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RESEARCH PAPER

Combined Impact of GGBS and Nanoparticle Surfaces on the Behavior of Calcined Kaolin Clay-based Self-Compacting Geo-Polymer Concrete

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ABSTRACT

Self-Compacting Geopolymer Concrete (SCGPC) combines the advantages of Self-Compacting Concrete and Geopolymer Concrete, offering enhanced sustainability and performance. This study investigated the effects of partially replacing calcined kaolin clay (CKC) with Ground Granulated Blast Furnace Slag (GGBS) and incorporating nano-alumina (NA) or nano-clay (NC) on the fresh and mechanical properties of SCGPC. Six binary mixtures were prepared using a binder content of 493 kg/m^3 and an alkaline liquid-to-binder ratio of 0.50, with CKC replaced by 40%, 50%, and 60% GGBS, while the control mix contained 100% CKC. Based on fresh and hardened properties, the optimum binary mixture was selected and modified by adding 2% NA or 2% NC to produce ternary mixes. Workability was evaluated using slump flow, V-funnel, and L-box tests. Results showed that GGBS significantly improved workability, whereas the addition of nanoparticles slightly reduced it; however, all mixtures satisfied EFNARC requirements. Mechanical properties, including compressive and splitting tensile strengths, were determined at 7 and 28 days. The 50% GGBS mixture exhibited the best performance among binary mixes. Nano-modified mixtures further enhanced strength, with 2% NA increasing compressive and tensile strengths by 39.9% and 31.6%, respectively, at 28 days compared with the control mix.

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INTRODUCTION

Self-compacting geopolymer concrete (SCGC) is a concrete variant that integrates the concepts of self-compacting concrete (SCC) with geopolymer binders [1]. The components of SCGPC are chosen based on criteria including client demand, cost factors, and strength specifications. [2]. SCGPC generally consists of a cementitious binder made from industrial by-products and naturally occurring materials rich in alumina and silica, including GGBFS, fly ash, and metakaolin, among others.[3]. SCGPC can be regarded as a specific variant of GPC, since it is formulated utilizing the same methods but does not necessitate further mechanical energy during compaction, exhibiting better fresh properties, durability, and microstructural characteristics [4]. SCGPC relies on the fundamental principle of Self-Compacting Concrete (SCC): achieving high flowability, passing ability, and segregation resistance without external vibration [5]. Self-

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Compacting Concrete (SCC) comprises cement, aggregates, water, mineral fillers, and chemical admixtures. Unlike conventional concrete, SCC uses specific proportions and special admixtures to attain increased flowability and segregation resistance [6]. Self-Compacting Concrete (SCC) necessitates a substantial quantity of Ordinary Portland Cement (OPC) due to the need for an excessive paste volume. Consequently, SCC contributes significantly to CO_2 emissions, as OPC is a major source of carbon dioxide in construction [7]. Concrete, the world's most used material after water, relies on cement production, which emits CO_2, dust, and GHGs. Cement contributes ~5% of global anthropogenic CO_2 [8], with over 2.8 billion tons produced annually (5–6% of total CO_2 emissions). Each ton of OPC generates one ton of CO_2 at 1300–1500°C, driving climate change and demanding reduced cement use [9]. GPC technology decreases worldwide CO_2 emissions by up to 80% relative to OPC by utilizing aluminosilicate as a complete substitute, so fostering sustainable development and a cleaner environment [10]. Abundant kaolinite clay deposits (kaolin clay, ball clay, kaolinitic claystone) exist in Iraq's Western Desert, Anbar province [9]. The environmental benefits, combined with the superior strength and durability of geopolymer concrete, have motivated Iraqi researchers to utilize local metakaolin as the primary source of silica and alumina for producing sustainable geopolymer concrete [8]. The utilisation of Ground Granulated Blast Furnace Slag (GGBS) as a partial substitute for calcined kaolin clay (CKC) in self-compacting geopolymer concrete (SCGC) is predicated on its synergistic chemical composition

Table 1. Mineral composition of CKC and GGBS.

Chemical composition (%)	CKC	GGBS
SiO_2	54.7	35.9
Al_2O_3	37.4	13.1
Fe_2O_3	1.72	0.6
CaO	0.84	37.9
MgO	0.42	8.9
Na_2O	0.37	0.3
K_2O	0.54	0.7
SO_3	0.13	0.7
P_2O_5	0.29	2.0
TiO_2	0.68	1.9
LOI	2.91	1.91

Table 2. Physical properties of CKC and GGBS.

Binding Materials	Physical property				
	Physical form	Color	Median particle size (μm)	Surface area (m2/kg)	Specific gravity
CKC	powder	Off-white	14.3	1640	2.61
GGBS	powder	white	13.8	450	2.98

Table 3. Characteristics of NA, NC.

Property	Nano Alumina	Nano Calcium Carbonate
purity%	99.9	99.9
Physical form	Powder	Powder
Color	White	White
Particle size, nm	30	80
Specific Surface area m^2/g	40-60	40
Specific gravity	3.1	2.5
Morphology	spherical	Cubic

and physical characteristics.[11]. GGBS supplies supplementary amorphous silica, alumina, and calcium oxide, promotes particle packing owing to its finer particle size and angular morphology, and improves workability while facilitating long-term strength development through continuous pozzolanic and hydraulic processes [12]. Research studies confirmed GGBS enhances mechanical, durability, and microstructural properties in metakaolin-based systems [13]. Research indicates that replacing CKC with 30-50% GGBS optimizes microstructure, reduces porosity, and improves compressive strength [14]. This combination produces a synergistic effect in which CKC allows quick early strength development, while GGBS enhances densification, durability, and mechanical qualities over time [15]. Studies have shown nanoparticle utilization (including nano-alumina, nano-silica, or nano-lime) in cement mortars and provided foundational insights on nano-filling and nucleation mechanisms transferable to geopolymer concrete [16]. Nanomaterials-enhanced geopolymer concrete (GPC) has become a research focus due to its superior performance and versatile modification methods [17]. Nano-calcium carbonate (NC) is relatively inexpensive due to abundant limestone and marble sources. It acts as a filler and nucleation agent in cementitious composites [18]. In fly ash-based geopolymer concrete, optimal NC dosage is up to 2%, improving mechanical properties, while 3% reduces performance [19]. Nano-alumina (NA) has high purity and fineness, making it effective for enhancing concrete mechanical properties. NA improves strength through filler effects and hydration reactions, forming calcium-alumina-silicate-hydrate (C-A-S-H) gel that densifies microstructure [20]. Alomayri [21] studied NA particles (50 nm) in fly ash pastes, geopolymer at (1%, 2%, and 3%) by mass of fly ash.Nanoparticles significantly enhance CKC-based SCGC, reporting compressive strength gains of 15.8% (2% NA or NC) and 28.34% (2% NA+2% NC) at 28 days [22]. This research proposes a novel approach to enhance strength using multi-blended ternary SCGPC mixtures (CKC + GGBS + NA or CKC + GGBS + NC) while maintaining satisfactory workability. Locally sourced calcined kaolin clay (CKC) from Iraq is utilized to develop sustainable SCGPC products, offering reduced transportation costs,

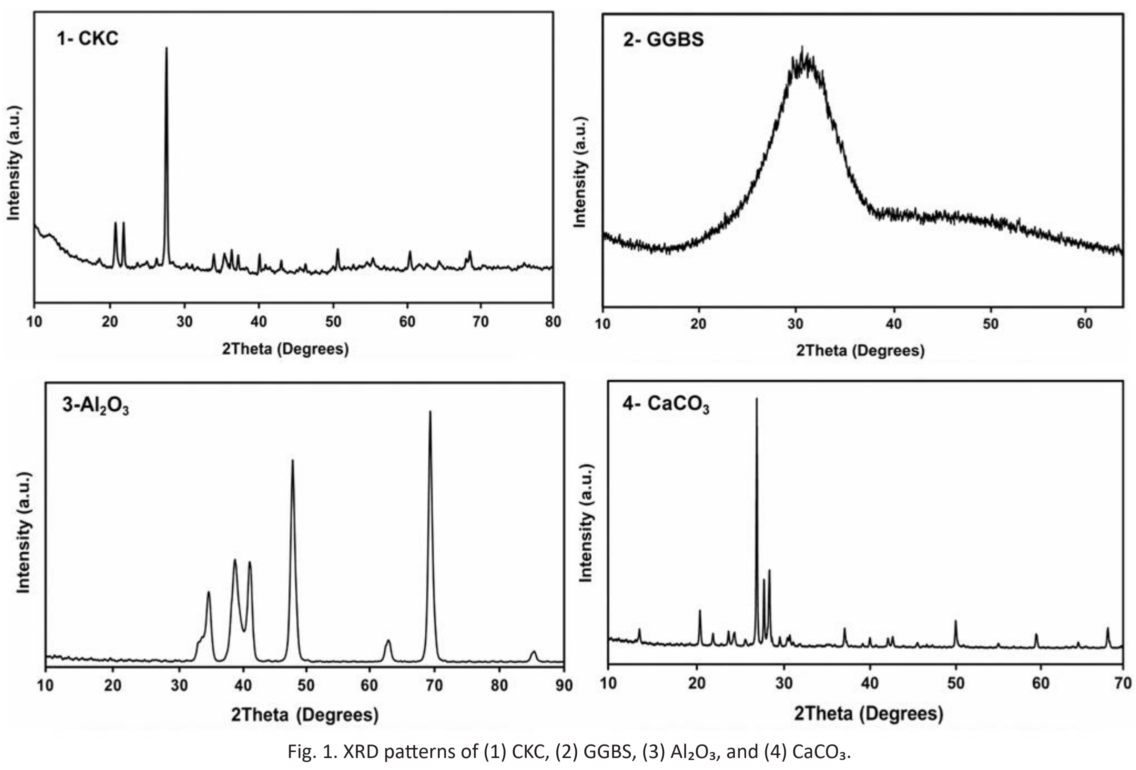

Fig. 1. XRD patterns of (1) CKC, (2) GGBS, (3) Al_2O_3, and (4) $CaCO_3$.

a lower carbon footprint, and support for local resource utilization. The results will be essential in enhancing the efficacy of novel SCGPC products formulated from locally sourced, environmentally sustainable pozzolanic ingredients obtained from geological resources. This literature review offers systematic insights to researchers and engineers, facilitating the adoption of this novel material in contemporary civil engineering.

MATERIALS AND METHODS

Materials

The materials employed in the production of the SCGPC are illustrated in Fig. 1 shows the XRD.

Calcined Kaolin Clay (CKC)

CKC was synthesized from kaolin clay sourced from the Dewekhla region in the Al Ramadi Desert (west of Baghdad, Iraq), which was subsequently crushed and calcined at 700°C for one hour [22]. The physical and chemical characteristics of CKC are compliant with ASTM C618 [23], as shown in Tables 1 and 2.

Ground Granulated Blast furnace Slag(GGBS)

GGBS utilized in this investigation demonstrated a specific gravity of 2.98 and a surface area of 450. The chemical, mineral composition, and physical characteristics of GGBS conform to ASTM C989 [24], as illustrated in Tables 1 and 2.

Nano-Al_2O_3 and Nano-$CaCo_3$

Nano aluminum oxide (NA) and Nano calcium carbonate (NC) utilized in the current investigation were sourced from China. Their properties are shown below in Table 3.

Sodium Hydroxide (NaOH)

NaOH flakes (99% purity) were dissolved in distilled water for the preparation of a 12 M activator solution. The solution must be utilized within 24–36 hours, as it turns semi-solid thereafter. Preparation details follow ASTM E291 [25].

Sodium Silicate (Na_2SiO_3)

Sodium silicate is a transparent compound consisting of sodium and silica oxides. Sodium silicate (Na_2SiO_3) is manufactured in the United Arab Emirates. The characteristics of Na_2SiO_3 solution are Na_2O% content (13.1-13.7), SiO_2% concentration (32-33), density (51 ±0.5), specific gravity (1.534-1.551), and viscosity (600-1200).

Water and Superplasticizer

Consuming tap water that meets standards with IQS No. 1703 [26] was used in the SCGPC mix design to improve workability. A high water-

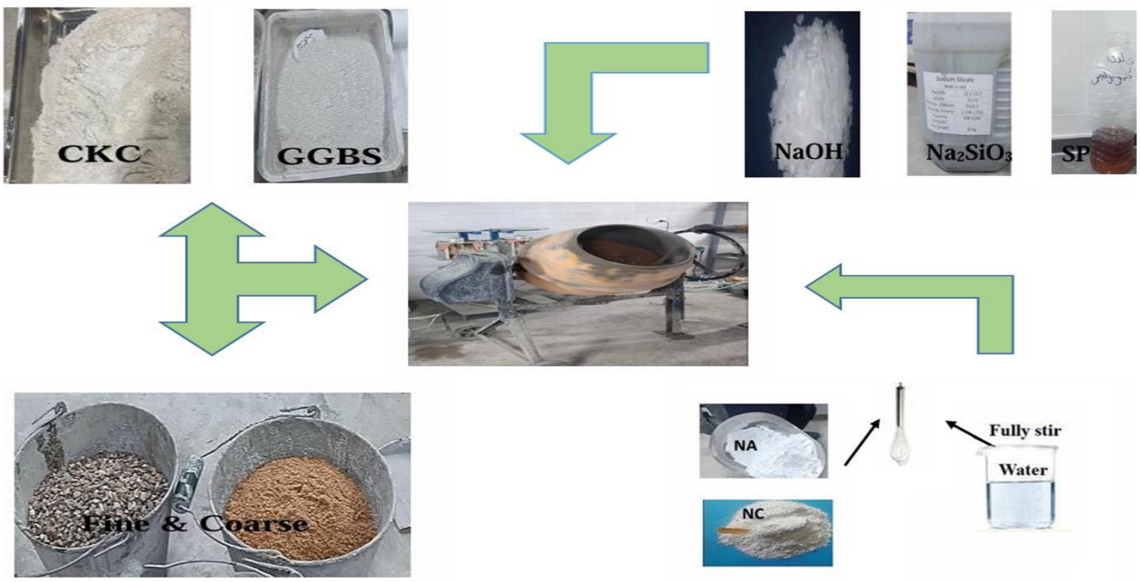

Fig. 2. The ingredients utilized in SCGPC Production.

reducing admixture (HWRA), Sika Viscocrete-180G (modified polycarboxylic ether), provided by Sika Iraq, was utilized to attain the necessary workability for SCGPC per ASTM C494 [27].

Coarse Aggregate

The coarse material utilized was crushed and washed gravel sourced from the Al-Nabai'i region, with a maximum size of 10 mm. The grading and sulfate content conformed to Iraqi Standard IQS 45 [28]. The specific gravity, SO_3 concentration, and absorption were 2.6, 0.03%, and 0.5%, respectively.

Fine Aggregate

The fine aggregate was local sand from the Al-Ukhaidher region, satisfying the third grading zone criteria and complying with Iraqi Standard IQS 45 [28]. Its specific gravity and SO_3 content were 2.65 and 0.3%, respectively as shown in Fig. 2.

SCGPC Manufacturing

The experimental work is divided into two main categories. The initial section emphasizes the optimization of the CKC mix in SCGPC concrete by substituting a portion of CKC to formulate a binary mix utilizing varying proportions of GGBS, aiming to identify the optimal binary mix concerning compressive strength and the qualities of new concrete, which are critical for self-compacting concrete. The second section examines the substitution of a portion of CKC in the ternary mixture with nanoparticle proportions (2%NA or 2%NC) to create multi-blended binder systems and assess the fresh and mechanical characteristics of SCGPC.

Fig. 3. illustrates the specimen preparation procedure, including (a) materials, (b) alkaline liquid mixing, (c) casting, (d) curing, and (e) demoulded specimens.

Table 4. The Mix Proportions of SCGPCs (kg/ m3).

Mix	Binder Components (%)	W/B	Quantities of ingredients (kg/m³)								
			CKC	GGBS	NA	NC	FA	CA	SP%	NHS	NSS
M1	CKC100% Control	0.39	493	0	0	0	848	860	3	70	175
M2	CKC60%+ GGBS40%	0.39	295.8	197.2	0	0	848	860	3	70	175
M3	CKC50%+ GGBS50%	0.39	246.5	246.5	0	0	848	860	3	70	175
M4	CKC40%+ GGBS60%	0.39	197.2	295.8	0	0	848	860	3	70	175
M5	GGBS50%+CKC48 %+ NA2%	0.39	236.64	246.5	9.86	0	848	860	3	70	175
M6	GGBS50%+ CKC48%+ NC2%	0.39	236.64	246.5	0	9.86	848	860	3	70	175

Alkaline Activator Solution (AAS)

First, a sodium hydroxide solution was prepared by dissolving 99% purity NaOH flakes in distilled water. The NaOH solution must be prepared 24 hours prior to use and used within 36 hours, as it becomes semi-solid beyond this period. Various molarities were calculated to determine the optimum. For a 12 M solution, 362 g of NaOH solid was dissolved in distilled water to make one liter [29]. The alkaline liquid was prepared by mixing the NaOH solution with the sodium silicate solution at room temperature. The mass ratio of Na_2SiO_3 solution to NaOH solution was kept at 2.5, while the alkaline activator-to-binder ratio (by mass) was fixed at 0.5 [30,31].

Mix Design and Preparation of SCGC

Since no specific mix design procedure exists for SCGC, proportions were determined through trials based on EFNARC SCC guidelines [32]and fly ash (Class F) geopolymer concrete principles [33]. The following constants were maintained: water-to-binder ratio (w/b) of 0.39, total binder content of 493 kg/m³, and superplasticizer dose

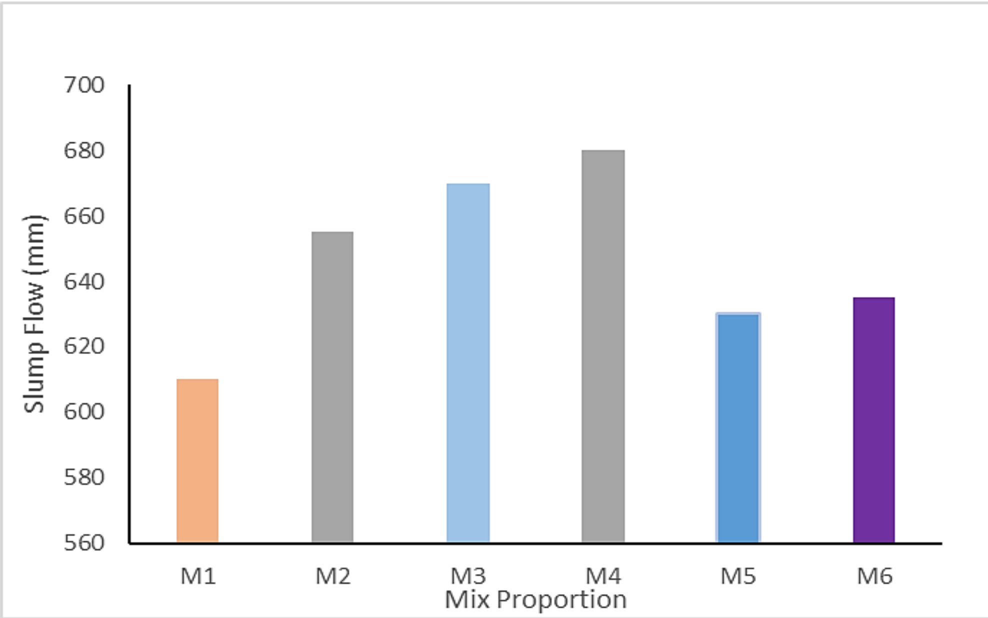

Fig. 4. Influence of GGBS, NA, and NC on Slump Flow Values of SCGPCs.

Table 5. Workability Results for different types of mixtures.

Mix	Types of Mixes	Slump Flow-D (mm)	V- Funnel Time (Sec)	L-Box height ratio (H2/H1)
M1	CKC100% Control	610	11.3	0.834
M2	CKC60%+ GGBS40%	655	10.7	0.849
M3	CKC50%+ GGBS50%	670	10.2	0.856
M4	CKC40%+ GGBS60%	680	9.8	0.878
M5	GGBS50%+ CKC48%+ NA2%	630	11.1	0.837
M6	GGBS50%+ CKC48%+ NC2%	635	10.7	0.841

of 3% by weight of binder (per EFNARC) [32]. Curing at 60–70 °C for 24 hr yields higher strength and denser microstructure than ambient curing [34]. Mixing followed the procedure of [35]: dry materials (aggregates, GGBS, CKC) were mixed for 30 seconds. One-third of the alkaline activator was added and mixed for 60 seconds. The remaining activator, superplasticizer, and extra water were then added, followed by mixing for 3 minutes, a 2-minute rest, and finally 2 minutes of mixing. Nanoparticles (NA, NC) were dispersed separately in water and alkaline solution using a hand-held electric mixer to prevent agglomeration [36] (see Fig. 3). They were then added in solution form. Finally, the fresh concrete was hand-mixed for an additional 2–3 minutes to ensure homogeneity. Specimens were cast without vibration and cured at 70 °C or ambient temperature [37]. Mix proportions are detailed in Table 4, and the preparation procedure is shown in Fig. 3 depicts the preparation procedure for SCGC specimens.

Testing Procedure

Workability Properties of SCGPC

Fresh properties of SCGPC mixes (filling ability, passing ability, and segregation resistance) were evaluated using slump flow, T_{50} slump flow, V-funnel, and L-box tests per European SCC guidelines [38] illustrated in Fig. 4.

Mechanical characteristics of SCGPC

The compressive and splitting tensile strengths of all SCGPC mixtures were assessed following BS EN 12390-3 [39] and ASTM C496 [40], respectively. Compressive strength was tested using 100 mm cube specimens. The splitting tensile strength was evaluated utilizing 100 × 200 mm cylindrical specimens.

RESULTS AND DISCUSSION

Workability characteristics of SCGPC

Measure the Slump Flow Values

The apparatus of the slump flow test used in this study is shown in Fig. 4. The result reflects the filling ability and stability of the self-compacting geopolymer concrete. The slump flow test utilizes an Abrams cone. The slump flow results are shown in Table 5 and illustrated in Fig. 4. All the mixtures exhibited a diameter ranging from 610 mm to 680 mm. The maximum diameter (680 mm) was recorded for mix M4 (CKC40% + GGBS60%). The control mix M1 (100% CKC) gave a slump flow of 610 mm, which was the minimum. Comparing binary and nano-modified blends,

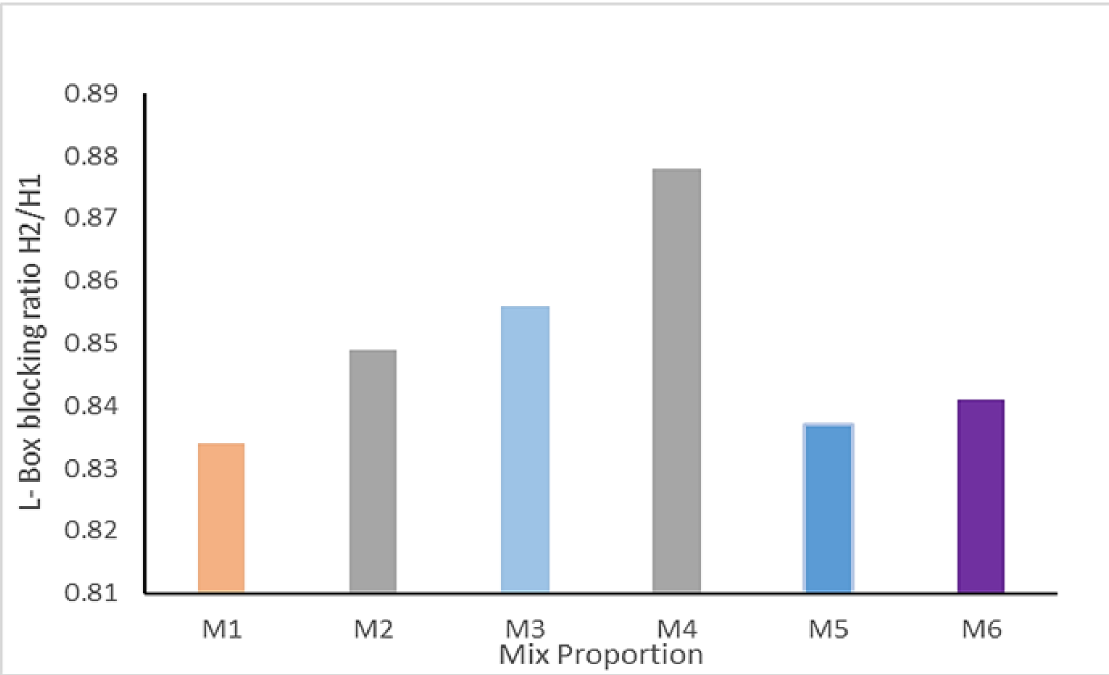

Fig. 5. Influence of GGBS, NA, and NC on Blocking Ratio Values of SCGPCs.

the binary mixes (M1–M4), which contain only CKC and GGBS, showed a clear trend: increasing GGBS content from 0% to 60% progressively improved slump flow from 610 mm to 680 mm. This enhancement is ascribed to the superior particle size and smooth surface texture of GGBS, which optimizes particle packing, reduces internal friction, and improves lubrication within the fresh concrete mixture [15]. In contrast, the nano-modified mixes (M5 and M6), which incorporate 2% nano-materials alongside 48% CKC and 50% GGBS, exhibited lower workability compared to the binary mix with the same GGBS content (M3: 50% GGBS, no nano). Specifically, M3 recorded 670 mm, while M5 (with 2% NA) dropped to 630 mm, and M6 (with 2% NC) dropped to 635 mm. This decrease is ascribed to the extensive surface area. of nano-particles, which increases liquid demand [41]. In contrast, the nano-modified mixes (M5 and M6), which incorporate 2% nano-materials alongside 48% CKC and 50% GGBS, exhibited lower workability compared to the binary mix with the same GGBS content (M3: 50% GGBS, no nano). Specifically, M3 recorded 670 mm, while M5 (with 2% NA) dropped to 630 mm, and M6 (with 2% NC) dropped to 635 mm. This decrease is ascribed to the elevated surface area of nanoparticles, which amplifies liquid requirements [41]. The minimum flow diameter among nano-modified mixes was 630 mm (M5), while the overall maximum among all mixes was 680 mm (M4). According to EFNARC specifications [32], the control mix (M1) and the nano-modified mixes (M5 & M6) fell within the SF1 class (550–650 mm), while the binary GGBS mixes (M2, M3, M4) exhibited higher workability corresponding to the SF2 class (660–750 mm). These results correspond with those attained by previous studies [42,43].

Measure L-Box Values

The apparatus of the L-Box Test used in this study is shown in Fig. 5. The L-Box test assesses the flowability of SCGPC in the presence of reinforcing obstacles, evaluating its capacity to pass without segregation or blockage. According to EFNARC criteria[32], the blocking ratio (BR = H2/H1) must be ≥ 0.8 to attain the requisite passing ability requirements. As shown in Table 5 and Fig. 5, all SCGPC mixes exhibited BR values within the range of 0.834 to 0.892, which exceeds the minimum requirement of 0.8. Therefore, all mixes possessed suitable passing ability with no blockages observed. The highest blocking ratio of 0.892 was recorded for M4 (40% CKC + 60%

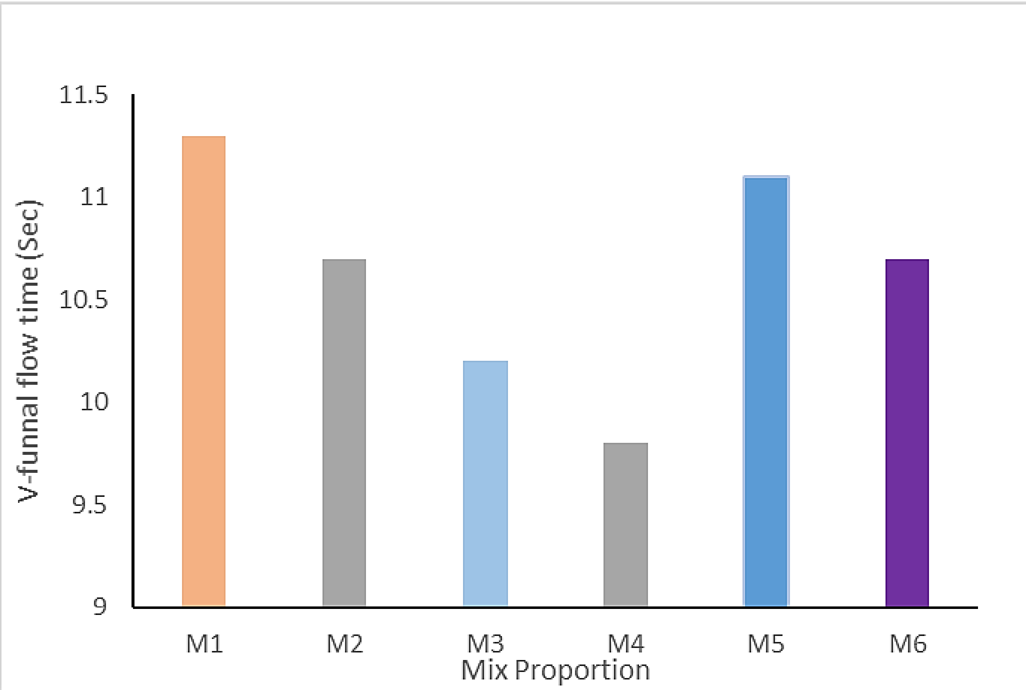

Fig. 6. Influence of GGBS, NA, and NC on V-Funnel Flow Values of SCGPCs.

GGBS), while the lowest blocking ratio of 0.834 was recorded for the control mix M1 (100% CKC). Increasing GGBS content in binary mixes from M1 to M4 progressively improved the passing ability, as reflected by the increasing BR values from 0.834 to 0.892. The enhancement is ascribed to the smaller particle size and refined surface texture of GGBS, which optimizes particle packing, diminishes internal friction, and augments lubrication within the fresh self-compacting geopolymer concrete (SCGC) mixture [15]. When incorporating nano-materials, the blocking ratio decreased compared to the binary mix with the same GGBS content. Specifically, M3 (50% GGBS, no nano) recorded a BR of 0.856, while M5 (with 2% NA) decreased to 0.837, and M6 (with 2% NC) decreased to 0.841. Between the two nano-materials, NA (M5) caused a greater reduction in blocking ratio than NC (M6), because NA reacts more rapidly with the alkaline solution, producing a more viscous paste that reduces passing ability [41,44]. During assessment, none of the six mixes exhibited any

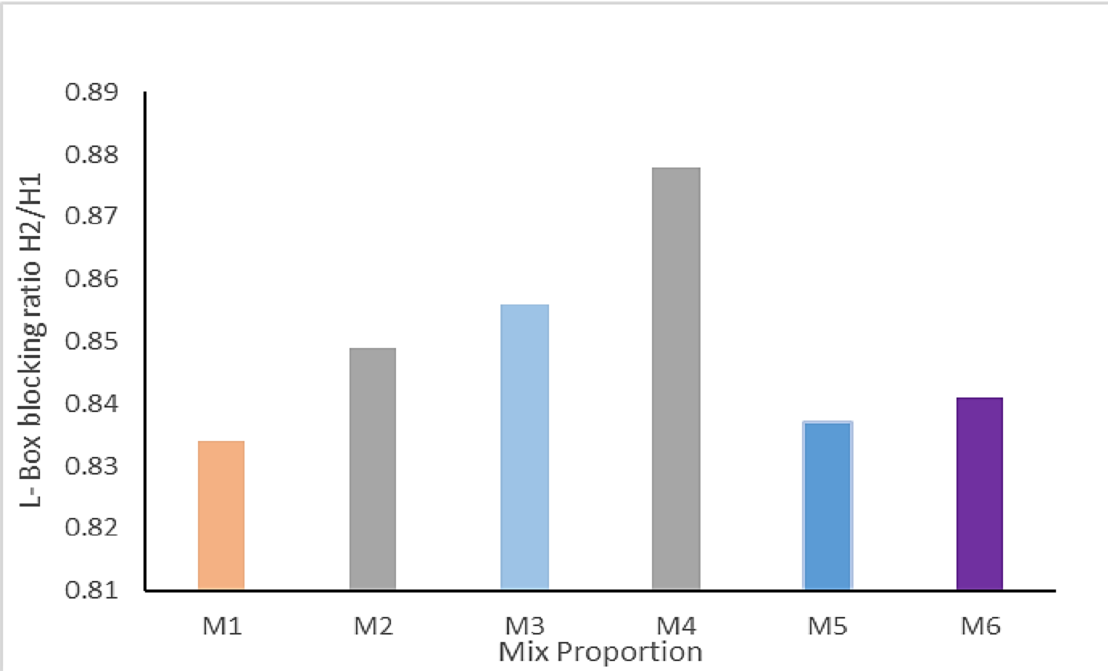

Fig. 7. Influence of GGBS, NA, and NC on Blocking Ratio.

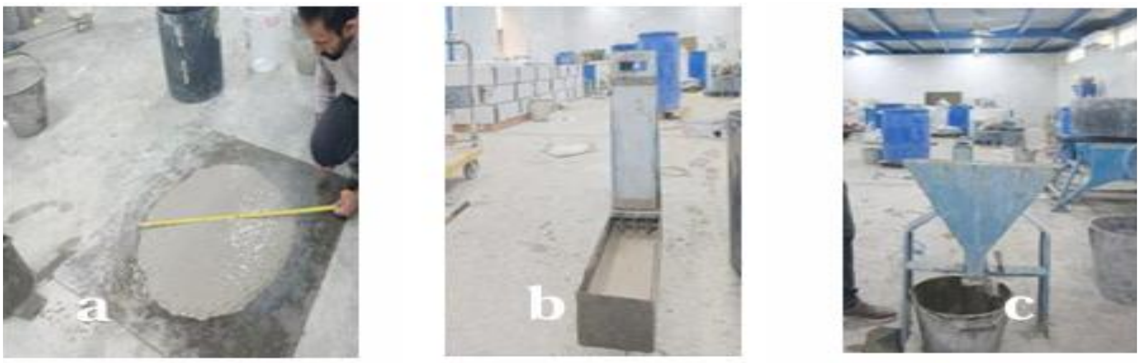

Fig. 8. Fresh Tests: a. Slump Flow, b. L-Box, and C. V-Funnel Flow.

blockages when passing through the L-box bars.

Measure V-Funnel Flow Values

The apparatus of the V-funnel Flow used in this study is shown in Fig. 6. The V-funnel test is utilized to evaluate the filling ability and viscosity of SCGPC [30]. The Tv values ranged between 9.8 and 11.3 seconds. According to [32], self-compacting concrete is separated into two V-funnel classes: VF1 (≤ 8 sec) and VF2 (9–25 sec). According to the V-funnel results, as condensed in Table 5 and illustrated in Fig. 7, all mixtures conformed to the VF2 viscosity classification. As per EFNARC [32], the VF2 class exhibits increased segregation and bleeding resistance, alongside reduced formwork pressure. The V-funnel flow time decreased with increasing GGBS content in binary mixes. Specifically, M1 (0% GGBS) recorded the highest flow time of 11.3 sec, while M4 (60% GGBS) recorded the lowest flow time of 9.8 sec. This improvement in workability is attributed to the finer particle size and smooth surface texture of GGBS, which enhances particle packing as shown in Fig. 8, reduces internal friction, and improves lubrication within the fresh self-compacting geopolymer concrete (SCGC) mixture[15]. Incorporating nanoparticles raised the V-funnel flow time relative to the binary mixture with equivalent GGBS content. M3 (50% GGBS, no nano) recorded 10.2 sec, while M5 (with 2% NA) increased to 11.1 sec, and M6 (with 2% NC) increased to 10.7 sec. Between the two nano-materials, NA (M5) caused a greater increase in flow time (lower workability) than NC (M6), because NA reacts more rapidly with water and alkaline solution, producing a more viscous and thick liquid [41,44].

Mechanical Properties of SCGPC

Compressive Strength Test

A key attribute of hardened concrete that evaluates the degree of geopolymerization is compressive strength. The compressive strength Test values at 7 and 28 days for each one of the SCGPCs are illustrated in Fig. 9. All binary and nano-modified mixtures exhibited superior compressive strengths compared to the control mixture (M1) [41,44]. This indicates that 50% GGBS replacement is optimal for compressive strength. Among binary mixes (CKC + GGBS), M3 (50% GGBS) achieved the highest compressive strength at both ages: 45.3 MPa at 7 days and 60.1 MPa at 28 days, followed by M2 (40% GGBS) with 41.8 MPa at 7 days and 58.3 MPa at 28 days, and

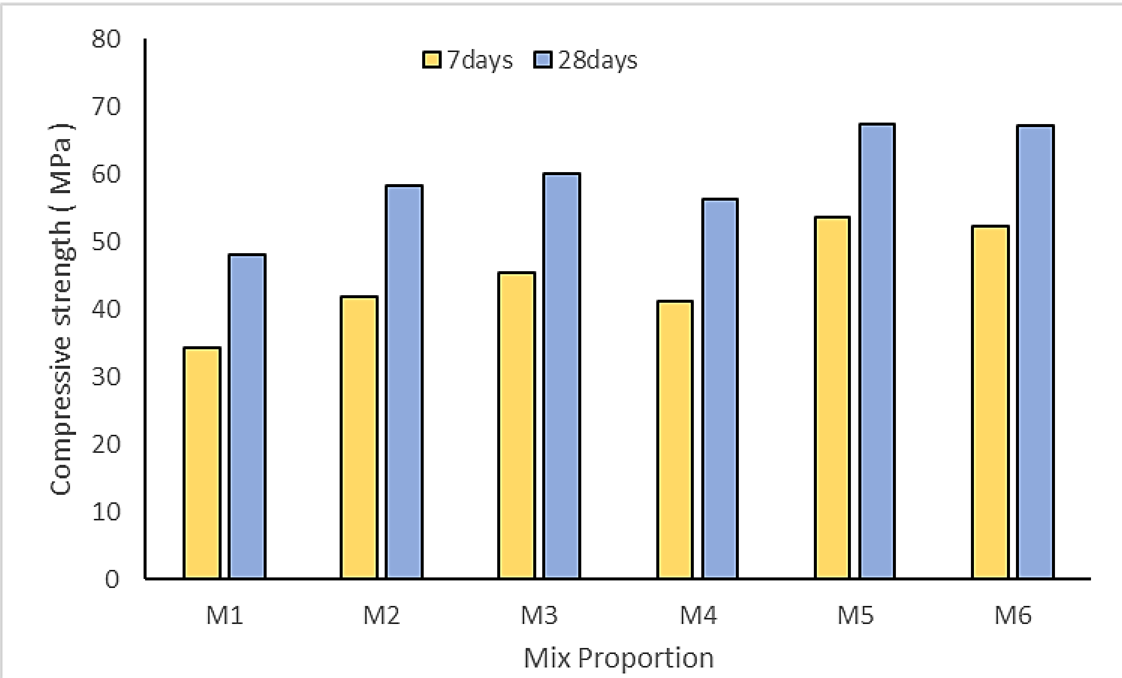

Fig. 9. Influence of GGBS, (NA), and (NC) with CKC on compressive strength of SCGPCs at 7 and 28 days.

M4 (60% GGBS) with 41.1 MPa at 7 days and 56.2 MPa at 28 days [41,44]. This indicates that 50% GGBS replacement is optimal for compressive strength. The lower strength at 40% GGBS (M2) is attributed to insufficient GGBS content to produce an adequate amount of geopolymer gel (N-A-S-H), while the excess CKC cannot fully compensate for the limited geopolymerization reaction [45]. At 60% GGBS (M4), the reduction in strength is due to lower CKC content, which provides less calcium for C-S-H gel formation, resulting in a less dense matrix [46]. Incorporating nanoparticles significantly improved compressive strength compared to the binary mix with the same GGBS content (M3: 50% GGBS, no nano = 45.3 MPa at 7 days, 60.1 MPa at 28 days). M5 (with 2% NA) achieved 53.5 MPa at 7 days and 67.3 MPa at 28 days, while M6 (with 2% NC) achieved 52.3 MPa at 7 days and 67.1 MPa at 28 days [44]. Compared to M3, M5 achieved +8.2 MPa (18.1%) higher at 7 days and +7.2 MPa (12.0%) higher at 28 days. M6 achieved +7.0 MPa (15.5%) higher at 7 days and +7.0 MPa (11.6%) higher at 28 days. Compared to the control mix M1 (100% CKC = 34.3 MPa at 7 days, 48.1 MPa at 28 days), M5 (with 2% NA) increased strength by 56.0% at 7 days and 39.9% at 28 days, while M6 (with 2% NC) increased strength by 52.5% at 7 days and 39.5% at 28 days.

Splitting Tensile Strength Test

Fig. 10 illustrates the outcomes of the splitting tensile strength of self-compacting geopolymer concrete (SCGPC) at 7 and 28 days. The splitting tensile strength of all mixtures exhibited a similar trend to that of compressive strength. All binary and nano-modified mixtures exhibited superior splitting tensile strengths compared to the control mixture (M1). Among binary mixes (CKC + GGBS), M3 (50% GGBS) achieved the highest splitting tensile strength at both ages: 3.6 MPa at 7 days and 4.7 MPa at 28 days, followed by M2 (40% GGBS) with 3.4 MPa at 7 days and 4.5 MPa at 28 days, and M4 (60% GGBS) with 3.4 MPa at 7 days and 4.3 MPa at 28 days. This indicates that 50% GGBS replacement is optimal for splitting tensile strength in binary mixes. The use of nanoparticles markedly enhanced the splitting tensile strength relative to the binary mixture with equivalent GGBS content (M3: 50% GGBS, no nano with 3.6 MPa at 7 days, 4.7 MPa at 28 days). M5 (with 2% NA) achieved 4.2 MPa at 7 days and 5.0 MPa at 28 days, while M6 (with 2% NC) achieved 4.0 MPa at 7 days and 5.0 MPa at 28 days [44]. The multi-binder ternary system (CKC + GGBS + nano) is more effective than

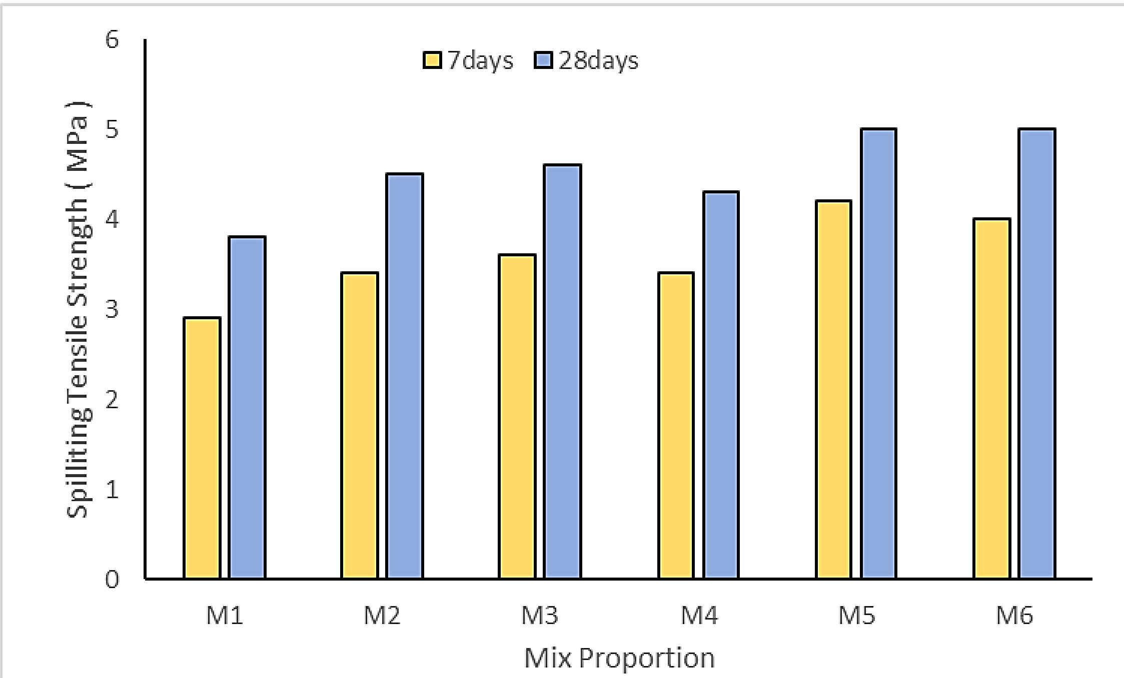

Fig. 10. Effect of GGBS, NA, and NC with CKC on splitting tensile strength of SCGPCs at 7 and 28 days.

any binary system.NA actively participates in the geopolymerization reaction and optimizes the Si/Al ratio, while NC primarily acts as a physical filler and does not undergo geopolymerization, limiting its contribution compared to NA [46]. Compared to the control mix M1 (100% CKC = 2.9 MPa at 7 days, 3.8 MPa at 28 days), M5 (with 2% NA) increased splitting tensile strength by 44.8% at 7 days and 31.6% at 28 days, while M6 (with 2% NC) increased strength by 37.9% at 7 days and 31.6% at 28 days.

CONCLUSION

The fresh characteristics of SCGPC were strongly influenced by the incorporation of GGBS and nanoparticles with calcined kaolin clay (CKC) in both binary mixes (CKC + GGBS) and nano-modified mixes (CKC + GGBS + NA or NC), resulting in increased V-funnel flow duration values, decreased slump flow diameter, and lowered L-box blocking ratios. All mixtures, nonetheless, adhered to the EFNARC criteria.

In binary mixtures, the use of GGBS improved workability compared with calcined kaolin clay alone, as demonstrated by reduced V-funnel flow time, elevated L-box ratio, and higher slump flow.

The multi-binder ternary mixes (with 2% NA or 2% NC) with GGBS and calcined kaolin clay (CKC) further reduced slump flow and L-box ratio and increased V-funnel time compared to binary and control mixes.

Both nano-materials (NA and NC) similarly reduced the workability of SCGC compared to the binary mix (M4). No significant difference was observed between NA and NC in tests of slump flow, V-funnel time, or L-box ratio, indicating that both nano-additives have comparable effects on fresh properties at 2% replacement.

The V-funnel test results demonstrated that all SCGPC combinations adhered to the VF2 viscosity categorization (9–25 seconds) as per EFNARC, signifying effective resistance to bleeding and segregation, as well as little formwork pressure.

Incorporating GGBS in binary mixtures significantly enhanced the splitting tensile and compressive strengths at all ages compared to the control mix (M1). M3 (50% GGBS) exhibited the highest compressive strength among binary mixes at both 7 and 28 days, and it also demonstrated the superior splitting tensile strength at both intervals. Consequently, it was selected as the foundation for the nano-modified ternary mixes (M5 and M6).

The multi-binder ternary mixtures (including 2% NA or 2% NC) with GGBS and calcined kaolin clay (CKC) exhibited superior mechanical qualities relative to the control mix (M1). The incorporation of both nano-materials markedly improved the splitting tensile and compressive strengths relative to the binary mix M3 (50% GGBS, devoid of nano). M5 and M6 had the maximum compressive strength at both 7 days and 28 days. Both M5 and M6 attained the maximum splitting tensile at 7 days and 28 days.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript.

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