aiming to address both economic and environmental challenges in the construction industry (Tombulca & Çavuş, 2023).

Gasification is a key process that converts carbon-based materials, like biomass or fossil fuels, into syngas (or producer gas). This process offers numerous benefits and has significant potential for renewable energy and sustainable waste management, making it a promising technology for various applications (Soni and Naik, 2016). Moreso, gasification process involves the thermal decomposition of organic materials in a controlled atmosphere, typically with a limited amount of oxygen. This process produces a syngas that consists mainly of carbon monoxide, hydrogen, and methane (Kayode & Oladimeji, 2025). Gasification is more efficient than traditional combustion because it gets more energy out of the same amount of fuel (Olayanju et al., 2020).

Additionally, gasification not only creates energy, it also produces a solid by-product, ash, that can be used as a supplementary cementitious material (SCM). Unlike other high-temperature processes like calcination, gasification operates at a lower temperature. This allows it to preserve important minerals in the ash, such as amorphous silica, that are beneficial for pozzolanic activity.

This makes gasification a promising way to create SCMs from organic and agricultural waste (Olatoyan et al., 2023).

Recent studies show that agricultural waste ashes (AWA), such as rice husk ash and coconut husk ash, can replace some of the cement in concrete. These ashes contain reactive silica and alumina, which help improve the concrete's strength and durability (Kumar and Satyanarayana, 2022). Incorporating AWAs in concrete can improve workability, mechanical properties, and durability while reducing environmental impact (Zaffar et al., 2022; Endale et al., 2023). However, proper processing, including controlled combustion and grinding, is crucial to achieve optimal pozzolanic properties and concrete performance (Endale et al., 2023).

Agricultural and industrial wastes with pozzolanic properties can partially replace cement, meeting standards like BS EN 197-1 (2011). Offering a sustainable solution in construction (Becerra-Duitama & Rojas-Avellaneda, 2022). For instance, using plant ashes like maize cob, sawdust, and sugarcane bagasse as cement replacements in concrete can reduce environmental degradation and construction costs, while producing stronger blended concrete with longer curing periods (Okwadha, 2016; Raheem and Ibiwoye, 2018; Ugwuanyi and Onuamah, 2018).

In pursuit of this objective, researchers are exploring supplementary cementitious materials (SCMs) from agricultural waste to partially replace cement in concrete, reducing consumption while maintaining or improving concrete's properties (Odeyemi et al., 2024). Guinea Corn Husk Ash (GCHA) has been found to possess pozzolanic properties, making it a potential replacement for a proportion of cement in concrete, offering a cost-effective and sustainable solution ASTM C618 (2023).

Pozzolan is a siliceous or siliceous and aluminous material that, when finely divided and in the presence of water, reacts with calcium hydroxide to form cementitious compounds, despite having little to no inherent cementitious value itself (Derrouiche et al., 2025). However, Pozzolanas are materials that, while not inherently cementitious, react with calcium hydroxide in the presence of moisture to form compounds with cementitious properties, making them useful in concrete production (Ndububa and Aburime, 2021).

Moreso, pozzolanas combine with free lime during hydration, producing stable compounds that enhance concrete's resistance to sulphates, salts, and chlorides. They come in natural and artificial forms, offering benefits like reduced costs, improved concrete performance, and lower energy consumption and carbon emissions in cement production (Rao et al., 2024). Additionally, pozzolanas like fly ash, rice husk ash, and slag improve concrete's strength and durability while reducing heat of hydration and the environmental impact of cement production (Rao et al., 2024).

Common agricultural residues for gasification include: rice husks, sugarcane bagasse, wood sawdust and activated paper sludge. These materials have high carbon content and low inorganic content, making them suitable for gasification, which can produce syngas (a mixture of CO and H_2) and other valuable products. The composition of the resulting ashes, as well as their properties and applications, varies depending on factors such as incineration temperature and duration (Adebakin et al., 2021).

Recent studies show that Bamboo Leaf Ash (BLA) can be used as a supplementary cementitious material (SCM) in high-performance concrete. When heated to temperatures between 500–700 °C, BLA becomes rich in amorphous silica, which gives it a high pozzolanic reactivity (Adeniyi et al., 2025).

Similarly, studies have shown that GCHA can be successfully used as a partial cement replacement in HPC, improving its mechanical properties. GCHA contains a high percentage of silicon and aluminium oxide, making it suitable as a supplementary cementitious material. Up to 5% GCHA and 10% GCHA replacement can be used for the production of concrete grade 50, provided the minimum curing days are 56 days. Furthermore, Concrete with 5% GCHA replacement demonstrated increased compressive strength, enhanced durability, and improved microstructure compared to control specimens (Odeyemi et al., 2020).

This study explores a new material to reduce the amount of cement used in concrete, which could lower construction costs and lessen the environmental impact of concrete production.

2. Materials and Methods

2.1 Materials

Dangote Portland Limestone Cement was used as the binder in this study. It conformed to the Nigerian Industrial Standard NIS 444–1 (2003) and EN 197–1 (2011). Fine aggregates were sourced from the University of Ilorin dam, Kwara state, passed through a 4.75 mm sieve, and met the specifications of BS EN 12620 (2013). Coarse aggregates comprised 12 mm granite obtained from Kam Quarry and Mines Ventures, Ilorin, also conforming to BS EN 12620 (2013). Potable water used in all mixes complied with BS EN 1008 (2002). The granite was kept at room temperature in the laboratory to attain surface dry conditions. Treated coconut fibres were sourced from Egbejila, Ilorin West Local Government and conform to ACI 522. 1-08/ ACI 522R-10 and ASTM C1092 (2020). Konkreto SP430 superplasticiser manufactured by Pure Chem Manufacturing Limited, located at km 38, Lagos-Abeokuta expressway, Sango-Otta, Ogun State, Nigeria, were used and met the specifications of ASTM C494M-19el (2019). Guinea corn husks (Figure 1), obtained from Egbejila, Ilorin, were handpicked, dried and stored for the gasification process. The coconut fibre used in the research and the ash produced from the gasification process are presented as Figures 2 and 3, respectively.

Figure 1: Guinean corn

Figure 2: Coconut fibre

Figure 3: Guinea corn husk ash

2.2 Methods

Guinea corn husk ash was produced using a top-lit updraft reactor (Figure 4), featuring a compact gasification chamber centrally located within the unit. This chamber included air vents at its base and a vertical outlet at the top for releasing combustion gases. In the experiment, 2000 grams of guinea corn husk were placed inside the chamber, while biomass stems—used as fuel—were loaded into the surrounding area known as the heating space. The fuel was ignited from the top, allowing air to flow upward through the bottom vents into the combustion zone.

Temperature readings were taken every 10 minutes at the bottom, middle, top, and centre to determine the average temperature at which the gasification took place, using a CASON CA380 infrared thermometer. The procedure was carried out under normal atmospheric conditions and concluded once the reactor's temperature stabilised to match the ambient environment. The highest temperature recorded during the process was 323°C, reached after 520 minutes, which is lower than the temperature used for calcination of most pozzolans found in literature, which ranges from 400 ^{0}C to 800 ^{0}C.

After gasification, the ash was cooled in ambient air for 4 hours until it reached approximately room temperature (25–30 °C). The cooled ash was then milled using a ball mill at 200 revolutions per minute (200rpm) with a 10:1 ball-to-ash ratio, ensuring the particles were finely ground. After milling, the ash was sieved using a 90 µm sieve to remove larger particles and ensure uniformity. The processed ash was subsequently stored in airtight containers in a cool, dry environment to preserve its pozzolanic properties and prevent contamination before determining chemical composition, microstructure and mechanical properties.

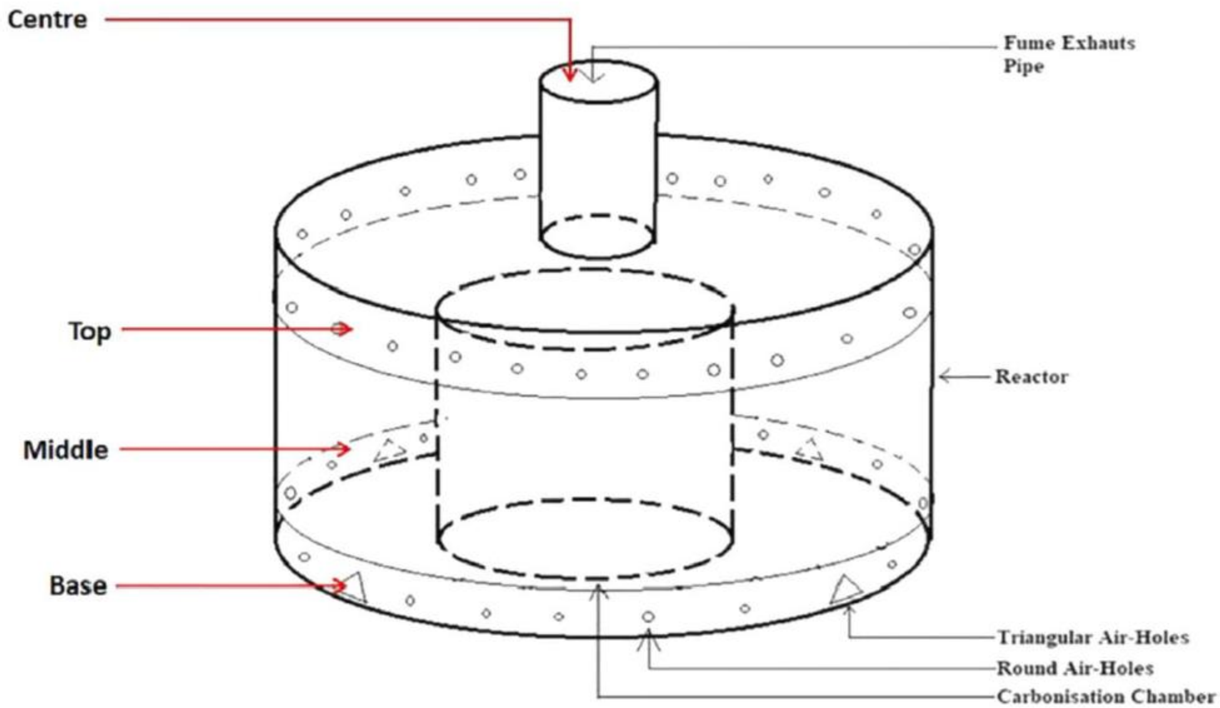


Figure 4: Schematic diagram of the Reactor used for the gasification process (Odeyemi et al., 2025)

The ash sample was ground into a fine powder to prepare it for Scanning Electron Microscopy (SEM). The scanning electron microscope (SEM) image of the GCHA was captured at a magnification of 4,000×, with a working distance of 10.5 mm and an accelerating voltage of 20 kV. The horizontal field width (HFW) spans approximately 145 µm, providing a detailed visualisation of the surface features. In accordance with ASTM E1508 standards, the sample was mounted on SEM stubs and coated with a thin conductive layer to prevent surface charging during electron exposure. SEM was then used to examine the surface morphology of the ash particles, producing high-resolution images that facilitated the assessment of texture, particle size, and structural characteristics. This analysis was carried out at the Integrated Research Laboratories in Ibadan, Oyo State.

To identify functional groups and chemical bonds, the ash sample was also analysed using Fourier Transform Infrared (FTIR) spectroscopy. After being finely ground, the sample was exposed to infrared radiation, and the resulting absorption peaks revealed details about the chemical composition of the gasified ash. This test was likewise conducted at the Integrated Research Laboratories in Ibadan.

The cement used in the study met the BS EN 196–3 specifications, with a specific gravity of 2.8, an initial setting time of 48 minutes, a final setting time of 510 minutes, a fineness of 6.5%, and a standard consistency of 31%. Locally sourced fine aggregate had a fineness modulus of 3.3, a specific gravity of 2.58, water absorption of 2.5%, and a bulk density of 1.50 g/cm³. The coarse aggregate exhibited a fineness modulus of 6.7, a specific gravity of 2.61, and a water absorption rate of 1.4%. All aggregate characteristics complied with the standards outlined in BS EN 12620.

The fresh concrete was prepared using a mix ratio of 1:0.79:1.46 (cement: sand: coarse aggregate) and a water–binder ratio of 0.41. This ratio, recommended by Odeyemi et al. (2020), served as the control framework for batching and was chosen for its optimisation in strength and workability characteristics. Workability was assessed using the slump test in accordance with BS EN 12350–2 (2019). Cement was partially replaced with the gasified GCHA. The concrete was cast into cube moulds measuring 100 mm × 100 mm × 100 mm and cylinder moulds measuring 100 mm × 200 mm and allowed to cure for 7, 28, and 56 days, following BS EN 12390–3 (2019).

All concrete specimens were cured by submerging them in water under standard laboratory conditions. To maintain consistency in temperature and moisture exposure, a single curing tank was used throughout the curing period. Once curing was complete, the compressive strength of the cube samples was evaluated using a universal testing machine (UTM), which measured the maximum load each specimen could bear before failure. These tests were carried out in the concrete laboratory at the University of Ilorin, Nigeria.

In accordance with BS EN 12390–6 (2019), split-tensile strength tests were conducted on cylindrical specimens measuring 100 mm in diameter and 200 mm in height. These tests were performed at curing intervals of 7, 28, and 56 days. A compressive force was applied vertically along each cylinder until it fractured, and the peak load at failure was used to determine the tensile strength. This procedure also took place at the University of Ilorin's concrete laboratory.

The collected results were subjected to statistical analysis, including regression modelling and response surface analysis, to identify significant trends and determine the most effective mix configuration. Statistical analysis was conducted using Design Expert software with the Mixture Methodology (MM) approach, which helps reduce the number of trials while examining the combined influence of factors such as guinea corn husk ash content and coconut fibre dosage on strength. The experimental runs generated by the Design Expert software were randomized to eliminate systematic bias, resulting in twelve different mix combinations shown in Table 1. Regression analysis was also applied to generate predictive models for strength based on the experimental results. Finally, the optimized concrete mix was validated by repeating the experiments and comparing the measured results with the model predictions, confirming that the desired mechanical properties of HPC could be consistently reproduced across multiple trials.

Table 1: Design Interface

Run	Cement %	Biochar %	Fibre %
1	90	9.2	0.8
2	90	10	0.0
3	91	8.0	1.0
4	93	7.0	0.0
5	94	5.6	0.4
6	94	5.0	1.0
7	96	4.0	0.0
8	97	3.0	0.0
9	97	2.0	1.0

10	98	2.0	0.0
11	99	0.3	0.7
12	100	0.0	0.0

3. Results and Discussion

3.1 Elemental composition of GCHA

The elemental composition of the sample, obtained from the electron diffraction spectrum, identified carbon (C), aluminium (Al), calcium (Ca) and silicon (Si) as the predominant elements in the GCHA. These elements are essential indicators of pozzolanic potential, with silicon in particular playing a central role in forming calcium silicate hydrates (C-S–H) when reacting with calcium hydroxide in cement paste. The combined content of silicon and aluminium (~50%), indicates strong pozzolanic potential through the formation of C–S–H and C–A–S–H gels. Carbon content at 19% suggests significant organic matter, beneficial for water retention but potentially affecting early hydration. Calcium at 15.4% reflects the presence of lime or calcium-rich ash, which may accelerate setting. Sulfur (4.1%) likely exists as sulfates, posing a risk of expansion if not properly managed. Minor alkali metals (Na, K <2%) could contribute to alkali–silica reaction in reactive aggregate systems. These elemental traits imply good pozzolanic activity, improved internal curing, and potential durability concerns if not properly balanced in the mix design.

Table 2: Elemental composition of the gasified GCHA

Element	Weight %
Si	40.0
Mg	1.0
C	19.0
O	4.6
Ca	15.4
Fe	4.6
S	4.1
Na	0.2
K	1.4
Al	10.0

3.2 Oxide composition of GCHA

The oxide composition of the GCHA is presented in Table 3.

Oxides	Weight %
SiO_2	58.45
MgO	1.14
CaO	14.71
Fe_2O_3	4.50

SO_3	7.00
Na_2O	0.18
K_2O	1.15
Al_2O_3	12.91

Table 3: Oxide Composition of GCHA

The combined oxides of SiO_2, Al_2O_3, and Fe_2O_3 in GCHA account for 75.86 %, with SiO_2 being the most prevalent. This meets the BS EN 197-1 (2011) standard for supplementary cementitious materials. Notably, the total oxide content exceeding 70 % aligns with Odeyemi et al., (2020); Ndububa and Nurudeen (2015).

3.3. EDX Analysis of GCHA

The EDX results of GCHA are presented in Figure 5

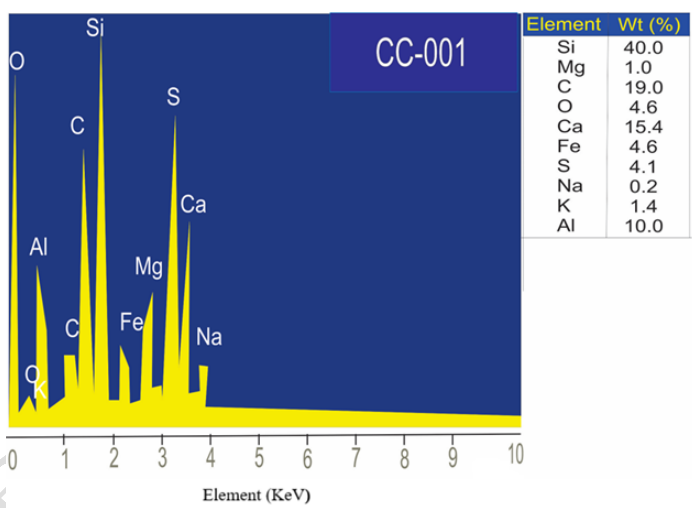


Figure 5: EDX analysis of GCHA

The EDX analysis of GCHA in Figure 5 reveals a high combined content of silicon and aluminium (~50%), indicating strong pozzolanic potential through the formation of C–S–H and C–A–S–H gels. Carbon content at 19% suggests significant organic matter, beneficial for water retention but potentially affecting early hydration. Calcium at 15.4% reflects the presence of lime or calcium-rich ash, which may accelerate setting. Sulfur (4.1%) likely exists as sulfates, posing a risk of expansion if not properly managed. Minor alkali metals (Na, K <2%) could contribute to alkali–silica reaction in reactive aggregate systems. These elemental traits imply good pozzolanic activity, improved internal curing, and potential durability concerns if not properly balanced in the mix design.

3.4 SEM ANALYSIS OF GCHA

The scanning electron microscope (SEM) image of the GCHA presented in Figure 6 provides a detailed visualisation of the surface features. The surface morphology reveals a highly porous network characterised by irregularly shaped voids and interconnected channels, with pore sizes ranging from the nanoscale to several micrometres. These pores form a continuous internal framework throughout the biochar particles. The pore walls appear rough and uneven, indicating a high specific surface area and a reactive surface texture.

Key microstructural observations include interconnected macropores (on the order of tens of micrometres), which can trap water and promote internal curing, and abundant micropores (<2 µm) that significantly increase the surface area available for pozzolanic reactions. The rough texture of the pore walls enhances mechanical interlocking with the cement matrix. At the same time, the irregular edges of the biochar particles offer potential anchorage sites when used in combination with reinforcing fibres in composite materials.

These morphological characteristics have notable implications for concrete performance. The microporous structure enhances water retention, thereby reducing autogenous shrinkage and supporting prolonged hydration. The increased surface area contributes to improved pozzolanic activity, accelerating secondary calcium silicate hydrate (C–S–H) formation and boosting strength development, particularly beyond the conventional 28-day curing period. Furthermore, the rough and uneven surface morphology fosters stronger mechanical bonding at the biochar–cement interface, enhancing the overall toughness of the composite. Finally, the intricate pore structure may help reduce permeability, offering improved resistance to chloride ingress and freeze–thaw deterioration, thereby contributing to the long-term durability of the concrete.

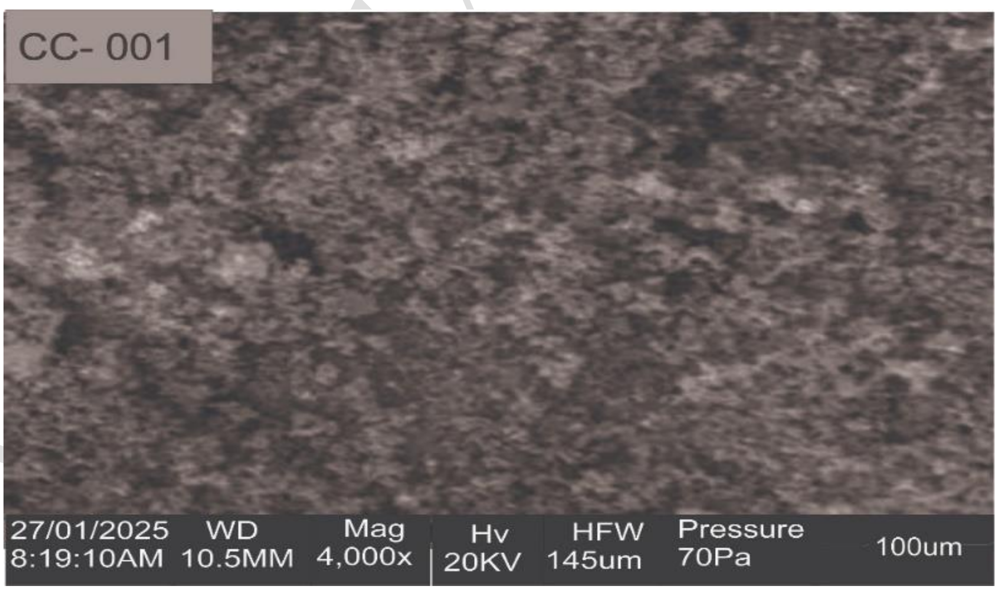


Figure 6: SEM image of the GCHA

3.5 Fourier Transform Infrared (FTIR) analysis

The Fourier Transform Infrared (FTIR) analysis presented in Figure 7 appears to characterise GCHA, revealing several significant absorption bands that correspond to specific functional groups. These functional groups are critical in understanding how the ash may interact chemically within a cementitious matrix when used as a partial cement replacement or additive in concrete.

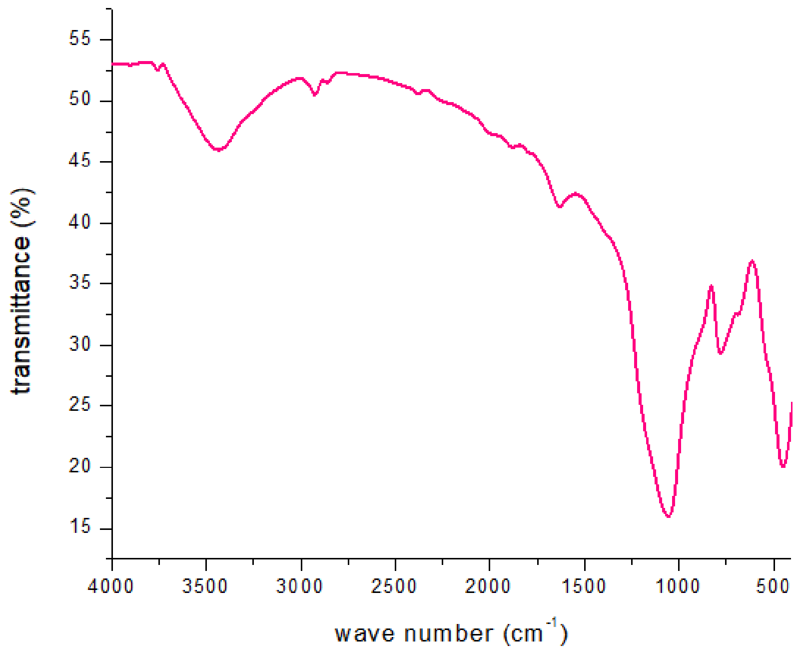


Figure 7: Fourier Transform Infrared (FTIR) analysis of GCHA

From the FTIR spectrum, prominent peaks observed around 3425 cm^{-1} suggest the presence of –OH stretching vibrations, typical of hydroxyl groups from alcohols or phenols, which imply the presence of polar surface groups capable of forming hydrogen bonds. This characteristic enhances the surface reactivity of GCHA, allowing it to potentially bond well with hydration products like calcium silicate hydrate (C-S-H) in concrete. Another key peak near 2924 cm^{-1} indicates C–H stretching, often from aliphatic chains, while bands near 1630 cm^{-1} likely correspond to C=C or C=O stretching, indicative of aromatic rings or carbonyl groups. These features point to partially aromatic structures and oxygen-containing groups, both of which influence the pozzolanic or filler properties of GCHA.

The region near 1030–1100 cm^{-1}, where a strong band is typically observed, corresponds to Si–O–Si or Si–O–Al stretching vibrations, particularly if the ash source contains siliceous ash or if it has been treated or derived from mineral-rich biomass. This can mimic the behaviour of natural pozzolans, improving the pozzolanic reaction with calcium hydroxide in concrete and contributing to long-term strength development and durability.

3.5 Split tensile strength

Figure 8(a–f) presents the experimental and model-predicted split tensile strength of high-performance concrete (HPC) incorporating varying proportions of gasified guinea corn husk ash

(GCHA) and coconut fibre at curing ages of 7, 28, and 56 days. The figure consists of six plots: Figures 8(a), 8(c), and 8(e) show the response surface plots of split tensile strength at 7, 28, and 56 days, respectively, while Figures 8(b), 8(d), and 8(f) compare the corresponding actual experimental values with the values predicted by the regression model.

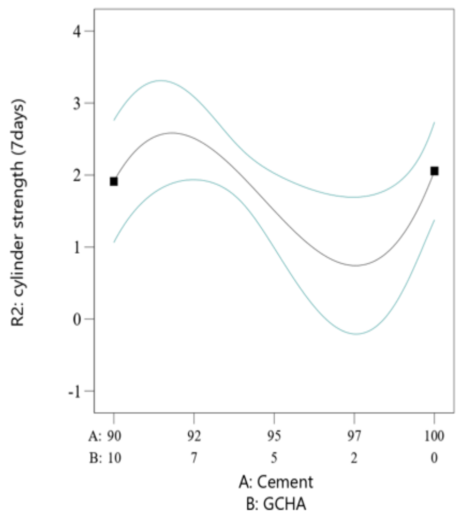
Figure 8 (a) shows that at early age (7 days), the split tensile strength is primarily governed by cement hydration, with limited contribution from GCHA. The curves show that mixes with higher cement content exhibit higher tensile strength, while increasing GCHA replacement leads to a reduction in early-age tensile strength. This behaviour is attributed to the relatively slow pozzolanic reaction of GCHA, which does not significantly contribute to strength development at early ages. Although the inclusion of fibres provides some crack-bridging capability, their effect at 7 days is marginal due to incomplete fibre–matrix bonding and insufficient matrix stiffness. In Figure 8 (b) the close clustering of data points around the line of equality indicates strong agreement between experimental and predicted values, confirming the adequacy of the regression model in capturing early-age tensile behaviour despite the dominance of cement hydration.

Figure 8 (c) shows that at 28 days, the response surface shows a noticeable improvement in tensile strength for mixes containing low to moderate GCHA contents (approximately 3–5%). At this stage, secondary pozzolanic reactions between the reactive silica/alumina in GCHA and calcium hydroxide released during cement hydration become more pronounced, leading to the formation of additional C–S–H gel. This densifies the matrix and improves stress transfer across microcracks. Fibre inclusion further enhances tensile performance through crack arrest and bridging mechanisms. However, at higher GCHA contents (>7–10%), tensile strength declines due to dilution of cement and incomplete pozzolanic compensation. The strong correlation between measured and predicted values shown in Figure 8 (d) confirms that the model reliably represents the combined effects of cement, GCHA, and fibre on tensile strength at intermediate curing age.

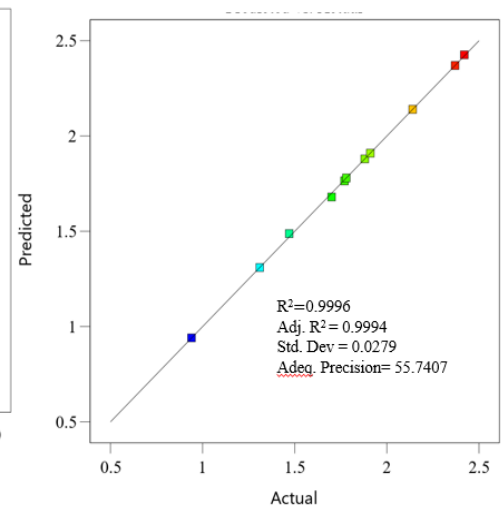
Figure 8 (e) shows that at 56 days, the curves clearly indicate that mixes containing approximately 5% GCHA and fibre achieve the highest split tensile strength. At this later age, the pozzolanic activity of GCHA is fully mobilised, resulting in significant secondary C–S–H formation, pore refinement, and improved interfacial transition zone (ITZ). The fibres play a more effective role at this stage by bridging microcracks and delaying crack propagation, thereby enhancing tensile resistance. Beyond the optimum GCHA level, excessive ash content leads to reduced cementitious phases and weaker fibre–matrix bonding, which explains the observed decline in tensile strength at higher replacement levels. The near-linear alignment of data points in Figure 8 (f) demonstrates excellent predictive capability of the developed model for long-term tensile performance, validating the statistical significance observed in the ANOVA results.

In all, the split tensile strength results show a strong dependence on curing age, cement content, and optimal GCHA replacement. While GCHA does not significantly enhance early-age tensile strength, its contribution becomes substantial at later ages due to pozzolanic reactions and microstructural densification. The optimum performance observed at approximately 5% GCHA with fibre inclusion confirms a balanced interaction between matrix densification, crack-bridging action of fibres, and sustained hydration. Although the tensile strength improvement achieved with GCHA-based HPC is lower than that reported for silica fume and fly ash based HPC systems

((Subbulakshmi et al., 2014; Ismeik, 2009; Kannan, 2017 and Magudeaswaran and Eswaramoorthi, 2013), the results remain significant considering the lower processing temperature, local availability, and sustainability benefits of GCHA.



(a)



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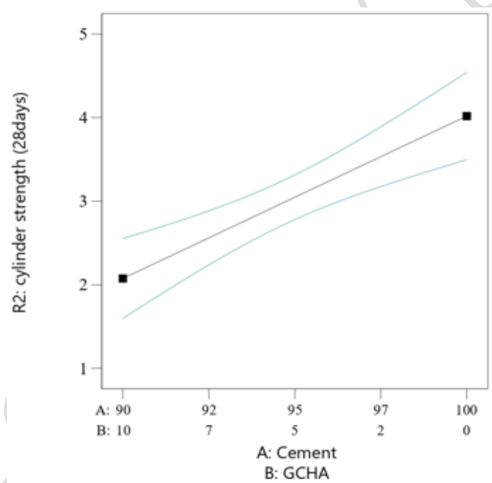
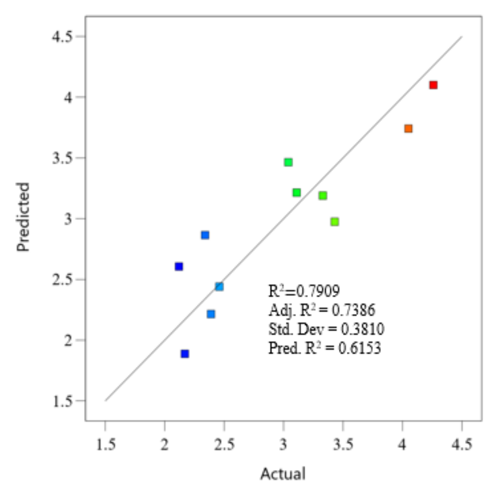
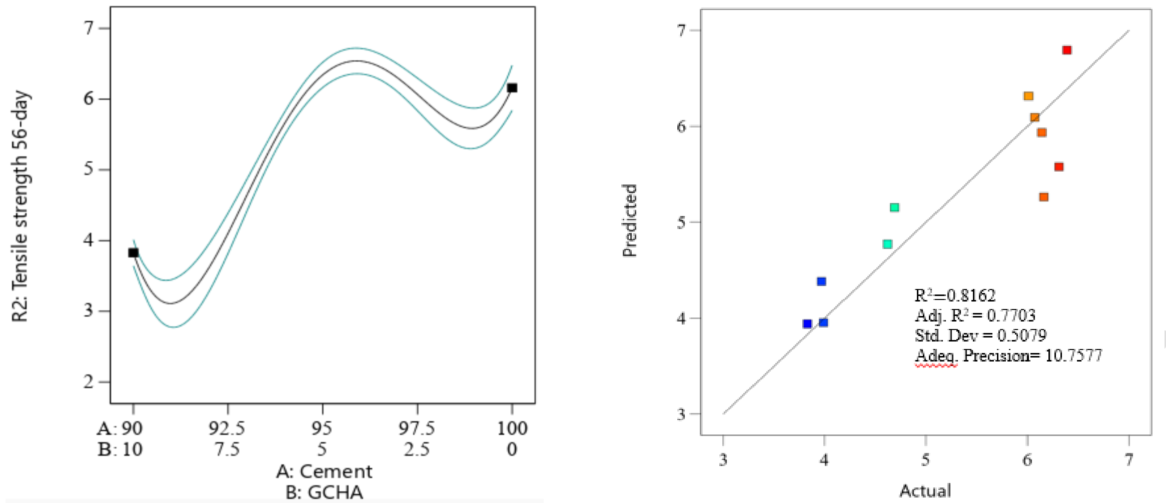


(c)



(d)



(e) (f)

Figure 8: Split tensile strength of the HPC (a) 7-day split tensile strength (b) Actual and Predicted Value at 7 days (c) 28-day split tensile strength (d) Actual and Predicted Value at 28 days (e) 56-day split tensile strength (f) Actual and Predicted Value at 56 days

3.6 Compressive strength

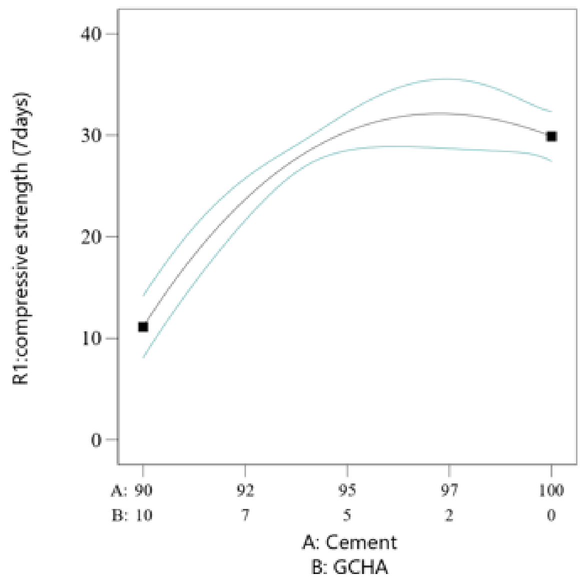
Figure 9(a–f) presents the experimental and model-predicted compressive strength of high-performance concrete (HPC) incorporating varying proportions of gasified guinea corn husk ash (GCHA) and coconut fibre at curing ages of 7, 28, and 56 days. The figure consists of six plots: Figures 9(a), 9(c), and 9(e) show the response surface plots of compressive strength at 7, 28, and 56 days, respectively, while Figures 9(b), 9(d), and 9(f) compare the corresponding actual experimental values with the values predicted by the regression model.

Figure 9(a) shows that at early age (7 days), compressive strength is predominantly controlled by the hydration of Portland cement. The response surface indicates that mixes with higher cement content exhibit higher early compressive strength, whereas increasing GCHA replacement results in a reduction in strength at this stage. This reduction is mainly due to the dilution effect, where partial replacement decreases the quantity of clinker available for primary hydration and early C–S–H formation. Since the pozzolanic reaction of GCHA is relatively slow and depends on the availability of calcium hydroxide released during hydration, its contribution at 7 days remains limited. Fibre inclusion shows negligible influence on compressive strength at this age because fibres primarily enhance post-cracking behaviour rather than compressive load-bearing capacity. In Figure 9(b), the close clustering of data points around the line of equality indicates strong agreement between experimental and predicted values, confirming that the regression model adequately captures early-age compressive behaviour.

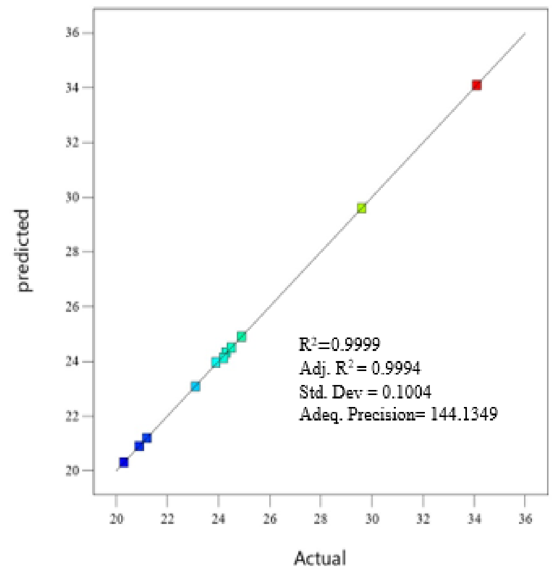
Figure 9(c) shows that at 28 days, the response surface reveals improved compressive strength for mixes containing low to moderate GCHA contents (approximately 3–5%). At this curing age, secondary pozzolanic reactions between reactive silica and alumina in GCHA and calcium hydroxide become more pronounced, resulting in additional C–S–H gel formation. This contributes to matrix densification, refinement of pore structure, and improvement of the interfacial transition zone (ITZ). Consequently, mixes with optimal GCHA replacement begin to approach or surpass the control mix performance. However, at higher replacement levels (>7–10%), compressive strength declines due to excessive dilution of cementitious material, where the reduction in primary hydration products is not fully compensated by secondary pozzolanic reactions. The strong correlation between measured and predicted values shown in Figure 9(d) confirms that the model reliably represents the combined effects of cement, GCHA, and fibre at intermediate curing age.

Figure 9(e) shows that at 56 days, the curves clearly indicate that mixes containing approximately 5% GCHA achieve the highest compressive strength. At this later age, the pozzolanic activity of GCHA is fully mobilised, leading to significant secondary C–S–H formation, pore refinement, and improved particle packing through micro-filling effects of the finely ground ash. These mechanisms collectively enhance load transfer capacity within the cementitious matrix and strengthen the ITZ. The maximum compressive strength of 54.45 MPa recorded at 5% GCHA demonstrates that a balanced replacement level can optimise both hydration and pozzolanic contributions. Beyond the optimum level, excessive ash content reduces total cementitious phases and limits the availability of calcium hydroxide necessary for sustained pozzolanic reaction, resulting in reduced compressive strength. The near-linear alignment of data points in Figure 9(f) demonstrates excellent predictive capability of the developed model for long-term compressive performance, consistent with the high R^2 value and statistically significant ANOVA results.

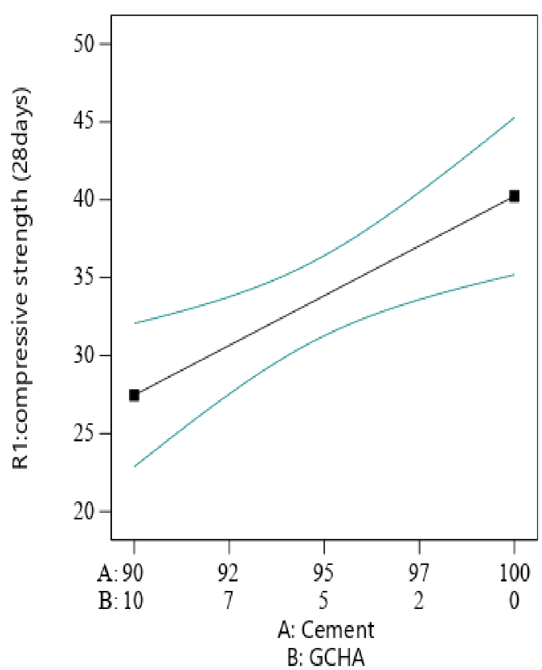
In all, the compressive strength results demonstrate a clear dependence on curing age, cement content, and optimal GCHA replacement. While higher GCHA levels reduce early-age strength due to dilution, moderate replacement (around 5%) enhances later-age performance through sustained pozzolanic reactions and microstructural densification. The findings confirm that GCHA behaves as a slow-reacting supplementary cementitious material whose benefits are more pronounced at extended curing periods. The optimum replacement level of approximately 5% provides a balanced interaction between primary hydration, secondary C–S–H formation, and improved matrix integrity, thereby making GCHA a viable and sustainable alternative in high-performance concrete production.


R1:compressive strength (7days)
40
30
20
10
0
A: 90
B: 10
92
7
95
5
97
2
100
0
A: Cement
B: GCHA

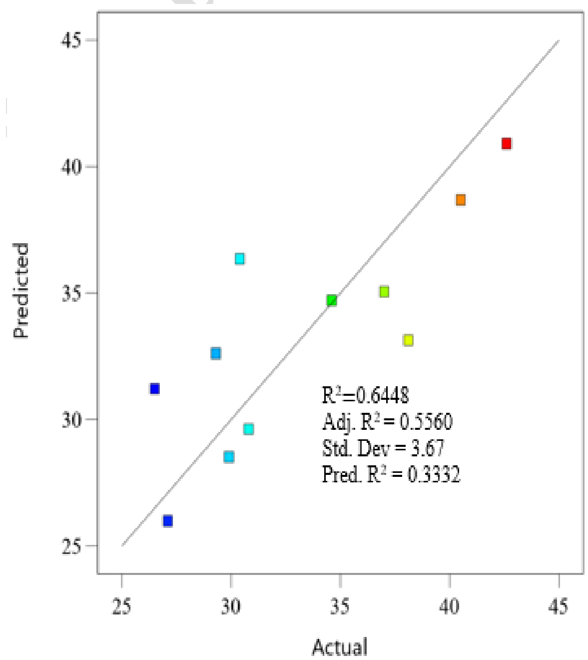
(a)


predicted
36
34
32
30
28
26
24
22
20
22
24
26
28
30
32
34
36
Actual
R²=0.9999
Adj. R² = 0.9994
Std. Dev = 0.1004
Adeq. Precision= 144.1349

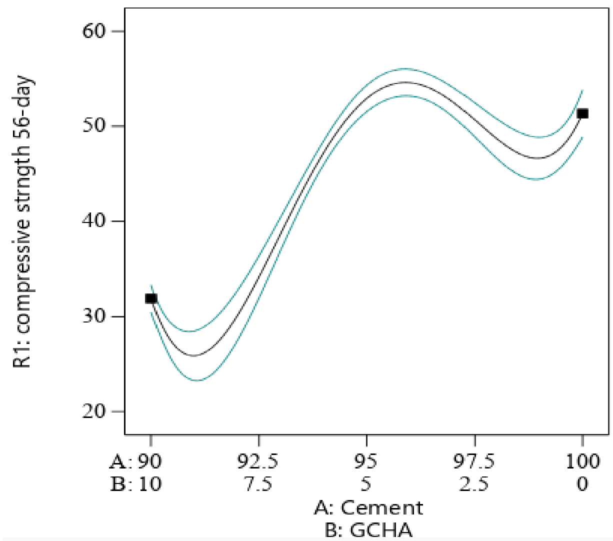
(b)


R1:compressive strength (28days)
50
45
40
35
30
25
20
A: 90
B: 10
92
7
95
5
97
2
100
0
A: Cement
B: GCHA

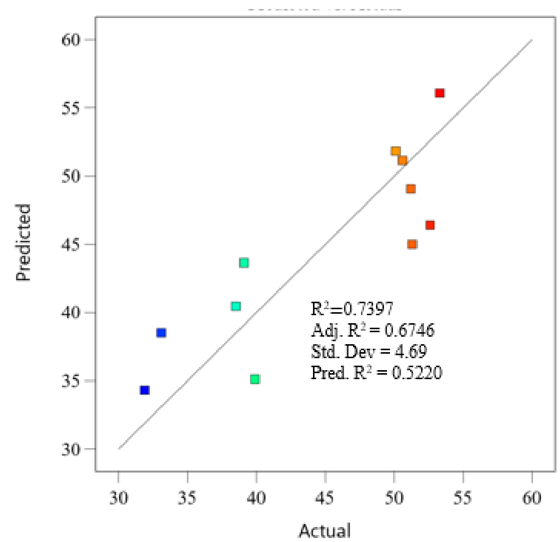
(c)


Predicted
45
40
35
30
25
30
35
40
45
Actual
R²=0.6448
Adj. R² = 0.5560
Std. Dev = 3.67
Pred. R² = 0.3332

(d)



(e)



(f)

Figure 9: Compressive strength of the HPC (a) 7-day compressive strength (b) Actual and Predicted Value at 7 days (c) 28-day compressive tensile strength (d) Actual and Predicted Value at 28 days (e) 56-day compressive tensile strength (f) Actual and Predicted Value at 56 days

3.7 OPTIMISATION

The optimisation process was carried out after a 56-day curing period, with a focus on maximising the use of guinea corn husk ashes, fibre and mechanical strengths in the process of minimising the cement content in the concrete. Fig. 10 shows the optimised result of 9% guinea corn husk ash, 1% fibre, and 94% cement. This resulted in a compressive strength of 54.45 N/mm² and split tensile strength of 6.54 N/mm², complying with the BS EN 12390-3 (2019) and BS EN 12390-6 (2009) standards. Result has desirability value of 1.000. The optimised compressive strength of 54.45 N/mm² is almost the same as the results presented for concrete containing 5% GCHA at a 0.31 water-cement ratio reported by Odeyemi et al. (2020). The optimised split-tensile strength of 6.54 N/mm² in this study is higher than the highest splitting tensile strength of 5.75 N/mm² at 5% of GCHA reported by the same author. The optimised compressive strength obtained in this study also exceeds the value of 31.34 N/mm² at 10% GCHA combined with 8.5% of RHA reported by Odeyemi et al. (2024), while the split-tensile strength in this study surpasses the highest value of 3.07 N/mm² at 10% GCHA combined with 8.5% of RHA reported by the same author. However, the study of Odeyemi et al. (2024) was limited to normal concrete.

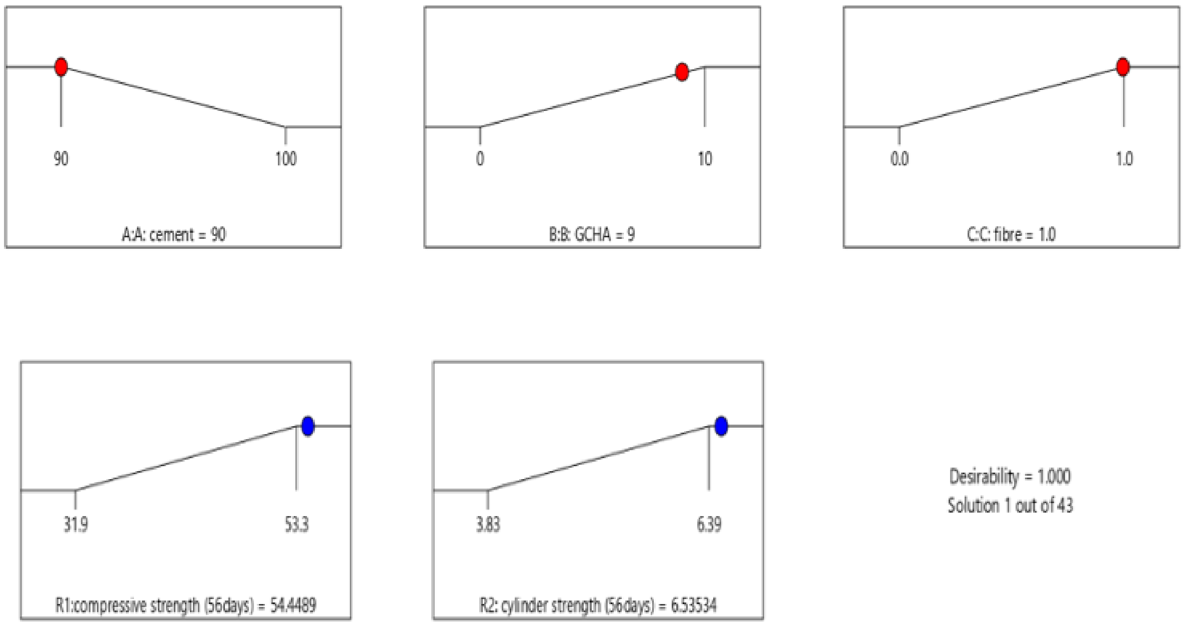


Figure 10: Optimisation results

3.8. MODEL VALIDATION TABLES

Before presenting the ANOVA results, it is important to clarify that the statistical analysis was conducted using Design-Expert software (Stat-Ease Inc., USA) based on the Mixture Methodology (MM) described in Section 2.2. The experimental runs generated from the mixture design were analysed using regression modelling to establish empirical relationships between the independent variables (cement, GCHA, and fibre contents) and the response variables (compressive strength and split tensile strength).

Analysis of Variance (ANOVA) was performed within the Design-Expert environment to evaluate the statistical significance of the developed mixture models. The procedure involved fitting a suitable polynomial mixture model to the experimental data, computing sums of squares using Type I (sequential) methods, and determining F-values and corresponding p-values to assess the significance of the overall model and of individual linear and interaction terms. Model adequacy was further evaluated using statistical indicators, including R^2, adjusted R^2, predicted R^2, standard deviation, coefficient of variation (C.V.%), and Adequate Precision ratio.

Tables 4 - 7, therefore, represent the output generated directly from the Design-Expert mixture design analysis, confirming the statistical validity, predictive capability, and adequacy of the developed compressive and split tensile strength models.

The ANOVA results for both compressive strength (Table 4) and split tensile strength (Table 6) confirm that the developed mixture models are statistically significant and robust. For compressive strength, the model F-value of 102.34 with a p-value < 0.001 indicates that the regression model is highly significant and that the probability of the observed variation occurring due to random noise is extremely low. Similarly, the split tensile strength model shows an even higher F-value of 123.03 with $p < 0.001$, further confirming strong model significance. In both cases, the linear mixture terms are highly significant ($p < 0.001$), demonstrating that the proportions of cement, GCHA, and fibre have a direct and statistically meaningful influence on strength development.

The interaction terms (AB, AC, BC) and higher-order mixture components (ABC and reduced quadratic terms such as AB(A–B), AC(A–C), BC(B–C)) are also statistically significant for both responses, as evidenced by their low p-values (< 0.01). This indicates that the mechanical properties are not governed solely by individual component effects but also by synergistic interactions among cement, GCHA, and fibre. In particular, the significance of AC and BC terms suggests that the interaction between GCHA and fibre, and between cement and fibre, plays an important role in modifying matrix behaviour. The relatively small residual sums of squares (5.55 for compressive strength and 0.0806 for split tensile strength) indicate minimal unexplained variability, confirming good agreement between experimental and predicted values.

The fit statistics (Tables 5 and 7) further validate the adequacy and predictive capability of the developed models. For compressive strength, the coefficient of determination ($R^2 = 0.9935$) indicates that 99.35% of the variability in strength is explained by the model. The adjusted R^2 (0.9838) is very close to R^2, confirming that the model is not overfitted and that the included terms are meaningful. The predicted R^2 (0.938) shows strong predictive reliability when estimating new observations within the design space. Similarly, for split tensile strength, $R^2 = 0.9946$ and adjusted $R^2 = 0.9865$ demonstrate excellent model fit and stability. The low standard deviation values (0.9619 for compressive and 0.1159 for tensile strength) and low coefficients of variation (2.19% and 2.24%, respectively) indicate high precision and reproducibility of the experimental data.

Adequate Precision values of 28.2494 for compressive strength and 28.0446 for split tensile strength are far greater than the minimum desirable value of 4, indicating an excellent signal-to-noise ratio and confirming that the models can be reliably used to navigate the design space. Overall, the ANOVA and fit statistics collectively demonstrate that the mixture models developed using Design-Expert software are statistically sound, exhibit strong predictive capability, and adequately capture the combined and interactive effects of cement, GCHA, and fibre on both compressive and split tensile strength of the high-performance concrete.

Table 4: ANOVA Table for compressive strength results

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	852.19	9	94.69	102.34	< 0.001 (significant)
Linear Mixture	604.31	2	302.16	326.57	< 0.001
AB	40.56	1	40.56	43.84	< 0.0006
AC	123.68	1	123.68	133.67	< 0.001
BC	122.98	1	122.98	132.89	< 0.001
ABC	124.32	1	124.32	134.32	< 0.001
AB(A-B)	24.77	1	24.77	26.77	< 0.0021
AC(A-C)	124.87	1	124.87	134.96	< 0.001
BC(B-C)	122.75	1	122.75	132.67	< 0.001
Residual	5.55	6	0.9252		
Lack of Fit	5.55	1	5.55		
Pure Error	0	5	0		

Cor Total	857.74	15

Table 5: Fit Statistics Table for compressive strength

Statistic	**Value**
Std. Dev.	0.9619
Mean	43.88
C.V. %	2.19
R^2	0.9935
Adjusted R^2	0.9838
Predicted R^2	0.938
Adeq Precision	28.2494

Table 6: ANOVA Table for split tensile strength results

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	14.88	9	1.65	123.03	< 0.001 (significant)
Linear Mixture	12.3	2	6.15	457.68	< 0.001
AB	0.5876	1	0.5876	43.76	0.0005
AC	1.3	1	1.3	96.82	< 0.0001
BC	1.3	1	1.3	96.82	< 0.0001
ABC	1.31	1	1.31	97.57	< 0.0001
AB(A-B)	0.3551	1	0.3551	26.43	0.0021
AC(A-C)	1.29	1	1.29	96.39	< 0.0001
BC(B-C)	1.31	1	1.31	97.57	< 0.0001
Residual	0.0806	6	0.0134		
Lack of Fit	0.0806	1	0.0806		
Pure Error	0	5	0		
Cor Total	14.96	15			

Table 7: Fit Statistics Table for Split Tensile Strength

Statistic	Value
Std. Dev.	0.1159
Mean	5.165
C.V. %	2.24
R^2	0.9946
Adjusted R^2	0.9865
Adeq Precision	28.0446

4. CONCLUSIONS

This study investigated the suitability of gasified guinea corn husk ash (GCHA) as a supplementary cementitious material in high-performance concrete (HPC, Grade 50), with emphasis on its microstructural characteristics, mechanical performance, and statistical optimisation. Based on the experimental results and analyses, the following conclusions are drawn:

1. Gasification of guinea corn husk at relatively low temperature (~323 °C), followed by milling and sieving, produced an ash rich in reactive oxides. The combined content of SiO_2, Al_2O_3, and Fe_2O_3 (≈ 75.9%) satisfies the requirements for pozzolanic materials, while SEM and FTIR analyses confirmed a highly porous structure, rough surface texture, and the presence of functional groups conducive to pozzolanic reactions and enhanced bonding with cement hydration products.
2. The incorporation of GCHA influenced mechanical performance in a curing-age-dependent manner. At early ages (7 days), strength development was governed mainly by cement hydration, and increasing GCHA content led to reduced compressive and split tensile strengths due to dilution effects and limited pozzolanic activity.
3. At later curing ages (28 and 56 days), the pozzolanic contribution of GCHA became significant. Moderate replacement levels promoted secondary C–S–H formation, pore refinement, and improved interfacial transition zone (ITZ), resulting in enhanced mechanical performance. Excessive GCHA replacement, however, reduced strength due to insufficient cementitious phases.
4. The optimum mechanical performance was achieved at approximately 5% GCHA replacement combined with 1% coconut fibre. At 56 days, this mix attained a compressive strength of 54.45 MPa and a split tensile strength of 6.54 MPa, exceeding the target strength for Grade 50 HPC. Fibre inclusion contributed mainly to tensile performance through crack-bridging and crack-arrest mechanisms, particularly at later ages.
5. Statistical analysis using Design-Expert software confirmed the robustness of the developed mixture models. ANOVA results showed highly significant models for both compressive and split tensile strengths ($p < 0.001$), with strong interaction effects among cement, GCHA, and fibre contents. High R^2 values (> 0.99), low coefficients of variation (< 3%), and high Adequate Precision ratios (> 28) demonstrated excellent model fit, reliability, and predictive capability.

In all, gasified guinea corn husk ash can be effectively used as a sustainable supplementary cementitious material in high-performance concrete at moderate replacement levels, contributing to improved long-term mechanical performance while supporting environmentally responsible construction practices.

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Declaration of computing interests

The authors confirm that there are no financial or personal conflicts of interest that could have impacted the research presented in this paper.

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