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Development of a novel cementitious blend derived from calcined pozzolanic materials and nanoparticles of self-compacting high-performance concrete

ABSTRACT

This research includes an experimental study of the potential use of pozzolanic and nanomaterials, including nano calcium carbonate (CC) and calcined clay (CK), throughout the manufacturing process of self-compacting high-performance concrete (SCHPC). Binary and ternary mix systems were prepared using 475 kg/m3 of cement and a fixed water-to-binder ratio (0.35). CK was used in proportions ranging from 6 to 24% of the total mass of cementitious materials. As for the ternary mixes, samples of (6% CK 1.5% CC, 12% CK 1.5 CC, 18% CK 1.5 CC, and 24% CK 1.5% CC) were prepared by partially replacing the weight of cement with CK and CC. The properties of the new SCHPC were assessed by slump flow (D (mm) and T500 (s)), V-funnel, L-box, and segregation resistance tests. Mechanical properties, including compressive and tensile strengths, were measured, and an ultrasonic pulse velocity test of the concrete was performed. Durability properties, including porosity and water absorption, were also measured. The findings demonstrated that adding calcined kaolin clay to concrete significantly improved its durability and mechanical properties. The best improvement was for binary and ternary mixtures at a 12% replacement ratio of calcined kaolin clay, where compressive strength improved by 20.9% and porosity and water absorption decreased by 15.6% and 19.9%, at 56 days compared to the reference mixture. The ternary mixtures also improved better than the ternary mixtures for the same replacement ratios of calcined kaolin clay for all ages. For example, the 12CK1.5CC mixture recorded a 25.5% improvement in compressive strength and a 21.3% and 40.8% reduction in porosity and water absorption compared to the reference mixture at the age of 56 days. This study accomplished its goals by sustainably producing eco-friendly concrete through the reduction of cement content via pozzolanic and nanoparticles.

Keywords: *Calcined clay; nano calcium carbonate; segregation resistance; eco-friendly concrete; durability properties*

1. INTRODUCTION

Self-compacting concrete (SCC) is an advanced concrete employed in ground-breaking projects and practical uses. It infiltrates the thick reinforcement, penetrates every nook of the formwork, and is consolidated by its mass. SCC ensures stability while delivering various features without segregation or leakage [1, 2]. Benefits include reduced concrete construction time due to high efficiency, reduced noise from vibrating and concrete pouring operations, significantly enhanced components, and improved consistency of concrete on site, resulting in superior working conditions and exceptional surface quality of the concrete produced [3]. Moreover, high-performance concrete is engineered to provide superior strength and exceptional durability. Over the last several decades, HPC has been widely utilized in the construction sector but has undoubtedly evolved. This arises from the growing need for durable concrete with extended service life while simultaneously minimizing maintenance expenses for concrete structures. A novel concrete variant, termed high-performance self-compacting concrete (SCHPC), has been created to incorporate the attributes of both SCC and HPC [4]. A SCHPC is a unique type of concrete that meets service life requirements under certain materials, loads, and exposure conditions. It has outstanding flowability and stability, high strength, and remarkable durability qualities. Constructing concrete buildings requires meticulous placement and effective

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compaction of new concrete to get superior hardened characteristics and endurance [3]. The optimal placement and compaction of standard concretes, even when executed by proficient labor, was not consistently attainable. The deficiency of skilled labor was a significant issue in the building sector as well [5]. The SCHPC concept initially emerged in Japan to construct resilient concrete structures and address the shortage of construction labor. Over the past decade, SCHPC's technology has been modified and advanced in Japan. SCHPC was marketed by the Japanese concrete industry under the trade name "Non-vibrated concrete" [6]. During the same era, SCHPC has grown extensively established in North America, Europe, and other regions globally [7].

In its fresh and hardened forms, self-compacting high-performance concrete (SCHPC) differs from conventional concrete primarily due to exceptional constituent components and combination proportions. This requires a lot of special ingredients in addition to the basic materials used for normal vibrated concrete (NVC), such as high-range water-reducing (HRWR) admixture for sufficient flowability and a large quantity of powder materials and/or viscosity-modifying admixture (VMA) to attain high segregation resistance. SCHPC's component material proportions frequently deviate significantly from NVC's [8]. Compared to normal concrete, SCHPC has a significantly greater binder concentration, less water, more fine aggregate, and less coarse aggregate. SCHPC's water/binder ratio (W/B) is also significantly lower than NVC's [9],[10]. A modest amount of coarse aggregate and expanded cementing materials at a low W/B ratio, or the use of a VEA can provide maximum resistance to segregation [11,12]. Additionally, the aggregate size influences SCHPC's resistance to segregation as well as its capacity to flow [13].

Adeyemi [14] examined the combined effects of limestone as an inert additive and metakaolin as a pozzolanic additive on the microstructure, strength, and rheological characteristics of SCC. SCC mixes were created with different amounts of metakaolin and limestone added. Samples of seven different SCC concrete formulations were examined at 7, 28, and 56 days. The addition of limestone improves the flowability of SCC while preserving a suitable viscosity, according to preliminary findings. When metakaolin is used in place of limestone, there are encouraging gains in workability and compressive strength. After 56 days, samples with 100% metakaolin had the highest strength, closely followed by samples with 80% metakaolin and 20% limestone. The samples that included 80% limestone and 20% metakaolin also had the lowest strength. According to the SEM Microstructural data, concrete mixes with a high metakaolin concentration have less voids and are more homogeneous and consistent.In the study conducted by Hashem et al.[15], Portland cement was partially substituted with metakaolin and nano-silica. Two mixing schemes were used: binary and ternary. As a partial cement replacement for the two mixes, the metakaolin replacement ratios were 4%, 8%, 12%, and 16% (by weight). Nano silica was added to the ternary system mix at a rate of 2%, using the metakaolin at the same ratios as in the binary mixes. With increasing partial replacement by metakaolin and nano silica (viscosity, filling capacity, and resistance to segregation), the results showed that the slump flow and V-funnel flow times decreased. The SCC mixes with 2% nano-silica as a partial replacement, and metakaolin demonstrated better compressive strength at ages 7, 28, 56, and 90 days when compared to the control mix. For all ages, the compressive strength performance of ternary mixes comprising metakaolin and 2% nano-silica was shown to be superior to that of mixtures including metakaolin for the same replacement levels. Du and Pang [16] investigated the characteristics of high-performance concrete made using limestone and burnt kaolin clay at cement replacement percentages of 30% and 45%, respectively. The medium-grade kaolin clay was heated to 800 degrees Celsius. For a maximum of six months, the hydration, strength, shrinkage, and transport characteristics were assessed. The XRD results showed that within the first week, burnt clay will undergo a pozzolanic reaction and work in concert with limestone. The self-shrinkage was noticeably greater. The synthesized carbon aluminate phases and C-A-S-H gels may significantly improve the elastic modulus and compressive strength after seven days.

Meanwhile, more convoluted pathways were found to greatly boost the concrete's resistance to moisture and fluid infiltration. An investigation by Hashem et al. [17], examined the effects of partially substituting cement material with nanomaterials, specifically nano-metakaolin (NMK), on the fresh and hardening properties of High-Performance Self-Compacting Concrete (SCHPC). The substitution was made in varying proportions, specifically 1.25, 2.5, and 3.75. Four combinations were created: the first reference mixture and the other three, in which the cement was partially substituted with the amounts previously stated. According to the results, the L-box and slump flow values drop as the proportion of cement that is partially replaced by nano-metakaolin rises. T 50 cm and V- funnel time, on the other hand, rise when the partial substitution rate for cement with nano metakaolin increases. As the fraction of cement that is partially replaced with nano-metakaolin rises, so do the compressive and tensile strengths.

Considering the current focus in civil engineering on sustainable development, it is essential to create a new generation of concrete, termed self-compacting high-performance concrete (SCHPC), utilizing eco-friendly materials in the construction sector while maintaining cost-effectiveness and minimizing environmental impacts to mitigate carbon dioxide emissions from the cement industry overall. Furthermore, SCHPC is indisputably novel to the Middle East region. No comprehensive research studies have been conducted to address the pertinent difficulties related to its use, as the technology remains relatively nascent in the region. The production and use of SCHPC, which includes pozzolanic materials and nanoparticles, appears to be a promising and energy-efficient development in the field of sustainable building and construction technology. Consequently, more research on the properties of this newly formulated concrete is required. The main goal of this study was to develop SCHPCs as cement replacements using nano-calcium carbonate (CC) and calcined kaolin clay (CK) in binary and ternary mix systems. The fresh properties of SCHPC were assessed for flowability, pass ability, and viscosity, and the solid properties were determined by measuring compressive strength, splitting tensile strength, and ultrasonic pulse velocity. Additionally, the durability performance of the SCHPC created in the study was evaluated by evaluating water absorption and porosity.

2. MATERIALS AND METHODOLOGY

2.1. Materials

2.1.1. Cement

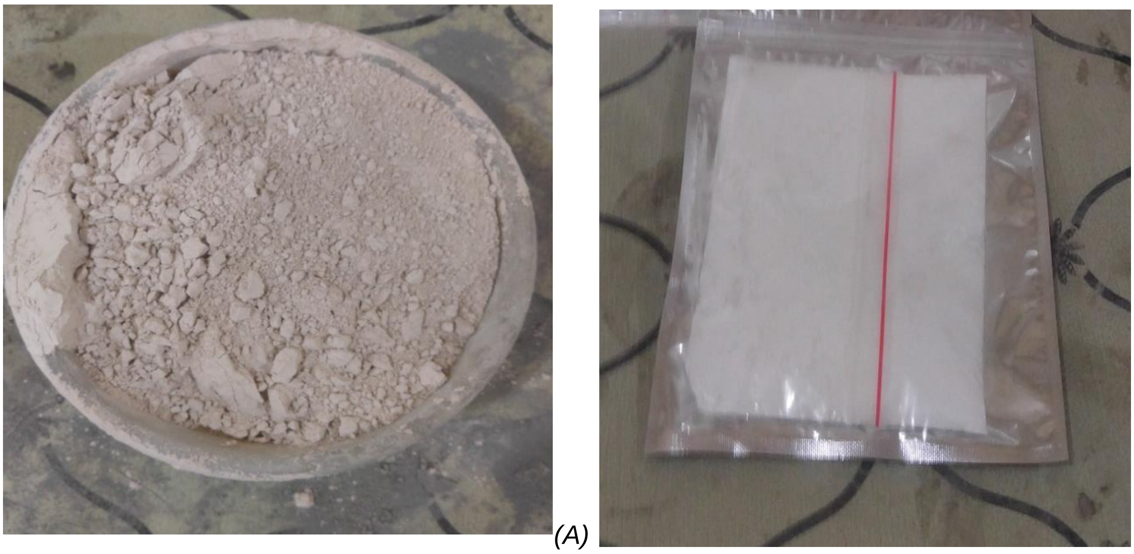
For all concrete combinations, ordinary Portland cement type I (OPC), which complies with ASTM C150 [18], was utilized. The chemical and physical characteristics of the cement are displayed in Tables 1 and 2, respectively.

Table 1. Cement's physical characteristics

Physical property	Test Result
Setting Time, min Initial Final	 110 180
Fineness (Blaine), in m2/Kg	376
Compressive Strength in MN/m^2, at 3 days 7 days	 21 32
Specific gravity	3.13
Median particle size (µm) (d50)	10.96
Colour	Grey

2.1.2. Calcined clay

Locally sourced calcined clay (CK) was employed, and its chemical composition was confirmed using XRF analysis, as can be seen in Table 2. Figure 1 illustrates the incinerated clay (KC). The fineness (m^2/kg), specific gravity, and average particle size (µm) are 2.59, 487, and 9.53, respectively.



(A) *(B)*

Figure 1. (A) Calcined clay and (B) nano calcium carbonate utilized in this investigation

Table 2. Chemical makeup of cement (OPC) and calcined clay (KC)

Chemical composition (%)	OPC	CK
Silicon dioxide (SiO_2)	19.36	52.5
Aluminium trioxide (Al_2O_3)	4.82	39.6
Iron oxide (Fe_2O_3)	3.28	1.38
Calcium oxide (CaO)	62.43	0.95
Magnesium oxide (MgO)	3	0.48
Sodium oxide (Na_2O)	0.29	0.41
Potassium oxide (K_2O)	0.56	0.61
Sulfur trioxide (SO_3)	2.26	0.14
Phosphorus pentoxide(P_2O_5)	-	0.28
Titanium dioxide (TiO_2)	-	0.66
Loss on ignition (LOI)	0.96	2.94

2.1.3. Nano calcium carbonate

The commercially available nano $CaCO_3$ material, which is between 15 and 40 nm in particle size, has a 97.5% calcite ($CaCO_3$) content, and is white, as seen in Figure 1 (B), was made by the Sky Spring nanomaterials firm and used in this investigation.

2.1.4. Aggregate

Fine and coarse aggregates locally available in Iraq which comply with the requirements of IQS NO.45/1984 were used. The fineness modulus of natural sand used as fine aggregate is 2.34 and its maximum size, specific gravity, and water absorption are 4.75 mm, 2.62, and 1.22% respectively. The coarse aggregate is crushed gravel with a maximum size of 10 mm and has a specific gravity of 2.57 and water absorption of 0.4%.

2.1.5. Superplasticiser

Sika's Visco Crete 180G, a water-reducing superplasticizer, was employed in this investigation. It satisfies ASTM C-494 (2015)'s specifications [19], type F. It was described as having a light-brownish colour, a specific gravity of 1.065±0.005 g/cm3, and a pH of 4-6 percent.

2.2. The proportions of the mixture

This work utilized the European standard (EFNARC, 2005) [20] to formulate concrete mixes for self-compacting concrete. The composition of the raw materials utilized in concrete mixes consisted of a total binder content of 475 kg/m3 and a water/binder ratio of 0.35. The superplasticizer is included in varying concentrations of 1.4% to 1.6% of the cement's weight. Nine concrete mixes were created to test high-performance self-compacting concrete. The initial mixture (control-CT) serves as a standard for binary blends with varying degrees of cement substitution by calcined clay CK in proportions of 6%CK, 12%CK, 18%CK, and 24%CK based on the weight of cement. Four ternary combinations were developed in which cement was partly substituted with calcined clays (CK) and Nano calcium carbonate (CC) in varying ratios: 6% CK and 1.5% CC, 12% CK and 1.5% CC, 18% CK and 1.5% CC, and 24% CK and 1.5% CC, based on the weight of the cement. It underwent curing for 28, 56, and 90 days following the molding process.

Table 3. Proportions of concrete mixture components

Mixture	W/C	Quantities of mix ingredients (kg/m3)					Superplasticizer (%)
		OPC	CK	CC	Fine Agg.	Coarse Agg.	
CT	0.35	475	--	--	840	852	1.4
6CK	0.35	446.5	28.5	--	840	852	1.4
12CK	0.35	418	57	--	840	852	1.4
18CK	0.35	389.5	85.5	--	840	852	1.4
24CK	0.35	361	114	--	840	852	1.4
6CK1.5CC	0.35	439.375	28.5	7.125	840	852	1.6
12CK1.5CC	0.35	410.875	57	7.125	840	852	1.6
18CK1.5CC	0.35	382.375	85.5	7.125	840	852	1.6
24CK1.5CC	0.35	353.875	114	7.125	840	852	1.6

2.3. Curing regimes

All concrete specimens must be cured before testing. After de-moulding, the specimens were positioned in a curing tank, where they were completely submerged in water whose temperature was regulated at 25 ± 2 °C to ensure uniform curing conditions. The specimens were maintained in the curing tanks until they attained the designated testing ages of 7, 28,56, and 90 days.

2.4. Testing procedures

2.4.1. Test of fresh properties

As to the [EFNARC, [20], fresh assessments of self-compacting high-performance concrete (SCHPC) are essential for evaluating the three workability characteristics: filling ability (flowability and viscosity), passing ability, and segregation resistance. To measure the three traits collectively, there isn't a single exam, though. In this experimental study, slump flow (D (mm) and T500 (s)), V-funnel, L-box, and resistance tests to segregation were used to evaluate the new characteristics of SCHPC. As shown in Figure 2 (A), the slump flow instrument was Abram's cone, which measured 30 cm in height, 10 cm in diameter at the top, and 20 cm at the bottom. The diameter average (D max. and d perp.) to the closest (10) mm is the slump flow. The slump flow time T500 mm, which is measured in seconds to the closest 1/10 second, is the interval between the cone's departure from the base plate and the SCC's initial contact with the 500 mm diameter circle.

The V-funnel examination is the test used to assess SCHPC's filling ability as shown in Figure 2 (B). European self-compacting concrete guidelines, 2005, describe the test protocol and equipment utilized. Concrete from SCHPC is poured into the funnel without any pressure. A straight edge is used to trim any extra concrete from the funnel's top. We open the gate after waiting for 10 ± 2 seconds, and the stopwatch begins at the same time. Next, we examine the funnel and stop the watch when we notice visible portions.

The L-Box assessment may be used to determine SCHPC's passage capacity to flow freely in the face of reinforcing obstacles, as shown in Figure 2 (C). to the extent specified in the 2005 European Self-Compacting Concrete Guidelines. Fresh SCC is poured into the L-box's vertical section. Allow the concrete to remain in the vertical part for one minute. During this period, concrete will be on show, regardless of its stability (segregation). The concrete is then allowed to flow out into the horizontal section when we raise the sliding gate. Consequently, the L-box's height was calculated by averaging the concrete heights at the start and finish of the horizontal section.

Segregation tests can evaluate the resistance to segregation (stability), the apparatus, and the testing technique as outlined in the European recommendations of 2005, as shown in Figure 2 (D). The capacity of a new blend to preserve the original, generally constant distribution of component items is known as resistance to segregation. A bucket was filled with around 10 liters of concrete, which was then covered to prevent moisture loss and left to settle for about 15 minutes. Then, using a sieve pan and a weight scale, a concrete specimen weighing 4.8 ± 0.2 kg was placed on a 5 mm by 350 mm sieve and given time to settle for two minutes to allow some mortar to pass through. The weight of the mortar divided by the weight of the original material on the sieve was employed to determine the segregation index.

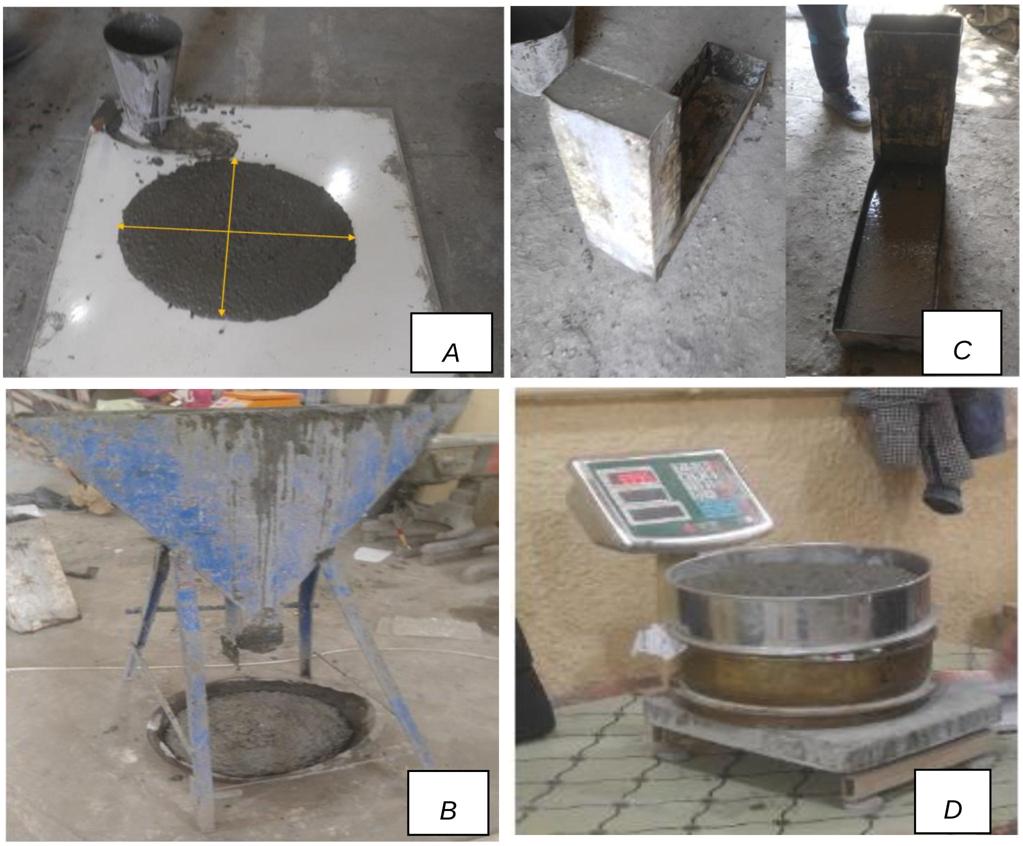


Figure 2. Fresh test procedures

2.4.2. Test of hardened properties

2.4.2.1. Compressive strength

A compressive strength test was performed under BS EN 12390 [21], utilizing a 2000 KN hydraulic compression apparatus at 18 MPa/minute for (100×100×100 mm3) cubes. At each test age (7, 28, 56, and 90 days), three cubes (100×100×100 mm3) were examined

2.4.2.2. Splitting tensile strength

The method outlined in ASTM 496/C 496M-2004 was used to assess the splitting tensile strength [22]. The cylinders that were used were 100 × 200 mm in size and were evaluated at 7, 28, and 90 days.

2.4.2.3. Ultrasonic pulse velocity

According to ASTM C597 [23], the UPV was measured using a portable ultrasonic non-destructive digital indicating tester (PUNDIT). The identical cube specimens used to assess compressive strength were examined after 3, 7, 28, 56, and 90 days of curing to calculate the UPV.

2.4.3. Test of durability properties

2.4.3.1. Water absorption

To evaluate the voids in hardened concrete and ascertain the rise in resistance towards water penetration in concrete, the concrete specimens' water absorption test was carried out in compliance with ASTM C642, 2013 [24], After the first 28-day curing period, three 100 mm cubic specimens of each SCHPC combination were made, and evaluated, and their average values were noted at the ages of 28, 56, and 90 days.

2.4.3.2. Porosity

The porosity of concrete was measured under ASTM C642, 2013 [24], and three cubes (100×100×100 mm3) of concrete samples were made for the test. The Samples have been examined following 28, 56, and 90 days of water curing

3. RESULTS AND DISCUSSION

3.1. Fresh tests results

Table 4, Fig. 3, 4, and 5 show slump flow diameter, T500mm, and V-funnel flow time, respectively, to display the degree of SCHPC viscosity. The figures show that the T500mm and V-funnel flow time rose while the slump flow diameter (mm) reduced when comparing the binary mixes (6CK, 12CK, 18CK, and 24CK) to the reference mix. T500mm and V-funnel flow time rose by 12.90, 45.62, 51.61%, and 8.33, 18.05, 41, 66, and 56.94%, respectively, whereas slump flow decreased by around 2.61, 5.22, 7.32, and 12.41.

Table 5 shows that whereas the control concrete had the lowest T500 mm and V-funnel flow durations (3.1 s and 7.2 s, respectively), the mixture including 24CK had the highest T500 mm and V-funnel flow times (4.9 s and 11.3 s). When CK was introduced to the binary system, the concrete generally became more viscous. This might be because, in addition to the fine particle size of CK, which has much larger surface areas than cement that absorbs water, the CK particles are long, hexagonal plates that become obstacles in the fresh mix and increase friction between the particles [25].

Table 4. The results of rheological properties tested of SCHPC

Types of Mixes	Slump flow (mm)	T500 (Sec)	V- Funnel Time (Sec)	L-Box height ratio (H2/H1)	GTM (%)	Classification		
						Flow class	Viscosity class	Passing ability
CT	765	3.1	7.2	0.940	11.7	SF3	VS2\VF1	PA1
6CK	745	3.5	7.8	0.921	10.5	SF2	VS2\VF1	PA1
12CK	725	4.5	8.5	0.889	9	SF2	VS2\VF2	PA1
18CK	709	4.7	10.2	0.870	8.4	SF2	VS2\VF2	PA1
24CK	670	4.9	11.3	0.838	7.5	SF2	VS2\VF2	PA1
6CK1.5CC	735	3.8	8.1	0.903	10.1	SF2	VS2\VF2	PA1
12CK1.5CC	720	4.6	9.6	0.871	8.8	SF2	VS2\VF2	PA1
18CK1.5CC	695	4.8	11.2	0.839	8.2	SF2	VS2\VF2	PA1
24CK1.5CC	662	5.3	12.4	0.819	7.3	SF2	VS2\VF2	PA1

When compared to the reference mixture, the ternary mixtures (6CK1.5CC, 12CK1.5CC, 18CK1.5CC, and 24CK1.5CC) showed a decrease in slump flow diameter value and an increase in T500mm and V-funnel flow time, similar to the binary mixtures. However, it was more evident that the flow diameter decreased by approximately 3.92, 5.88, 9.15, and 13.46 percent, while the T500 and funnel flow time V increased by 22.58, 48.39, 54.83, and 70.96%, and 12.5, 33.33, 55.54, and 72.22 percent, respectively. The calcined kaolin clay particles' size and shape, as well as the finer CK and CC particles' surface areas, which absorb water more readily and leave less free water to contribute to flowability, may be the cause. Additionally, because CC particles are finer than OPC particles, the filler effect occurs, allowing finer CC particles to fill in the gaps between cement particles. [16, 26, 27].

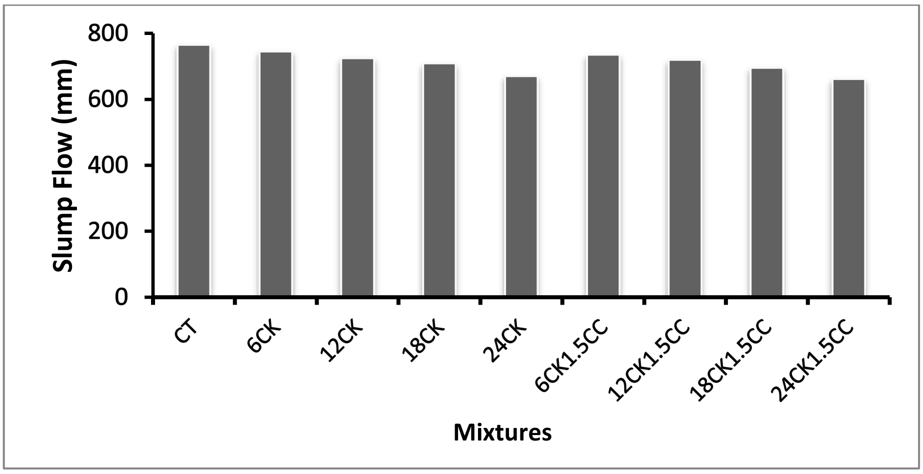


Figure 3. Slump flow diameter test results

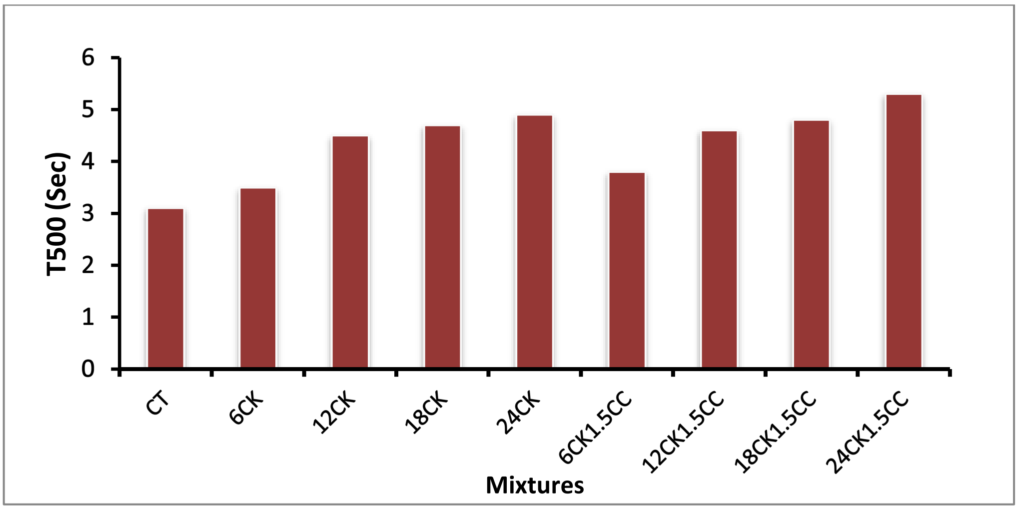


Figure 4. T500 results test results

The binary mixes (6CK, 12CK, 18CK, and 24CKC) had an inferior passing ability than the CT mixture, by around 2.02%, 5.42, 7.45%, and 10.85%, respectively, as shown in Figure 6. The more cement that was partially substituted, the lower the L-Box height ratio value. Similar to how it decreases the capacity to fill, the percentage and fineness of calcined clay (CK) also decrease the ability to pass. Comparable outcomes were reported by [27].

This impact amplifies with the ternary combinations (6CK1.5CC, 12CK1.5CC, 18CK1.5CC, and 24CK1.5CC) by about (3.93, 7.43, 10.74, and 12.87) % relative to the unblended mixture (100% OPC). No blocking or segregation phenomena were seen in the mixtures during the testing process. These findings are analogous to the results of the research [27].

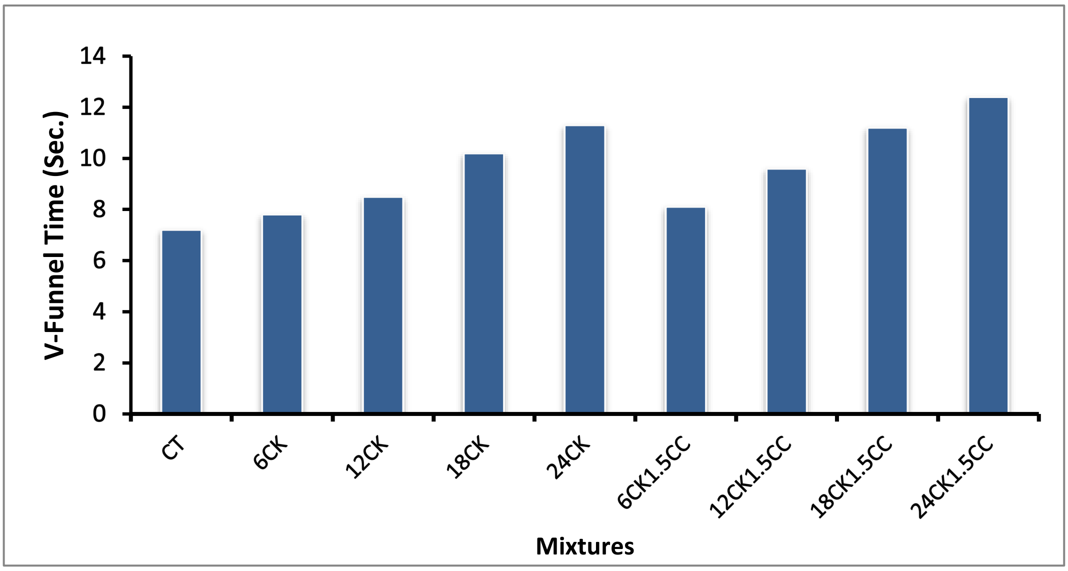


Figure 5. V-funnel time test result

Previous studies on fresh testing of blended SCHPC indicate that substituting CK or CK+CC for cement increases water use because of their reactivity with cement and fineness [26], [28].

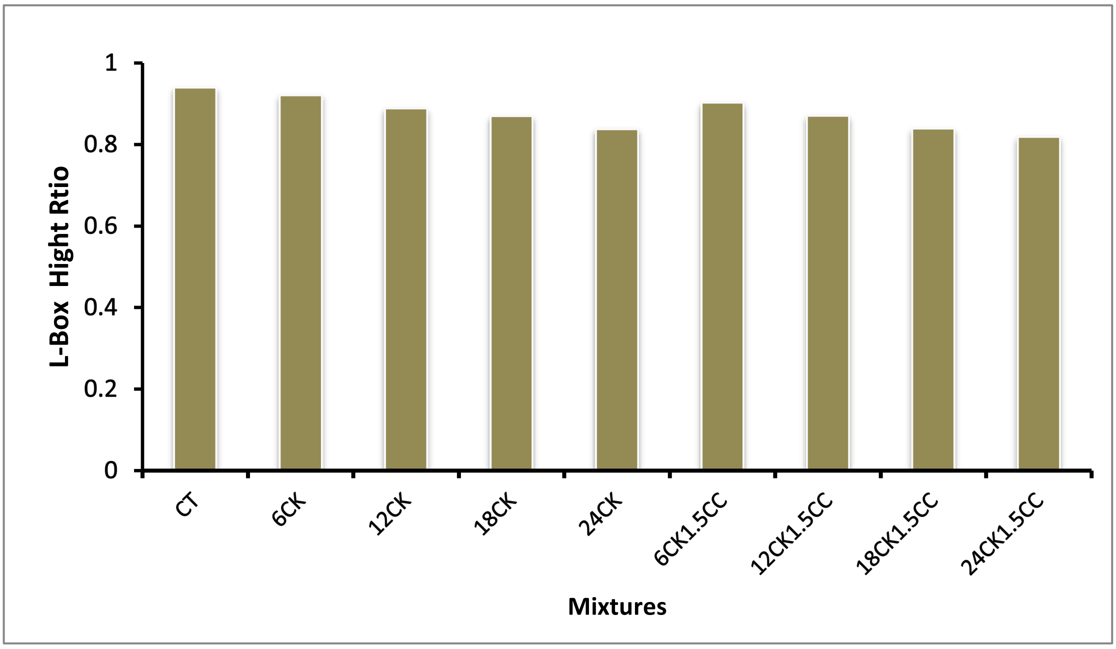


Figure 6. L-Box test results

Figure 7 displays the segregation resistance test outcomes for SCHPC mix binary and ternary blends. The binary mixtures (6CK, 12CK, 18CK, and 24CK) have greater segregation resistance than the CT mix, as the percentage of segregation falls as the percentage of partial replacement increases. For the binary mixes mentioned above, the percentage of reduction was around (10.25, 23.08, 28.21, and 35.90) %, respectively. In contrast, reference mixes and binary mixtures of comparable proportions exhibit lower segregation resistance than ternary combinations (6CK1.5CC, 12CK1.5CC, 18CK1.5CC, and 24CK1.5CC). In other words, the segregation ratio drops by around (13.67, 24.78, 29.91, and 37.60) %, respectively, in the ternary mixtures. This could be the result of the nanoparticles' increased surface area, which raises their viscosity and, in turn, their segregation resistance. Results were comparable to earlier studies [28].

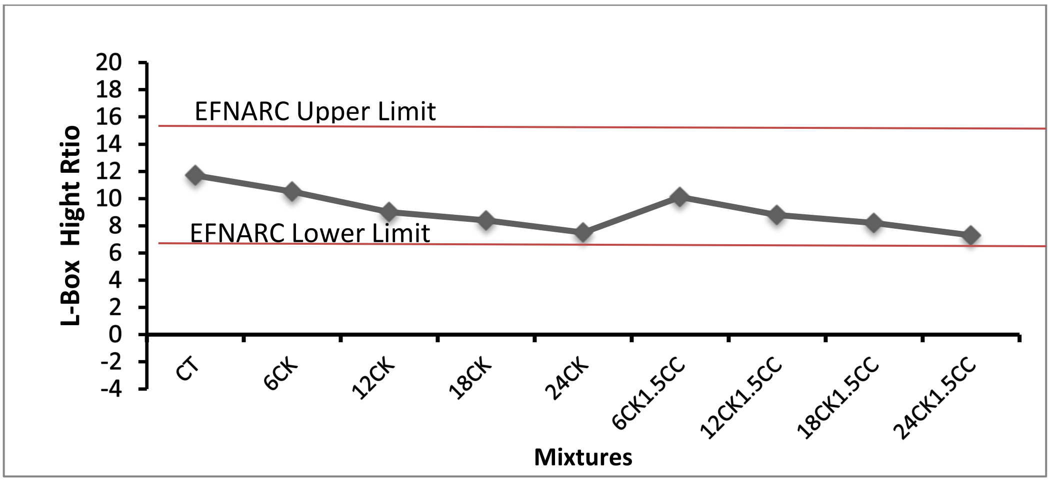


Figure 7. Segregation resistance test results

EFNARC [20], states that SCC is classed as VS1/VF1 when T500 mm and V-funnel flow time are less than or equal to 2 s and 8 s, and as VS2/VF2 when T500 mm is more than or equal to 2 s and V-funnel flow time is between 9 and 25 s. As a result, according to EFNARC, as indicated in Table 4, all ternary blends may be categorized into the VS2/VF2 class, whereas all binary blends of CK, except for the 6CK combination, fall within the ranges of the VS2/VF1 class.

3.2. Hardened examination results

3.2.1. Compressive strength of SCHPC

Fig. 8 shows the compressive strength findings obtained for the experiment's binary and ternary mixtures. At 7 days, the SCHPC mixture (6CK, 12CK, 18CK, and 24CKC) had a compressive strength that was roughly (11.9, 19.3, 16, and 12.8) % higher than the control-CT mixture; at 28 days, it was (9, 19.9, 13.5 and 13) % higher; at 56 days, it was (10.4, 21, 14 and 12.7) % higher; and at 90 days, it was roughly (9.6, 17, 11.3, and 7.7) % higher.

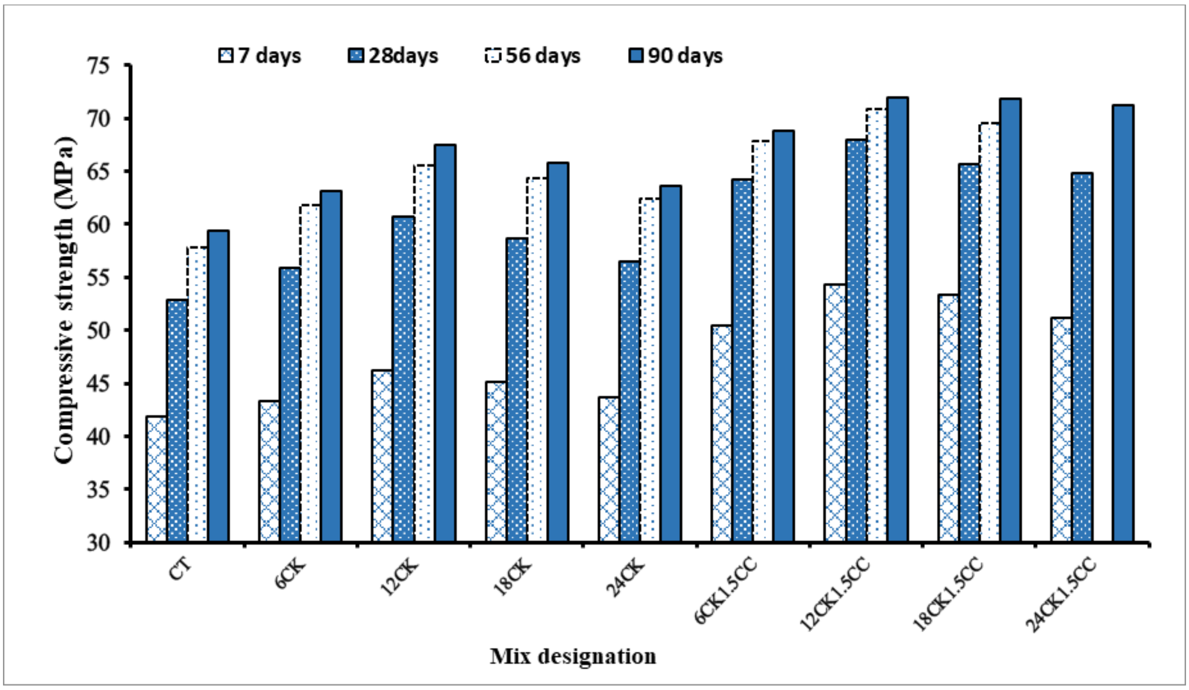


Figure 8. Compressive strength examines results at (7, 28, 56, and 90) days

The pozzolanic processes of the calcined clay are responsible for the increase in compressive strength. For ternary mixes, 12CK1.5CC mix revealed the maximum enhancement by about (34, 31.2, 25.5, and 21.8) % at (7, 28, 56, and 90) days, respectively. followed by 18CK1.5CC by (31.7, 26, 23, and 21.5) %, 24CK1.5CC by (26, 25.5, 20.9, and 20.5) %, and finally 6CK1.5CC by (11.9, 9, 10.4 and 9.7) %, respectively, compared with CT mix. Several factors contributed to this result: The impact of CK particle filling and its pozzolanic interaction with CaOH2 liberated during cement hydration. It significantly reduces concrete's CaOH2 content and forms C-S-H gel, (iii) accelerating early cement hydration (mainly at early ages), and (iv) a nano CaCO3 reaction with the aluminate phase from the hydration product's higher volume. Previous research on pozzolanic materials and nanoparticle concrete mixtures supported this tendency [5, 29, 30].

3.2.2. Splitting tensile strength

Fig. 9 showed that, in comparison to the CT mix, binary mixes (6% CK, 12% CK, 18% CK, and 24% CK) have a greater indirect tensile strength. Where the increase rate was (2, 9.4, 6.9, and 3.8) %, (3.3, 12.7, 9.6, and 4.9) %, (7.1, 11.4, 9.5, 7.7) %, and about (4.7, 12.3, 9.4, and 6.6) at 7, 28, 56, and 90 days, respectively. The causes include the fact that calcined clay has a larger surface area than cement, which causes the reaction to speed up. Adding 1.5 % nano-CaCO3 to ternary mixtures as a partial cement weight replacement (6% CK +1.5% CC, 12% CK+ 1.5% CC, 18% CK+ 1.5% CC, and 24% CK+ 1.5% CC), for ages (7, 28, 56, and 90) days, the values of splitting tensile strength rise further by (8.5, 14.8, 10.5, and 9.5) %, (26.6, 33.9, 30.8, and 29.3) %, (27.4, 33.3, 31.1, and 28.5), and (41.1, 31.6, 30.3, and 26.2) %, over the CT mix. as seen in Fig. 12. This may be the same reason indicated in compressive strength. The results were confirmed with previous studies[31]. Overall, the effect of CK and CC on the splitting tensile strength is similar to that on the compressive strength due to the stronger bonding between the cement paste and aggregate [32].

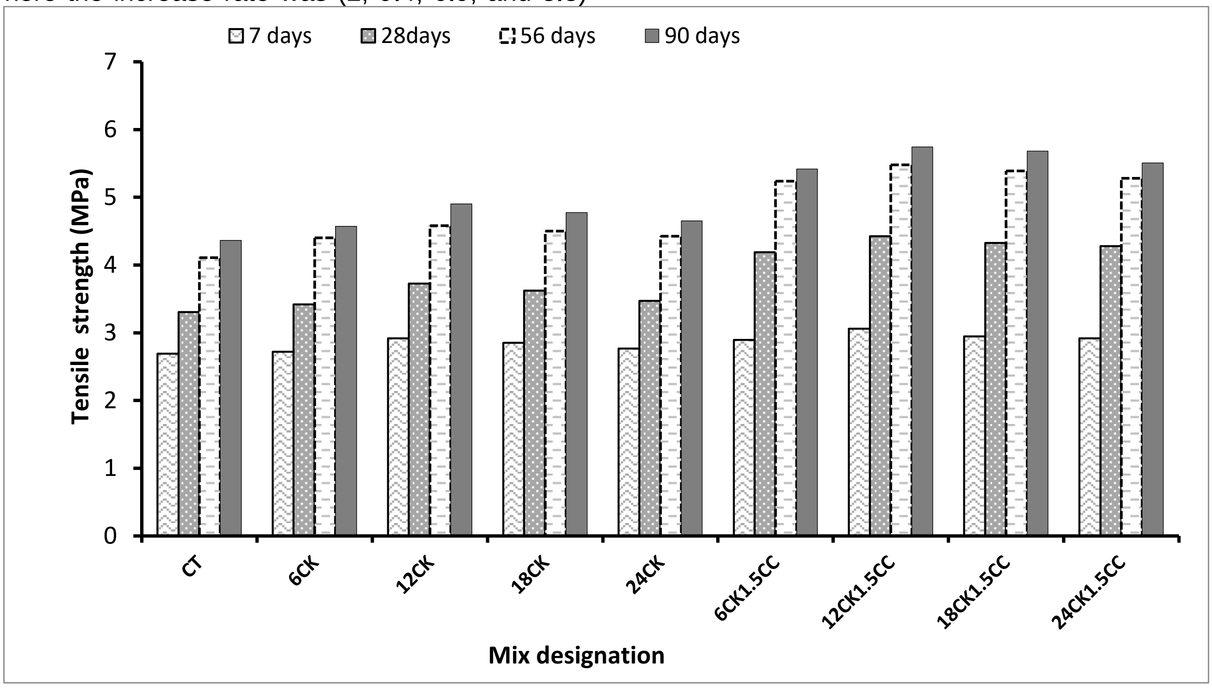


Figure 9. Splitting tensile strength results of control, binary, and ternary blended SCHPC mixes

3.2.3. Ultrasonic Pulse Velocity

Fig.10 illustrates the results of the UPV experiment of binary blended mixes (6CK, 12CK, 18CK, and 24CK) and ternary blended mixes (6CK1.5CC, 12CK1.5CC, 18CK1.5CC, and 24CK1.5CC) at 7, 28, 56, and 90 days. As expected, the results of the UPV showed a similar general trend to the compressive strength results, increasing with the age of the specimens. At the same age, the UPV of the concrete incorporating CK and CC as ternary blends were observed to be better than those of concrete containing CK as the binary blends with the same replacement levels. This can be due to the rapid pozzolanic reaction of CC at 7 days and later ages, which produced additional C-S-H leading to declined porosity. The pulse velocity through voids is lower than that through solid matter, so the lower porosity and denser internal structure of the concrete lead to an increase in pulse velocity [33,34]. At the age of 7 days onward, the effect of CK on UPV value was generally increased at different partial replacement percent 6%CK, 12%CK, 18%CK, and 24%CK were ranged from 4405 to 4460 m ⁄s; at 7 days, 4560 to 4590 m ⁄s at 28 days, 4640 to 4750 m ⁄s at 56 days and 4750 to 4820 m ⁄s at 90 days. It also can be noticed that the UPV measurements for the mixture containing 12% CK were higher than for the specimens with 6%, 12%, 18%, and 24% CK and CT mixture. For ternary mixes at 7 days onward, the UPV values changed from (4340 to 4845), (4440 to 4920), (4425 to 4890), and (4380 to 4860) m/s for 6CK1.5CC, 12CK1.5CC, 18CK1.5CC, and 24CK1.5CC mixes respectively. This result is affected by the pozzolanic reactive (high silica content) with $Ca(OH)_2$ and produces additional C-S-H, adding to that the small size of CK and CC which can fill the voids between the large cement particles and the reduction of porosity which that leading to a higher UPV. Previous experiments on SCC incorporating pozzolanic materials provided similar findings [35,36].

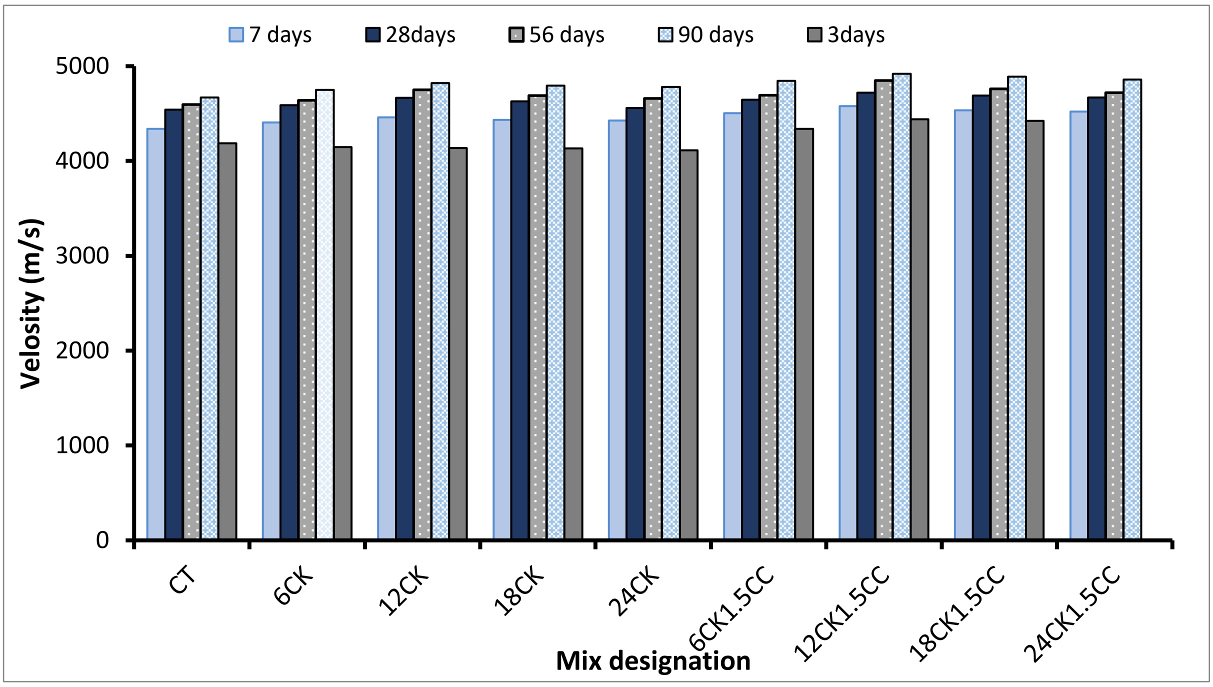


Figure 10. Ultrasonic pulse velocity values for control, binary, and ternary blended SCHPC mixtures incorporating CK and nano-CaCO3 at various ages

3.3. Durability examination results

3.3.1. Water absorption

The average results of the tests of self-compacting high-performance water-absorbing concretes (SCHPC), made of calcined kaolin clay and nano-calcium carbonate from binary and ternary mixtures, at 28, 56, and 90 days are shown in Fig. 11. It can be observed that the water absorption values decrease with increasing curing period for all binary and ternary SCHPC mixtures containing CK and nano-calcium carbonate in different proportions, compared to the reference CT concrete, due to the decrease in pore volume with hydration products, The lowest water absorption value was obtained at long-term ages (90 days) for all concrete mixtures. Compared to T C mix, CK concrete experienced a decrease in WA for 6% CK, 12% CK, 18% CK and 24% CKC mixes, which were recorded at about (9.22, 18.69, 17, and 22.65) %, (9.44, 19.90, 18.11 and 13.78) % and (3.98, 18.75, 11.64 and 7.95) %, respectively at 28, 56 and 90 days.

This finding can be attributed to the fact that these mixes have fewer interconnected pores as C-S-H is formed from the primary hydration and secondary pozzolanic reactions of CK, gradually filling the water-filled spaces. In addition, CK had high fineness as it acts as a filler between cement particles and may also contribute to this phenomenon. Hence, the CK-containing SCHPC blends produced in this study were of low absorption type and showed improved durability[27,37]. As for the ternary blends, the water absorption ratios of 6 CK1.5CC, 12 CK1.5CC, 15 CK1.5CC, and 24 CK1.5CC blends were 2.65 to 2.94; 2.32 to 2.63; 2.23 to 2.61 and 2.23 to 2.45% at ages ranging from 28 to 90 days, respectively. It can be observed that the water absorption ratio improved with lower values in the ternary blends upon partial replacement of cement with different proportions of calcined kaolin clay and nano calcium carbonate compared to the control CT blend. Due to the activity of pozzolanic material, it reacts with Ca $(OH)_2$, forming C-S-H addition in the pores and reducing water absorption, as well as the fineness of CK and CC which plays an important role in reducing water absorption. The research found that the 12% CK1.5 CC mixture was the best as it gave lower absorption rates for all ages. In general, all the binary and ternary blended SCHPC mixes investigated in the present study had a water absorption rate of less than 5%, which can be classified as good quality [38]. This reading indicates the durability of "good" concrete.

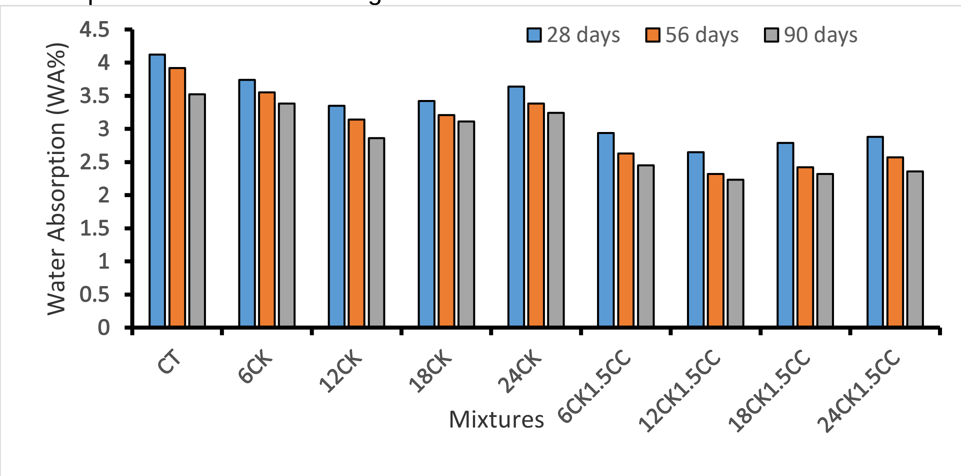


Figure 11. Water absorption of binary and ternary mixes for SCHPCs incorporating CK and nano-$CaCO_3$ at various ages

3.3.2. Porosity

The porosity results for all SCHPC containing calcined clay (CK) and nano calcium carbonate (CC) in binary and ternary mix systems at 28, 56, and 90 days are shown in Fig. 12. The incorporation of burnt kaolin clay up to 24% for binary mixes of SCHPC resulted in more reduction in porosity than the standard mix at different ages of 28, 56 and 90 days, as shown in Fig. 13. The recorded porosity of the mix using 12% CK was lower for all ages compared to the other binary concrete samples. However, the porosity of all mixes containing CK remained significantly lower than the standard concrete. The replacement mixes of CK at 6%, 12%, 18% and 24% were found to have significantly lower porosities of (10.34%, 9.63%, 9.78%, and 10.26%); (9.42%, 8.32%, 8.52 and 9.34%) and (8.52%, 7.86%, 8.14%, and 8.28%) for the progressive curing age of 28, 56, and 90 days, respectively. This may be attributed to the smaller size of CK particles and pozzolanic reaction, where CK particles fill the porous system because they are finer than cement, and CK reduces porosity by producing additional C-S-H gel[32,39].

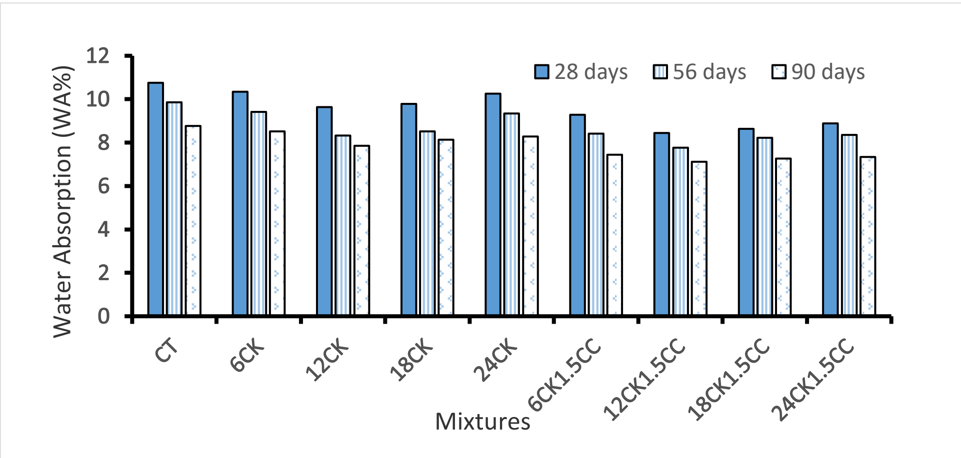


Figure 12. Porosity of binary and ternary mixes for SCHPC incorporating CK and nano-$CaCO_3$ at various ages

From Figure 12, the 12CK1.5CC mixture gave the lowest porosity values of 8.45%, 7.76%, and 7.12%, followed by 18CK1.5CC with 8.63%, 8.22% and 7.26%, then 24CK1.5CC with 8.77%, 8.35% and 7.39%, and finally, 6% CK1.5CC mixture gave 9.28%, 8.42% and 7.44% at (28, 56 and 90) days respectively. It was observed that all ternary mixtures performed better in terms of porosity than binary mixtures with CK for the same replacement levels. We conclude that the presence of C in SCHPC provides a more prominent effect in reducing absorption. The high fineness of burnt pozzolanic materials and nanoparticles used in this research may provide a filler effect for ternary composite concrete and contribute to reducing the absorption value. These results conformed with the study [39].

4. CONCLUSION

- The following conclusions may be made based on the findings of this experimental investigation.
- In binary mixed mixes comprising calcined clay (CK), fresh properties such as slump flow diameter, L-box height ratio, and segregation resistance decrease when CK is partially substituted. T500mm and V-funnel time, however, both increases.
- Compared to binary mixes, the fresh qualities of ternary blended mixtures (which contain CK and nano-CaCO3 (CC)) have a greater impact.1.5% dose of CC as partial substitution of cement weight in ternary SCHPC blend improves the strength of all mixtures for all ages.
- The binary mixes of SCHPC with 12% CK had better compressive strength than those with 6%, 18%, and 24% CK in all ages. The optimal CK concentration for sustaining SCHPC is 12%.
- The SCHPC ternary mixes had higher compressive strength at 7, 28, 56, and 90 days. CK-containing ternary blends with 1.5% CC had superior compressive strength than binary blends at all ages. SCHPC ternary blends with CK at 12% and 1.5% CC had greater compressive strength than binary, control, and other ternary mixes at all ages.
- SCHPC mixes' splitting tensile strength generally showed a similar pattern to their compressive strength, but the increases were slower than those shown in the SCHPC mixes' compressive strength.
- In general, the durability properties such as (water absorption, and porosity) were adversely impacted by increasing the partial substitute of CK and CC by cement weight.
- The UPV results showed a similar trend to the results of increasing compressive strength with age. At the age of 7 days onwards, the effect of CK on UPV value is a general increase at different partial replacement ratios.
- The UPV values of SCHPC ternary mixes at ages 7, 28, 56, and 90 days were higher than those of standard CT concrete. The UPV value of both concretes containing CK and NC as ternary mixes was higher than that of concretes including CK as binary mixes at the same replacement rates
- The optimal for calcined clay was 12% by cement weight for improvement of the strength and durability properties values.

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IZVOD

RAZVOJ NOVE CEMENTNE MEŠAVINE DOBIJENE OD KALCINISANIH PUCOLANSKIH MATERIJALA I NANOČESTICA SAMOZBIJAJUĆEG BETONA VISOKIH PERFORMANSI

Ovo istraživanje uključuje eksperimentalnu studiju o potencijalnoj upotrebi pucolanskih i nanomaterijala, uključujući nano kalcijum karbonat (CC) i kalcinisanu glinu (CK), tokom procesa proizvodnje samozbijajućeg betona visokih performansi (SCHPC). Binarni i ternarni sistemi mešanja pripremljeni su korišćenjem 475 kg/m3 cementa i fiksnog odnosa vode i veziva (0,35). CK je korišćen u proporcijama od 6 do 24% ukupne mase cementnih materijala. Što se tiče ternarnih mešavina, uzorci (6% CK 1,5% CC, 12% CK 1,5 CC, 18% CK 1,5 CC i 24% CK 1,5% CC) su pripremljeni delimičnom zamenom mase cementa sa CK i CC. Osobine novog SCHPC-a su procenjene testovima sleganja (D (mm) i T500 (s)), V-levka, L-kutije i otpornosti na segregaciju. Izmerena su mehanička svojstva, uključujući čvrstoću na pritisak i zatezanje, i izvršeno je ultrazvučno ispitivanje brzine pulsa betona. Takođe, merena su svojstva izdržljivosti, uključujući poroznost i upijanje vode. Nalazi su pokazali da dodavanje kalcinisane kaolinske gline u beton značajno poboljšava njegovu trajnost i mehanička svojstva. Najbolje poboljšanje je bilo za binarne i ternarne smeše sa 12% zamene kalcinisane kaolinske gline, gde je čvrstoća na pritisak poboljšana za 20,9%, a poroznost i upijanje vode smanjeni za 15,6% i 19,9%, za 56 dana u poređenju sa referentnom smešom. Trostruke mešavine su se, takođe, poboljšale bolje od ternarnih mešavina za iste omere zamene kalcinisane kaolinske gline za sve uzorke. Na primer, mešavina 12CK1.5CC zabeležila je poboljšanje čvrstoće na pritisak od 25,5% i smanjenje poroznosti i upijanja vode od 21,3% i 40,8% u poređenju sa referentnom smešom u periodu od 56 dana. Ova studija je ostvarila svoje ciljeve održivom proizvodnjom ekološki prihvatljivog betona kroz smanjenje sadržaja cementa putem pucolanskih i nanočestica.

Ključne reči: *kalcinisana glina; nano kalcijum karbonat; Otpor segregaciji; ekološki prihvatljiv beton; Durabiliti Properties*

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