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ORIGINAL RESEARCH ARTICLE

DURABLE AND LOW-CARBON CONCRETE: ENGINEERING PROPERTIES OF CEMENT BLENDED WITH SOYBEAN HUSK ASH AND SUGARCANE BAGASSE ASH

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ABSTRACT

The growing demand for sustainable, low-carbon construction materials has sparked interest in using crop residues in replacing supplementary cementitious materials (SCMs). This study evaluated the Engineering performance and durability under Sulphate attack using a ternary blend of cement, with SHA and SBA fully and partially replaced. Four agricultural residues, soybean husk, Bambara nut shell, melon husk, and sugarcane bagasse, were screened using the modified Chapelle test at calcination temperatures of 500, 600, 700, and 800°C. Soybean husk and sugarcane bagasse were the most reactive when calcined at 700°C, fixing 1620.19 and 879.99 mg Ca(OH)2 per gram, respectively, and were consequently selected and processed into SHA and SBA for physical and chemical characterization, including oxide composition, particle-size distribution and specific gravity. Concrete was proportioned as one OPC control and nine ternary OPC SHA SBA blends spanning 5-35% total ash replacement, mixed at three water-cement ratios (0.30, 0.40 and 0.45). Each mix was evaluated for fresh-state performance (initial and final setting time, slump) and for hardened compressive strength after 28 days of water curing followed by prolonged exposure to magnesium sulphate. The inclusion of SHA and SBA progressively retarded both the initial and final setting and reduced the slump from 58 mm (control) to 45 mm at the highest replacement level, indicating reduced workability at high ash contents. Cubes were monitored for compressive strength at nine ages up to 360 days. Under sulphate exposure, all mixes lost strength over time; the control (100-0-0) at 0.30 w/c fell from 33.86 MPa (1 day) to 19.82 MPa (360 days). The ternary 75-15-10 blend (75% OPC, 15% SHA, 10% SBA) showed the best long-term sulphate resistance, retaining 20.52 MPa at 360 days and exceeding the control's 360-day strength by about 12% (0.45 w/c). The combined SiO_2 + Al_2O_3 + Fe_2O_3 content was 85.42% for SHA and 91.26% for SBA, both exceeding the 70% threshold specified in ASTM C618-19. The findings demonstrate the viability of soybean husk ash and sugarcane bagasse ash as eco-friendly cement replacements, with moderate replacement levels (≤15% of total) offering the best balance of strength and sulphate resistance.

1.0 Introduction

Concrete is one of the most commonly used construction materials in the world, with an estimated ten billion tonnes produced each year, driving heavy reliance on raw materials such as cement (Ibrahim *et al.*, 2024; Griffiths *et al.*, 2023; Li *et al.*, 2022). The production of Ordinary Portland Cement (OPC) accounts for approximately 5–7% of global anthropogenic CO_2 emissions and contributes significantly to environmental degradation and climate change (Jha *et al.,* 2020; Akintayo *et al.,* 2024; Shivaprasad *et al.,* 2024). Athe mining of raw materials for cement production also leaves lasting footprints on the land surface, in the form of gullies and craters, ultimately degrading the land (Evuti *et al.,* 2023). To reduce these impacts, there is growing interest in the partial replacement of Portland cement with other cementitious materials (SCMs) such as industrial by-products or agricultural waste ashes (Fode *et al.,* 2023; Alsharari, 2025; Onyenokporo, 2022; Singh *et al.,* 2024; Chen *et al.,* 2024).

The use of SCMs, particularly those acquired from industrial by-products or domestic and agricultural waste, has emerged as a promising decarbonisation strategy (Sakir *et al.,* 2019; Šupić *et al.,* 2021; Olaiya *et al.,* 2023; Almeshal *et al.,* 2020; Olaiya *et al.,* 2025). Beyond lowering embodied carbon, well-processed SCMs has the capacity to enhance the durability by reducing permeability and pore structure and through the secondary formation of calcium-silicate-hydrate (C–S–H) gel (Durai *et al.,* 2025; Fode *et al.,* 2023). Among this waste are sugarcane bagasse ash (SBA) and rice husk ash, abundantly generated as a by-product of agricultural products, is a particularly promising candidate owing to its high silica content, amorphous structure and demonstrated potential to improve the strength and durability at replacement levels up to about 20% (Farrant *et al.,* 2022; Amjad *et al.,* 2025; Prabhath *et al.,* 2023).

Concrete containing SBA can exhibit reduced water absorption, improved sulphate resistance and reduced chloride ingress, particularly when the ash is properly calcined and ground, although these benefits are frequently accompanied by delayed setting and reduced early-age workability (Prabhath *et al.,* 2023). Treated SBA exhibits pozzolanic reactivity comparable to that of fly ash. Similarly, soybean husk ash (SHA), an abundant local agro waste, has demonstrated pozzolanic potential, producing concrete with acceptable strength and long-term performance when adequately processed and blended, particularly in ternary systems incorporating other ashes (Šupić *et al.,* 2021).

Despite this progress, three gaps still remain unfilled. Although SBA and, to a lesser extent, SHA have each been studied individually, very few investigations have examined combined SHA–SBA ternary cementitious systems, in which the two ashes may act complementarily, the higher-silica SBA promoting pozzolanic densification and the alumino-ferric SHA contributing additional reactive phases. Second, most durability assessments of bagasse- and husk-based concretes are limited to short exposure periods; long-term magnesium-sulphate ($MgSO_4$) durability data extending to 360 days are scarce, even though $MgSO_4$ attack is among the most aggressive degradation mechanisms for blended cements because it destabilises both portlandite and C–S–H. Third, the interaction between ash replacement level and water–cement ratio under sustained sulphate exposure has rarely been mapped across multiple w/c ratios, yet this interaction governs permeability, which controls sulphate ingress. The present study directly addresses these gaps.

Based on the aforementioned, the objectives of this study are: to screen four agricultural residues by the modified Chapelle test and identify the most reactive pozzolans; to characterise the selected ashes through oxide composition, particle-size distribution and specific gravity; to evaluate the fresh-state behaviour (setting time and slump) of PLC–SHA–SBA blends; and to quantify the compressive-strength evolution of these blends under prolonged $MgSO_4$ exposure at three water–cement ratios (0.30, 0.40 and 0.45), thereby establishing the replacement level that best balances workability, strength and sulphate durability.

2. Materials and Method

The principal binder used was Portland Limestone Cement type due to its relevant National Standard. River sand (fine aggregate) and crushed granite (coarse aggregate) were sourced locally. Four agricultural residues, soybean husk, Bambara, nutshell, melon husk and sugarcane bagasse were sourced from OLAM agricultural facilities and associated processing locations within the study area, and were air-dried, in the Civil Engineering laboratory of the Federal University of Agriculture, Makurdi Benue State, calcined and ground prior to reactivity screening; the two most reactive residues were retained as ashes (SHA and SBA) for concrete production. A polycarboxylate-based super-plasticiser was used in the low w/c mixes (0.30 0.40 and 0.45), where the reduced water content limited workability during mixing.

2.1 Modified Chapelle

The modified Chapelle test was conducted to determine the pozzolanic reactivity for each of the material by measuring the mass of $Ca(OH)_2$ fixed per gram of test material. One gram of pozzolan powder was placed in a dry, clean Erlenmeyer flask; 250 mL of water was added using a calibrated pipette; and 2 g of CaO was

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weighed and added. The flask was placed on a heated magnetic stirrer and held at 85 ± 5 °C for 16 hours, after which it was allowed to return to room temperature. A blank without pozzolan was run in parallel.

The flask was filled with freshly prepared saccharose (60 g per 250 mL H 2O), which was mixed for 15 min; about 200 ml was filtered, and an aliquot of 25 ml was drawn off with a volumetric pipette. The aliquot was titrated with 0.1 N HCl using phenolphthalein indicator. For a material to be classified as reactive, the quantity of Ca $(OH)_2$ fixed should be at least 650 mg per gram of pozzolan. The titration reactions are:

$$CaO + 2HCl \rightarrow CaCl_2 + H_2O \qquad 1$$

$$Ca(OH)_2 + 2HCl \rightarrow CaCl_2 + 2H_2O \qquad 2$$

Results are expressed as mg of Ca $(OH)_2$ fixed by the pozzolan. As shown in Table 1, the most reactive agricultural residues were soybean husk and sugarcane bagasse, which fixed 1620.19 mg and 879.99 mg of Ca $(OH)_2$, respectively, when calcined at 700 °C. Soybean husk ash (SHA) and sugarcane bagasse ash (SBA) were, therefore, selected for blending with cement. The negative values recorded for the melon residue are physically meaningless a sample cannot fix less lime than the blank and reflect experimental scatter; that residue was treated as non-reactive.

2.2 Particle-size Distribution

The particle-size distributions of soybean husk ash, sugarcane bagasse ash, coarse aggregate and fine aggregate were measured. Sieve-size distribution test was conducted by placing air-dried specimens and shaking them through a nest of BS standard test sieves (BS 3406-4:1993). The mass on each sieve was weighed, and the cumulative size percentage was determined. Each sieve was perfectly dry and clean prior to beginning use.

2.3 Specific Gravity

The specific gravity of the aggregates and ashes was determined as the ratio of the unit weight of the material to that of water, in accordance with BS 812-103.2 (1989). Specific gravity was calculated using Equation 3:

$$Gs = \frac{B}{P+B-PS} \qquad 3$$

Where: B is the sample weight, P is the weight of the pycnometer + water, and PS is the weight of the pycnometer + water + sample.

2.4 Initial and Final Setting Time

Setting time and hardening are both important physical consequences of a paste based on the binder that is subjected to hydration and are regarded as primary. The initial set indicates when the paste ceases to be plastic, and the final set indicates when it is no longer plastic or liable to distortion but has not yet hardened. This test has been carried out in a Vicat apparatus complete with needle, mould, initial and final needles, balance and gauging trowel. The materials have been mixed to a standard consistency, mixing times was noted and for the initial set the 1mm (3mm) diameter 0.1g rod had been dropped on the surface at 10 min intervals with, the interval being over when the 1mm diameter rod no longer penetrates to within 0.5cm (1mm) 5mm below the surface of mould, BS 4550 (1978), and for the final set the final set needle had been repeated with the annular piece when penetration to within 0.5cm of bottom is only registered by ring in the case of fine setting and complete without leaving any impression with true setting (true and rapid set).

2.5 Concrete Production and Sulphate Exposure

Concrete cubes (100 × 100 × 100 mm) were casted to determine compressive strength. After demoulding, the cubes were cured in water at 20 ± 1 °C for 28 days and later transferred to a magnesium-sulphate ($MgSO_4$) solution of 5% concentration by mass; compressive strength was determined at 1, 7, 14, 21, 28, 58, 90, 180 and 360 days of exposure. Three water–cement ratios (0.30, 0.40 and 0.45) were investigated to address the low-permeability criterion (Tables 2 and 3). A superplasticiser was used for the 0.30 and 0.40 w/c mixes, where the low water content limited workability on mixing.

2.6 Experimental Matrix

The full test programme is summarised in Table 2. Ten binder systems (one OPC control and nine ternary OPC–SHA–SBA blends) were cast at each of three water–cement ratios and tested at nine exposure ages. Three replicate cubes were tested at every mix × w/c × age combination, and the mean is reported. The compressive-strength programme, therefore, comprised 10 × 3 × 9 × 3 = 810 cubes.

Table 1: Summary of the experimental programme (compressive-strength specimens).

Parameter	Detail
Binder systems (mixes)	10 (1 OPC control + 9 ternary OPC–SHA–SBA blends)
Water–cement ratios	3 (0.30, 0.40, 0.45)
Exposure ages	9 (1, 7, 14, 21, 28, 58, 90, 180, 360 days)
Replicates per mix × w/c × age	3 cubes (mean reported)
Cube size	100 × 100 × 100 mm
Curing/conditioning	28 d water curing (20 ± 1 °C), then $MgSO_4$ immersion
Total compressive-strength cubes	10 × 3 × 9 × 3 = 810

Table 2: Mix proportions per 0.001 m³ (one 100 × 100 × 100 mm cube).

Cement (%)	SHA (%)	SBA (%)	Cement (kg)	SHA (kg)	SBA (kg)	Sand (kg)	Gravel (kg)
100	0	0	0.3816	0	0	0.5511	0.9286
90	5	5	0.3625	0.0191	0.0191	0.5511	0.9286
85	10	5	0.3243	0.0382	0.0191	0.5511	0.9286
85	5	10	0.3243	0.0191	0.0382	0.5511	0.9286
80	10	10	0.3052	0.0382	0.0382	0.5511	0.9286
75	15	10	0.2862	0.0572	0.0382	0.5511	0.9286
75	10	15	0.2862	0.0382	0.0572	0.5511	0.9286
70	15	15	0.2672	0.0572	0.0572	0.5511	0.9286
65	20	15	0.2481	0.0763	0.0572	0.5511	0.9286
65	15	20	0.2481	0.0572	0.0763	0.5511	0.9286

Table 2 summarises the experimental investigation, which aimed to assess the compressive strength of ten binder systems comprising an OPC control concrete and nine OPC-SHA-SBA ternaries over the age at test and for three water/cement ratios. Three w/c ratios (0.30, 0.40, 0.45) and nine ages were studied. From each mixture design, three 100 x 100 x 100 mm concrete cubes were cast, for a total of 810 cubes in the investigation programme. All concrete cubes were cured for 28-days in the water at 20 ± 1 °C and tested in a magnesium sulphate solution for both strength and sulphate resistance. Table 3 presents the concrete mixture design for each cube. The total replacement percentage of SHA and SBA for OPC was varied from 10% to 35%, while the aggregate mix ratios were unchanged, to study the effect of binder content only.

Plate 1: Curing concrete samples.

Plate 2: Cube-crushing of concrete samples.

2.8 Compressive-Strength (Cube-Crushing) Test

Compressive strength tests were conducted in accordance BS 1881: Part 116 (1983) using the ELE International Digital 2000 kN Concrete Cube Compression Testing Machine. Cube specimens (100 × 100 ×

100 mm), which were taken out of their curing or exposure solutions containing sulphate and used immediately, were centred between the loading platens. The disks were then uniformly loaded at an approximate rate of 15 MPa/min until failure such that the two formed faces came into contact with the platens and their respective opposite formed faces were also against the platens. The load applied at ultimate failure was recorded, and the compressive strength was calculated by dividing this load by the cross-sectional area, with results expressed in MPa.

3. Results and Discussion

3.1 Preliminary Characterisation of the Reactive Materials

The preliminary pozzolanic reactivity of the four agricultural waste materials was evaluated using the modified Chapelle test after calcination at four temperatures (500, 600, 700, and 800°C). The results, expressed as milligrams of $Ca(OH)_2$ fixed per gram of pozzolan, are presented in Table 3.

Table 3: Pozzolanic reactivity of agricultural wastes calcined at various temperatures (mg $Ca(OH)_2$ fixed per gram of pozzolan).

Sample	Temperature (°C)	Reactivity (mg $Ca(OH)_2$ fixed)
Soybean husk	500	906.81
	600	950.38
	700	1620.19
	800	725.83
Bambara nutshell	500	89.76
	600	698.11
	700	209.43
	800	468.78
Melon	500	−578.91
	600	−515.99
	700	440.48
	800	−1170.41
Sugarcane bagasse	500	494.58
	600	424.20
	700	879.99
	800	430.90

Table 3 shows the modified-Chapelle reactivity of the four candidate residues at four calcination temperatures (500, 600, 700, and 800°C) relative to the 650 mg Ca(OH)2/g threshold used to classify a material as pozzolanically reactive (Section 2.2). For both soybean husk and sugarcane bagasse, reactivity increases with calcination temperature of up to 700°C and then falls sharply at 800°C, yielding peak values of 1620.19 mg/g and 879.99 mg/g, respectively. This non-monotonic trend is consistent with the known thermal behaviour of plant-derived silica: at lower temperatures (500-600°C), combustion of the residual organic matter is incomplete, leaving carbon and less-ordered material that dilutes the reactive fraction; at 700°C, organic matter is fully burnt off while the silica remains predominantly amorphous and therefore highly reactive; beyond 700°C (800°C), the amorphous silica begins to sinter and recrystallise into low-reactivity crystalline phases (e.g. cristobalite), which is why reactivity drops again at the highest temperature. On this basis, 700°C was identified as the optimum calcination temperature for both residues, and both exceed the 650 mg/g threshold by a wide margin at that temperature (2.5× and 1.35×, respectively).

By contrast, bambara nutshell only exceeds the reactivity threshold at 600°C (698.11 mg/g), and even then, only marginally, while its values at 500, 700 and 800°C (89.76, 209.43 and 468.78 mg/g) remain well below the threshold; the absence of a consistent temperature trend suggests an intrinsically lower and less reliable pozzolanic potential, and it was therefore not selected for further use. Melon residue performed worst of all: three of its four readings were negative (−578.91, −515.99 and −1170.41 mg/g at 500, 600 and 800°C), and it's one positive reading (440.48 mg/g at 700°C) still falls short of the threshold. A negative fixed-lime value is not physically meaningful, since a sample cannot remove less lime than the blank already contains; these results most likely reflect a combination of negligible intrinsic reactivity and experimental/titration scatter around zero, and melon residue was accordingly treated as non-reactive and excluded from further work. Soybean husk and sugarcane bagasse, calcined at 700°C, were therefore the only two residues that were both reliably reactive and reactive by a comfortable margin, justifying their selection for processing into SHA and SBA (Section 2.3) and use in the concrete blends reported in the remainder of this paper.

To assess their suitability as pozzolanic materials for partial cement replacement, the selected ashes were subjected to oxide composition analysis, sieve analysis, and specific gravity measurement.

These three properties were selected deliberately because each governs a different stage of performance: oxide composition determines whether a material can chemically react as a pozzolan at all (Section 3.2); particle-size distribution governs its fineness, water demand and packing behaviour in the fresh mix (Section 3.3); and specific gravity is required to convert the mix proportions in Table 3 from mass to volume so that the ashes correctly displace cement and aggregate rather than simply adding to the mix (Section 3.4). The results of all three are interpreted together with the fresh-state (Sections 3.5-3.6) and hardened-state (Section 3.7) results to build a coherent explanation of why the ash blends behave as they do, rather than being read as isolated data sets.

3.2 Oxide Composition

From the oxide compositions in Tables 4 and 5, both sugarcane bagasse ash (SBA) and soybean husk ash (SHA) and qualify as pozzolans for partial replacement of cement, since their combined SiO_2 + Al_2O_3 + Fe_2O_3 content meets the requirement of the ASTM C618 requirement (≥ 70% for Class N/F pozzolans).

Table 4: Oxide composition of soybean husk ash (SHA).

S/No	Oxide	Composition (%)
1	SiO_2	46.82
2	Al_2O_3	20.12
3	Fe_2O_3	18.48
4	CaO	5.21
5	MgO	1.76
6	MnO	0.61
7	Na_2O	0.86
8	K_2O	0.82
9	P_2O_5	0.32
10	SO_3	0.61
11	LOI	6.94

The combined content of the three principal oxides (SiO_2, Al_2O_3, Fe_2O_3) totals 85.42%, well above the 70% stipulated by ASTM C618 for Class F/N pozzolans (Taku & Amartey, 2018), confirming SHA as a reactive pozzolan capable of forming additional C–S–H gel and enhancing long-term strength and durability. The moderate CaO content (5.21%) contributes to early hydration without the expansion risks associated with high-calcium systems, while the low SO_3 content (0.61%) is well within the ASTM limit (≤ 4%), minimising the likelihood of delayed ettringite formation under sulphate exposure (Taku & Amartey, 2018; Subedi *et al.,* 2019).

Table 5. Oxide composition of sugarcane bagasse ash (SBA).

S/No	Oxide	Composition (%)
1	SiO_2	68.54
2	Al_2O_3	14.20
3	Fe_2O_3	8.52
4	CaO	1.31
5	MgO	0.20
6	MnO	0.40
7	Na_2O	–
8	K_2O	2.49
9	P_2O_5	0.33
10	SO_3	0.26
11	LOI	7.60

For SBA, the three principal oxides sum to approximately 91.26%, comfortably exceeding the 70% benchmark for Class F pozzolans (Chekol & Ftwi, 2024) and confirming SBA as a highly reactive pozzolan that contributes substantially to secondary C–S–H formation. The silica content (68.54%) is consistent with literature values of 65–76% (Xu *et al.*, 2018). The loss on ignition of 7.60%, although slightly elevated, remains within acceptable limits for effective pozzolanic activity; SBA with LOI below about 10% generally performs well as an SCM (Chekol & Ftwi, 2024). The low CaO (1.31%) and SO_3 (0.26%) contents indicate that SBA primarily acts as a pozzolanic and filler additive, reducing the risk of detrimental expansion or delayed ettringite formation under sulphate exposure.

Tables 4 and 5 explain much of the durability behaviour reported later in Section 3.7. Both ashes are markedly lower in CaO and SO3 than Portland cement, so replacing cement with SHA or SBA reduces the total amount of portlandite and sulphate-reactive calcium-aluminate phases available in the hardened paste. Since magnesium-sulphate attack proceeds primarily by consuming portlandite and decalcifying C-S-H, a matrix with proportionally less portlandite to begin with, and additional C-S-H formed from the pozzolanic reaction, is intrinsically less vulnerable to this attack, provided the replacement level is not so high that early strength and matrix continuity are compromised. This is consistent with the finding that moderate replacement (10-15%) outperformed both the unblended control and the highest-replacement blends under long-term sulphate exposure, the oxide chemistry sets an upper bound on how much of the vulnerable phase can be removed, while the physical dilution of the clinker fraction sets a lower bound on how far replacement can go before strength suffers.

3.3 Particle-Size Distribution

Figures 1, 2, 3, and 4 show the results of sieve analysis for coarse and fine aggregates. It appears that the fine aggregate (sand), coarse aggregate (gravel), sugarcane- bagasse-ash (SBA) and sugarcane soybean-husk-ash (SHA) are well-graded materials. For all samples, the ashes produced a retention peak in the sieves with about 0.425-0.30 mm, with about 96-97 % below sieve 0.85 mm. This implies that a fine, well-graded powder is produced by both ashes, and its fineness increases the specific surface area required for the pozzolanic reaction and enhances packing; however, it also demands more water content, as observed in the slump section 3.5.

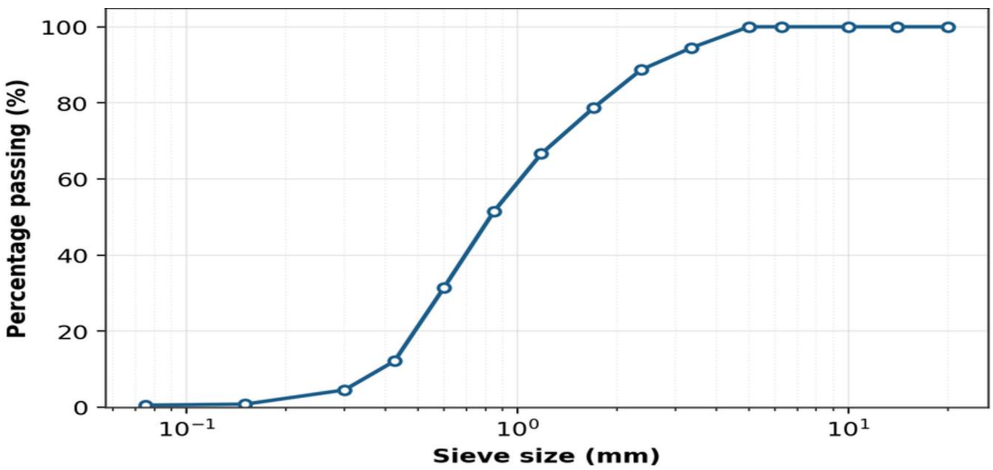

Figure 1: Sieve analysis of fine-aggregate (sand).

The sand gradation (Figure 1) shows a smooth, continuous curve typical of a well-graded natural river sand, with no large gaps between successive sieve fractions. Continuous grading of this kind minimises void volume between particles, which reduces the paste volume needed to fill those voids and coat the particles; this supports the workability of the control mix and provides a reference against which the effect of adding fine ash particles can be judged

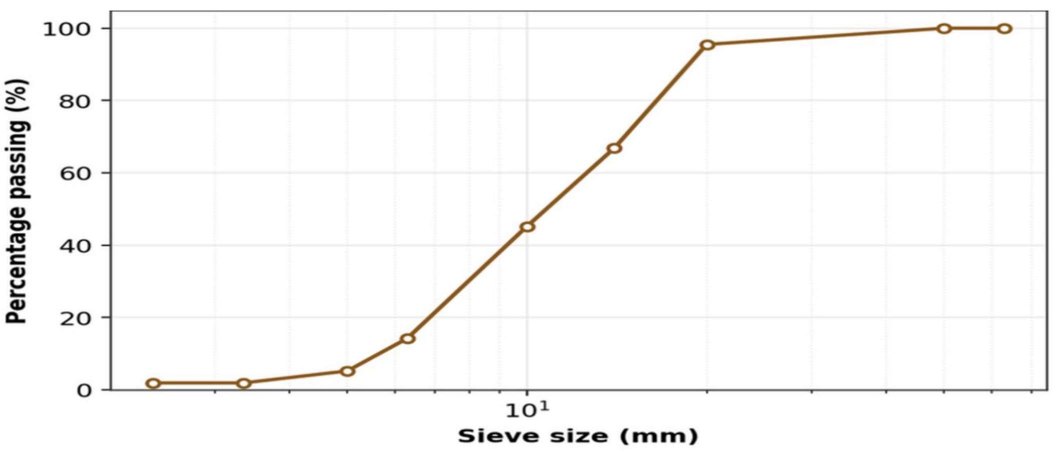

Figure 2: Sieve analysis of coarse-aggregate (gravel).

The coarse-aggregate gradation (Figure 2) shows a steep drop in percentage passing between the 20 mm and 6.3 mm sieves, characteristic of a single-sized crushed granite rather than a graded aggregate spanning multiple size fractions. Single-sized coarse aggregate typically requires a higher proportion of fine material (sand, and here also the fine ash particles) to fill the larger inter-particle voids it creates; this partly explains why even the control mix required a moderate water content to achieve workable consistency, and why the added fineness of SHA and SBA had a measurable effect on slump.

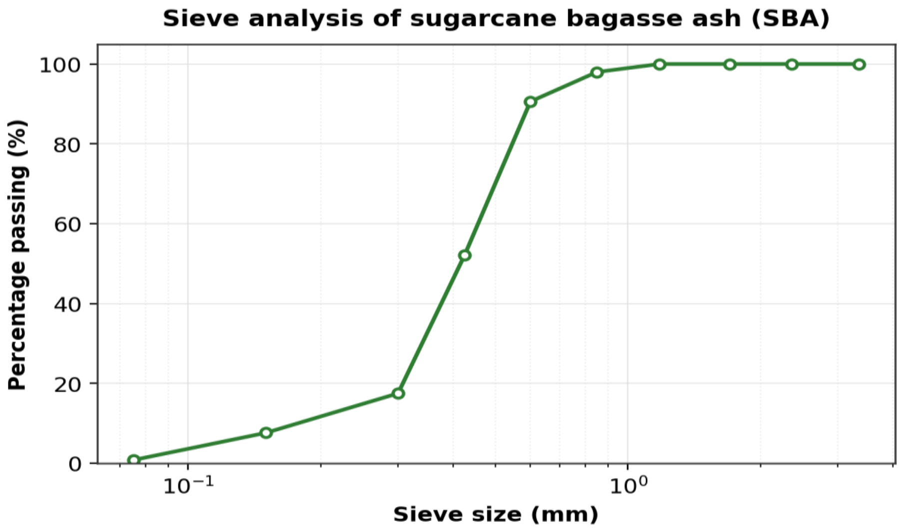

Figure 3: Sieve analysis of sugarcane bagasse ash (SBA).

SBA (Figure 3) is remarkably finer than either aggregate, with roughly 90% passing the 0.6 mm sieve and a steep decline, thereafter, concentrating most particles in the 0.15–0.6 mm range. This fineness is what gives SBA its pozzolanic reactivity (a greater surface area is available for reaction with portlandite) but is also what increases its water demand relative to cement of similar mass, since finer particles require more water to wet their larger combined surface area.

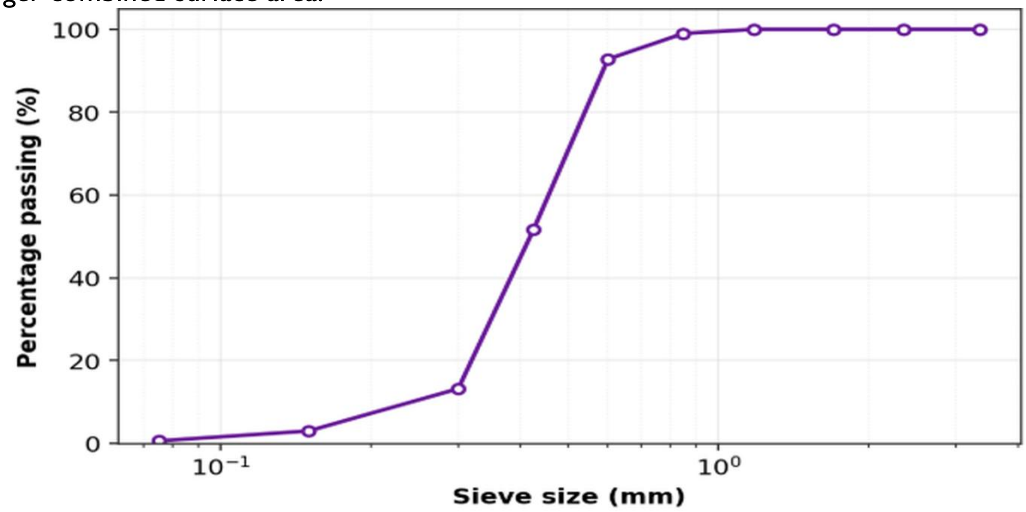

Figure 4: Sieve analysis of soybean husk ash (SHA).

SHA (Figure 4) follows a trend very similar to that of SBA, with about 93% passing 0.6 mm, and is marginally finer overall. The close similarity between the two gradations (Figures 3 and 4) suggests that any difference in setting behaviour or strength contribution between SHA- and SBA-rich blends (Sections 3.5 and 3.7) is more likely attributable to their differing oxide chemistry (Section 3.2) than to a difference in particle fineness, since the two ashes present a comparable surface area to the mixing water.

3.3 Specific Gravity

The specific gravities of sugarcane bagasse ash, soybean husk ash, sand and crushed granite are presented in Table 2. The aggregate values fall within the 2.50–3.00 range characteristic of natural construction materials. Sugarcane bagasse ash averaged about 2.50, consistent with reported ranges for SBA (1.78–2.88) and lower than the specific gravity of cement (2.9–3.15) (Mora-Ruiz *et al.,* 2022; Ahmad *et al.,* 2021). A lower specific gravity means that, at equal mass, the ash contributes a greater volume of cementitious material, which must be accounted for in absolute-volume mix-design calculations. Because pozzolans such as SBA and SHA combine lower specific gravity with higher fineness, they tend to increase water demand and can delay setting unless the water or admixture dosage is adjusted (Ullah *et al.,* 2025).

Table 6: Specific gravity of the sample.

Procedure	SBA	SHA	River Sand	Crushed Granite
Weight of sample, B (g)	10.0	10.0	600	600
Weight of density bottle, empty (g)	29.5	29.5	589	589
Weight of bottle + water, P (g)	104.73	104.73	1593	1590
Weight of bottle + sample (g)	39.5	39.5	1189	1189
Weight of bottle + water + sample, PS (g)	110.60	110.47	1966.33	1964.33
Average specific gravity, G_s	**2.50**	**2.35**	**2.65**	**2.69**

Table 6 shows that, Soybean husk ash (SHA) recorded the lowest average specific gravity at 2.35, making it the lightest material in the group. This is consistent with the porous, organic nature of husk-derived ash, which tends to have more internal void space and lower particle density. Sugarcane bagasse ash (SBA) followed at 2.50, slightly denser than SHA but still well below the aggregates. The difference between the two ashes suggests that SBA particles are more compact, possibly due to differences in the combustion process or the original plant structure from which each ash was derived. River sand, used as the fine aggregate, returned an average specific gravity of 2.65, which falls squarely within the typical range expected for natural sand (generally 2.6 to 2.7). Crushed granite, the coarse aggregate, came in slightly higher at 2.69, reflecting its mineral composition of quartz, feldspar, and mica, which are inherently denser than the organic-derived ashes.

3.4 Initial and Final Setting Time

Figure 5 shows the setting time increased systematically with the proportion of SHA and SBA, relative to the control (100-0-0), which set initially at 72 minutes and finally at 98 minutes, the ash-blended pastes set progressively later: even a modest 5% + 5% blend (90-5-5) almost doubled the times to 142 and 237 minutes, and the highest replacement (65-15-20) reached 416 and 572 minutes, roughly six times the control's initial set. This deceleration takes place, because in substitution with cement calcium quantity as well as very early heat of hydration are declined so that crystal growth rate of hydration products become slower; additional C-S-H is created through pozzolanic action from ashes but the later one starts a bit more delayed so it can take the final setup place after a while (Senhadji *et al.,* 2012).

The minimum initial time of setup is to take 45minutes, and optimum for final time setup has been prescribed of no more then 10h for usage. (BS 12, 1996). All the OPC/SHA/SBA pastes satisfy both limits: the initial sets exceed the 45-minute minimum, and the final sets (up to 572 minutes, or 9 h 32 min) remain within the 10-hour maximum. The prolonged set acts effectively as a built-in retarder, extending the available working time, but it would compromise rapid construction cycles at high replacement levels; mixes with 20% or more total replacement (initial/final sets of about 416/572 minutes) would benefit from accelerating admixtures or a higher clinker fraction to remain practical.

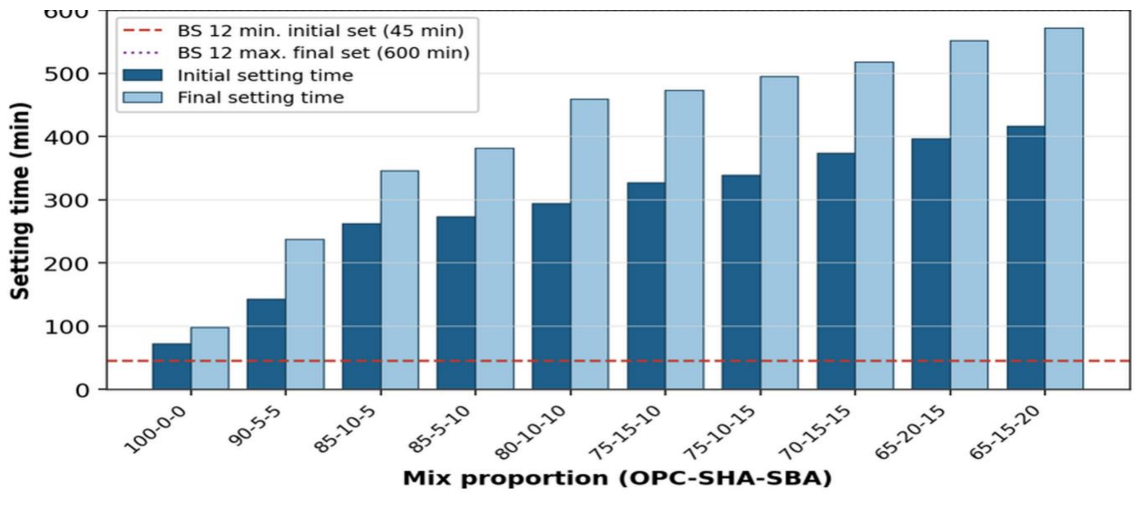

Figure 5: Initial and final setting times of the cement blends.

3.5 Slump (Workability)

Figure 6 shows the effect of SHA/SBA content on slump. The control (100-0-0) gave a slump of 58 mm (medium workability). Minor replacements (90-5-5, 85-10-5 and 85-5-10) maintained similar values (about 59–60 mm), indicating that up to roughly 15% combined ash has a negligible effect on fresh consistency. Beyond this, slump fell progressively to 45 mm at 65-15-20, a reduction of about 22% relative to the control.

The physical properties of the ash particles control this behaviour, and there appears to be little or no chemical effect in the fresh state. Because the SAH and SBA (Section 3.3) have very fine particle size distributions, substantially finer than cement, they provide a greater surface area per unit volume to adsorb mixing water onto their surfaces, resulting in reduced mobility for lubrication of the mix. A typical angular morphology, possibly partly porous, also enhances interparticle friction in the mixes and the internal water requirement for ashes; additionally, the porous nature of the carbonaceous residue (as evidenced by a loss on ignition) acts as an internal water reservoir. The combined result is a lower free-water content at constant w/c and hence reduced slump. These mechanisms are consistent with reports that high replacement levels of fine, angular pozzolanic particles reduce workability due to increased surface area and water demand (Chandio *et al.,* 2020; Memon *et al.,* 2022; Wageti *et al.,* 2023).

Although some studies (Prabhath *et al.,* 2023; Olaiya *et al., 2025)* report slight workability gains with coarser bagasse ash at low replacement levels, in the present ternary system, the finer combined particle characteristics dominate as total ash content increases. Up to 15% total ash, the concrete remained workable (slump 58–60 mm) and suitable for general applications without mix design changes; beyond 15%, the slump dropped below 50 mm. To preserve workability at high ash contents (≥ 20%), the water content or plasticiser dosage should be increased to ensure proper placement, compaction and uniform curing.

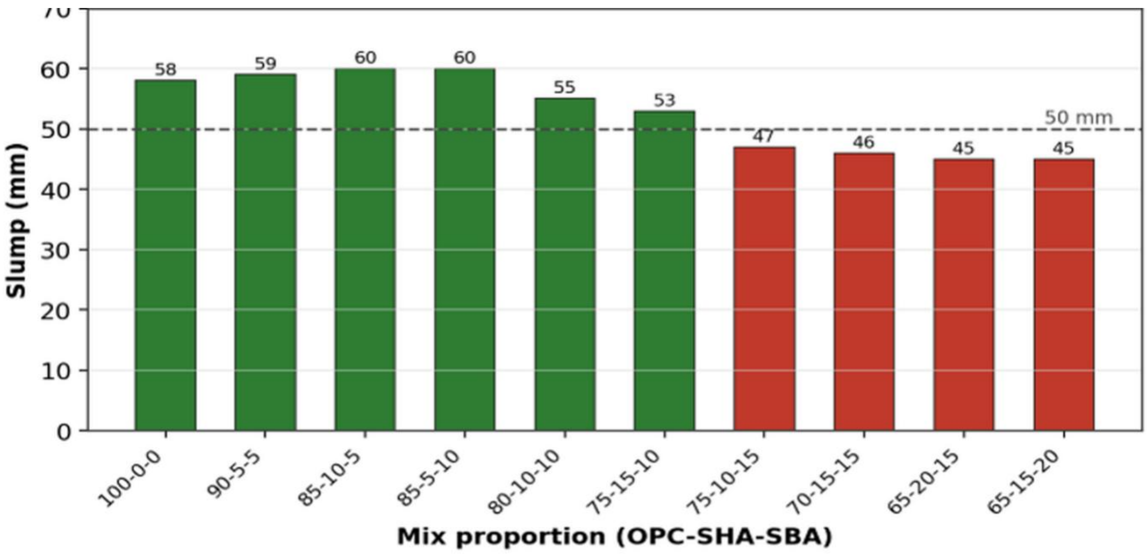

Figure 6: Variation of slump with cement-replacement level.

3.6 Compressive Strength under Sulphate Exposure

Figures 7-9 illustrate compressive strength values for cubes w/c =0.30, 0.45 and 0.40, respectively, after being cured in water for 28 days, and consequently immerged into the MgSO4 solution, for various soaking periods, up to 360 days. Attention is placed when analysing the three simultaneous processes for such plots, to consider the effect of each individually. During the initial 28-day water-curing period (before sulphate immersion), continued cement hydration and the onset of the pozzolanic reaction build strength, which is why the ash blends, though lower than the control at 1 day, develop comparatively dense matrices. Once specimens are transferred to $MgSO_4$ solution, two opposing effects then operate simultaneously: ongoing pozzolanic densification, which tends to raise strength, and sulphate-induced deterioration, which tends to lower it. The measured strength at any age is the net result of this competition.

The deterioration mechanism is characteristic of magnesium-sulphate attack, aiding sulphate ions to react with calcium-bearing hydrates, forming an expansive gypsum and ettringite, while Mg^{2+} displaces Ca^{2+} in the C–S–H and portlandite to form non-cementitious brucite ($Mg(OH)_2$) and, ultimately, weak magnesium-silicate-hydrate. This decalcification destabilises the C–S–H binding, generates internal expansion and microcracking, increases porosity and permeability, and accelerates further ingress in a self-reinforcing cycle that manifests as the gradual strength decline observed across all mixes (Oymael, 2008; Adewumi *et al.,* 2025). At 0.30 w/c, the control fell from 33.86 MPa (1 day) to 19.82 MPa (360 days), a 41% reduction.

The benefit of moderate replacement is best understood through pore refinement. The pozzolanic reaction consumes free portlandite, the phase most vulnerable to sulphate and magnesium attack, and converts it into additional C–S–H that subdivides and blocks the capillary pore network. This refined, less-connected pore structure lowers permeability and slows the ingress of aggressive Mg^{2+} and SO_4^{2-} ions, so moderate ternary blends deteriorate more slowly than the control over the long term. At high replacement (≥ 20% total), however, there is insufficient cement to sustain early strength and to generate enough portlandite to drive the pozzolanic reaction to completion; the dilution of clinker dominates, early strength is low, the matrix is more porous, and durability suffers. The optimum, therefore, lies at intermediate replacement: the 75-15-10 mix retained 20.52 MPa at 360 days, exceeding the 360-day strength of the control, whereas the 65-15-20 mix fell from 20.32 to 12.51 MPa. This explains why moderate replacement outperforms both the plain control and the high-replacement blends in long-term sulphate resistance, despite its lower early strength.

Water–cement ratio strongly influenced retention. The mixes of 0.30 w/c consistently retained the highest strengths, also, the mixed of 0.45 w/c had the lowest, while that mixes of 0.40 w/c were intermediate, confirming that a lower w/c reduces capillary porosity, limits sulphate-ion ingress, and slows degradation (Hanafiah *et al.,* 2018; Diab *et al.,* 2017). For the control, the 360-day strengths were 19.82 MPa at 0.30 w/c, 18.37 MPa at 0.45 w/c, and 17.78 MPa at 0.40 w/c. For the 75-15-10 blend, the difference between water–cement ratios at 360 days were small, indicating that moderate ternary blends become less sensitive to w/c over the long term as the pozzolanic reaction densifies the matrix. Overall, moderately ash-blended mixes (10–15% replacement) preserved about 18–20 MPa at 360 days, within usable thresholds for sulphate-exposed concrete.

3.6.1 Compressive strength at 0.30 w/c

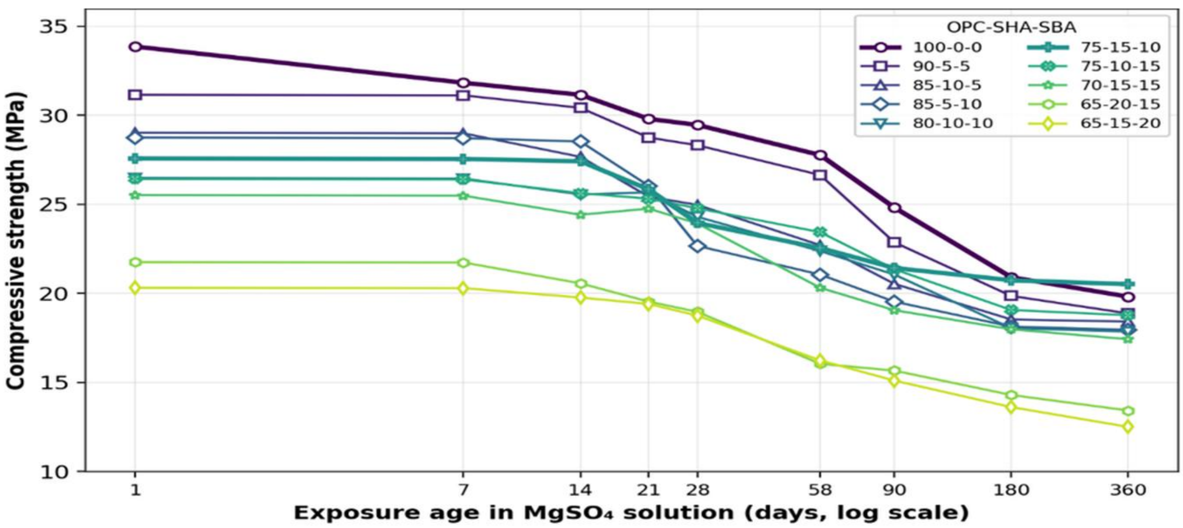

Figure 7: Concrete cubes' compressive strength at 0.30 w/c under $MgSO_4$ exposure.

At 0.30 w/c, the control fell from 33.86 MPa (1 day) to 19.82 MPa (360 days), a 41% reduction. The 75-15-10 ternary blend retained 20.52 MPa at 360 days, the highest of all mixes at this w/c ratio, while blends with 20% or more total ash replacement declined to 13.43 and 12.51 MPa, indicating that clinker dilution outweighs pore-refinement benefits once replacement exceeds about 15%.

3.6.2 Compressive strength at 0.45 w/c

At 0.45 w/c, the control fell from 32.68 MPa (1 day) to 18.37 MPa (360 days). The 75-15-10 blend showed the most pronounced benefit of all three w/c ratios here, retaining 20.52 MPa at 360 days against the control's 18.37 MPa, about 12% higher. Because this series did not include superplasticiser (Section 2.6), this comparison is the least confounded by admixture effects, though see the SP caveat recorded there.

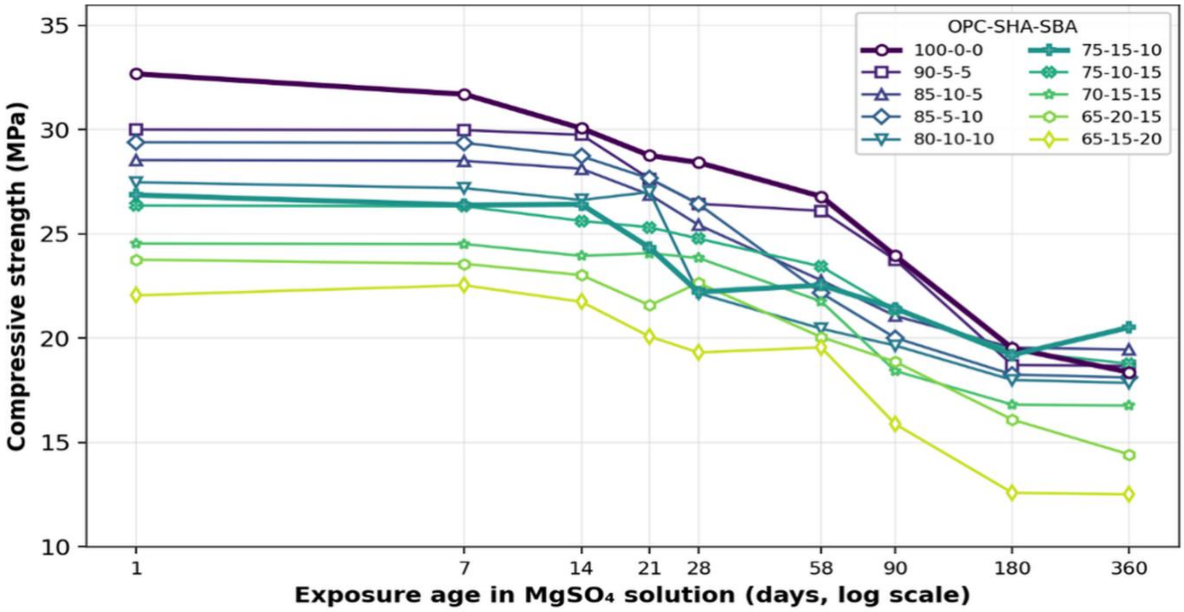

Figure 8: Concrete cubes' compressive strength at 0.45 w/c under $MgSO_4$ exposure.

3.6.3 Compressive strength at 0.40 w/c

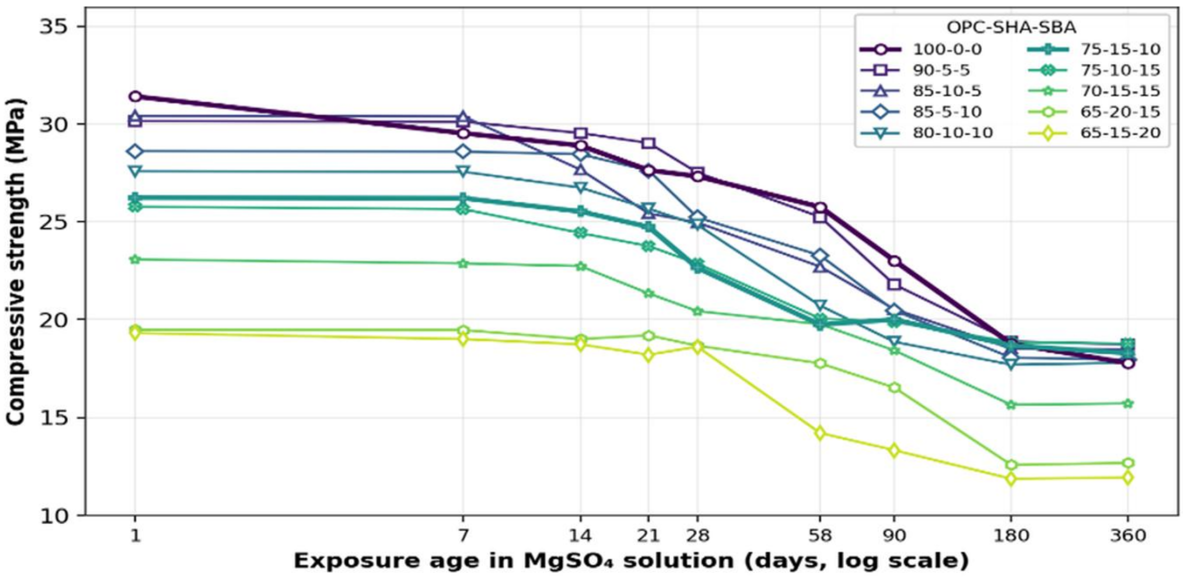

Figure 9: Concrete cubes' compressive strength at 0.40 w/c under $MgSO_4$ exposure.

At 0.40 w/c, the control declined from 31.41 MPa (1 day) to 17.78 MPa (360 days). The 75-10-15 blend performed best at 360 days (18.78 MPa), narrowly ahead of 75-15-10 (18.29 MPa). As at the other two w/c ratios, the highest-replacement blends (65-20-15, 65-15-20) recorded the lowest 360-day strengths (12.68 and 11.93 MPa), reinforcing that moderate replacement (10-15%) is the more durable choice across w/c ratios.

4. Conclusion

This study confirmed soybean husk ash (SHA) and sugarcane bagasse ash (SBA) as reactive, chemically suitable pozzolans capable of partially replacing Ordinary Portland Cement. Ternary blending of OPC with SHA and SBA improved resistance to magnesium sulphate attack compared to the control, with moderate replacement levels offering the best balance of strength and durability, while higher replacement levels became counterproductive. A lower water-cement ratio further strengthened this resistance.

Although increasing SHA-SBA content progressively affected setting time and workability, all blends remained within standard limits, confirming their practical usability. Overall, the study demonstrates that moderate ternary blending with SHA and SBA offers a viable, low-carbon pathway to more durable concrete, and a moderate-replacement blend at a low water-cement ratio is recommended for reinforced-concrete elements exposed to sulphate-bearing ground conditions.

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