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Effect of Partial Replacement of GGBFS with Wheat Husk Ash (10–30%) on the Compressive Strength of Low-Alkali Geopolymer Concrete under Ambient Curing



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ABSTRACT

Geopolymer Concrete (GPC) has gained acceptance as a solution for concrete applications, particularly those activated at low-alkali conditions and containing industrial or agricultural wastes, due to the increasing demand for more sustainable alternatives to Ordinary Portland Cement (OPC). This study investigates the effect of partial replacement of ground granulated blast furnace slag (GGBFS) with wheat husk ash (WHA) at 10%, 20%, and 30% on the compressive strength of geopolymer concrete. A combination of sodium hydroxide (6M) and sodium silicate solution at a concentration of 6M and 10% by weight silica fume to enhance active ability. At 7, 28 and 90 days compressive strength was determined. The improvement of long-term strength (90 days) was observed, with a 10% replacement of GGBFS by WHA showing almost complete retention of the control performance (up to 20% replacement of GGBFS by WHA). X-ray fluorescence (XRF) analysis indicated that the incremental increase of WHA raised SiO_2 concentration and decreased CaO concentration which impacted the gel composition and led to the increase in strength. WHA was found to be an attractive and a sustainable pozzolanic material in low-alkali geopolymer systems, owing to its mechanical and green benefits, which the study concludes.

Key words: GGBFS, geopolymer concrete; low-alkali activator, wheat husk ash, compressive strength, XRF

1. INTRODUCTION

1.1 Scope

This study investigates the development of low-alkali geopolymer concrete using Ground Granulated Blast Furnace Slag (GGBFS) and wheat husk ash (WHA) as sustainable binders. Geopolymer concrete (GPC), as an alternative to Ordinary Portland Cement (OPC), offers reduced carbon emissions and utilizes industrial or agricultural waste materials [1], [2].

1.2 General

OPC production is responsible for nearly 8% of global CO_2 emissions due to its energy-intensive process and limestone calcination [1], [2]. In contrast, geopolymer technology uses aluminosilicate-rich materials activated by alkaline solutions to form durable Si–O–Al networks [3], [4].

GGBFS, with its high calcium content, is widely used as a precursor due to its rapid reaction kinetics under low-temperature curing [5]–[7]. However, high-concentration alkali activators like NaOH and Na₂SiO₃ present cost and safety issues [8], [9]. Research now focuses on low-alkali systems (≤ 6 M NaOH) supplemented with silica fume or reactive agricultural ashes [10], [11], which improve workability and reduce efflorescence [12], [13].

WHA, obtained from controlled combustion of wheat husks, contains 75–85% reactive SiO₂ and shows promising pozzolanic behaviour [14]–[19]. Previous studies suggest that partial replacement of GGBFS with silica-rich ashes improves compressive strength, though excessive replacement may reduce Ca²⁺ availability and hinder gel formation [20]–[25]. Studies show that mixtures containing WHA can produce both N-A-S-H and C-A-S-H gels, which are key to strength development [26]–[30].

However, most studies on WHA are under high-alkali activation. There is limited research on its performance in low-alkali geopolymer systems and little understanding of long-term strength (90 days) in ambient curing conditions [31]–[35]. Also, the influence of oxide composition from WHA on gel chemistry requires further investigation [36]–[40].

The current study explores the compressive strength of GPC mixes with 10%, 20%, and 30% WHA replacing GGBFS. The activator was used 6M NaOH with sodium silicate, and 10% silica fume was included to enhance reactivity. Compressive strength was tested at 7, 28, and 90 days. Additionally, X-ray fluorescence (XRF) analysis performed to correlate chemical composition with strength development.

GGBFS is one of the most widely used low-carbon supplementary binders in concrete, but its availability relies heavily on steel production and may vary from region to region. Moreover, the growing global demand for slag has prompted studies on various agricultural waste-based supplementary materials. Wheat husk ash (WHA) with its high amount of reactive silica could be a potential replacement material in geopolymer systems. Hence, further systematically exploration of utilizing WHA as a partial replacement for GGBFS could facilitate the diversification of sustainable binder sources along with agricultural residues utilization.

There is growing attention on the use of agricultural waste materials in geopolymer systems due to their potential environmental benefits and that they may help reduce dependency on conventional, industrial precursors. Nevertheless, an all-encompassing environmental appraisal would necessitate a complete life-cycle assessment (LCA), which is outside of the current analysis.

2. MATERIALS AND METHODS

2.1 Materials

Ground granulated blast furnace slag (GGBFS) used for mixing in this study was sourced from a local steel manufacturing plant. The material had specific gravity of 2.88 and Blaine fineness of 420 m²/kg. XRF analysis showed that the most abundant oxides were CaO, SiO₂, Al₂O₃, and MgO (>90% of total).

Wheat husk ash (WHA) was produced by controlled combustion of wheat husk residues in a muffle furnace at 600–700°C for 2 hours, followed by grinding and sieving through a 75 µm sieve to obtain fine ash suitable for geopolymer applications.

It was found from XRF testing that the specific gravity of resultant ash was equal to 1.38 and was composed of about 78% reactive silica, some alumina and traces of other oxides.

The raw materials used in this study include sodium hydroxide, GGBFS, WHA, and Silica Fume (SF), as shown in Figure 1.

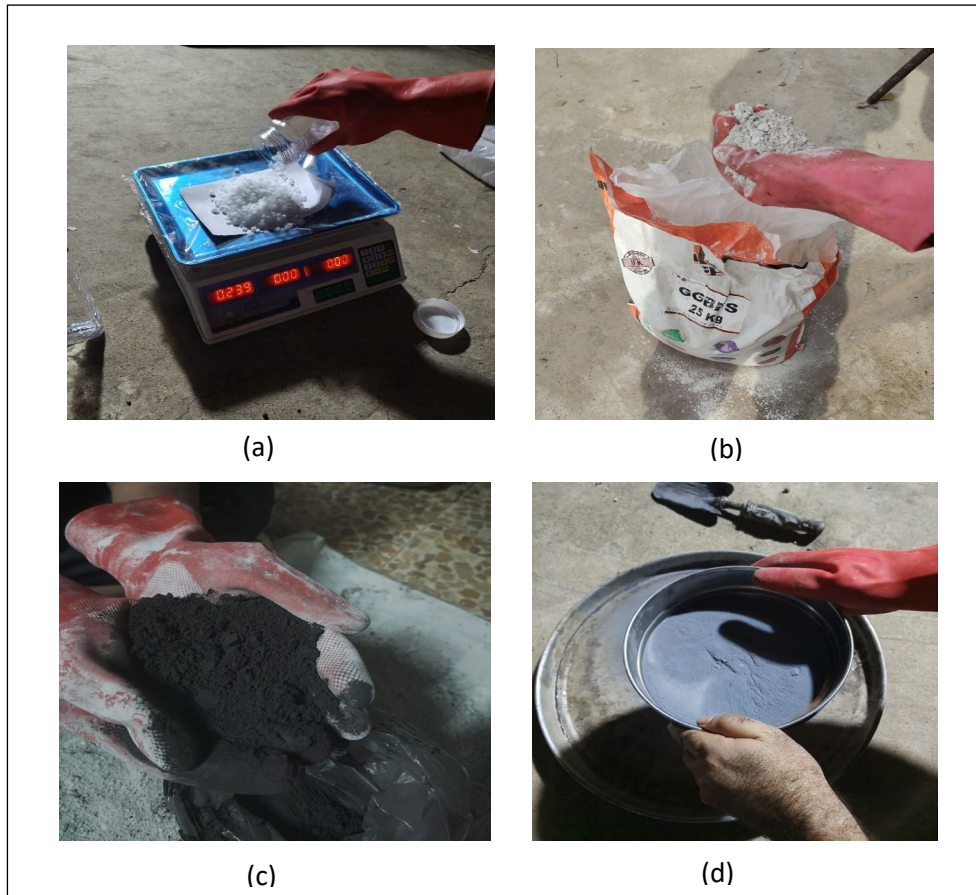


Figure 1 – Raw materials used in the study: (a) NaOH, (b) GGBFS, (c) WHA, (d) SF.

A commercial pozzolanic admixture >92% SiO_2 scale commercially, HIKOTEQC® 930, with a specific gravity of about 2.2 was used as silica fume.

Alkaline activator consisted of 6M sodium (NaOH) solution which was prepared by dissolving solid flakes in distilled water and sodium silicate (Na_2SiO_3) solution containing 28.5% SiO_2 , 9.5% Na_2O and 62% of water. The mass-based $\text{Na}_2\text{SiO}_3/\text{NaOH}$ activator ratio was controlled to be 2.0.

The fine and coarse aggregates used were natural river sand (fineness modulus: 2.65) and crushed coarse aggregate (10 mm max size) having specific gravities of 2.6 and 2.7 respectively. Before mixing, all aggregates were dried in an oven at $110 \pm 5^\circ\text{C}$ for about 24 h until constant mass was achieved, in accordance with ASTM C566.

Table 1 – Physical and chemical properties of raw materials used in the study

Material	Property	Value
GGBFS	Specific gravity(-)	2.88
GGBFS	Blaine fineness	420 m ² /kg
GGBFS	Major oxides	CaO, SiO ₂ , Al ₂ O ₃ , MgO
WHA	Specific gravity(-)	1.38
WHA	Reactivity (SiO ₂ content)	≈ 78%
WHA	Sieve size	75 μm
Silica Fume	SiO ₂ content	>92%
Silica Fume	Specific gravity(-)	2.2
NaOH	Molarity	6 M
Na₂SiO₃	SiO ₂ / Na ₂ O / H ₂ O	28.5% / 9.5% / 62%
Sand	Fineness modulus	2.65
Coarse agg.	Max size / Specific gravity(-)	10 mm / 2.7
SP (Viscrete 180)	Dosage	1% of binder weight

Superplasticizer, Viscrete 180 (polycarboxylate-based), was added at 1% by weight of the total binder to enhance workability and delay setting.

2.2 Mix proportioning

Four geopolymer mixes were prepared: a control mix (0% WHA) and three mixes where GGBFS was partially replaced by WHA at 10%, 20%, and 30% by binder weight. A constant binder content of 400 kg/m³ and alkaline-to-binder ratio of 0.50 were maintained. Silica fume was kept constant at 10% of the binder in all mixes. The mix proportions of the geopolymer concrete with varying WHA content are summarized in Table 2.

Table 2 – Mix proportions of geopolymer concrete with partial replacement of GGBFS by WHA

Mix ID	GGBFS (kg)	WHA (kg)	S.F (kg)	NaOH 6M (kg)	Na ₂ SiO ₃ (kg)	Sand (kg)	Coarse Agg. (kg)	SP (L)
Ref (0%)	400	0	40	100	170	1000	1167	4
M10 (10%)	360	40	40	100	170	1000	1167	4
M20 (20%)	320	80	40	100	170	1000	1167	4
M30 (30%)	280	120	40	100	170	1000	1167	4

Note: All values are per mix batch (1 m³)

Mixing and casting procedures the geopolymer concrete samples were conducted manually using a mechanical mixer, followed by casting into molds. The process is illustrated in Figure 2.

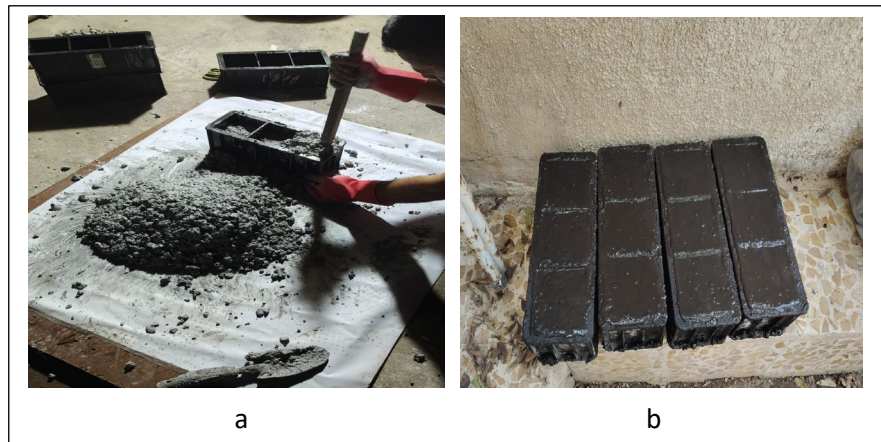


Figure 2 – (a) Mixing and casting of geopolymer concrete (b) Fresh samples after demolding

2.3 Testing procedures

Compressive Strength Test

The compressive strength tests were conducted according to ASTM C109 using 100 mm cube specimens. After demolding at 24 hours, samples were cured under ambient laboratory conditions (25–30 °C) with an approximate relative humidity of 50–60%. Average strengths were recorded at 7, 28, and 90 days using three specimens per mix as showing in Figure 3.

Khudhair and Basher [41] employed a similar strength testing approach on pumice concrete; however, their work utilized a different curing method. The testing protocol itself remains consistent and methodologically relevant to the present study.



Figure 3 – Compressive Strength Test

X-Ray Fluorescence (XRF) analysis

Each binder mix was analyzed for its chemical oxide composition using portable X-Ray Fluorescence (XRF) spectrometer. All samples were analyzed for chemical composition (major oxides [SiO_2 , CaO , Al_2O_3 , MgO , etc.]) and correlation was done between chemical composition and mechanical performance.

In Figure 4 shows the oxide composition of the control mix (0% WHA) obtained from XRF analysis. The results for the most abundant oxides (SiO_2 , CaO , Al_2O_3 and MgO) represented the > 90 % of the total. Although the control mix did not have any WHA, the increased SiO_2 content present in this mix (47.15%) was decided based on high silica obtained from the GGBFS and fixed dosage of silica fume (10%) in all mixes. This combined input is what we feel justifies the high base line % silica of the XRF results.

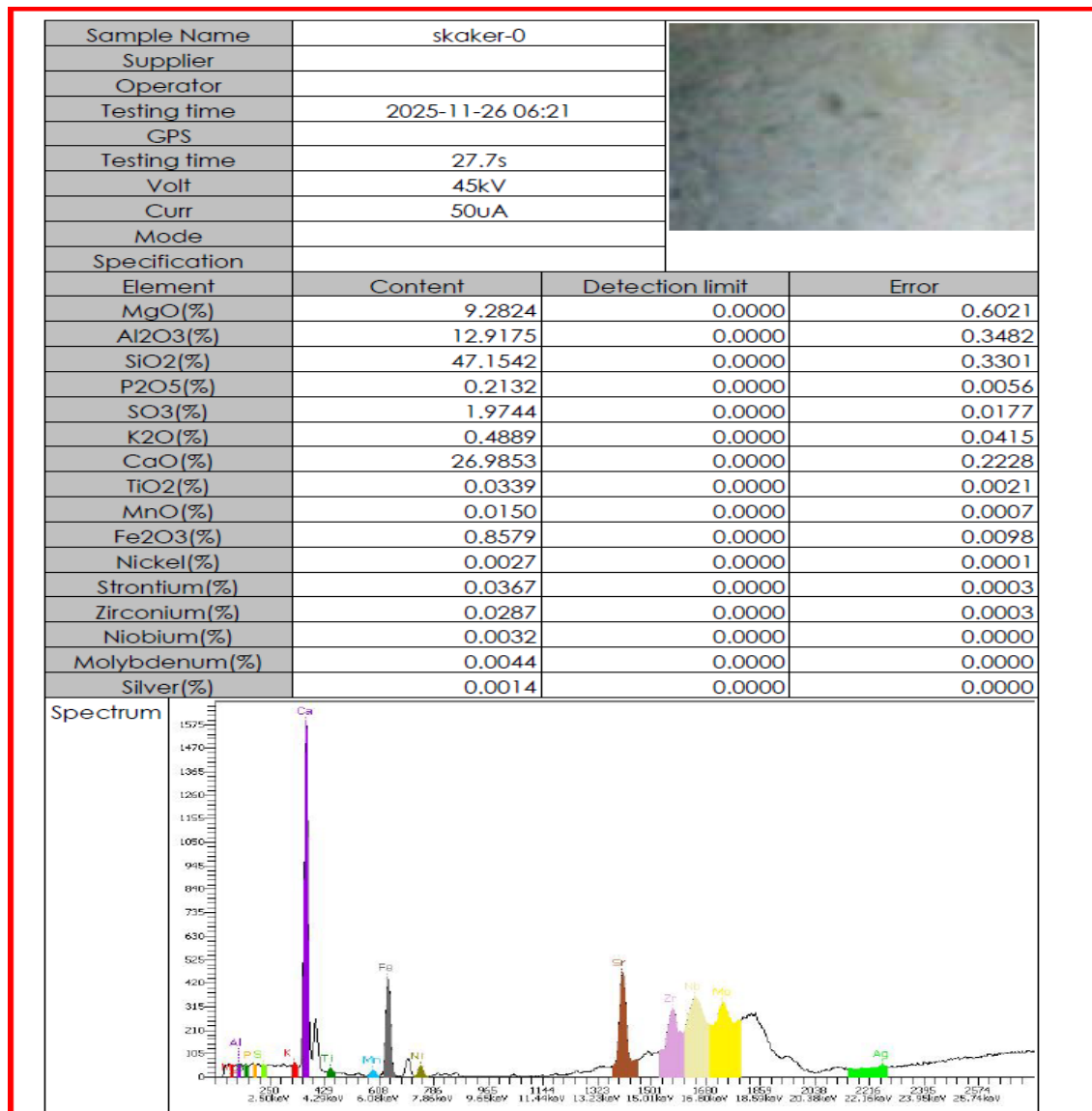


Figure 4 - XRF spectrum of the control geopolymer binder 0% Wheat Husk Ash(WHA).

Figure 5 shows the XRF spectrum and oxide composition of the 10% WHA mix. And SiO₂ is the most oxides of about 54.3%, followed by CaO (21.7%) and Al₂O₃ (11.3%). The high content of SiO₂ is due to the silica-rich wheat husk ash and the use of silica fume in the mixture. The reason is the rise in silica content, which aids the geopolymerization process by forming aluminosilicate gel networks that are directly responsible for strength development.

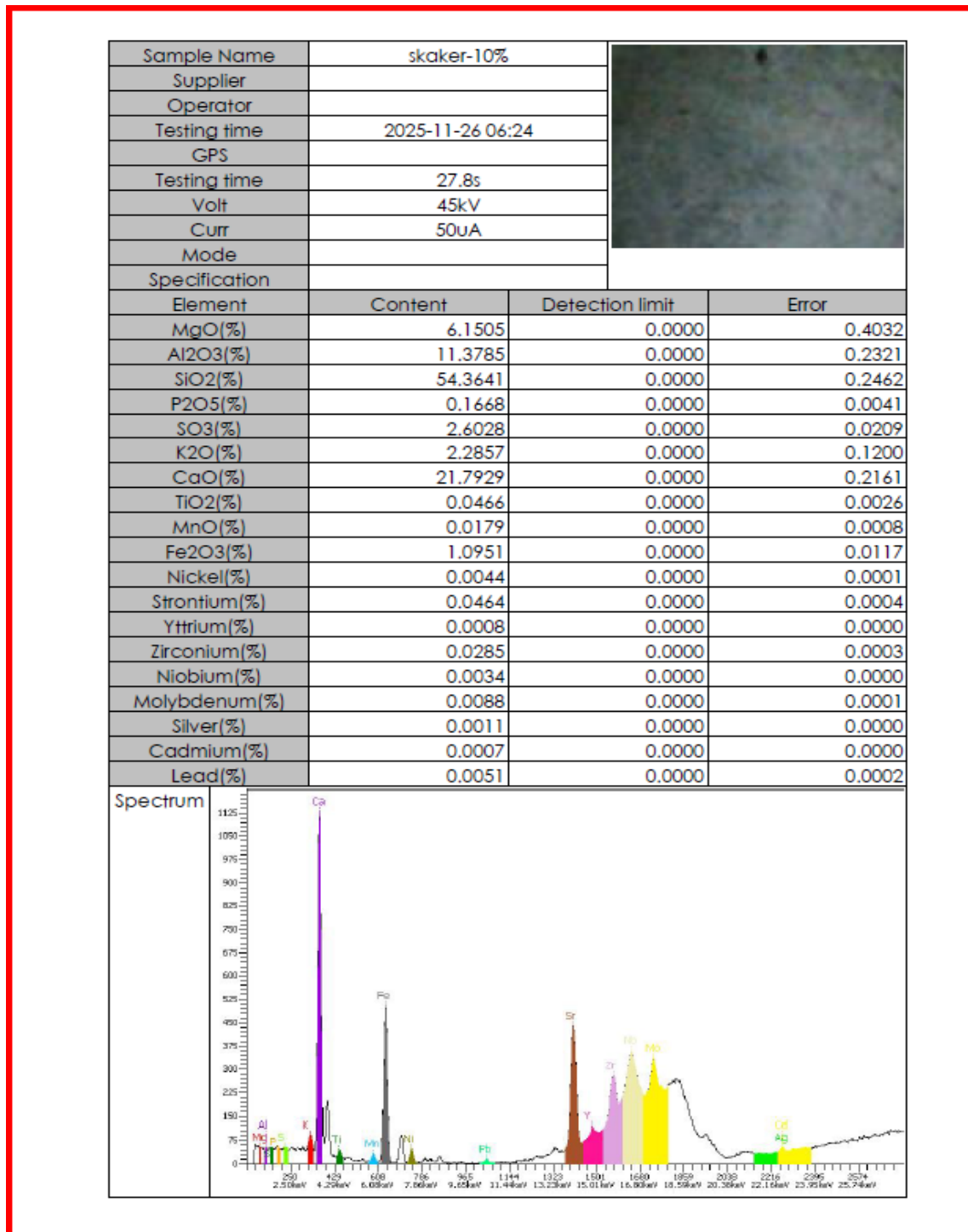


Figure 5- XRF spectrum and chemical oxide composition of geopolymer binder with 10% Wheat Husk Ash (WHA) replacement.

In Figure 6, the 20% WHA mix exhibited a further increase in SiO₂ content to 54.5%, along with a continued reduction in CaO (16.5%). This trend reinforces the influence of reactive silica-rich WHA in the geopolymer matrix, contributing to enhanced polymerization potential and reduced calcium dominance.

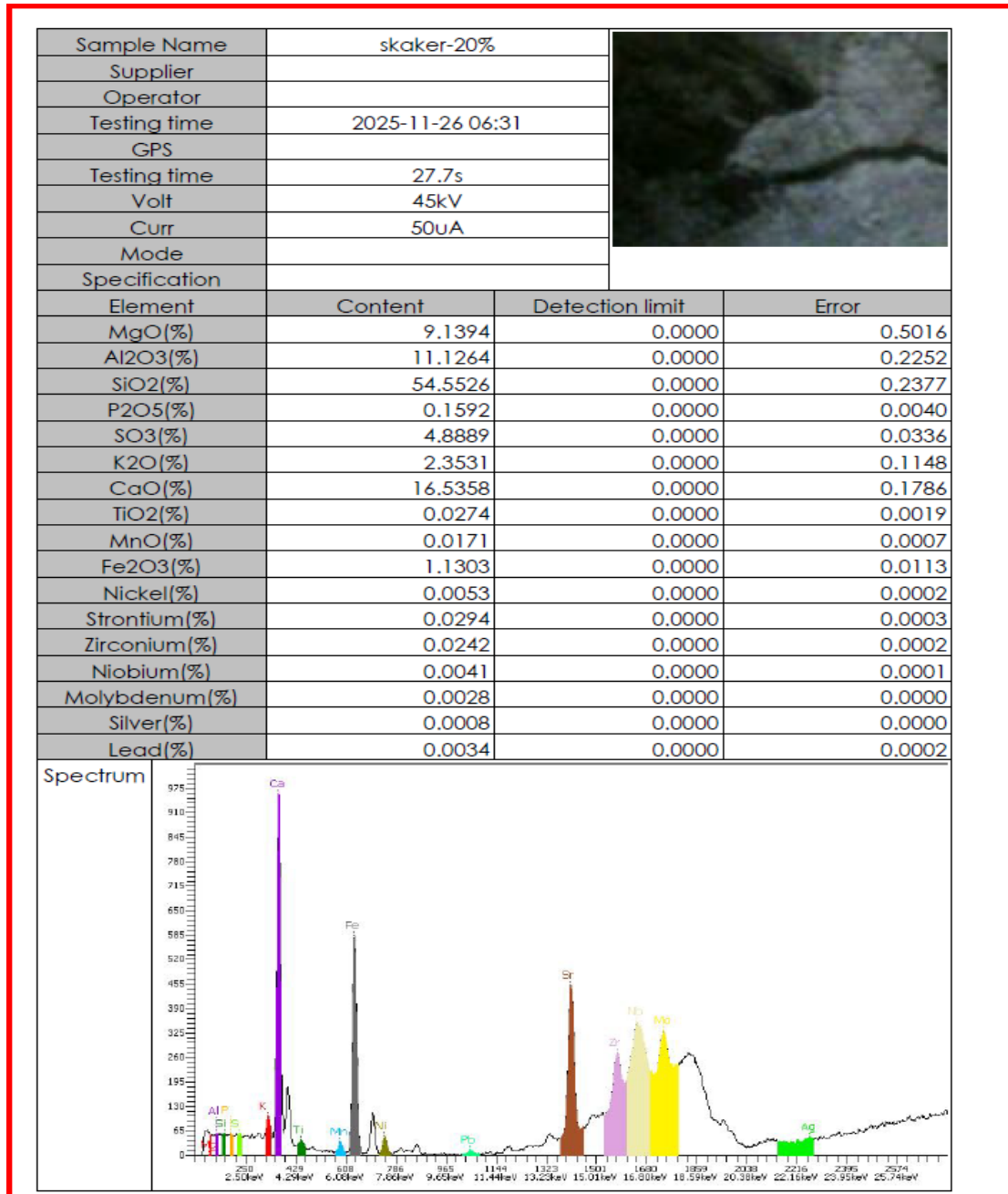


Figure 6 -XRF spectrum and oxide composition of geopolymer binder with 20% Wheat Hask Ash (WHA) replacement.

Figure 7 presents the XRF results for the 30% WHA mix, which exhibited the highest SiO₂ content (62.4%) among all mixes. This significant increase aligns with the higher dosage of reactive silica contributed by WHA. Concurrently, CaO content dropped to 11.85%, indicating a reduced availability of calcium for C–A–S–H gel formation, which may explain the slight decline in compressive strength at this replacement level.

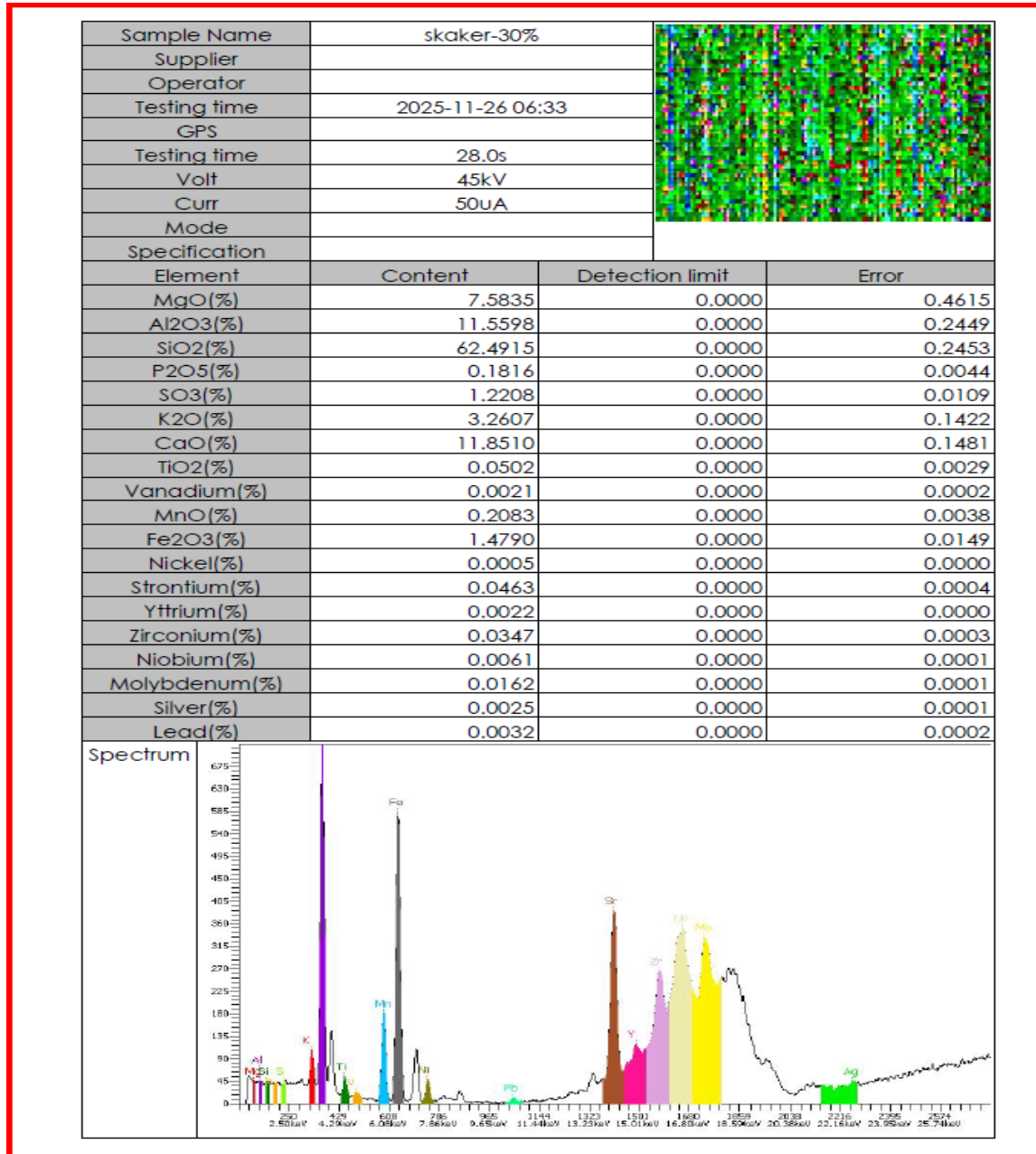


Figure 7 - XRF spectrum and oxide composition of geopolymer binder with 30% Wheat Husk Ash(WHA) replacement.

3. RESULTS AND DISCUSSION

3.1 Compressive strength development

Development of compressive strength for all mixes with 0%, 10%, 20%, and 30% WHA replacement level were assessed at 7, 28 and 90 days, respectively Figure 8. shows the results of the analysis. The compressive strength of the control mix (0% WHA) showed a strength of 56.1 MPa at 7 days and was consistent with little decrease with time, achieving a compressive strength of 55.0 MPa at 90 days.

The 10% WHA (M10) mix exhibited a similar strength trend with 54.41 MPa at 90 days and 99% strength retention with respect to the control. This is meaningful since it shows that a 10% replacement is able to preserve mechanical performance but at the same time enhance sustainability.

A significant decrease in compressive strength was found for higher replacement levels (M20 and M30) and this result is consistent with the findings in previous studies. For M20, compressive strength at 90 days was 48.7 MPa (88% retention) and for M30 compressive strength at 90 days was 38 MPa (70% retention). These findings indicate that excessive WHA may decrease the amount of C–A–S–H (calcium-activated silicate hydrate) gels, consequently limiting both early-age strength and total polymerization.

The general trend provides supports that WHA can be safely used at 10% in geopolymer systems activated with low-alkali solutions at ambient conditions without a loss of the strength. The obtained compressive strength results are consistent with previous studies on geopolymer systems incorporating agricultural ashes. Similar trends were reported in the literature, where moderate replacement levels of agricultural ashes maintained compressive strength, while higher replacement levels resulted in a reduction in strength due to lower calcium availability in the system [15], [18]. These findings are in agreement with the results of the present study.

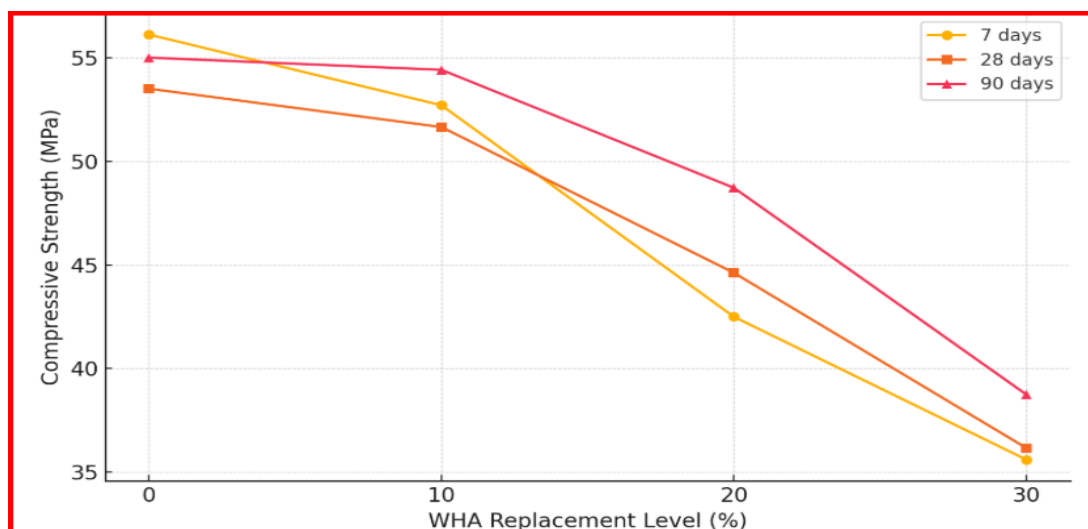


Figure 8 – Compressive strength development of geopolymer concrete incorporating WHA at different curing ages (7, 28, and 90 days)

3.2 XRF-based chemical analysis of binders

X-ray fluorescence (XRF) analyses were carried out to assess the effect of Wheat Husk Ash (WHA) on the chemistry of the geopolymer binder for all four mixes, Ref (0% WHA), M10 (10%), M20 (20%), and M30 (30%). Here, the highlight was on the two major oxides (SiO_2 and CaO) that influence the mechanical behaviour through equilibrium of geopolymerisation and gel formation.

As illustrated in Figure 9, the results show a consistent increase of SiO_2 content, with the control mix containing the lowest value (47.1% SiO_2) and specimens with 30% WHA replacement approximately 62.4%, which is due to the predominantly amorphous silica content in WHA. On the other hand, CaO decreased from 27% to 11.8% due to gradually diluted calcium-rich GGBFS.

This behaviour indicates that WHA serves as an in situ precursor for N-A-S-H gels at the same time minimizes the formation of C-A-S-H gels due to lower calcium origin from WHA. This change in gel chemistry helps explain the strength behaviour seen: moderate replacement (10–20%) provides the right compromise while over-replacement (30%) can upset the calcium–silicate balance necessary for strength development. We found by XRF analysis that increased WHA resulted in increased oxides namely SiO_2 and decreased CaO with increasing WHA. This shift influenced the balance between N-A-S-H and C-A-S-H gel phases, affecting long-term mechanical properties.

Consequently, the XRF analysis corroborates the previously discussed compressive strength results, as it reaffirms that significant portions of WHA (of up to 20%) can safely be replaced without severely diminishing the chemical reactivity of the binder or its potential to form the necessary dense gel. Figure 9 shows the major oxide contents, including SiO_2 and CaO , as a function of WHA replacement level. The inverse relationship between them is evident in that WHA was increasing, the SiO_2 content and the CaO content was decreasing, which verifies the siliceous characteristic of WHA and the dilution of the CaO -rich GGBFS.

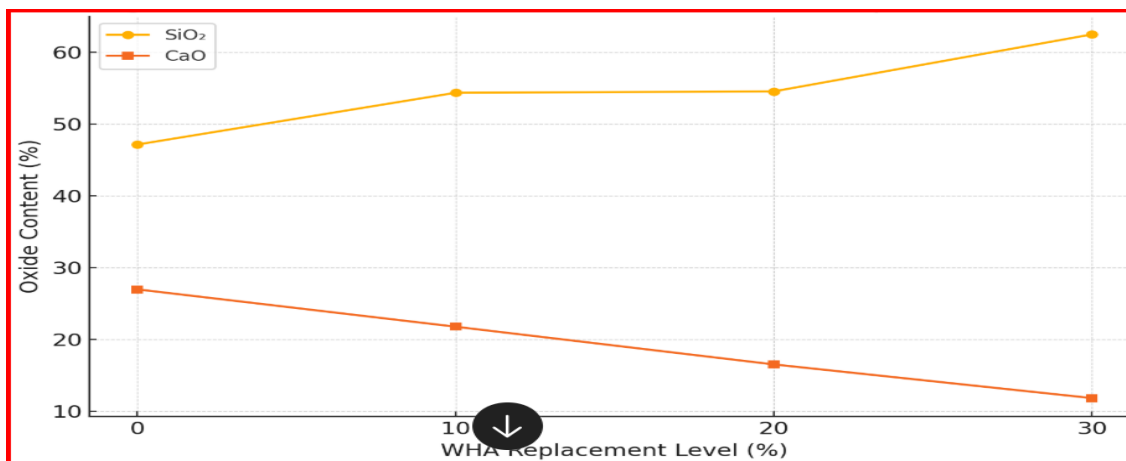


Figure 9 – Variation in SiO_2 and CaO contents based on WHA replacement level in geopolymer binder system.

It should be noted that the present study focuses primarily on the compressive strength development and chemical composition of the geopolymer binder system under ambient curing conditions. Durability aspects such as freeze–thaw resistance, chloride penetration, carbonation

resistance, and reinforcement corrosion were not investigated in this work and should be addressed in future studies, particularly for applications in cold climatic regions.

4. CONCLUSIONS

This study investigated the effect of partial replacement of Ground Granulated Blast Furnace Slag (GGBFS) with Wheat Husk Ash (WHA) at levels of 10%, 20%, and 30% on the compressive strength and chemical composition of low-alkali geopolymer concrete cured under ambient conditions. The following conclusions can be drawn:

1. WHA demonstrated potential as a sustainable pozzolanic material, with a high SiO₂ content (up to 62% at 30% replacement) contributing to geopolymeric gel formation.
2. Compressive strength results showed optimal performance at 10% WHA, maintaining 99% of the strength of the control mix at 90 days. At 20%, strength was moderately reduced (88%), while a sharp decline was observed at 30% (70%).
3. XRF analysis revealed a direct correlation between WHA dosage and oxide content, with increasing SiO₂ and decreasing CaO. This shift influenced the balance between N-A-S-H and C-A-S-H gel phases, influencing the compressive strength development of the geopolymer system.
4. Up to 20% WHA replacement can be considered optimal for maintaining mechanical performance while encouraging the utilization of agricultural waste in sustainable geopolymer systems.

Future work is recommended to investigate the durability performance (e.g., permeability, sulphate resistance) of GGBFS–WHA systems and explore the microstructural evolution using SEM/EDS and FTIR techniques.

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