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Assessing Performance of Alkali Activated Calcined Kaolin Clay Based Self-Compacting Geopolymer Concrete Using Nanoparticles and Micro Steel Fiber

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Keywords:
Calcined kaolin clay (CKC); Fresh and mechanical properties; Micro steel fiber; Nanoparticles; Self-compacting geopolymer concrete.

Highlights:

- *Nano-alumina (NA) and nanocalcium carbonate (NC) were utilized in binary and ternary mixes of development self-compacting geopolymer concrete (SCGPC).*
- *Adding nanoparticles decreased the fresh properties of all SCGPC mixes.*
- *Mixes, including nano-alumina, were observed to be more cohesive and had better mechanical properties than mixes with NC.*

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Abstract: The sustainable production of self-compacting geopolymer concrete (SCGPC) is eco-friendly and has less carbon footprint than normal concrete. On the other hand, nanoparticles have been added to SCGPC in previous studies to enhance its characteristics. However, limited studies have concentrated on using nano-alumina and nanocalcium carbonate in SCGPC. Hence, in the present study, self-compacting geopolymer concrete was developed from locally available calcined kaolin clay (CKC) using two types of nanoparticles: nano alumina (NA) and nano calcium carbonate (NC), in light of the evaluation of its fresh and hardening properties. All SCGPC mixes were formulated with the total binder amount was 484 kg/m^3 and a constant ratio of alkaline liquid to binder (AL/B) of 0.50. These mixes were divided into two systems, namely binary and ternary mixture systems. 100% of CKC was used in the control mix, while a combination of (98%CKC+2%NA) and (98%CKC+2%NC) was used separately in the first system (binary) and the second system (96%CKC +2%NA+2%NC) were mixed (ternary). Microsteel fibers (SF) were added to all SCGPC mixtures (SCGPCs) with a constant content of 0.5% of the volume of concrete. To evaluate the fresh properties of these mixtures, several tests were conducted. The tests were slump flow, L-box test, and flow time via V-Funnel. Also, the mechanical performance of SCGPCs was evaluated in light of the compression and splitting tensile strength tests. The results of fresh properties indicated a reduction in workability for all binary and ternary mixes compared to the control mix. However, the workability test results of all SCGPCs were in the required range determined by EFNARC. Moreover, incorporating NC and NA in binary and ternary mixes improved mechanical properties for all ages. However, the compressive and splitting tensile strengths were considerably enhanced up to (15.8% and 14.66%) for NA and (14.3% and 12.83%) for NC in the binary mixes, respectively. Meanwhile, the improvement reached (28.34% and 25.92%) in the ternary mixture at the age of 28 days.

تقييم أداء خرسانة جيوبوليمرية ذاتية الرص قائمة على طين الكاؤولين المكلس المنشط قلوياً باستخدام جسيمات نانوية وألياف فولاذية دقيقة

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الخلاصة
يُعدّ الإنتاج المستدام للخرسانة الجيوبوليمرية ذاتية الرص صديقًا للبيئة وله بصمة كربونية أقل مقارنةً بتلك الموجوده في الخرسانة التقليدية. ومن ناحية أخرى، تمت إضافة الجسيمات النانوية إلى الخرسانة الجيوبوليمرية ذاتية الرص في الدراسات السابقة لغرض تعزيز خصائصها. ومع ذلك، فإن هنالك دراسات محدودة ركزت على استخدام نانو الألومينا ونانو كربونات الكالسيوم معًا في الخرسانة الجيوبوليمرية ذاتية الرص. ومن ثمّة ففي هذه الدراسه تم تطويرخرسانة جيوبوليمرية ذاتية الرص (SCGPC) من طين الكاؤولين المكلس (CKC) والمتوفر محليا بأستخدام نوعين من الجسيمات النانوية: نانو كاربونات الكالسيوم (NC) ونانو الومينا (NA) في ضوء تقييم خصائصها الطرية والميكانيكية. إذ تم تحضيرجميع الخلطات الخرسانية الجيوبوليمرية ذاتية الرص بكمية كلية للمادة الرابطة تبلغ ٤٨٤ كغم / م³ ونسبة ثابتة من المحلول القلوي الى المادة الرابطة تبلغ ٠,٥ وتم تقسيم هذه الخلطات الى نظامين وهما نظام الخليط الثنائي والثلاثي. وقد تم استخدام ١٠٠% من طين الكاؤولين المكلس (CKC) في الخلطة المرجعية بينما تم استخدام مزيج (٩٨٪CKC +٢٪NA) و(٩٨٪ CKC+٢٪NC) بشكل منفصل في النظام الاول (الثنائي) وايضا (٩٦٪CKC +٢٪NA +٢٪NC) قد تم خلطها معا في النظام الثاني(الثلاثي) .وقد تمت اضافة الياف فولاذية دقيقة في جميع الخلائط الخرسانيه الجيوبوليمرية ذاتية الرص (SCGPCs) بمحتوى ثابت يبلغ ٠,٥ % من حجم الخرسانة. ولتقييم الخواص الطرية لهذه الخلائط اجريت اختبارات متعددة وهذه الاختبارات هي اختبار هطول الانسياب واختبار الصندوق على شكل حرف (L) وزمن الانسياب باستخدام القمع على شكل حرف (V) . وقد تم تقييم الاداء الميكانيكي في ضوء اختبار مقاومه الانضغاط والشد. اشارت نتائج الخصائص الطرية الى نقصان قابلية التشغيل لكل الخلطات الثنائية والثلاثية مقارنة مع الخلطة المرجعية مع ذلك كانت نتائج اختبارات قابلية التشغيل لجميع الخلائط الجيوبوليمرية ذاتية الرص ضمن النطاق المطلوب الذي حدده (الاتحاد الاوربي) EFNARC . فضلًا على ذلك أدى دمج كل من NC و NA في الخلطات الثنائية والثلاثية الى تحسُّن في الخصائص الميكانيكية لجميع الاعمار. ومع ذلك، تحسنت مقاومة الانضغاط والشد بشكل كبير حتى (١٥,٨٪ و١٤,٦٦٪) للـNA و(١٤,٣٪ و١٢,٨٣٪) للـNC في الخلطات الثنائية على التوالي.بينما بلغ التحسُّن (٢٨,٣٤٪ و ٢٥,٩٢٪) في الخليط الثلاثي عند عمر ٢٨ يوماً.

الكلمات الدالة: الالياف الفولاذية الدقيقة، الجسيمات النانوية، الخرسانة الجيوبوليمرية ذاتية الرص، الخواص الطرية والميكانيكية، طين الكاؤولين المكلس.

1.INTRODUCTION

Concrete is the second highest consumed material after water. It includes more than 20% of Portland cement. The manufacture of Portland cement is responsible for around 8% of the world's carbon dioxide emissions [1]. Producing a ton of cement releases approximately a ton of CO2 emissions into the atmosphere [2]. Hence, discovering green and sustainable construction components with reduced energy consumption and a lower environmental impact is becoming more necessary regarding mechanical properties, durability, and energy consumption. Geopolymers are one of the new sustainable binders that have the ability to replace Portland Cement (PC) in concrete applications [3]. Geopolymers are inorganic polymers produced at relatively low temperatures, usually below 100 °C [2]. Geopolymer concrete (GPC) might be synthesized by geological or waste materials with a highly alkaline liquid [4]. PC completely replaces it to create GPC. GPC must be appropriately compacted to avoid failure due to its high viscosity. Self-Compacting Geopolymer Concrete (SCGPC) was proposed to address this problem [5]. Self-compacting concrete (SCC) is a unique concrete that flows and compacts under its weight without compaction [6]. SCGPC combines the characteristics of GPC and SCC is created by fully eliminating PC and does not require vibration when put in place [7,8]. Most of the published studies concentrated on producing geopolymer concrete from fly ash as a raw material source; however, one ton of geopolymer cement made from fly ash comprising 50% by weight of fly ash is related to 16.5 tons of carbon dioxide emission [9]. Thus, producing cement from fly ash is not a longer-term option. The solution is to use and develop geopolymer systems that only use geological resources, as these are readily available worldwide and have long-term stability [10]. The present study investigates the possibility of producing and developing SCGPC made of available local material in Iraq called calcined kaolin clay (CKC). It is produced from calcination kaolin clay, which is of geological origin and rich in silicon and alumina. CKC is a possible raw material for synthesizing geopolymers due to their abundant availability in nature, low cost of extraction, and comparably smaller environmental impact [11]. GPC is more brittle and has a lower elastic modulus [12]. Hence, including steel fiber in concrete decreases crack initiation and improves the concrete's mechanical properties under different loading conditions [13]. Due to the need for improved infrastructure, nanoparticles have been incorporated into geopolymers to get new properties and retain sustainability [14]. Nanoparticles (NP) are commonly used to describe ultrafine powder having a nanoscale of less than 100 nm. [15]. Utilizing steel fiber and nanomaterials together considerably increased the SCGC specimens' bond strength and flexural performance [16]. Also, nanoparticles cause a dense matrix, preventing the fiber pull-out by enhancing the interfacial bonding between the fiber and matrix [17]. Safiuddin et al. [18] indicated that incorporating nanoparticles in concrete could reduce maintenance and rehabilitation costs.

Nanoparticles used in the production of GPC are NanoCalcium Carbonate (NC) and Nano-Alumina (NA). NanoCalcium Carbonate (NC) is relatively cheap due to the abundant supply of Calcium Carbonate in limestone and marble. Also, due to its filler and nucleation agent advantages, it is utilized in cementitious composites [19-21]. NC has been employed in geopolymers of several previous investigations to examine their influence on various geopolymer properties. For example, Assaedi et al. [22] studied using NanoCalcium Carbonate up to 3% concentration in GPC based on fly ash. The GPC mechanical characteristics can be improved by increasing the quantity of NC up to 2%; however, increasing the amount of NC to 3% reduced the GPC mechanical behavior. The same results were also noted by Alomayri [17] for microsteel fiber-reinforced fly ash-based geopolymer pastes added to NC. Ge et al. [23] examined the effect of nanocalcium carbonate dosages and sizes in cement paste and self-consolidating concrete. The results demonstrated that the compressive strength of concrete and paste increased, while the compressive strength decreased with increasing particle size. Concrete with a low nanocalcium carbonate content (≤ 2.5%) had satisfactory workability. Otherwise, nano-alumina of high purity and fineness can be utilized to enhance the concrete's mechanical characteristics [24]. Alomayri [25] investigated the impact of adding nano-alumina particles (50nm) to geopolymer pastes based on fly ash at various levels of (1%, 2%, and 3% by weight of fly ash). The author stated that when the content of nanoparticles was smaller than 3%, the microstructure became more compact and had fewer pores, which improved the mechanical characteristics of geopolymer paste. The author also indicated that the optimum content of NA was 2%. The same outcomes were noted by Zidi et al. [26] for geopolymer paste created from mixing calcined kaolin clay, an alkaline solution, and nano-alumina. Based on the authors' knowledge, very little study has been conducted on mixing calcined kaolin clay with nanocalcium carbonate and nano-alumina to make and develop SCGPC, as proposed in the present study. Moreover, Raj et al. [20] pointed out inadequate literature on including NA and NC in geopolymer products. Further, the present research proposed a new approach to enhance strength using a novel combination of ternary and binary mixtures (CKC+NC+NA) and achieving satisfactory workability. Therefore, the findings from this study will be valuable for better performance of new products of SCGPC on a single line with consumption of locally available and more eco-friendly pozzolanic materials produced from geological resources.

2.EXPERIMENTAL PROGRAM

2.1.Materials

The following are materials used in producing SCGPC mixtures, as shown in Fig. 1.

2.1.1.Calcined Kaolin Clay (CKC)

Calcined kaolin clay is made from kaolin clay obtained from the Dewekhla region of the Al-Anbar Governorate, ground, and then burnt for one hour at a regulated temperature of 700 °C [27]. The CKC was then milled at Baghdad's AL-Zahra'a Shop to produce reactivity material of smaller grain size. The chemical analysis and physical properties of Calcined Kaolin Clay (CKC) comply with ASTM C618 [28], as indicated in Tables 1 and 2.

2.1.2.Nanoparticles

Nano-alumina (NA) and nanocalcium carbonate (NC) used in the present study were imported from China, the product center-Hangzhou. The properties of nanoparticles are presented in Table 3.

Table 1 Chemical Compositions of Calcined Kaolin Clay (CKC).

Oxide	Content percent%	ASTM C618 requirements
SiO_2	54.7	The sum of values more than 70%
Al_2O_3	37.4	
Fe_2O_3	1.72	
CaO	0.84	Max4%
MgO	0.42	
SO_3	0.13	
Na_2O	0.37	Max10%
K_2O	0.54	
L.O. I	2.91	

Table 2 Physical Properties of Calcined Kaolin Clay (CKC).

Property	CKC
Fineness [m^2/kg]	1640
Specific gravity	2.61
Median particle size [μm]	14.3
Color	Off-White

Table 3 Properties of Nano Alumina and Nano Calcium Carbonate According to the Manufacturer.

Properties	Nano-alumina	Nanocalcium Carbonate
Morphology	Spherical	Cubic
Color	White	White
Purity	99.9%	99.9%
Phase	Alpha	-
Specific surface area[m2/g]	40-60	≥40
Particle size	30nm	80nm

2.1.3.Sodium Hydroxide (NaOH)

NaOH flakes that are available commercially have a 99% purity grade. To create an activator with the specified molarity (12), solid flakes must first be dissolved in distilled water. The NaOH solution used in this experiment is further described in ASTM E291 [29].

2.1.4.Sodium Silicate (Na_2SiO_3)

The concentration of sodium silicate may be determined based on the proportion of Na_2O to SiO_2 and H_2O. (Na_2SiO_3) produced in the U.A.E. The properties of Na_2SiO_3 solution are Na_2O% content (13.1-13.7), SiO_2% content (32-33), density (51), specific gravity (1.534-1.551), and viscosity (600-1200).

2.1.5. Water and Superplasticizer

Drinking tap water was added to the mix design of SCGPC to improve workability, and it complies with IQS No. 1703 [30]. A commercial chemical admixture (Sika Viscocrete-180G) supplied by Sika Iraq was employed to increase the workability to the required level for SCGPC to meet the requirements of ASTMC494 [31] type F. It included no chloride and had a specific gravity of 1.065 ± (0.005) g/cm^3.

2.1.6. MicroSteel Fiber

The microsteel fiber's properties were length, diameter, tensile strength, and density of 13mm, 0.2mm, 2600 MPa, and 7800 kg/m^3, respectively.

2.1.7. Coarse Aggregate

The crushed gravel with a 10mm nominal maximum size was used. The results demonstrated that the coarse aggregate grading and sulfate content complied with IQS No.45 [32]. The specific gravity, SO_3 content, and absorption were 2.6, 0.03%, and 0.5%respectivly.

2.1.8. Fine Aggregate

A natural sand that complied with zone III of IQS No.45 [32] was utilized. Its characteristics were a specific gravity of 2.65 and a SO_3 content of 0.3%.

Fig. 1 Materials Used in SCGPC Mixtures: (a) Na_2Sio_3, (b) Steel Fiber, (c) Calcined Kaolin Clay, (d) Superplasticizer, (e) NA and NC, and (f) Flakes NaOH.

2.2. Self-Compacting Geopolymer Concrete Manufacturing

2.2.1. Alkaline Solution Preparation

When producing SCGPC, the alkali solution should be prepared first. The sum of the weight of the sodium hydroxide solution with the sodium silicate solution gives the weight of the alkali solution. In this study, the sodium silicate to sodium hydroxide ratio was set at 2.5:1. After dividing the alkali solution by 3.5, a sodium hydroxide solution was obtained; however, multiplying the latter by 2.5 obtained a sodium silicate solution. Table 4 shows the sodium hydroxide flakes' weight.

Table 4 NaOH Solids Content for 1 kg of Solution at a Specific Molarity [33].

Molarity (mole/l)	Sodium Hydroxide in weight %	Weight NaOH Flakes (gm)	Weight of Water (gm)
8	26.2	262	738
10	31.4	341	686
12	36.2	362	638
14	40.4	404	596
16	44	440	560

2.2.2. Mixture Design and Mixing

Because there are no standard codes for SCGPC mix design, EFNARC guidelines [6] and Rangan's method [34] were followed in the present study to produce four SCGPC mixes with a total powder content of 484 kg/m^3 and a constant content of steel fibers (SF) of 0.5% by volume. Two kinds of nanoparticles were utilized, i.e., Nanocalcium Carbonate (NC) and Nano-Alumina (NA). The SCGPC mixtures (SCGPCs) made of 100% (CKC) only without nanoparticles (control mix), and two systems of nano mixtures (binary and ternary) were evaluated. The binary mixture systems included two mixtures: (98%CKC +2 %NA) and (98%CKC +2 %NC), while the ternary mixture system was (96%CKC + 2%NA +2 %NC). The detailed investigation of all SCGPCs mix proportions is shown in Table 5. The SCGPCs were mixed in stages according to the procedure outlined in Gülşan et al. [35] (See Fig. 2(a)). In addition, using the steps provided by Shahrajabian and Behfarnia [36] for dispersing nanoparticles. Also, to reduce the impacts of clumping and aggregation, fibers were added by hand to the mixer Al-Ameeri [37]. Several laboratory tests were performed to confirm the validity of employing ternary and binary mixtures into SCGPC. The optimal percentages for both nanoparticles were determined in this study. All binary and ternary SCGPCs were prepared using optimal dosages, i.e., nano-alumina was 2%, and nano calcium carbonate was 2% added as a partial replacement by the weight of CKC. Whereas inappropriate addition decreased the properties of this concrete. However, after molding the specimens resting for 24 hours at room temperature with the molds covered with plastic sheets to prevent the alkaline solution from evaporation [38], specimens were de-molded and heated to 60 °C [39] for just one day [40, 41]. To prevent moisture loss, samples were left at room temperature (from 22 to 30 °C) while being wrapped in plastic until the day of the test (See Fig. 2 (b) and (c)).

2.2.3.Testing Methods

2.2.3.1.Fresh Properties of self-Compacting Geopolymer Concrete

The filling ability (slump flow, V-Funnel) and passing ability (L-box) of SCGPCs were tested by procedures of European guidelines for self-compacting concrete [6], as shown in Fig. 3.

2.2.3.2.Mechanical Properties of Self-Compacting Geopolymer Concrete

The compressive strength test and splitting tensile strength test were investigated for all SCGPCs according to the procedures provided in BS1881: Part 116 [42] and ASTM C496 [43] standards, respectively. Compression strength and splitting tensile strength tests were conducted using cube specimens of (100 mm) and cylindrical specimens of (100×200 mm), respectively.

3.RESULTS AND DISCUSSION

3.1.Fresh Properties of Self-Compacting Geopolymer Concrete

3.1.1.Slump Flow Test

Slump flow examination using an Abrams cone was used to evaluate the flowability of fresh concrete. The results of the slump flow experiments are presented in Table 6 and Fig. 4. All the mixes had a slump flow diameter between (594-630) mm. The highest slump flow diameter (630mm) was measured for the control mix, including 100% (CKC) only (SCGPC1). The higher slump flow diameter values mean higher workability for the SCGPC mixtures. The results showed that incorporating nano-alumina and nanocalcium carbonate in SCGPC mixes reduced the slump flow diameter for all mixes compared with the control mix. This reduction is attributed to the high surface area of NA and NC [44], increasing the liquid demand. Also, according to the results of this study, it was observed that the decrease in the slump flow diameter for binary mixture with 2% NA(SCGPC2) was higher than the decrease in binary mixture with 2% NC with respect to control mix that attributed to NA could rapidly react with water and alkaline solution more than NC, producing a viscous and thick liquid [36, 45]. A minimum flow diameter (594 mm) was observed for the ternary mixture (SCGPC4) incorporated NC and NA due to finer particles' sizes than the geopolymer source material and higher specific surface (combined effect) of NC and NA led to the high viscosity of these mixtures which in turn decreased slump flow diameters [46, 47]. According to the EFNARC specifications [6], all slump flow values were within the SF1 class range. The results correspond with those attained by [46-48].

Fig. 2 Preparation of SCGPCs: (a) Mixing, (b) De-Molded Samples After 24 Hours, and (c) Casting Samples Were Wrapped with Plastic Until Their Mechanical Characteristics Were Tested.

Table 5 The Mix Proportions of SCGPCs (kg/ m^3).

Mix	Mix Symbol	CKC kg/ m^3	NC kg/ m^3	NA kg/ m^3	w/ B	NHS kg/ m^3	NSS kg/ m^3	F. Agg kg/ m^3	C. Agg kg/ m^3	SP%	Micro steel fiber By vol%
Control Mix(100%CKC)	SCGPC1	484	0	0	0.4	69	173	850	862	3.5	0.5
98%CKC+2%NA	SCGPC2	474.32	0	9.68	0.4	69	173	850	862	3.5	0.5
98%CKC+2%NC	SCGPC3	474.32	9.68	0	0.4	69	173	850	862	3.5	0.5
96%CKC+2%NA +2%NC	SCGPC4	464.64	9.68	9.68	0.4	69	173	850	862	3.5	0.5

where (CKC: Calcined Kaolin Clay), (NC: Nano Calcium Carbonate), (NA: Nano Alumina), (W: Water), (B: Binder), (NHS: Sodium Hydroxide Solution), (NSS: Sodium Silicate Solution), (F. Agg: Fine Aggregate), (C. Agg: Coarse Aggregate), and (SP: Superplasticizer).

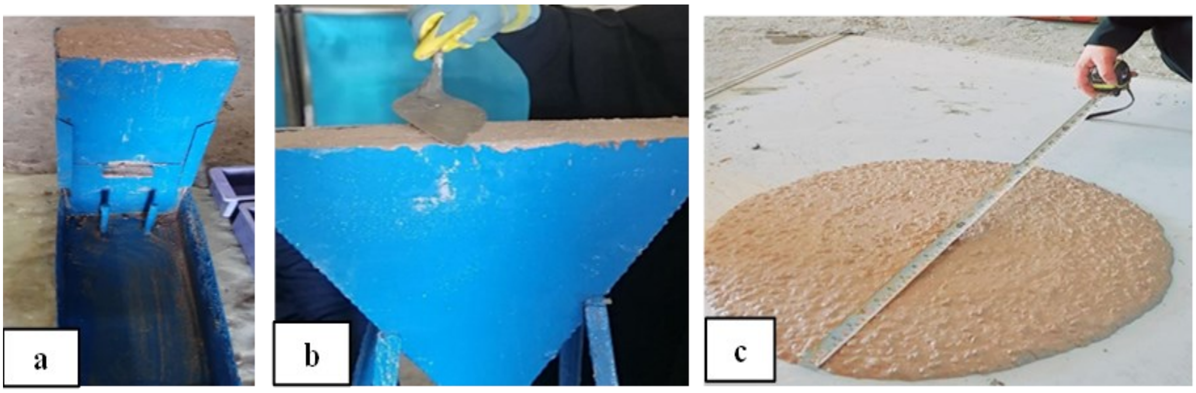

Fig. 3 Fresh Properties Tests: (a) L-Box test, (b) V-Funnel Flow Time, and (C) Slump Flow Test.

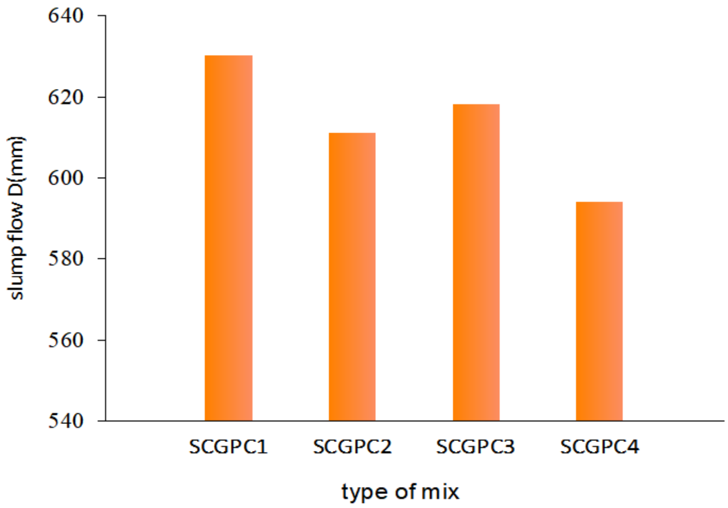

Fig. 4 Influence Nano-Alumina and NanoCalcium Carbonate on Slump Flow Test of SCGPCs.

Table 6 Fresh Properties Results.

Mix	Mix Symbol	Slump flow diameter mm	V-funnel flow time (Tv) (sec)	Blocking Ratio (BR)
Control Mix 100%CKC	SCGPC1	630	11.2	0.867
98%CKC + 2%NA	SCGPC2	611	11.7	0.853
98%CKC + 2%NC	SCGPC3	618	11.4	0.860
96%CKC+2%NA +2%NC	SCGPC4	594	12.4	0.842

3.1.2. V-Funnel Flow Time

The flowability and viscosity of SCGPC are reflected in the V-funnel flow time (Tv) [35]. Longer V-funnel flow test timings indicate less workability since the mixture takes more time to empty the funnel, demonstrating less filling ability. The (Tv) values range was (11.2-12.4) second. SCC is divided into two categories: VF1 (≤ 8 sec) and VF2 (9-25) sec [6]. It can be concluded from V-Funnel results, summarized in Table 6 and plotted in Fig. 5, that all mixtures fell within the VS2/VF2 viscosity class range. According to EFNARC [6], VS2 / VF2 had high segregation and bleeding resistance and low formwork pressure, and (Tv) increased by incorporating nanoparticles for all SCGPCs compared with the control mix. However, the binary mixture with nano alumina (SCGPC2) had a higher flow time than that with nanocalcium Carbonate (SCGPC3). Also, it is noted that (Tv) for the ternary mixture (SCGPC4) was higher than all other mixtures due to similar reasons and mechanisms for the slump flow test results.

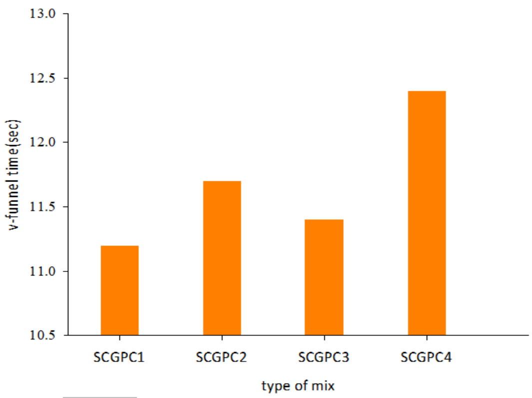

Fig. 5 Influence Nano-Alumina and NanoCalcium Carbonate on V-funnel Flow Time.

3.1.3. L-Box Test (Passing Ability)

In the present investigation, the L-Box with two bars was employed to evaluate the passage ability of SCGPCs. Table 6 and Fig. 6 show that the Blocking Ratios findings (BR=H2/H1) of SCGPCs must be more than or equal to 0.8 to achieve the necessary passing ability requirements following the EFNARC criteria. The findings of the Blocking Ratios fell in the range of (0.842-0.867). All SCGPCs had suitable passing ability (BR ≥ 0.8). The findings showed that the BR decreased with incorporating NC and NA in binary and ternary mixtures. When assessing the fresh concrete's ability to pass through the L-box's bars, it was found that none of the four mixes exhibited any blockages.

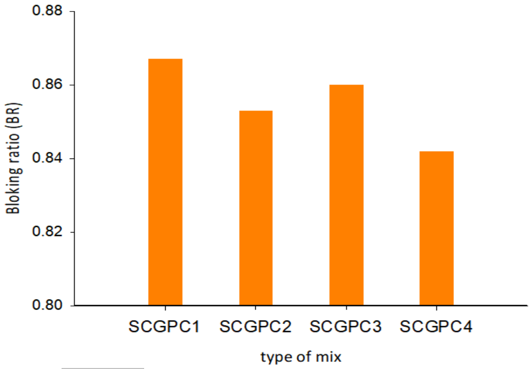

Fig. 6 Influence Nano-Alumina and NanoCalcium Carbonate on Blocking Ratio.

3.2.Mechanical Properties of Self-Compacting Geopolymer Concrete

3.2.1.Compressive Strength

One of the hardened concrete's most important properties is compressive strength. It is an effective property for evaluating the geopolymerization degree. The compressive strength test results at 7 and 28 days for all SCGPCs are demonstrated in Fig.7. It is clear that all ternary and binary mixes showed higher compressive strengths than the control mix (SCGPC1). Additionally, the results of all binary mixtures showed that adding nanoparticles had remarkable effects by increasing compressive strength by (31.5% and 15.8%) for the binary mixture with nano-alumina (SCGPC2) and by (27.27%,14.3%) for the binary mixture with nanocalcium carbonate (SCGPC3) at 7 and 28 days, respectively. These improvements may be due to enhancing the products' geo-polymerization reaction with nanoparticles and leading to a denser matrix [20]. Moreover, it is clear from the ternary system that adding two different cementitious components with a nanoscale might enhance the performance of geopolymers. In comparison with (SCGPC1), the ternary mixture (SCGPC4) results showed that the incorporation of two nanoparticles significantly increased the compressive strength by (57.95% and 28.34%) at 7 and 28 days, respectively. Based on these results, the ternary mixture had a higher strength than the control and binary mixtures for all ages because of the combined pozzolanic action and optimal distribution for both nanoparticles in this mixture. These results agree with previous studies [49, 50]. However, binary mixtures containing 2% NA showed higher compressive increments than those with 2% NC due to nano-alumina's role in geopolymer reaction and modification of Si/Al ratio in alkali activators, increasing the geopolymerization extent, besides its use as a filling material [25, 51]. Meanwhile, NC does not undergo the geopolymerization process and only acts as nanofillers reinforcing the geopolymer matrix [17, 52].

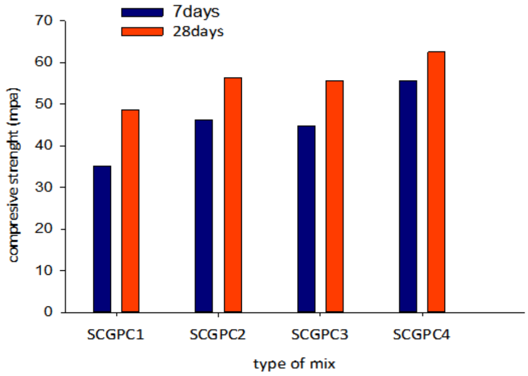

Fig. 7 Influence Nano-Alumina and NanoCalcium Carbonate on Compression of Strength of SCGPCs.

3.2.2.Splitting Tensile Strength

Figure 8 shows self-compacting geopolymer concrete's splitting tensile strength findings at 7 and 28 days. Splitting tensile strength mixtures exhibited a similar trend as compressive strength. However, all binary mixtures with nanoparticles produced higher splitting strength than the control mixture (SCGPC1) by (26.19% and 14.66%) for (SCGPC2) and by (23.47% and 12.83%) for (SCGPC3) at 7 and 28 days, respectively. The increase in splitting tensile strength resulted from the enhanced bond strength between the fibers and the matrix, which can be attributed to the incorporation of nanoparticles that enhance interfacial adhesion and prevent the fibers' pull-out. The combined effect of the fibers and nanoparticles enhanced crack growth resistance, resulting in a dense microstructure and, subsequently, a significant increase in splitting tensile strength [17, 35]. Compared to the control mix (SCGPC1), the ternary mixture SCGPC4 demonstrated a notable effect from adding nanoparticles, as evidenced by a substantial increase in splitting tensile strength, specifically at 7 and 28 days. Including nanoparticles remarkably enhanced splitting tensile strength by approximately 46.94% and 25.92%, respectively. According to these findings, mix SCGPC4 (ternary) strength increased more than mix SCGPC1, SCGPC2, and SCGPC3. Higher increases in strength are related to the combined effect of the pozzolanic activity of the two types of nanoparticles and the presence of fibers in this concrete; a similar observation was found by [17, 35, 50, 53].

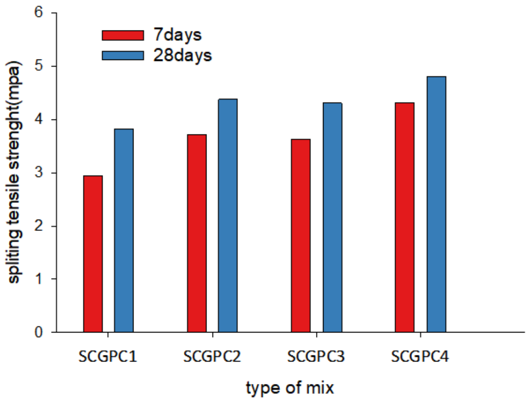

Fig. 8 Influence Nano Alumina and Nano Calcium Carbonate on Splitting Tensile Strength of SCGPCs.

4. CONCLUSIONS

- Overall, the fresh properties of SCGPC were significantly affected by adding nanoparticles in binary and ternary mixes, increasing the V-funnel flow time values, and decreasing the slump flow diameter and the L-Box blocking ratios. However, all mixes met the EFNARC's specifications.
- The V-funnel results showed that all SCGPC mixes fell within the VS2/VF2 viscosity class range according to EFNARC, which had good bleeding and segregation resistance and low formwork pressure.
- In binary mixes, nano-alumina increased the V-funnel flow time values and decreased the L-box ratio and slump flow values more than nanocalcium carbonate.
- The ternary mix further reduced the L-box ratio and slump flow values and more of and increased the V-funnel flow time values than the binary and control mixes.
- Including NA and NC in binary and ternary mixtures considerably improved all ages' splitting tensile and compressive strengths. While the ternary mixture showed higher mechanical properties than the control mix and all binary mixtures.
- The compressive and splitting tensile strength test results showed the significant importance of NA and NC for developing the strength of SCGPC. However, NA demonstrates more strength than NC.
- The present study highlighted the potential of employing NA and NC at an optimal percentage of 2% for each other in SCGPC to create low-carbon binders, which would provide sustainable SCGPC with better performance, thus promoting the movement towards sustainable concrete construction practices.

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