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Predicting the optimal composition of sugarcane bagasse ash (SCBA) and ground granulated blast furnace slag (GGBS) in ternary blended supplementary cementitious system

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This paper has presented experimental work proposing an optimal proportion of sugarcane bagasse ash (SCBA) and ground granulated blast furnace slag (GGBS) in ternary blended supplementary cementitious systems. In the first phase, the physical, chemical, and morphological characterizations of these pozzolans have been evaluated to ascertain their suitability as supplementary cementitious materials. The physical properties of SCBA and GGBS have been evaluated in accordance with Indian Standard IS 1727. The chemical composition has been analysed using X-Ray Fluorescence Spectroscopy (XRF), while the mineralogical composition has been characterized using X-Ray Diffraction (XRD). The morphological features of these materials have been examined by Scanning Electron Microscopy (SEM) in conjunction with energy-dispersive X-ray spectroscopy (EDX). In the second phase, twelve mortar mixtures have been prepared with a constant cement content while varying the proportions of SCBA and GGBS, maintaining constant workability. The strength activity index of these blended pozzolanic cement mortars has been evaluated by compressive strength testing, and it has been found that a supplementary cementitious material composed of 40% SCBA and 60% GGBS has achieved a pozzolanic activity index greater than 1 and has been identified as the optimal SCBA–GGBS blend.

Keywords: Cement/Cementitious material, Characterization techniques, GGBS, Material characterization, Microstructure, Pozzolanic activity, Scanning electron microscopy, Sugarcane bagasse ash

1 Introduction

For nearly two centuries, the escalating demand for cementitious materials driven by infrastructure needs and extensive industrialization has significantly boosted global cement production. This surge not only depletes natural resources and energy but also releases substantial amounts of carbon dioxide and other air pollutants, contributing to environmental degradation[1-3]. In cement manufacturing nearly 0.9 tonnes of carbon dioxide is emitted during the production of one tonne clinker, which is responsible for 5–10% of greenhouse emissions, a figure expected to rise, exacerbating environmental impacts[4-6]. To mitigate these issues, it is essential to incorporate diverse industrial and agricultural by-products into cement production. This approach not only reduces carbon dioxide emissions but also decreases the volume of waste destined for landfills, thereby creating environmentally friendly materials with enhanced mechanical properties for the global market[7-11]. Current research focuses on understanding the properties of binders derived from waste materials such as metakaolin, rice husk ash (RHA), silica fume, fly ash, sugarcane bagasse ash (SCBA), and ground granulated blast furnace slag (GGBS)[12-16]. Supplementary cementitious materials by integrating agro-industrial by-products enhances the performance of cementitious materials and also constitutes a major step toward sustainable development in the construction industry[16-19].

SCBA and GGBS are two pozzolanic materials that have attracted attention in the construction field because of their remarkable performance when used as substituents for cement and are the focus of research. SCBA is a waste generated in sugar manufacturing plants after the extraction of juice from sugarcane. A substantial volume of SCBA is generated in South India, highlighting the need for effective disposal methods. Chemical analysis reveals that raw bagasse ash produced is rich in alumina and silica with high LOI. A combination of sieving and grinding approach in processing bagasse ash will improve the compressive strength and as well as its strength activity index of SCBA[20]. The compressive strength of SCBA blended concrete where greater compared to control concrete up to 20% replacement of cement with the SCBA[21]. The effect of SCBA on an aggressive environment was studied by conducting chloride ion ingress at different replacement levels of SCBA. Results show that even at 5% replacement of cement by SCBA, the chloride penetration depth has reduced to approximately 50% of that of control one. The chloride resistance has improved drastically with the incorporation of SCBA up to 25% replacement of cement. This indicates that SCBA has significant potential for effective use in structural concrete in aggressive environments[22].

Similarly GGBS is a by-product from the iron manufacturing industry mainly composed of silica and calcium. The performance of GGBS was quite known to the research community. Incorporation of GGBS on partial replacement of cement results in improving the later age strength of concrete and long term durability characteristics of concrete due to its pozzolanic property. Thus GGBS is widely used as supplementary cementitious material in cement composites and helps in tackling major environmental problems by eliminating and reducing the environmental pollution due to the land filling of it.

The strength of cement mortar is primarily influenced by C3S and C2S, which constitute 70-80% of the cement and react with water during hydration to form Calcium Silicate Hydrate (C-S-H) and calcium hydroxide (CH). While C-S-H imparts essential properties to the cement matrix, excess CH interaction with sulfates in soil or water, causing deterioration of the cement matrix.

Incorporating an optimal amount of blended SCM of GGBS and SCBA into OPC can enhance the properties of cement matrix due to the generation of secondary C-S-H gel. GGBS which is latent hydraulic material and SCBA which has 45 - 55% amorphous silica after selective separation can react with excess portlandite to form secondary C-S-H in the presence of water[23, 24].

This study primarily aims to create a ternary blended cementitious system by integrating both Ground Granulated Blast Furnace Slag (GGBS) and Sugarcane Bagasse Ash (SCBA) as supplementary cementitious materials. This is accomplished by assessing the pozzolanic activity of various SCBA-GGBS blended proportions through compressive strength tests and proposing the optimal proportion for the blended supplementary cementitious material.

2 Materials and Methods

2.1 Materials

2.1.1 Ordinary portland cement (OPC)

OPC with specific gravity 3.15 confirming to IS 269 2015 was utilized in this experimental programme. The physical and chemical properties of cement utilized were in compliance with the specification in IS 12269: 2013 [25].

2.1.2 Ground granulated blast furnace slag (GGBS)

GGBS used in this experimental programme was supplied from Quality Polytech Mangalore. GGBS has met the requirement and also satisfies ASTM C 618 standards[26]. The specific gravity of the GGBS was reported as 2.94 with a specific surface area of 380 m^2/kg.

2.1.3 Sugarcane bagasse ash (SCBA)

SCBA was collected from Ponni Sugar Industry Erode. The gathered raw bagasse ash underwent drying at a temperature of 105-110 °C for a duration of 24 hours to eliminate any evaporable moisture. The resulting dried sample comprised both burnt fine particles and unburnt fibrous particles.

2.1.3.1 Processing of raw bagasse ash

The raw bagasse ash has been processed by a combination of sieving and grinding process. Initially the raw SCBA was sieved through 300 µm to remove unburnt fibrous particles. The sieved BA of around 2 kg was taken in a Los Angeles Abrasion testing machine with 48 mm diameter cast iron spherical balls as abrasive charge. The machine was allowed to rotate at a speed of 40 rpm for 120 minutes and found the specific surface area of the sample is comparable with the cement fineness. These processed BA were stored in an airtight container for the further testing.

2.1.4 Manufactured sand (M sand)

M-sand with the fineness modulus 2.77 and the specific gravity 2.653 was used as a fine aggregate.

2.2 Characterization of constituent materials

Characterizing constituent materials is crucial for comprehending the physical and chemical properties of ternary blended supplementary cementitious materials. The distribution of grain size of the materials was determined by a liquid particle size analyzer. X-Ray Fluorescence Spectroscopy (XRF) was employed to analyze the chemical compositions of SCBA and GGBS, while their mineralogical compositions were examined using X-Ray Diffraction (XRD). The morphology of these materials was observed through SEM. The physical properties, such as grain size, fineness, and specific gravity of OPC, GGBS, and SCBA, were evaluated according to IS 1727 standards[27]. Additionally, the setting time and consistency of Ordinary Portland Cement were determined following IS 4031 guidelines[28, 29].

2.3 Evaluation of pozzolanic performance of blended supplementary cementitious material.

2.3.1 Specific gravity, consistency and setting time of SCBA - GGBS based ternary blended cementitious system (SCGTBC).

The SCGTBC was created by replacing cement with a blend of SCBA and GGBS pozzolana in a 0.2 N: 0.8 weight ratio, following IS 1727 standards[27]. The ratio N refers to the specific gravity of the SCBA - GGBS blend compared to cement. This ensured that the combined binder and pozzolana volume matched the control cement paste volume. The system's specific gravity, consistency, and setting time were evaluated as per IS 1727[27].

2.3.2 Proportioning of constituents for blended mortar and determination of flow characteristics

To determine flow characteristics, twelve mortar mixtures were prepared with constant cement content while varying SCBA and GGBS. The blend proportions (pozzolana, cement, standard sand) were set at 0.2 N: 0.8: 3 by weight, with N representing the specific gravity ratio as specified above. Mixtures SG1 to SG11 were formulated by adjusting the percentages of SCBA and GGBS, starting with 100% SCBA and 0% GGBS, down to 0% SCBA and 100% GGBS. M sand replaced standard sand. The water needed for a 100-110% flow in the flow table test was used for preparing mortar as specified IS 1727[27]. The required quantity of binding raw materials to produce six numbers of mortar cubes are given in Table 1.

2.3.3 Preparation, moulding and curing of specimen

Fresh mortar was mixed using an electrically controlled mechanical mixer with planetary and revolving motions. The dry materials and gauging water were mixed as per IS 1727 [27]. The mortar was placed in 50-mm cube molds in two layers and tamped 25 times. Specimens dried for 24 hours at room temperature, then demolded and cured in freshwater, which was renewed every seven days and kept at 27 ± 2°C.

2.3.4 Determination of Strength Activity Index of mortar

The strength activity index (SAI) was assessed via compressive strength tests on blended pozzolana cement mortar. Compressive strength was measured from three specimens per sample after 7 and 28 days of curing. Strength results were expressed as the ratio of the SCGTBC system's compressive strength to the control mortar, indicating the SAI.

3 Results and Discussion

3.1 Characterization of constituent materials

It is important to perform the characterization of constituent material for the better understanding of physical and chemical properties of the ternary blended supplementary cementitious material. The

Table 1 — Mixture proportions.

Mix No.	Nomenclature	Binding raw materials (Absolute Volume Basis for six numbers of mortar cube)					
		Cement		RHA		GGBS	
		%	Weight (g)	%	Weight (g)	%	Weight (g)
SG1	C(100S0G)	80	400	20	94.28	0	0
SG2	C(90S10G)	80	400	18	85.14	2	9.46
SG3	C(80S20G)	80	400	16	76.19	4	19.05
SG4	C(70S30G)	80	400	14	68.88	6	28.66
SG5	C(60S40G)	80	400	12	57.52	8	38.35
SG6	C(50S50G)	80	400	10	48.25	10	48.25
SG7	C(40S60G)	80	400	8	38.73	12	58.09
SG8	C(30S70G)	80	400	6	29.43	14	68.22
SG9	C(20S80G)	80	400	4	19.62	16	78.22
SG10	C(10S90G)	80	400	2	9.81	18	88.29
SG11	C(0S100G)	80	400	0	0	20	98.73
SG0	Control	100	500	0	0	0	0

chemical, physical and microstructural properties of the binder materials can be tested using XRF, XRD, SEM in conjunction with EDX, specific gravity, fineness, particle size distribution etc. The grain size distribution depicted in Fig. 1 indicates that GGBS possesses the finest particles and the processed SCBA and ordinary Portland cement (OPC) possess a similar grain size distribution. The D 80 value in cumulative distribution characterized by the fineness of materials indicates a similar fineness for SCBA and OPC with a specific gravity of 2.10 and 3.15 respectively, while GGBS possess a lower fineness of about 29 µm with a specific gravity of 2.94.

The chemical composition of the pozzolanic materials is presented in Table 2. SCBA, with a SiO_2+Al_2O_3+Fe_2O_3 content of more than 70%, meets the ASTM C 618[26] requirements for natural pozzolana. The chemical moduli of GGBS comply with ASTM C 618 [26] and BS 6699 standards[31]. The Loss of Ignition (LOI) values of GGBS and SCBA are lower than the max allowable limit (10%) stated in ASTM standards. X-ray diffraction analysis was employed for the mineralogical characterization of SCBA and GGBS. The diffraction pattern of SCBA reveals a distinct amorphous hump between 19° and 23° on the 2θ scale, indicating the presence of reactive silica, which undergoes chemical interaction with calcium ions and consequently enhances reactivity. Minor traces of quartz and cristobalite were identified in the diffraction pattern, as illustrated in Fig. 2. The occurrence of quartz is attributed to sand particles adhering to the sugarcane during the harvesting process. Similar analysis of GGBS shown in Fig. 3 indicates an amorphous hump at 2θ scale between 28° and 33° with minor crystalline mineral phases.

The structure of SCBA and GGBS was further analyzed using Scanning Electron Microscopy (SEM) in secondary mode. Additionally, Energy-Dispersive

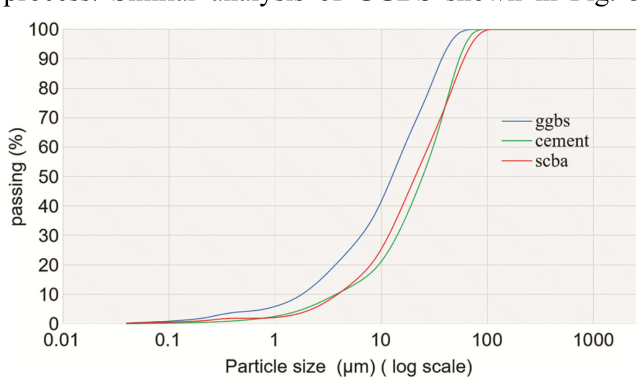

Fig. 1 — Distribution of grain sizes of OPC, GGBS and SCBA.

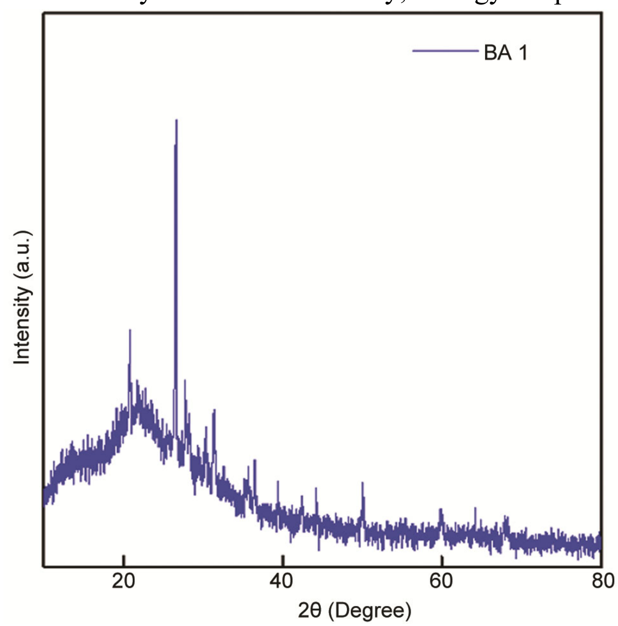

Fig. 2 — XRD pattern of SCBA.

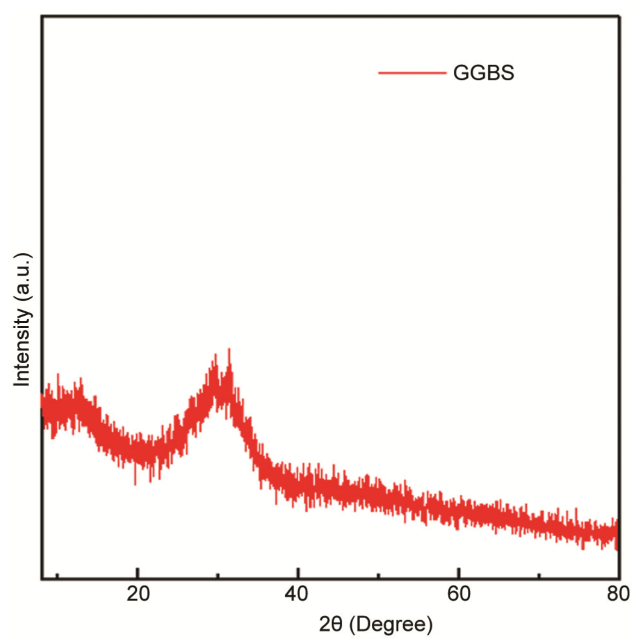

Fig. 3 — XRD pattern of GGBS.

Table 2 — Chemical composition of GGBS and RHA.

Composition of Oxide	CaO	SiO_2	Al_2O_3	MgO	Fe_2O_3	K_2O	Na_2O	SO_3	LOI	SiO_2+Al_2O_3 +Fe_2O_3
GGBS (%)	37.70	33.80	17.10	6.27	0.67	0.40	0.22	1.67	0.32	51.67
SCBA (%)	4.06	68.5	5.26	3.19	2.67	4.34	1.79	2.03	5.32	76.43

X-ray analysis (EDX) was employed alongside SEM to determine the elemental composition. In the bagasse ash, particles exhibited various shapes: prismatic, spherical, and irregular, as illustrated in Fig. 4. Prismatic particles had a well-defined structure and a high silicon content, as confirmed by the elemental composition shown in Fig. 5. Spherical particles were also observed in the SCBA microstructure and were found to contain oxides of silicon, aluminum, sodium, magnesium, potassium, oxygen, and minor amounts of calcium and iron, as depicted in Fig. 6. Irregular particles were also identified, displaying a silica-rich composition, as indicated by the elemental composition in Fig. 7.

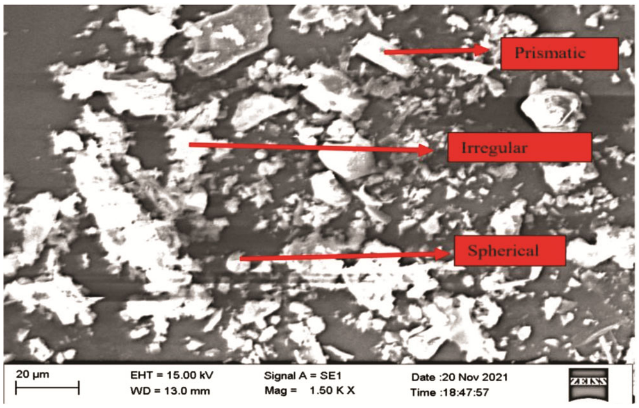

Fig. 4 — SEM image of SCBA.

Similarly while examining the microstructure of GGBS, it is observed that most of the particles of GGBS are not spherical in shape. GGBS is observed in an anomalous shape with clear edges and angles, which is due to the inter impacting and inter rubbing between steel balls in an abrasion machine. The elemental composition of the GGBS examined by EDX indicates the presence of Ca, Si, Al, O and a small amount of Mg as shown in Fig. 8.

By the result of XRD and SEM analysis, it is ascertained that GGBS which is known as latent hydraulic material can be utilized as a supplementary cementitious material due to presence of amorphous phases and high content of CaO, SiO_2, and Al_2O_3. Similarly, by analyzing the XRD and SEM images of SCBA, the presence of reactive Si and the higher

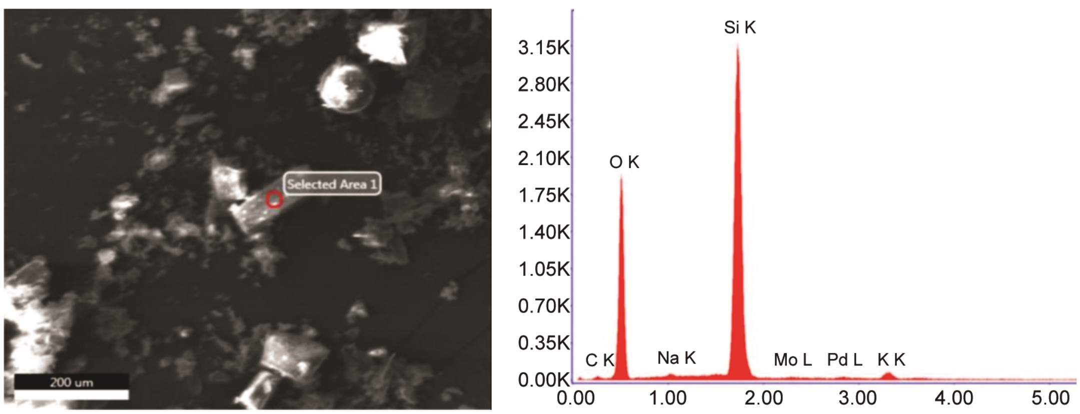

Fig. 5 — Chemical composition of Prismatic particles in SCBA by EDX.

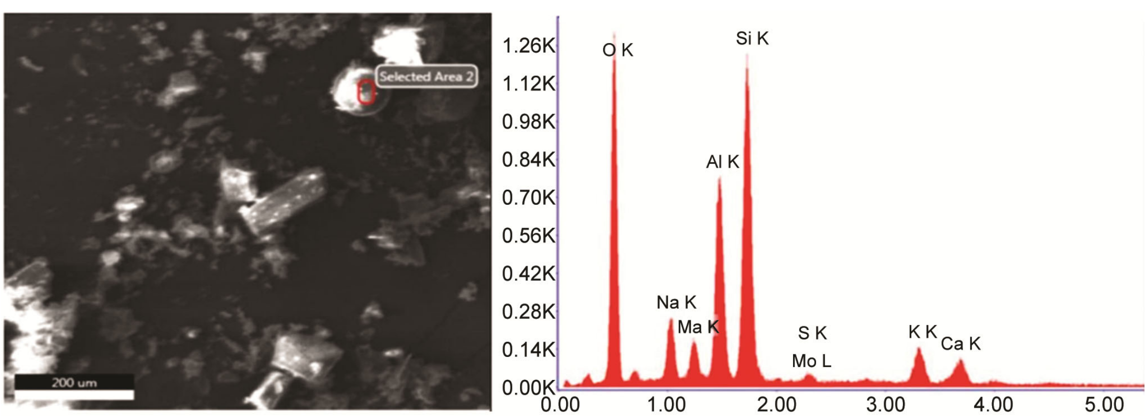

Fig. 6 — Chemical composition of Spherical particles in SCBA by EDX.

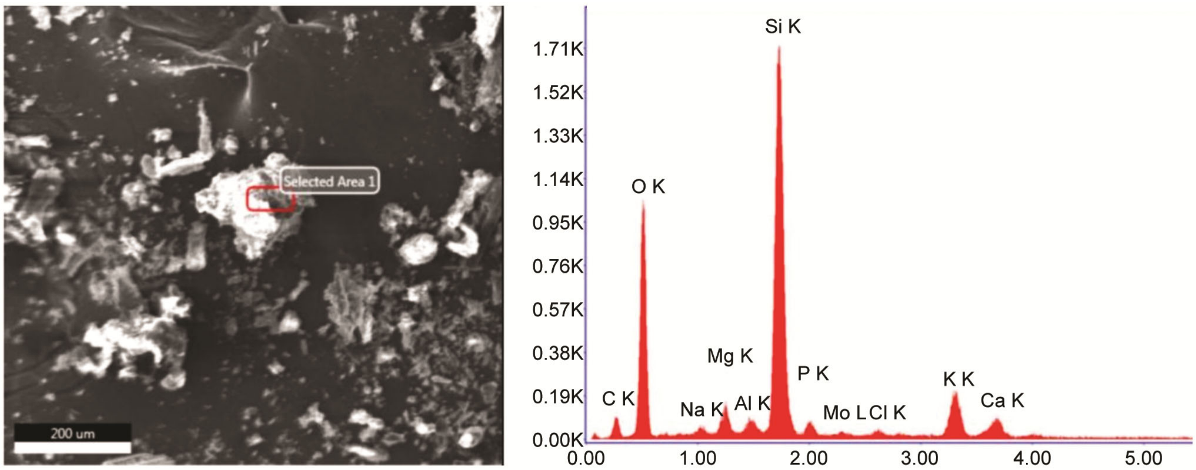

Fig. 7 — Chemical composition of Irregular particles in SCBA by EDX.

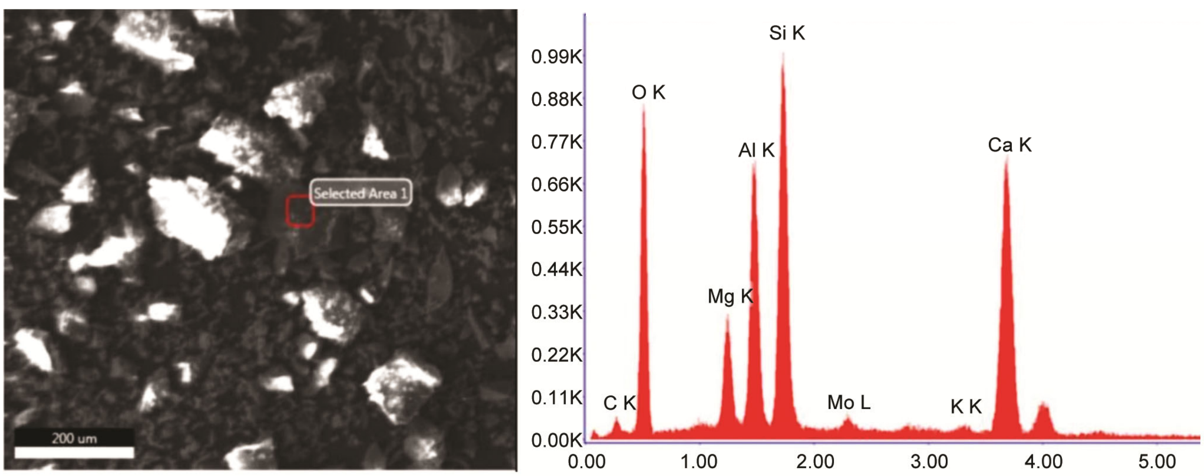

Fig. 8 — SEM image & chemical composition of particles in GGBS by EDX.

Table 3 — Specific gravity of SCGTBC.

Sample	SG 1	SG 2	SG 3	SG 4	SG 5	SG 6	SG 7	SG 8	SG 9	SG 10	SG 11
Specific gravity	2.94	2.96	2.98	2.99	3.01	3.02	3.04	3.06	3.07	3.09	3.11

content of SiO_2 indicates SCBA can react with the excess CH liberated due to the hydration process of blended cement, which enhances the hydraulic properties of the binder mix.

3.2 Specific gravity of SCGTBC

Table 3 displays the specific gravity of the SCGTBC. The specific gravity of a binary blended cementitious system based on SCBA was observed as 2.94, while that of binary blended cementitious system based on GGBS was observed as 3.11. It is also noticed that the specific gravity of ternary blended cementitious system based on SCBA and GGBS decreases as the SCBA content increases. The specific gravity reduction of these cementitious systems is due to lower relative density of SCBA.

3.3 Consistency and Setting time of SCGTBC

As illustrated in Fig. 9 (a), the water consistency of SCGTBC increases with the rising SCBA content in the blended pozzolana. The control paste shows a lower consistency value compared to the binary and ternary blended systems. This higher water demand for achieving workability in both binary and ternary systems arises from the increased powder volume due to the cement being replaced by blended pozzolana.

Moreover, Fig. 9(b) demonstrates the impact of adding SCBA and GGBS on the setting time of the

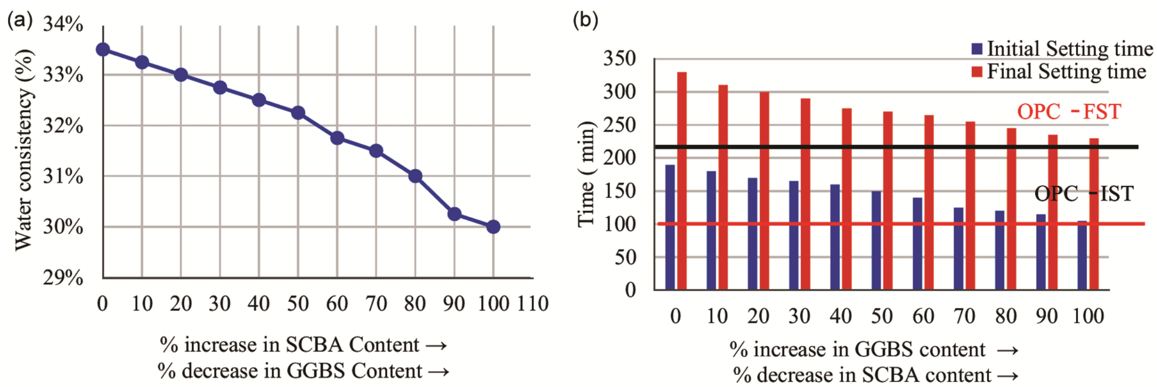

Fig. 9 — (a) Water consistency and (b) Setting time of SCGTBC.

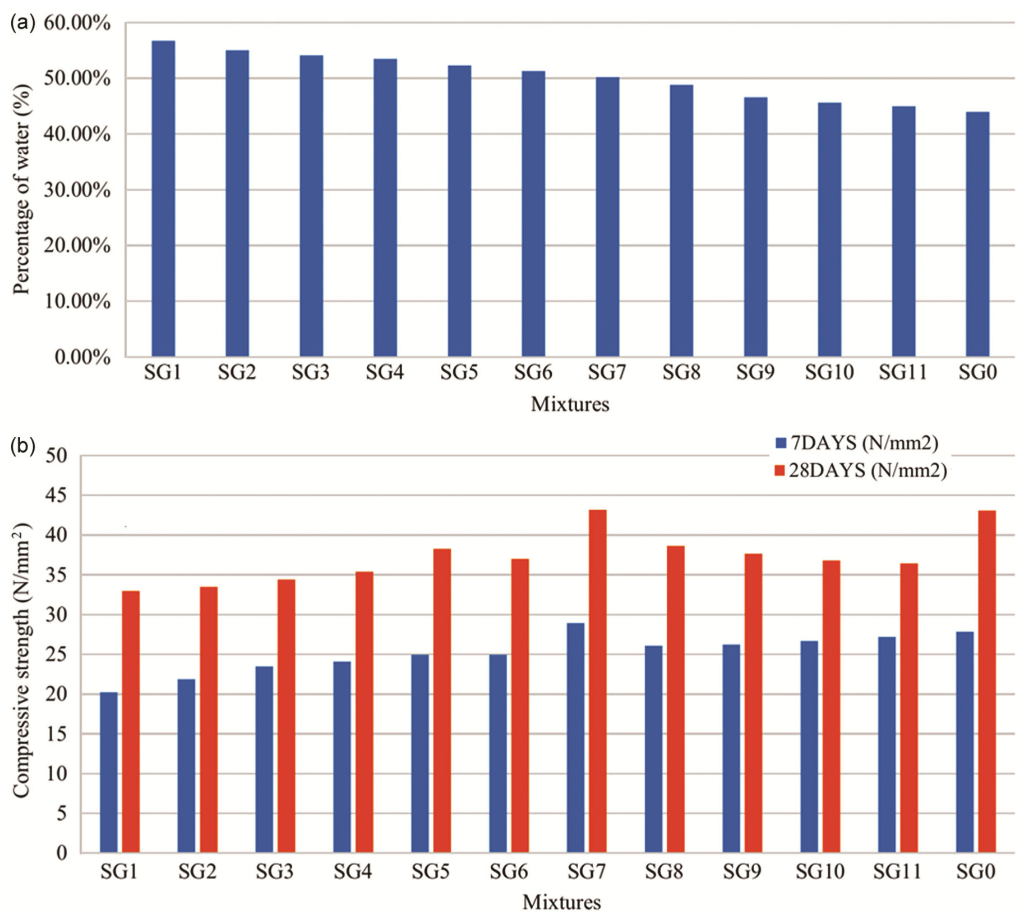

Fig. 10 — (a) Percentage of water for required flow value and (b) Compressive strength of ternary blended cement mortar.

blended pozzolana. When the cement content remains constant, the initial and final setting times differ based on the SCBA and GGBS proportions in the blend. Remarkably, the initial and final setting times for SCGTBC increase with higher SCBA content. The integration of pozzolana into cement decreases the C3S and C3A components, leading to a slower setting process.

3.4 Flow test and compressive strength of ternary blended cement mortar

Figure 10(a) illustrates the water volume necessary to achieve a flow range of 100-110% in flow tests for various mixtures. SG 1, the SCBA-blended binary cement mortar, required the highest amount of water, whereas SG 11, the GGBS-blended binary cement mortar, needed the least. The water needs for the other mixtures were intermediate between those of SG 1 and SG 11. Notably, the control mortar demanded less water than all other mixes. This variation suggests that the water requirement of the ternary blended cementitious system increases with higher SCBA content in the blended pozzolana, due to the larger particle sizes of SCBA compared to GGBS.

Figure 10(B) depicts the compressive strength development in SCBA-GGBS based ternary blended cement mortar at 7 and 28 days. It was observed that all replacement levels exhibited lower compressive strength values compared to the control mixture, attributed to variations in the water-binder ratio necessary to maintain consistent flow characteristics across mixtures. Remarkably, the 7 and 28-day compressive strengths of the SG 7 mixture (comprising 40% SCBA and 60% GGBS) were higher than those of other mixtures. Moreover, as the SCBA content in the blended pozzolana decreased from 100% to 0%, the compressive strength increased up to a 40% SCBA replacement level, after which it began to decline.

3.5 Strength activity index of SCBA - GGBS based ternary blended cement mortar

The compressive strength of ternary blended cement mortars containing SCBA-GGBS was assessed at 7 and 28 days, expressed as a percentage of the control mortar's strength using the Strength Activity Index (SAI). As per BS 3892[30], SAI values above 0.80 after 28 days suggest positive pozzolanic activity. Likewise, ASTM C 618[26] indicates that supplementary cementitious materials with SAI values exceeding 0.75 at both 7 and 28 days demonstrate pozzolanic activity.

Figure 11 illustrates that all blended proportions show positive pozzolanic activity, aligning with ASTM C 618 standards[26]. Mixtures from SG 3 to SG 11 also exhibit positive pozzolanic activity per BS 3892 criteria[30]. The SG 7 blend, composed of 40% SCBA and 60% GGBS, achieves a pozzolanic activity index of 1.04, marking the highest pozzolanic activity among the mixtures. As nearly all blends demonstrate pozzolanic activity, the SG 7 mixture, with the highest index at 28 days, is identified as the optimal SCBA-GGBS supplementary cementitious material.

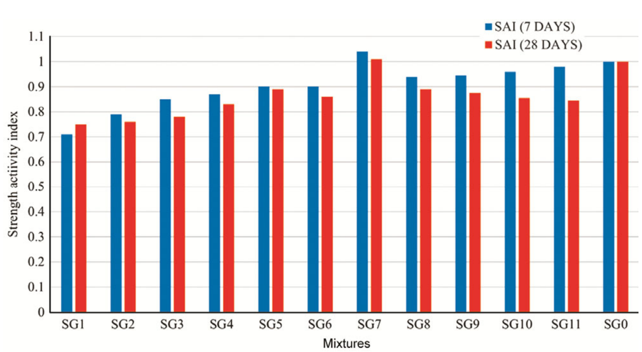

Fig. 11 — Strength Activity Index of ternary blended cement mortar.

4 Conclusion

This study comprehensively evaluated a ternary blended cementitious system comprising ordinary Portland cement (OPC), sugarcane bagasse ash (SCBA), and ground granulated blast furnace slag (GGBS). Initial chemical and physical characterizations confirmed that both SCBA and GGBS satisfy the fundamental requirements for supplementary cementitious materials. Particle size analysis revealed that GGBS exhibits a significantly finer grain size compared to OPC and SCBA, while OPC and SCBA display similar particle distributions.

Microstructural investigations elucidated the reactive potential of each pozzolan. X-ray diffraction (XRD) patterns identified crystalline silica phases in SCBA and predominantly amorphous content in GGBS, both of which underpin pozzolanic reactivity. Scanning electron microscopy (SEM) demonstrated that SCBA comprises a heterogeneous mix of prismatic, spherical, and irregular particles, whereas GGBS particles are chiefly angular. Energy-dispersive X-ray spectroscopy (EDX) further confirmed that silicon is the predominant elemental constituent in both materials, reinforcing their contribution to secondary C–S–H formation.

Rheological assessments revealed that increasing SCBA content leads to diminish workability and extended setting times. This behavior is attributed to the larger average particle size of SCBA, which modifies the water demand and packing density of the composite binder. Systematic evaluation of various SCBA–GGBS proportions established a clear correlation between blend composition and pozzolanic activity. Among the mixtures studied, the 40% SCBA & 60% GGBS combination demonstrated the highest pozzolanic reactivity, as evidenced by strength development and calcium hydroxide consumption metrics.

In light of these findings, the 40:60 SCBA–GGBS blend emerges as the optimal formulation for maximizing pozzolanic performance in ternary cementitious systems. Future work should explore long-term durability, microstructure evolution under service conditions, and the environmental impact of large-scale implementation to fully harness the sustainability potential of these industrial and agricultural by-products.

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