RESEARCH PAPER

Synergistic Effects of Fly Ash with Nanoparticles Additive on the Behavior of Calcined Kaolin Clay Based Self-Compacting Geopolymer Concrete

Zaid Hasan Jaber *, Haider M. Owaid

Civil Engineering Department, College of Engineering, University of Babylon, Iraq

ARTICLE INFO

Article History:
Received 19 April 2026
Accepted 09 July 2026
Published 01 October 2026

Keywords:
Fly ash
Mechanical properties.
Nanoparticles
Self-compacting geopolymer concrete

ABSTRACT

Self-compacting geopolymer concrete (SCGPC) is a sustainable construction material that eliminates the need for both mechanical compaction and Portland cement. This study investigated the effects of multi-blended binders and nanoparticles on the fresh and mechanical properties of calcined kaolin clay (CKC)-based SCGPC. Six mixtures were prepared with a constant binder content of 493 kg/m³ and an alkaline liquid-to-binder ratio of 0.50. The mixtures were divided into binary and nano-modified ternary systems. The control mix contained 100% CKC. In the binary system, fly ash (FA) replaced CKC at 40%, 50%, and 60%. The optimum binary mixture was then modified by replacing 2% of CKC with either nano-alumina (NA) or nano-calcium carbonate (NC) to produce ternary mixtures. Fresh properties were evaluated using slump flow, L-box, and V-funnel tests, while compressive and splitting tensile strengths were measured to assess mechanical performance. The incorporation of FA improved workability compared with the control mixture, with the 50% CKC–50% FA blend exhibiting the highest slump flow and lowest V-funnel time. Although the addition of NA or NC slightly reduced workability, all mixtures satisfied EFNARC requirements. Mechanically, the nano-modified ternary mixtures outperformed both the control and binary mixtures. Compared with the optimum binary mix, the 2% NA mixture increased compressive strength by 17.8% and 10.3% at 7 and 28 days, respectively, while the 2% NC mixture achieved corresponding increases of 13.7% and 9.5%. Both nanoparticles also enhanced splitting tensile strength, demonstrating their effectiveness in producing high-performance SCGPC with acceptable workability.

How to cite this article
Jaber Z., Owaid H. Synergistic Effects of Fly Ash with nanoparticles additive on the Behavior of Calcined Kaolin Clay Based Self-Compacting Geopolymer Concreter. J Nanostruct, 2026; 16(4):4510-4522. DOI: 10.22052/JNS.2026.04.002

INTRODUCTION

Concrete, the most utilized material globally after water, primarily relies on cement production, which generates carbon dioxide (CO_2), airborne particulates, and other greenhouse gases (GHGs), hence contributing to atmospheric pollution. The CO_2 emissions from cement production constitute roughly 5% of worldwide anthropogenic CO2[1]. Global cement production is projected to exceed 2.8 billion tonnes, representing 5% to 6% of global carbon dioxide emissions[2]. One ton of ordinary Portland cement (OPC) generates approximately

* Corresponding Author Email: eng397.zaid.hasan@student.uobabylon.edu.iq

one ton of CO_2 and necessitates a temperature range of 1300–1500°C, significantly contributing to global climate change, hence necessitating a reduction in cement output[3]. Self-compacting concrete (SCC) is frequently employed in civil engineering structures, especially in precast industries, high-rise buildings, and requiring congested reinforcement [4]. Self-compacting concrete (SCC) is a type of concrete that needs a relatively substantial quantity of common Portland cement (OPC) on account of the necessity of extreme-volume paste. The material and energy questions on account of emissions of carbon dioxide (CO2) increase during the day, and OPC is individual of the great sources of allure construction[5]. The introduction of GPC technology facilitates sustainable development by reducing global CO_2 emissions and ensuring a cleaner environment in the long term. Utilizing aluminosilicate as a complete substitute for Ordinary Portland Cement (OPC) may reduce CO2 emissions by as much as 80% [3]. Geopolymer concrete (GPC) provides a viable alternative by obviating the necessity for Ordinary Portland Cement (OPC) as a binding agent. Geopolymers are typically synthesized by mixing alumino-silicate materials with alkaline solutions. Materials such as fly ash, silica fume, slag, kaolinite, clays, zeolite, rice-husk ash, and crimson dust are utilized. The typical alkaline for geopolymerization consists of a mix (NaOH, KOH) and (Na_2SiO_3, K_2SiO_3) [6]. Geopolymer concrete is regarded as the future version of conventional concrete for application in the construction industry, due to its durability and high strength, as well as its environmental advantages that eliminate the need for ordinary Portland cement, thereby reducing global CO2 emissions [7]. Self-compacting geopolymer concrete (SCGC) is a concrete type based on the concepts of self-compacting concrete (SCC) with geopolymer binders [8]. SCGC binders provide numerous benefits compared to Portland cement, such as a reduced carbon footprint, enhanced durability, and increased resilience to chemical and sulfate attacks. SCGC can attain compressive strength and durability characteristics that are equivalent to or above those of conventional concrete [9]. SCGC binders are produced from industrial by-products, hence diminishing dependence on conventional cement production, a significant contributor to greenhouse gas emissions [10] . Iraq possesses a substantial quantity of sedimentary kaolinite clay, known by many designations such as kaolin clay, ball clay, and kaolinitic claystone. The majority of kaolin clay deposits in Iraq are mostly located within the Western Desert of the Anbar Region [9]. The environmental benefits, in addition to the shown superior hardness and durability of geopolymer concrete, have motivated researchers to utilize Iraqi metakaolin as the primary source of silica and alumina for the creation of sustainable geopolymer concrete. [8]. The selection of fly ash (FA) as a partial replacement for calcined kaolin clay (CKC) in SCGC is based on its complementary chemical composition and physical characteristics [11]. FA provides additional amorphous silica and alumina, enhances particle packing due to its spherical shape, and improves workability while contributing to long-term strength development through sustained pozzolanic reactions [12]. Studies have shown that replacing CKC with up to 30-50% FA optimizes the microstructure, reduces

Table 1. Composition of chemicals of CKC and FA.

Chemical composition (%)	CKC	FA
SiO_2	54.7	54.0
Al_2O_3	37.4	28.5
Fe_2O_3	1.72	6.12
CaO	0.84	6.32
MgO	0.42	1.16
Na_2O	0.37	0.42
K_2O	0.54	1.08
SO_3	0.13	0.39
P_2O_5	0.29	0.54
TiO_2	0.68	1.38
LOI	2.91	1.55

porosity, and enhances compressive strength [12]. This combination creates a synergistic effect where CKC ensures rapid early strength gain while FA contributes to densification and durability at later ages [13]. Researchers established fly ash as a primary precursor in geopolymer concrete, supporting its role in ternary fly ash-metakaolin-nanoparticle systems [14]. Nanoparticle-modified geopolymer concrete (GPC) has emerged as an important focus of research in recent years due to its enhanced application performance and multiple modification mechanisms [15]. Studies indicate that nanoparticles substantially influence the fluidity, mechanical characteristics, and microstructure of concrete [15]. Studies indicate nanoparticle effects on fresh properties and compressive strength of sustainable SCC containing calcined pozzolanic materials like metakaolin [16]. Nano-calcium carbonate (NC) is cost-effective owing to the plentiful availability of calcium carbonate in limestone and marble, and it is utilized in cementitious composites for its filler and nucleation agent advantages [17]. Studies have shown that NC can enhance the mechanical characteristics of fly ash-based geopolymer concrete when utilized at an optimal dosage of up to 2%; an increase in NC content to 3% diminishes mechanical performance. Research validated the "ternary outperforms binary" concept for calcined clay-nano lime systems, providing a methodological foundation for this study's multi-component blend [18,19]. Nano-alumina (NA), which exhibits excellent superior and fineness, can also be employed to enhance the mechanical characteristics of concrete. Research has demonstrated that NA improves concrete strength through its filler effect and participation in hydration reactions, forming (C-A-S-H) gel (calcium-alumina-silicate-hydrate) that densifies the microstructure [20]. Alomayri [21] examined the effects of incorporating nano-alumina particles (50 nm) into geopolymer pastes derived from fly ash at varying concentrations (1%, 2%, and 3% by mass of fly ash). Alomayri [21]indicated that the ideal nano-alumina substance was 2%, leading to a denser microstructure with reduced porosity, thereby enhancing the mechanical properties of the geopolymer paste. The current research introduced an innovative method for augmenting strength using a unique multi-blended ternary SCGPC blends (CKC + FA + NA) or(CKC + FA + NC) while achieving satisfactory workability. This study utilizes locally sourced calcined kaolin clay (CKC) from Iraq to develop sustainable SCGPC products, offering reduced transportation costs, a lower carbon footprint, and support for local resource

Table 2. The physical properties of CKC and FA.

Binding Materials	Property Physical				
	Physical form	Color	Median particle size (μm)	Surface area (m2/kg)	Specific gravity
CKC	powder	Off-white	14.3	1640	2.61
FA	pwder	grey	0.12	346	2.23

Table 3. Characteristics of Nanoparticles Alumina and Nanoparticles Calcium Carbonate.

Property	Nanoparticles Alumina	Nanoparticles 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

utilization .Therefore, the results will be important in improving the efficacy of SCGPC created from locally sourced, environmentally sustainable pozzolanic material components obtained from geological resources and Nanomaterials-modified.

MATERIALS AND METHODS

Materials of SCGPC

The subsequent components used in the production of SCGPC mixes are illustrated in Fig. 1.

Calcined Kaolin Clay (CKC)

Calcined kaolin clay is derived from kaolin clay sourced from Dewekhla district of the Desert of Al Ramadi west of Baghdad, Iraq, ground and subsequently burned for one hour at a controlled temperature of 700 °C [22] . The CKC was more ground at Al-Zahra Emporium in Baghdad, utilizing the air blast process to produce reactive material with higher fineness [18]. The chemical composition and physical characteristics of Calcined Kaolin Clay (CKC) conform to ASTM C618 [23], as shown by Tables 1 and 2. Fig. 2 shows the XRD.

Fly ash (FA)

The fly ash utilized in the study was Class F sourced from Eurobuild. The fly ash exhibited a specific gravity of 2.23 and a surface area of 346. The chemical analysis and physical properties of Fly ash (FA) conform to ASTM C618 [23] , as illustrated in Tables 1 and 2. Fig. 2 shows the XRD.

Nanoparticles

Nanoparticles -alumina (NA) and Nanoparticles -calcium carbonate (NC) utilized in this work were sourced from China, Hangzhou. Table 3 delineates the characteristics of nanoparticles. Fig. 2 shows the XRD.

NaOH (Sodium Hydroxide)

Commercially available NaOH flakes has a purity grade of 99%. NaOH is dissolved in distilled water to prepare an activator with the required molarity of 12. Sodium hydroxide must be prepared 24 hours before usage, and if it surpasses 36 hours, it will transition to a semi-solid liquid condition. The prepared solution must be utilized within this timeframe. So the prepared solution should be used within this time . The NaOH solution utilized in this experiment is elaborated upon in ASTM E291 [24].

Na_2SiO_3 (Sodium Silicate)

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

Superplasticizer and Water

High water-reducing (HWRA) (Sika Viscocrete-180G) based on modified polycarboxylic ether, the product provided by the Sika shop was utilized to enhance workability to the requisite standard for SCGPCs to comply with ASTM C494 specifications [25]. Incorporating tap water into the SCGPC mix design enhances workability and conforms to IQS

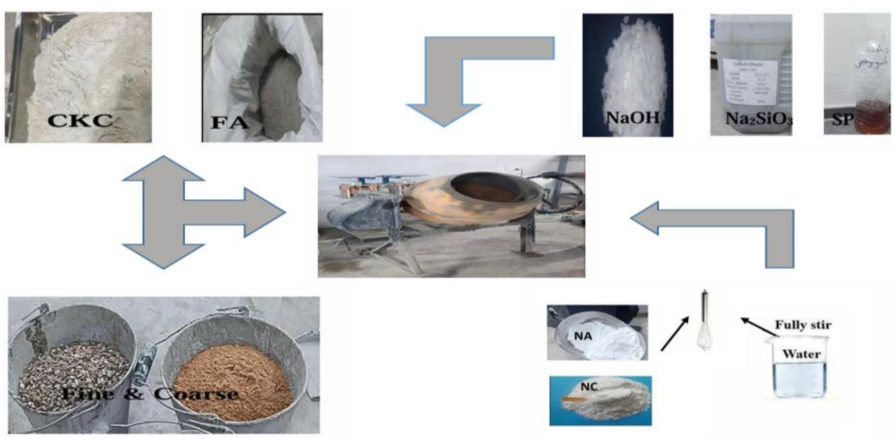

Fig. 1. Graphical Illustration of Materials Using in SCGPCs Production.

No. 1703 [26].

Coarse Aggregate

The coarse aggregate utilized is crushed and washed gravel sourced from the Al-Nabai'i region, with a maximum size of 10 mm. The test show indicated that the grading of coarse aggregate and sulfate content conformed to Iraqi standards IQS 45 [27]. The SO3 content, absorption,and specific gravity were, 0.03% ,0.5%, and 2.6 respectivly.

Fine Aggregate

The fine aggregate analyzed is local sand from the Al-Ukhaidher region, which satisfies the third grading zone criteria and complies with Iraqi standards IQS 45 [27]. The features included a SO3 content of 0.3% and a specific gravity of 2.65.

Self-Compacting Geopolymer Concrete Manufacturing

The first stage focuses on improving the CKC mixture in SCGPCs concrete by replacing portion of CKC to produce a binary mix using various quantities of FA, aiming for the optimal binary mix regarding best mechanical and fresh concrete characteristics, which are essential for self-compacting concrete. The second stage focuses on replacing part of CKC in the ternary mix with proportions of nanoparticles (2%NA or 2%NC) to form multi-blended binder systems and assess the

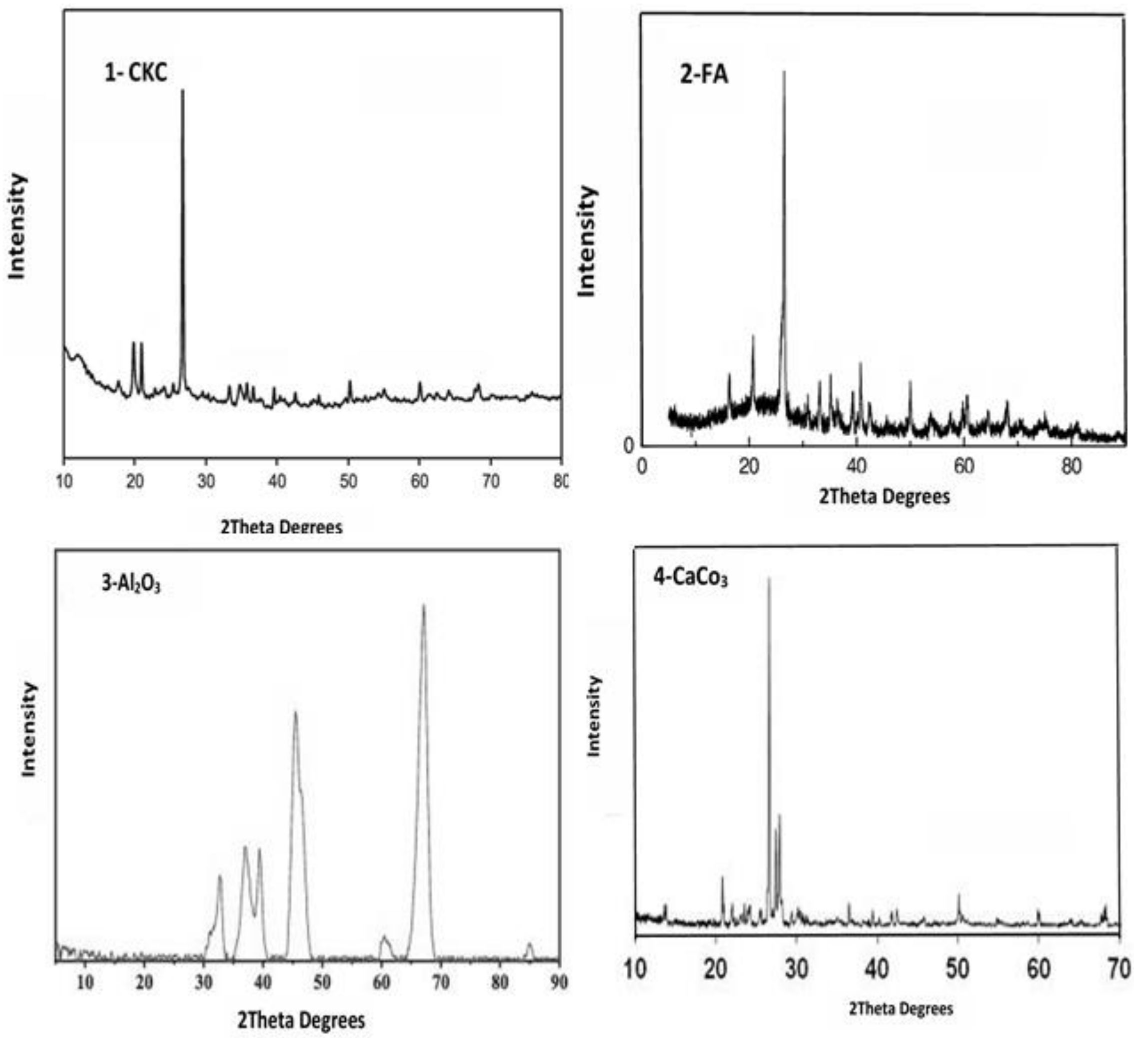

Fig. 2. XRD patterns of (1) CKC, (2) FA, (3) Al_2O_3, and (4) $CaCO_3$.

fresh and mechanical characteristics of SCGPCs.

Alkaline Activator Solution (AAS)

The initial stage involves making a sodium hydroxide solution by dissolving solid sodium hydroxide flakes in distilled water. A 12 molar NaOH solution is prepared using 362 grams of solid NaOH to produce one liter of solution [28]. Alkaline solutions are created by combining sodium hydroxide and sodium silicate at ambient temperature. The mass ratio of Na2SiO3 solution to NaOH solution is kept at 2.5, while the mass ratio of alkaline activator solution to binder is fixed at 0.5 [29,30].

Mix proportions

Due to the absence of a specified mix design technique for the production of SCGC, the proportions were established through several trials and based on the typical range of SCC mix composition proposed by EFNARC guidelines [31] standards, and basic principles of heat-cured low calcium fly ash-based geopolymer concrete are provided by [32]. In accordance with the experiments and current research, specific variables were held constant throughout the study. The SCGC mix was designed and cast at a water-to-binder (w/b) ratio of 0.39 and a total binder content of 493 kg/m3. The superplasticizer dosage was 3% by mass of cementitious material to fulfill performance requirements of SCC, according to EFNARC guidelines [31]. Curing for a total of 24 h at temperatures between (60 and 70) °C has been determined to yield higher levels of strength and a more compact microstructure relative to ambient curing conditions [33]. Nonetheless, the duration and sequence of mixing have significance in the SCGC production process in order to attain consistent and homogenous concrete in all SCGC, as stipulated in the protocols by [34] for mixing and batching. Fine and coarse aggregates, FA and CKC, were introduced into a power-driven

Fig. 3. The stages of making samples (a. Materials, b. Mixing of alkaline liquid, 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	FA	NA	NC	FA	CA	SP%	NHS	NSS
M1	CKC100% Control	0.39	493	0	0	0	848	860	3	70	175
M2	CKC60%+ FA40%	0.39	295.8	197.2	0	0	848	860	3	70	175
M3	CKC50%+ FA50%	0.39	246.5	246.5	0	0	848	860	3	70	175
M4	CKC40%+ FA60%	0.39	197.2	295.8	0	0	848	860	3	70	175
M5	FA50%+CKC48%+ NA2%	0.39	236.64	246.5	9.86	0	848	860	3	70	175
M6	FA50%+ CKC48%+ NC2%	0.39	236.64	246.5	0	9.86	848	860	3	70	175

revolving pan mixer and homogeneously mixed for 30 seconds. Subsequently, about one-third of the activated solution was introduced into the mixer, and mixing was allowed to continue for an additional 60 seconds. Subsequently, SP and more water, along with the residual activation solution, were incorporated into the mixer. The concrete was blended for 3 minutes and thereafter allowed to rest for 2 minutes. Finally, the mixture was blended for a further 2 minutes to complete the production process. According to [35] the nanoparticles(NA and NC) are dispersed separately in a certain amount of water and alkaline solution using a hand-electric mixer, Fig. 1 demonstrates, to obtain the best dispersion and to prevent agglomerations of nanoparticles because of their high surface area. Then, they were applied in solution form to the rest of the mixture in a control mixer. Finally, to guarantee mixture homogeneity, the fresh concrete mix was manually blended for an additional two to three minutes. The mixture was then produced and tested for fresh properties, and cast. All the mixtures were designed according to the standard SCGPC mix composition range recommended by EFNARC [31], which was set up with a similar grade of SCGPC. The details of all SCGPCs mix proportions are presented in Table 4. The SCGPCs were combined in phases as per the technique detailed in Gülş [29]. Subsequent to the mixing operation, the mixture was poured into steel molds and permitted to naturally occupy the spaces without needing compaction. Upon

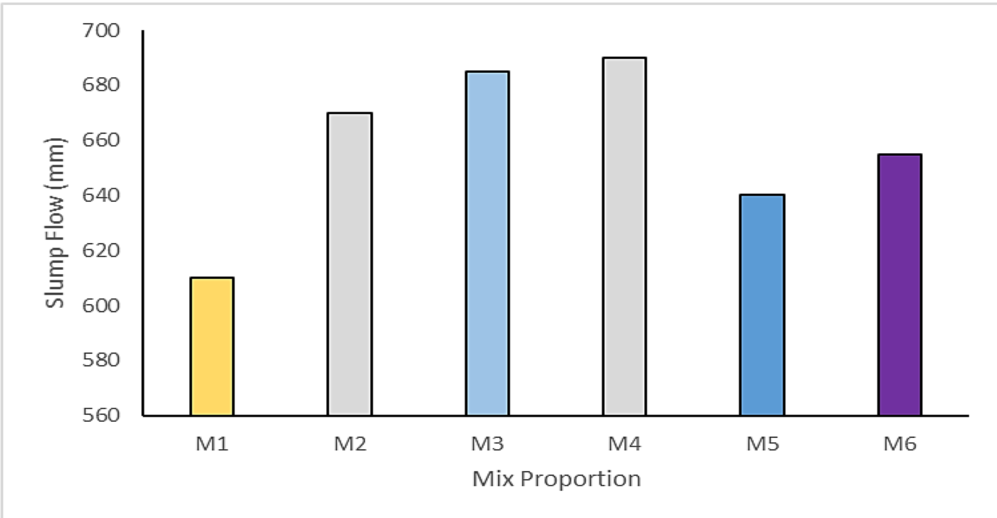

Fig. 4. Impact of Fly Ash, Nanoparticles Alumina and Nanoparticles Calcium Carbonate on the Slump Flow Test of SCGPCs.

Table 5. Results of Fresh Properties of SCGPCs.

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%+FA40%	670	10.5	0.856
M3	CKC50%+FA50%	685	9.9	0.882
M4	CKC40%+FA60%	690	9.5	0.892
M5	FA50%+CKC48%+NA2%	640	10.8	0.853
M6	FA50%+ CKC48%+NC2%	655	10.4	0.858

casting, the samples were subjected to curing, which varied from the technique utilized for OPC concrete. The samples were dried in ovens at 70°C and at ambient temperatures following casting [36]. Fig. 3 illustrates the preparation process for SCGPC samples.

Method Testing
Properties of Fresh SCGPC

The fresh properties of SCGC mixtures were assessed based on three basic characteristics of SCC: filling ability, passage ability, and segregation resistance. The properties were assessed using the Slump Flow test, T50 cm Slump Flow, V-Funnel test, and L-box test, following the procedures outlined in the European standards for self-compacting concrete [37] illustrated in Fig. 4.

Properties of Mechanical SCGPC

Tests for compressive strength and splitting tensile strength were performed utilizing cube specimens of (100 mm) and cylindrical specimens of (100×200 mm), respectively. The compressive strength and splitting tensile strength tests were conducted for all SCGPCs in accordance with the protocols outlined in BS EN 12390-Part 3 [38] and ASTM C496 [39] standards, respectively.

RESULTS AND DISCUSSION

Properties of Fresh SCGPC
Slump Flow Test

The flowability of fresh concrete was assessed using slump flow testing utilizing an Abrams cone. The slump flow results studies are depicted in Fig. 4 and Table 5. All the mixtures exhibited a slump flow diameter ranging from 610 mm to 690 mm. The maximum slump flow diameter (690 mm) was measured for mix M4 (CKC40% + FA60%). The control mix M1 (100% CKC) gave slump flow (610 mm), which was among the lowest. Comparing binary and ternary blends, the binary mixes (M2, M3, M4), which contain only CKC and FA, showed a clear trend: increasing FA content from from 40%, 50%, and 60%, respectively, improved slump flow from 610 mm to 690 mm, caused by the spherical morphology and ball-bearing properties of fly ash particles [40]. In contrast, the ternary blends (M5 and M6), which incorporate 2% nano-materials alongside 48% CKC and 50% FA, exhibited lower workability compared to the binary mix with the same FA content (M3: 50% FA, no nano). Specifically, M3 recorded 685 mm, while M5 (with 2% NA) dropped to 640 mm, and M6 (with 2% NC) dropped to 655 mm. This decrease is ascribed to the extensive surface area of nanoparticles [41], which increases liquid demand. Between the two nano-materials, NA caused a greater reduction (45 mm loss) than NC (30 mm loss),

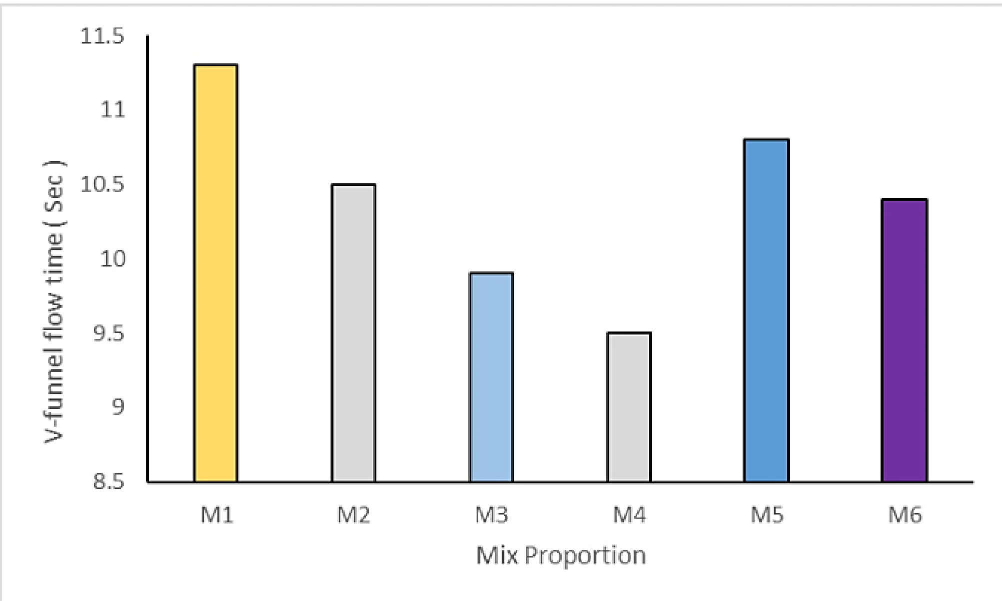

Fig. 5. Impact of fly ash, Nanoparticles Alumina, and Nanoparticles Calcium Carbonate on V-Funnel Flow test of SCGPCs.

due to NA faster reaction with water and alkaline solutions, it generates a denser and more viscous liquid. [42]. The minimum flow diameter among nano-modified mixes was 640 mm (M5), while the overall maximum among all mixes was 690 mm (M4). According to EFNARC specifications [31], the control mix (M1) and the nano-modified mixes (M5 & M6) fell within the SF1 class (550–650 mm), while the binary FA mixes (M2, M3, M4) exhibited higher workability corresponding to the SF2 class (660–750 mm). These results correspond with those attained by [43,18].

V-Funnel Flow test

The V-funnel flow time (Tv) reflects the flowability and viscosity of SCGPC [29]. Delayed V-funnel flow durations show reduced workability, as the mixes requires more time to flow from the funnel, reflecting lower filling capacity. The Tv values ranged between 9.5 and 11.3 seconds. According to [31], self-compacting concrete is classified into two V-funnel classes: VF1 (≤ 8 sec) and VF2 (9–25 sec). According to the V-funnel results, as shown in Table 5 and illustrated in Fig. 5, all mixtures categorized within the VF2 viscosity class. As per

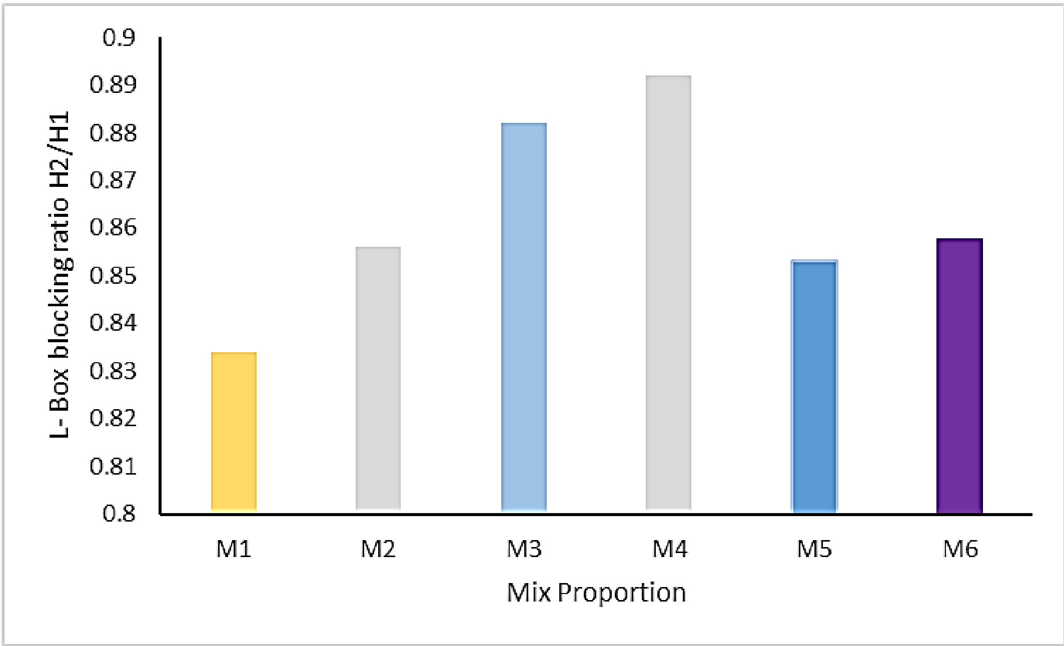

Fig. 6. Impact of fly ash, Nanoparticles Alumina, and Nanoparticles Calcium Carbonate on Blocking Ratio.

Fig. 7. Tests of Fresh Properties: a. Slump Flow Test, b. L-Box test, and C. V-Funnel Flow Time.

EFNARC [31], the VF2/VS2 classification reflects higher segregation and bleeding resistance, together with reduced formwork pressure. The V-funnel flow time diminished as the fly ash content in binary mixtures increased. Specifically, M1 (0% FA) recorded the highest flow time of 11.3 sec, while M4 (60% FA) recorded the lowest flow time of 9.5 sec. This improvement in workability is attributed to the spherical shape and ball-bearing effect of fly ash particles[41]. Incorporating nanoparticles increases the V-funnel flow time compared to the binary mix with the same FA content. M3 (50% FA, no nano) recorded 9.9 sec, while M5 (with 2% NA) increased to 10.8 sec, and M6 (with 2% NC) increased to 10.4 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 [41,42].

L-Box Test (Passing Ability) test

The current study utilized the L-box with two bars to assess the passing ability of SCGPCs. As per EFNARC criteria [31], the blocking ratio (BR = H2/H1) must be ≥ 0.8 to fulfill the requisite passing ability criteria. As shown in Table 5 and Figs. 6 and 7, 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% FA), while the lowest blocking ratio of 0.834 was recorded for the control mix M1 (100% CKC). Increasing fly ash content in binary mixes from M2 to M4 progressively improved the passing ability progressively improved the passing ability, as reflected by the increasing BR values from 0.856 to 0.892. This enhancement is ascribed to the spherical morphology and ball-bearing function of fly ash particles, which enhance flowability and reduce internal friction [41]. When incorporating nano-materials, the blocking ratio decreased compared to the binary mix with the same fly ash content. Specifically, M3 (50% FA, no nano) recorded a BR of 0.882, while M5 (with 2% NA) decreased to 0.853, and M6 (with 2% NC) decreased to 0.858. 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 [41,42]. During assessment, none of the six mixes exhibited any blockages when passing through the L-box bars.

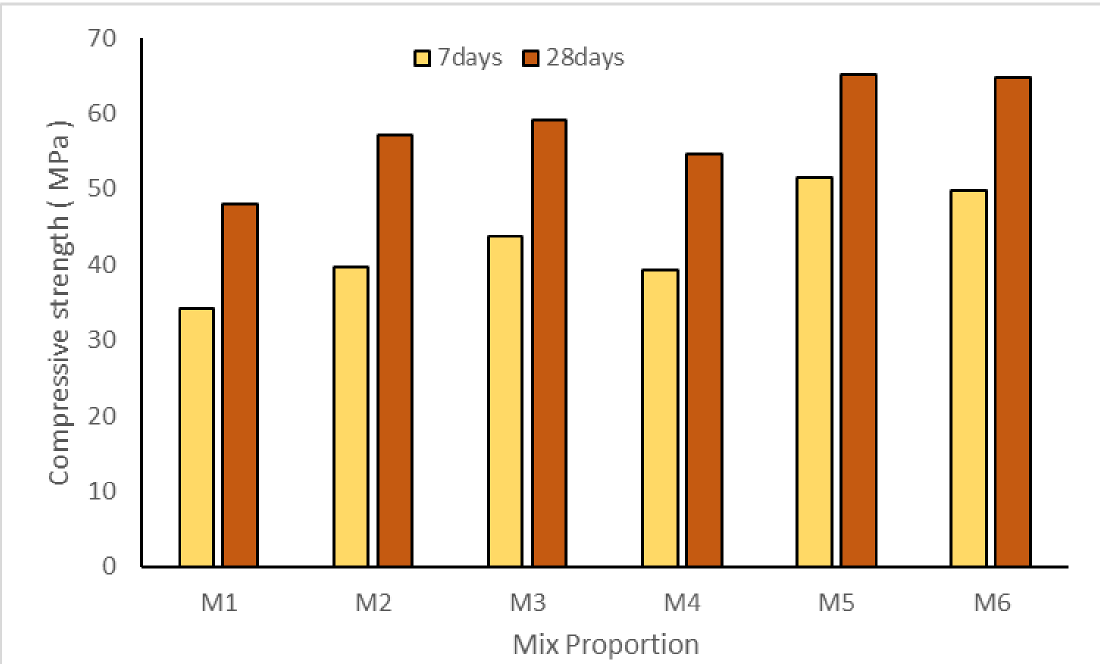

Fig. 8. Impact of fly ash, Nanoparticles Alumina, and Nanoparticles Calcium Carbonate on compressive strength at 7 and 28 days.

Properties of Mechanical SCGPC

Compressive Strength of SCGPC

Compressive strength is one of the most important characteristics of hardened concrete. This characteristic effectively assesses the degree of geopolymerization. Fig. 8 illustrates the compressive strength test results for all SCGPCs at 7 and 28 days. All binary and ternary mixtures exhibited higher compressive strengths compared to the control mixture (M1). Among binary mixes (CKC + FA), M3 (50% FA) achieved the highest compressive strength at both ages at 7 days and 28 days, followed by M2 (40% FA) and then M4 (60% FA) [41] [42]. This indicates that 50% FA replacement is optimal for compressive strength. The lower strength at 40% FA (M2) is attributed to insufficient fly ash 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 [44,45]. At 60% FA (M4), the diminished strength results from a reduced CKC concentration, which supplies insufficient calcium for C-S-H gel creation, resulting in a less dense matrix[46,47]. Incorporating nanoparticles significantly improved compressive strength compared to the binary mix with the same FA content. Compared to M3, M5 achieved (17.8%) higher at 7 days and (10.3%) higher at 28 days. M6 achieved (13.7%) higher at 7 days and (9.5%) higher at 28 days. In the multi-binder system (CKC + FA + nano), M5 (with 2% NA) and M6 (with 2% NC) achieved comparable compressive strengths, indicating that NA and NC have a similar effect on strength development in this system, despite their different reaction mechanisms, because NA actively participates in the geopolymerization reaction and optimizes the Si/Al ratio. In contrast, NC primarily acts as a physical filler and does not undergo geopolymerization [41,42,45]. Compared to the control mix M1, M5 (with 2% NA) increased strength by 50.4% at 7 days and 35.6% at 28 days, while M6 (with 2% NC) increased strength by 45.2% at 7 days and 34.5% at 28 days.

Splitting Tensile Strength of SCGPC

Fig. 9 presents the results of the splitting tensile strength of SCGPC concrete at 7 and 28 days. The splitting tensile strength combinations showed a comparable pattern 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 + FA), M3 (50% FA) achieved the highest splitting tensile strength at both ages: 3.5

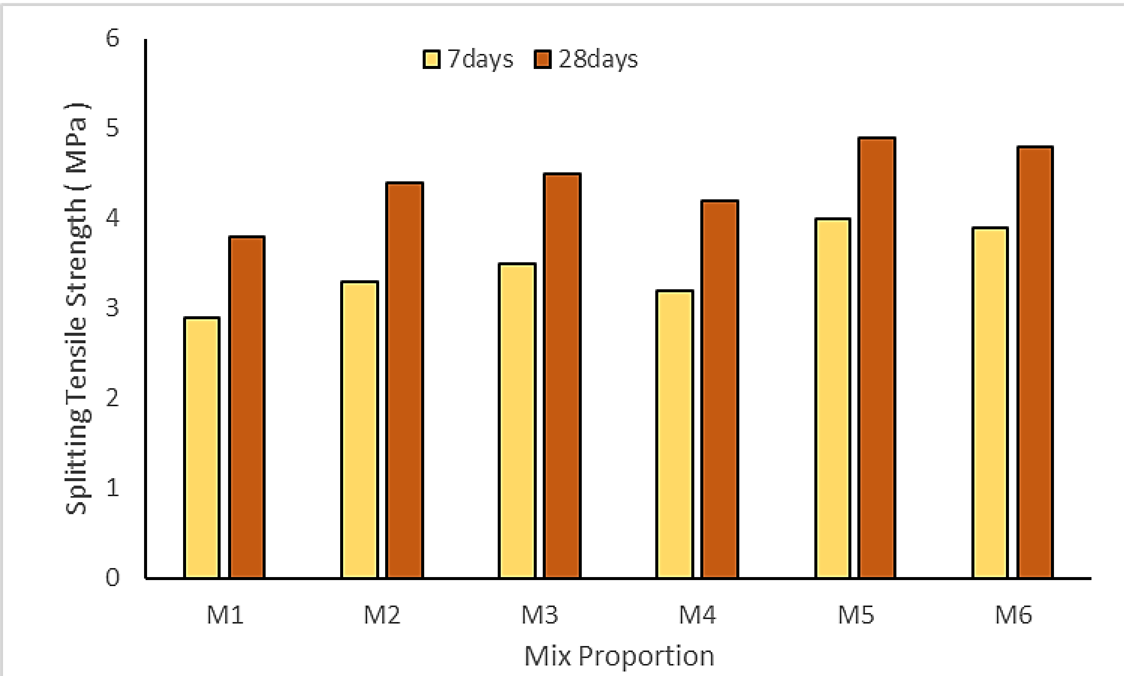

Fig. 9. Impact of fly ash, Nanoparticles Alumina, and Nanoparticles Calcium Carbonate on Splitting Tensile Strength at 7 and 28 days.

MPa at 7 days and 4.5 MPa at 28 days, followed by M2 (40% FA) with 3.3 MPa at 7 days and 4.4 MPa at 28 days, and M4 (60% FA) with 3.2 MPa at 7 days and 4.2 MPa at 28 days. This indicates that 50% FA replacement is optimal for splitting tensile strength. Incorporating nanoparticles significantly improved splitting tensile strength compared to the binary mix with the same FA content (M3: 50% FA, no nano = 3.5 MPa at 7 days, 4.5 MPa at 28 days). M5 (with 2% NA) achieved 4.0 MPa at 7 days and 4.9 MPa at 28 days, while M6 (with 2% NC) achieved 3.9 MPa at 7 days and 4.8 MPa at 28 days. In the multi-binder system (CKC + FA + nano), NA and NC achieved nearly identical splitting tensile strengths (4.9 MPa vs. 4.8 MPa at 28 days), demonstrating that both nanoparticles are similarly effective.

CONCLUSION

In summary, the properties of fresh SCGPCs were significantly influenced by adding fly ash and nanoparticles to CKC. Binary mixes (CKC + FA) showed improved workability with increasing FA content, while nano-modified ternary mixes (CKC + FA + NA or NC) showed slight reductions compared to the optimal binary mix. Nevertheless, all mixes met the EFNARC requirements for self-compacting geopolymer concrete.

In binary mixes, the addition of fly ash improved workability compared to calcined kaolin clay alone, as evidenced by decreased V-funnel flow time, increased L-box ratio, and increased slump flow.

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

Between the two nano-materials, NA was more effective than NC in reducing workability in nano-modified mixes (CKC + FA + NA or NC), as evidenced by lower slump flow, lower L-box ratio, and higher V-funnel time.

The V-funnel results indicated that all SCGPC mixtures conformed to the VF2 viscosity classification (9–25 seconds) according to EFNARC, signifying effective resistance to bleeding and segregation, as well as reduced formwork pressure.

Incorporating FA in binary mixtures significantly enhanced the splitting tensile and compressive strengths at 7 and 28 days compared to the control mix.

Among the binary mixes, (50% FA + 50% CKC) exhibited the highest strength, and was therefore selected as the base mix to be modified with nanoparticles (2%NA and 2%NC) in ternary mixes.

Nano-modified ternary mixes (2% NA and 2% NC) showed even higher mechanical properties compared to the control mix, and both nano-materials significantly enhanced splitting tensile and compressive strengths compared to the optimal binary mix (50% FA).

CONFLICT OF INTEREST

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

REFERENCES

1. Hason MM, Al-Sulttani AO, Abbood IS, Hanoon AN. Emissions Investigating of Carbon Dioxide Generated by the Iraqi Cement Industry. IOP Conference Series: Materials Science and Engineering. 2020;928(2):022041.
2. Luhar S, Ashour A, Luhar I. Decarbonising the Cement and Concrete Industry—A Step Forward to a Sustainable Future. Journal of Composites Science. 2026;10(5):226.
3. Adesina A. Recent advances in the concrete industry to reduce its carbon dioxide emissions. Environmental Challenges. 2020;1:100004.
4. Moravvej M, Rashidi M. Structural performance of self-compacting concrete. Self-Compacting Concrete: Materials, Properties and Applications: Elsevier; 2020. p. 371-387.
5. Athiyamaan V. Admixture-based self-compacted concrete with self-curing concrete techniques a state of art of review. Cleaner Engineering and Technology. 2021;5:100250.
6. Luhar I, Luhar S. A Comprehensive Review on Fly Ash-Based Geopolymer. Journal of Composites Science. 2022;6(8):219.
7. Amran M, Debbarma S, Ozbakkaloglu T. Fly ash-based eco-friendly geopolymer concrete: A critical review of the long-term durability properties. Construction and Building Materials. 2021;270:121857.
8. Mol J.S J, P DE. A Study On Self-Compacting Geopolymer Concrete. International Journal of Engineering Applied Sciences and Technology. 2021;5(10).
9. Pradhan J, Panda S, Dwibedy S, Pradhan P, Panigrahi SK. Production of durable high-strength self-compacting geopolymer concrete with GGBFS as a precursor. J Mater Cycles Waste Manage. 2023;26(1):529-551.
10. Khan S, Parveez M, Tantray MA. Self-compacting geopolymer concrete: advances, challenges, and future directions. Chemical Papers. 2025;80(4):3257-3275.
11. Luo Y, Zhang Q, Wang D, Yang L, Gao X, Liu Y, et al. Mechanical and microstructural properties of MK-FA-GGBFS-based self-compacting geopolymer concrete composites. Journal of Building Engineering. 2023;77:107452.
12. Qader DN, Jamil AS, Bahrami A, Ali M, Arunachalam KP. A systematic review of metakaolin-based alkali-activated and geopolymer concrete: A step toward green concrete. Reviews On Advanced Materials Science. 2025;64(1).
13. Devi SC, Khan RA, Rautela BS. Influence of Metakaolin on Chemical Resistance of Low Calcium Fly Ash Based

Geopolymer Concrete. IOP Conference Series: Materials Science and Engineering. 2018;431(9):092008.
14. Owaid HM, Al-Rubaye MM, Al-Baghdadi HM. Use of waste paper ash or wood ash as substitution to fly ash in production of geopolymer concrete. Scientific Review Engineering and Environmental Studies (SREES). 2021;30(3):464-476.
15. Xu Z, Huang Z, Liu C, Deng H, Deng X, Hui D, et al. Research progress on key problems of nanomaterials-modified geopolymer concrete. Nanotechnology Reviews. 2021;10(1):779-792.
16. Khoman RK, Owaid HM. Sustainable High-performance Self-compacting Concrete with Multi Blended of Materials Powders: Fresh and Hardened Properties. International Journal of Engineering. 2026;39(5):1101-1114.
17. Qiu J, Lyu JW, Yang JL, Cui KB, Liu HZ, Wang GF, et al. Review on Preparation, Modification and Application of Nano-Calcium Carbonate. Particle and Particle Systems Characterization. 2024;41(11).
18. Kadhum AO, Owaid HM. Experimental Investigation of Self-compacting High Performance Concrete Containing Calcined Kaolin Clay and Nano Lime. Civil Engineering Journal. 2020;6(9):1798-1808.
19. Assaedi H, Alomayri T, Kaze CR, Jindal BB, Subaer S, Shaikh F, et al. Characterization and properties of geopolymer nanocomposites with different contents of nano-CaCO3. Construction and Building Materials. 2020;252:119137.
20. Chirag RO. Mechanical Performance Optimization of Concrete Using Combined Nano-Silica and Nano-Alumina. Journal of Information Systems Engineering and Management. 2024;9(4s):1241-1253.
21. Alomayri T. Experimental study of the microstructural and mechanical properties of geopolymer paste with nano material (Al2O3). Journal of Building Engineering. 2019;25:100788.
22. Mejía De Gutiérrez R, Torres J, Vizcayno C, Castello R. Influence of the calcination temperature of kaolin on the mechanical properties of mortars and concretes containing metakaolin. Clay Minerals. 2008;43(2):177-183.
23. Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. ASTM International.
24. Test Methods for Chemical Analysis of Caustic Soda and Caustic Potash (Sodium Hydroxide and Potassium Hydroxide). ASTM International.
25. Modification of the Compressive Strength Requirements for the ASTM C494 Standard on Chemical Admixtures. SP-288: Tenth International Conference on Superplasticizers and other Chemical Admixtures: American Concrete Institute; 2012.
26. Specification of concrete quality. Concrete Mix Design, Quality Control and Specification: Taylor & Francis. p. 176-211.
27. Aggregates for concrete. Concrete Mix Design, Quality Control and Specification: CRC Press; 2006. p. 193-220.
28. Hardjito D, Wallah SE, Sumajouw DMJ, Rangan BV. Fly Ash-Based Geopolymer Concrete. Australian Journal of Structural Engineering. 2005;6(1):77-86.
29. Gülşan ME, Alzeebaree R, Rasheed AA, Niş A, Kurtoğlu AE. Development of fly ash/slag based self-compacting geopolymer concrete using nano-silica and steel fiber. Construction and Building Materials. 2019;211:271-283.
30. Aouan B, Alehyen S, Fadil M, El Alouani M, Khabbazi A, Atbir A, et al. Compressive strength optimization of metakaolin-based geopolymer by central composite design. Chemical Data Collections. 2021;31:100636.
31. Rully Angraeni S, Intan S. Penggunaan Karang Jahe Pada Self Compacting Concrete (SCC) Menggunakan Metode Efnarc. Konferensi Nasional Teknik Sipil (KoNTekS). 2025;2(1).
32. Noushini A, Castel A. The effect of heat-curing on transport properties of low-calcium fly ash-based geopolymer concrete. Construction and Building Materials. 2016;112:464-477.
33. Saini G, Vattipalli U. Assessing properties of alkali activated GGBS based self-compacting geopolymer concrete using nano-silica. Case Studies in Construction Materials. 2020;12:e00352.
34. Albidah A, Alghannam M, Abbas H, Almusallam T, Al-Salloum Y. Characteristics of metakaolin-based geopolymer concrete for different mix design parameters. Journal of Materials Research and Technology. 2021;10:84-98.
35. Shahrajabian F, Behfarnia K. The effects of nano particles on freeze and thaw resistance of alkali-activated slag concrete. Construction and Building Materials. 2018;176:172-178.
36. Sherwani AFH, Younis KH, Arndt RW. Fresh, Mechanical, and Durability Behavior of Fly Ash-Based Self Compacted Geopolymer Concrete: Effect of Slag Content and Various Curing Conditions. Polymers. 2022;14(15):3209.
37. Hatungimana D, Mardani ALI, Mardani N, Assaad J. Feasibility of Steel Fiber-Reinforced Self-Compacting Concrete Containing Recycled Aggregates – Compliance to Efnarc Guidelines. Elsevier BV; 2024.
38. Testing hardened concrete. BSI British Standards.
39. Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. ASTM International.
40. Ma J, Wang D, Zhao S, Duan P, Yang S. Influence of Particle Morphology of Ground Fly Ash on the Fluidity and Strength of Cement Paste. Materials. 2021;14(2):283.
41. Al Ghabban A, Al Zubaidi AB, Jafar M, Fakhri Z. Effect of Nano SiO_2 and Nano $CaCO_3$ on The Mechanical Properties, Durability and flowability of Concrete. IOP Conference Series: Materials Science and Engineering. 2018;454:012016.
42. Younus SJ, Mosaberpanah MA, Alzeebaree R. The Performance of Alkali-Activated Self-Compacting Concrete with and without Nano-Alumina. Sustainability. 2023;15(3):2811.
43. Bheel N, Awoyera P, Tafsirojjaman T, Hamah Sor N, sohu S. Synergic effect of metakaolin and groundnut shell ash on the behavior of fly ash-based self-compacting geopolymer concrete. Construction and Building Materials. 2021;311:125327.
44. Guo B, Song M, Yi J, Ni S, Shen T, Du Y. Improving the mechanical properties of carbon nanotubes reinforced pure aluminum matrix composites by achieving non-equilibrium interface. Materials and Design. 2017;120:56-65.
45. Huang Y, Han M. The influence of α-Al_2O_3 addition on microstructure, mechanical and formaldehyde adsorption properties of fly ash-based geopolymer products. J Hazard Mater. 2011;193:90-94.
46. Jumaa NH, Ali IM, Nasr MS, Falah MW. Strength and microstructural properties of binary and ternary blends in fly ash-based geopolymer concrete. Case Studies in Construction Materials. 2022;17:e01317.
47. Tchakoute HK, Rüscher CH, Djobo JNY, Kenne BBD, Njopwouo D. Influence of gibbsite and quartz in kaolin on the properties of metakaolin-based geopolymer cements. Applied Clay Science. 2015;107:188-194.