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Enhancing Mechanical Properties of Self-Compacting Concrete Through the Utilization of Pozzolanic Materials and Waste Products

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ABSTRACT

This investigation delineates the impact of pozzolanic constituents and industrial by-products on the mechanical properties of self-compacting concrete (SCC). Calcined kaolinitic clay (CKC), waste marble powder (WMP), and limestone powder (LP) were utilized as cementitious supplements in various binary, ternary, and quaternary formulations. Specimens were synthesized by varying the substitution ratios of CKC, WMP, and LP within the cement matrix. The fresh state characteristics, encompassing L-Box height ratio, segregation resistance, V-funnel flow time, and slump flow diameter, were quantitatively assessed. Concurrently, the hardened state properties were examined at 7, 28, and 56-day maturation periods. Results demonstrated that the optimal binary blend, containing 10% WMP and 10% LP, significantly augmented the fresh properties and compressive strength of SCC. Ternary mix compositions further enhanced both compressive and tensile strengths, as well as ultrasonic pulse velocity, with peak values reaching 57.8 MPa, 4.61 MPa, and 4670 m/s, respectively, thereby surpassing traditional mortar benchmarks. The study's findings substantiate the potential of integrating CKC, WMP, and LP to not only bolster the performance of SCC but also to curtail cement usage, thereby reducing associated CO_2 emissions and enhancing sustainability. This research offers a compelling narrative for the construction sector, advocating for the adoption of alternative materials in the production of advanced, high-performance self-compacting concrete.

1. INTRODUCTION

Self-compacting concrete (SCC), renowned for its ability to flow and consolidate under its own weight, is a pivotal innovation in the construction industry. It has revolutionized concrete placement by obviating the need for mechanical vibration, effectively navigating narrow passages amid reinforcement bars, and ensuring homogeneity [1]. SCC's intrinsic properties necessitate an elevated mortar volume to serve as a lubricant and carrier for the coarse aggregates, thus ensuring cohesiveness and stability.

To enhance the performance characteristics of SCC, an increased incorporation of powdered superplasticizers (S.P.) and viscosity-modifying additives (VMA) has been recognized as essential [1]. These admixtures are instrumental in addressing potential drawbacks such as bleeding, segregation, and settlement. The hallmark of SCC lies in its resistance to segregation, coupled with its exemplary filling and passing abilities. Nonetheless, it is imperative to acknowledge that SCC may not uniformly display high resistance and durability.

The current study introduces a novel methodology aimed at elevating the compressive strength of SCC through the adoption of binary, ternary, and quaternary mix designs [2]. This strategy not only ensures equitable distribution and seamless flow across densely arranged reinforcements but also circumvents the hazards associated with vibration induction. The benefits of this approach are manifold, encompassing diminished cement usage, conservation of natural resources, amplified mechanical strength, and reduced production costs. The substitution of cement with alternative materials stands at the forefront of this strategy.

The experimental framework pivots around calcined kaolin clay (CKC), a pozzolanic material, employed either independently or in combination with Portland cement. The introduction of metakaolin into SCC mixtures at varying replacement weights (10%, 15%, and 20%) correlates with an uptick in compressive strength over different maturation stages, corroborating findings from Ozcan and Kaymak [3].

Additionally, the integration of limestone powder as a filler into SCC mixtures has been shown to substantially improve residual compressive strength, outperforming mixtures that incorporate pigment and sand powder (M.P. and M.S.) by approximately 3-13% and 2-10% respectively [4]. Faiz et al. [5] emphasize the significant role of local metakaolin in modifying the rheological and mechanical properties of self-compacting limestone cement. Auntas et al. [6] report that the incorporation of a binary blend of Portland cement and marble powder into SCC adversely impacts the fresh properties, reducing slump flow diameter and increasing both slump flow and V-funnel flow times.

This study is poised to explore the impact of pozzolanic materials and waste products—namely calcined clay, waste marble powder (WMP), and limestone powder (LP)—on the strength attributes of SCC. An assortment of blending systems, including binary, ternary, and quaternary mixtures, will be scrutinized. Fresh properties such as L-Box, segregation resistance, V-funnel resistance, and slump flow diameter, alongside hardened properties will be evaluated at 7, 28, and 56-day intervals. The study's outcomes are anticipated to furnish the construction industry with critical insights, advocating for the adoption of alternative constituents in the fabrication of high-performance SCC. These insights are projected to contribute to a reduction in cement use, a decrease in CO_2 emissions, and an enhancement in the environmental sustainability of SCC.

2. PROPORTIONS OF THE MATERIALS AND MIX

2.1 Materials

2.1.1 Cement

This investigation adopted locally produced Type I cement from Karasta. This choice was made due to the alignment of its physical and chemical attributes with the stipulated requirements of the Iraqi standard (IQS No. 5 from 1984) [7].

2.1.2 Fine aggregate

Several critical factors in self-compacting concrete (SCC) production revolve around the fine aggregate's quantity, grade, and shape. For this purpose, the natural sand sourced from the Al-Akhdar region was selected in this study. The fineness modulus of this sand, measured at 2.31, was used as an indicator. Following Iraqi standard criteria, this value corresponds to the third gradation zone. These values were determined for the gravel as 2.65 for Specific Gravity, 0.94% for Absorption, and 0.309% for Sulfate Content as per IQS NO.45/1984 [8]. Detailed information regarding the physical attributes and content of sulphates in the fine aggregate is provided in Table 1, and Figure 1 showed the calcined kaolin clay utilized in this research

2.1.3 Coarse aggregate

This study employed washed gravel extracted from the Al-Nabai'i region, featuring a maximum size of 10 mm. This selection strictly adhered to the stipulated criteria outlined in IQS No. 45/1984, the Iraqi standard which mandates specific attributes such as Specific Gravity, Absorption, and Sulfate Content. These values were determined for the gravel as 2.58 for Specific Gravity, 0.5% for Absorption, and 0.03% for Sulfate Content [9].

2.1.4 Admixture for high-range water reduction

High water-reducing (HWRA) Sika® ViscoCrete®-180 G, a substance superplasticizer based on modified polycarboxylic ether, provided SCC with the required flowing capacity. To meet performance standards, representative tests must be run to determine the best Superplasticizer dose was created by the BASF Company and complies with TypeF (ASTM C494, 2017) [10].

2.1.5 Calcined kaolin clay

Iraqi kaolin clay was used to create calcined kaolin clay (CKC), obtained from the Dewekhla district of the Desert of Al Ramadi west of Baghdad, Iraq. Kaolin clay can be thermally activated for two hours at 800℃ to produce CKC. The CKC was then ground in Baghdad's Al-Zahra Shop using the air blast technique to create reactive material with a higher level of fineness. The manufactured (CKC) complies with ASTM C618-03 [11]. The chemical analysis and physical parameters of CKC used in this experiment are shown in Table 1.

Table 1. The chemical compositions of Kaolin clay (K.C.) and loss on ignition (LOI)

Chemical Composition (%)	Calcined Kaolin Clay
Silicon dioxide (SiO_2)	49.3
Aluminium trioxide (Al_2O_3)	33.8
Trone oxide (Fe_2O_3)	1.43
Calicume oxide (CaO)	0.71
Magnesium oxide (MgO)	0.57
Sodium oxide (Na_2O)	0.26
Potassiume oxide(K_2O)	0.41
Sulfur trioxide (SO_3)	0.19
Phosphorus pentoxide(P_2O_5)	0.31
Titanium dioxide (TiO_2)	0.52
Loss on ignition (LOI)	11.73

Figure 1. The calcined kaolin clay utilized in this research

2.1.6 Waste Marble Powder (WMP)

The Powdered waste marble (WMP) used in this study is a leftover from marble masonry. Sludge from companies in Iraq's Al-Hilla city, in the Middle Euphrates region, was collected as WMP industrial waste. It was acquired as a by-product of shaping and sawing marble. To assess the feasibility of using it in manufacturing mortar and concrete, the visual perspective of the WMP as it left the factory is shown in Figure 2.

Figure 2. WMP used in this study

2.1.7 Limestone powder

Limestone powder (LP) is a recently developed supplementary cement material. Limestone powders are widely used in various applications. It is also used as a raw material to create binders with calcareous granules. These two minerals have distinct crystal patterns but share the same chemical compound-calcium carbonate ($CaCO_3$). Limestone is not composed solely of calcium carbonate. It also includes "detritus", which consists of sands and dirt excreted by organisms, contaminating rivers or settling from the ocean floor. The visual perspective of the Limestone Powder as it left the factory is shown in Figure 3.

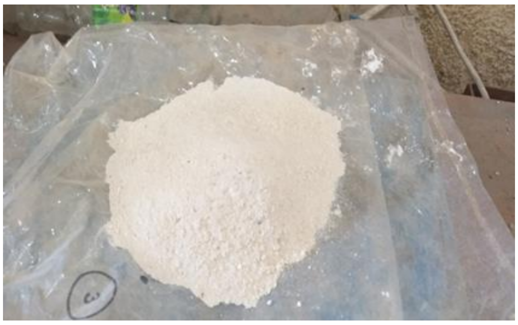

Figure 3. Photograph of the limestone powder

2.2 Mix proportions

This study created Mixes for self-compacting concrete using European standards (EFNARC, 2005) [12]. The raw materials utilized to create concrete mixtures consistently maintained a water-to-binder (w/b) ratio of 0.38 and a total binder concentration of 496 kg/m3. The superplasticizer was added to the cement at a rate of 2.5% of its weight. Eight combinations of concrete samples with dimensions of 10×10×10 cm were used to assess self-compacting concrete's compressive strength. Three binary combinations were employed to create the first mix (Reference-OP) as the reference mixture. These combinations involved varying ratios of calcined kaolin clay (CKC), marble dust (WMP), and limestone powder (LP): 30% CKC, 40%CKC,50%CKC 10% WMP, and 10% LP. The concrete specimens were 7, 28, and 56 days old at the moulding time. The concrete mixture ratios are presented in Table 2.

Furthermore, two ternary combinations were created by incorporating cement, limestone powder, and calcined clays sourced from CKC and marble dust. These components were employed to substitute portions of the adhesive in varying ratios: 30% CKC and 10% WMP, as well as 30% CKC and 10% LP And one quarterly mixture in which the cement was partially replaced with (CKC, WMP and LP) in different properties (30%CKC10%WMP10%LP).

2.3 Testing and curing procedures

2.3.1 Fresh properties test

To assess the three key flow characteristics— Resistance to segregation, passage capability, and flow and viscosity —of self-compacting concrete (SCC), new tests are required as outlined in EFNARC [12]. The slump flow test (D (mm)) is conducted to gauge the concrete mixes' flow ability. The determination of whether the consistency standards for fresh concrete specifications are met relies on the results of the first test, the T500 slump flow timing. The V funnel test is utilized to assess the filling capacity of SCC the 2005 European guidelines for self-compacting concrete detail the test method and equipment. SCC concrete is poured into the funnel without applying pressure in this test. The readings from the V-funnel test are reported as the flow time. The L-Box test can be conducted to determine if SCC can pass through reinforcing obstructions without experiencing segregation or blockage. Equipment, test methods, and segregation resistance (stability) can all be evaluated using a stability test with sieves by European standards from 2005. The ability of a new mixture to maintain the initial, largely uniform distribution of constituent materials is referred to as resistance to segregation. The sieve receiver was placed on the weighing machine and its mass (Wp g) was recorded. A sample of (4.8±0.2) kg of concrete was poured from a height of (500 ± 50) mm onto a 5 mm sieve with a diameter of 300 mm, and the actual mass of concrete (WC g) was recorded on the sieve. The concrete was placed in the sieve for (120±5) seconds to allow any laitance or mortar to pass through it while standing on the sieve receiver To compute the segregation index, the weight of the original material on the sieve is divided by the weight of the mortar.

2.3.2 Hardened properties tests

Bulk Density Any structure's self-weight entirely depends on the component materials' unit weights. As a result, it is an essential factor in mortar or concrete. As a result, the weight per unit volume of concrete is used to calculate the bulk density of concrete according to (BS 1881: Part 114, 1983) [13]. This test contributes to understanding the workability and flowability of SCC, which are crucial factors in achieving self-compacting properties without issues such as segregation or settlement.

Table 2. Proportions of the mix for concrete

Mix Notation	Cement kg/m^3	Calcined Clay kg/m^3	WMP kg/m^3	LP kg/m^3	Fine Aggregate kg/m^3	Coarse Aggregate kg/m^3	W/b %	Superplasticizer %
Control	496	0	0	0	835	865	0.38	2.5
10LP	446.4	0	0	49.6	835	865	0.38	2.5
10WMP	446.4	0	49.6	0	835	865	0.38	2.5
30CKC	347.2	148.8	0	0	835	865	0.38	2.5
40CKC	297.6	198.4	0	0	835	865	0.38	2.5
50CKC	248	248	0	0	835	865	0.38	2.5
30CKC10WMP	297.6	148.8	49.6	0	835	865	0.38	2.5
30CKC10LP	297.6	148.8	0	49.6	835	865	0.38	2.5
30CKC10WMP10LP	248	148.8	49.6	49.6	835	865	0.38	2.5

Compressive strength (1989) (BS 1881: Part 116) [14] (2000) K.N. a hydraulic compression machine with the compressive strength of cubes (10x10x10cm), was assessed at a loading rate of 18 MPa/minute. An average of three cubes were used for each test, which was carried out after 7, 28, and 56 days. This test is an essential evaluation conducted in this study to assess the hardened properties of self-compacting concrete (SCC). It plays a crucial role in understanding the overall mechanical performance and durability of SCC.

Splitting tensile strength The splitting tensile strength was tested using cylinders that met the requirements of the (ASTM C496-2004) [15] standard. The test entails measuring diametric compressive force at 1.4 MPa per minute along the length of a cylindrical concrete specimen up until failure. An average of two cylinders were obtained from each test and tested after seven and twenty-eight days. The Splitting Tensile Strength test is a significant evaluation to assess the mechanical properties of SCC and its ability to resist tensile forces in terms of its resistance to cracking and deformation.

Ultrasonic pulse velocity Generally, A solid material's density and elastic characteristics affect how quickly an ultrasonic pulse (UPV) travels through it. As a result, when concrete quality is high in terms of density, uniformity, and homogeneity, a relatively higher velocity is attained. Pulse velocity analysis is, therefore, a desirable method for studying structural concrete. Strong evidence suggests that higher UPV concrete is associated with increased compressive strength, though not necessarily in the same proportion. The UPV of the self-compacting concrete (SCC) mixes prepared with CKC, WMP, and LP was assessed in this study for 3, 7, 28, 56, and 90 days. Table 2 classifies the quality of concrete based on the pulse velocity that is possible according to IS 13311: Part 1 [16]. The UPV values should be more than 4500m/s for excellent concrete quality; in the range of 3500-4500 m/s for good concrete; in the range of 3000-3500 m/s for medium concrete; while for poor concrete, it is in the range of 2000-3000m/s; and less than 2000 m/s for very poor concrete [17]. By analyzing the ultrasonic wave propagation characteristics, the study gains insights into the effectiveness of incorporating different materials in improving the overall quality, integrity, and durability of SCC.

3. RESULTS AND DISCUSSION

3.1 Fresh, experimental results

Figures 4 and 5 reveal that the slump flow diameters range from 825 to 745, flow rates from 4.3 to 2.3, and V-funnel flow rates from 9.4 to 6.2. The 30% CKC mixture demonstrates class two (SF2) compliance, whereas the slump flow diameters of the control-PLC mix exhibit class three (SF3) characteristics. Class three (SF3) confirmation is evident in the 10% WMP and 10% LP mixtures. Class two (SF2) confirmation is achieved with 30% CKC combined with 10% LP and 30% CKC with 10% WMP. In Figure 6, the slump flow times (T500) of all SCC mixtures are validated as class two (SF2), indicating high consistency and workability in the filling. All SCC mixtures' T500 slump flow speeds are affirmed as class two (SF2). Using class two (SF2) criteria, the Control-PLC mix and the 30% CKC funnel flow times (s) are verified. However, the 30% CKC 10% WMP and 30% CKC 10% LP combinations are confirmed as class one (SF1). At the same time, the 30% CKC 10% WMP 10%LP combinations are confirmed as class one (SF3). These findings align with the acceptable SCC standards stipulated by EFNARC in 2005 [12]. On the other hand, it was apparent that the slump values were steadily declining as the replacement level of CKC was raised, which is consistent with [18].

Among the combinations, the 30% CKC + 10% WMP mixture demonstrates the longest flow time, recording 3.8 seconds for T500 and 8.9 seconds for V-funnel tests. In contrast, the control mixture exhibits the shortest T500 and V-funnel times, measuring 2.9 seconds and 6.8 seconds, respectively. The results of the SCC mixes' binary and ternary blends' sieve stability tests are shown in Figure 7. As can be seen, the binary mixtures (30CKC 10%WMP and 10%LP) exhibit more excellent segregation resistance than the reference mix because segregation percentages decrease as partial replacement percentages rise. Segregation is more prevalent than the binary mixtures (10WMP, 10LP). Ternary mixtures (30CKC10WMP and 30CKC10LP), compared to reference mixtures and binary mixtures with equal ratios, exhibited higher segregation resistance. Meanwhile, the percentage of segregation increases in the quarterly mixtures (30CKC10WMP10LP). This might be a result of the waste materials' increased surface area having an impact on their viscosity, and this makes segregation resistance stronger. Similar results were observed in earlier experiments [19, 20]. As partial cement substitution occurred, in Figure 8 the L-Box height ratio value decreased. the segregation test, it was found that the segregation rate was good for all mixtures, as it was between (8.7–13.2%), which were considered determinants of (EFNARC, 2005), which determined the segregation rate ≤15% (SR2 class).

The percentage and quality of calcined kaolin clay (CKC), waste marble powder (WMP), and limestone powder (LP), as well as their combined effects, are important factors that lessens passing ability similarly to how it decreases filling ability. Some studies reported similar outcomes [21-24]. The issue might be attributed to the long, hexagonal plates of the calcined kaolin clay, which hinder the smooth flow of the freshly mixed material and increase friction among the components. This outcome is influenced by their size and shape, respectively.

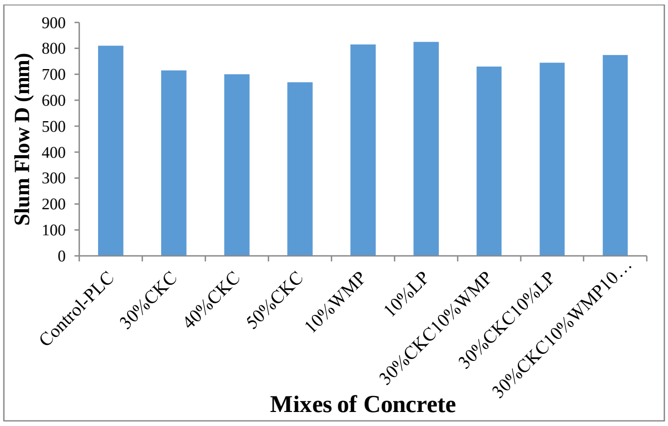

Figure 4. Test results for slump flow diameter

Figure 9 illustrates the relationship between the slump flow time (T500 (s)) and V-funnel flow times. According to (EFNARC, 2005) [12]., SCC is classified as VS1/VF1 when T500 mm and V-funnel flow time are ≤ 2 s and ≤ 8 s, respectively, while SCC is categorized as VS2/VF2 when T500mm exceeds 2 s and V-funnel flow time ranges from 9 to 25 s. Therefore, all the mixes could be classified into the VS2/VF2 class, which may be required for improving segregation resistance with increasing flow time. Except for the control mix, 10% WMP and 10% LP lay within the ranges of the VS2 and VF1 classes based on EFNARC [12].

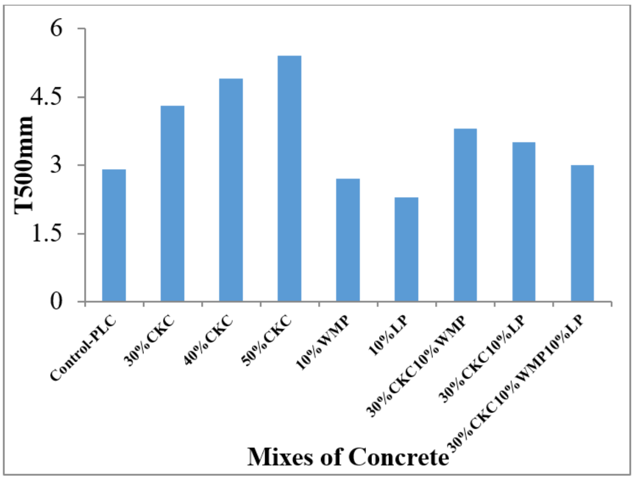

Figure 5. Test results for the slump flow time

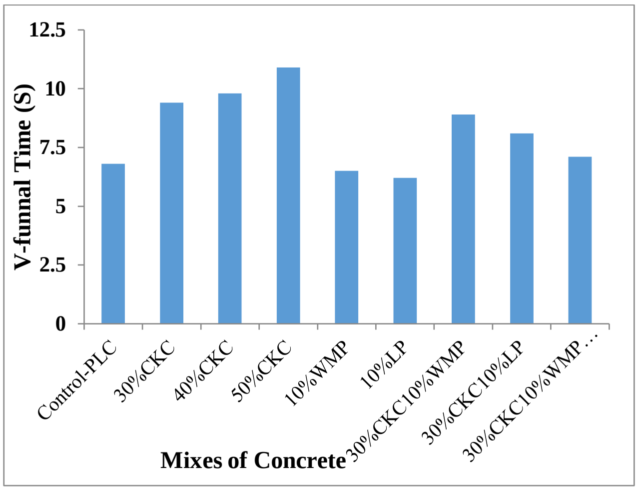

Figure 6. Results of the V-funnel time test

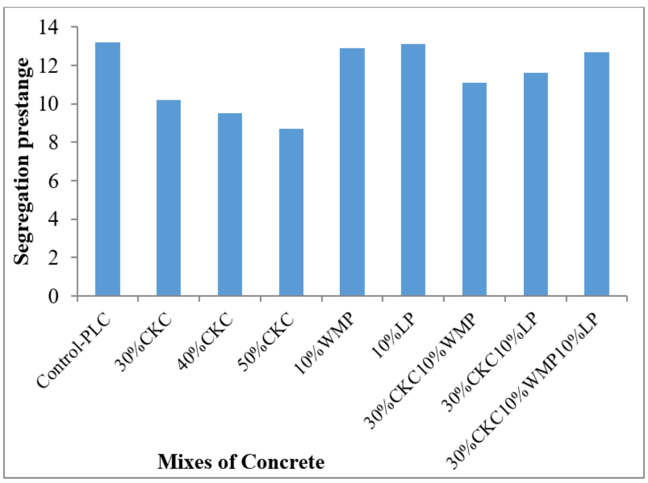

Figure 7. Test results for segregation resistance

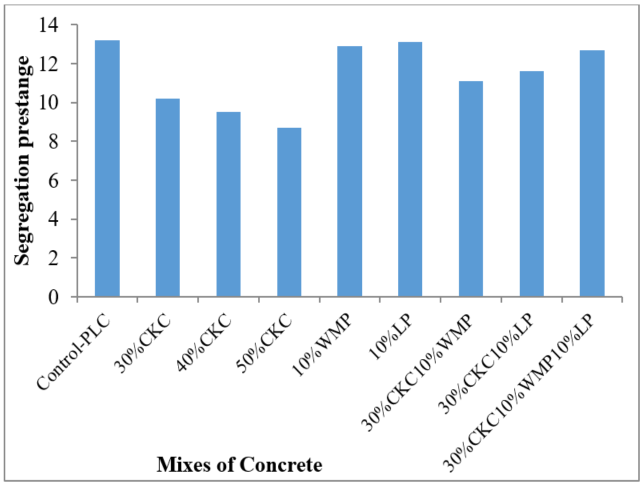

Figure 8. L-Box results of tests

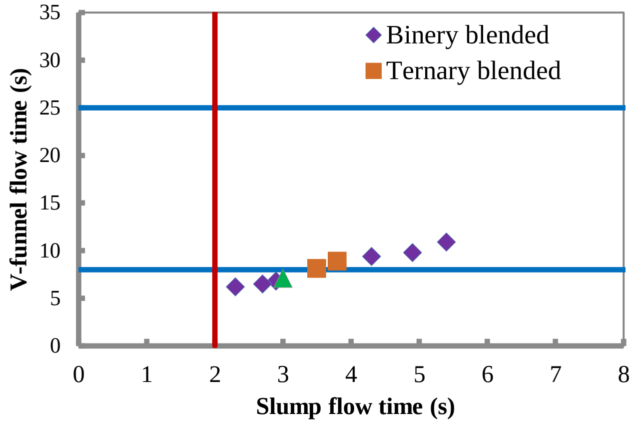

Figure 9. Variation of viscosity classes with T500 slump flow and V-funnel flow times of SCCs

3.2 Bulk density

The bulk density of blended cement concrete at 7 and 28 days is affected by the binders in binary, ternary, and quarterly mixes, as shown in Figures 10-12 respectively, blended self-compacting concrete (SCC) mixtures have lower bulk densities than the control concrete mix. In the ternary and binary mixtures, the lowest density values were recorded for The percentages of decrease in bulk density of SCCs (30%CKC, 40%CKC, 50%CKC, 10%WMP, 10%LP, 30%CKC 10%WMP, 30%CKC 10%LP, 30%CKC 10%WMP 10%LP) were (0.86, 1.14, 1.73, 0.12, 0.29, 1.73, 1.89 and 2.22)% at seven days; and (1.19, 2.39, 2.27, 1.05, 1.26,1.59, 2.27, 3.21)% at 28 days, respectively, compared with the control mixture. The bulk density decreased further in ternary and quaternary mixes. The lowest values of the density for binary systems was recorded for mixtures (50%CKC). This is because the specific gravity of CKC and WMP is significantly lower than cement's, resulting in reduced mass per unit volume. This result could be attributed to the specific gravity of the pozzolanic materials (CKC) and waste materials (WMP and LP) being lower than the specific gravity of cement. The specific gravity of CKC, WMP, and LP was measured to be 2.59, 2.68, and 2.66, respectively, this trend was also in line with findings from earlier research on pozzolanic components (CKC, WMP, and LP) in concrete mixtures [25].

3.3 Compressive strength

The Faculty of Engineering at Babylon's Department of Civil Engineering University conducted lab testing on self-compacting concrete mixtures.

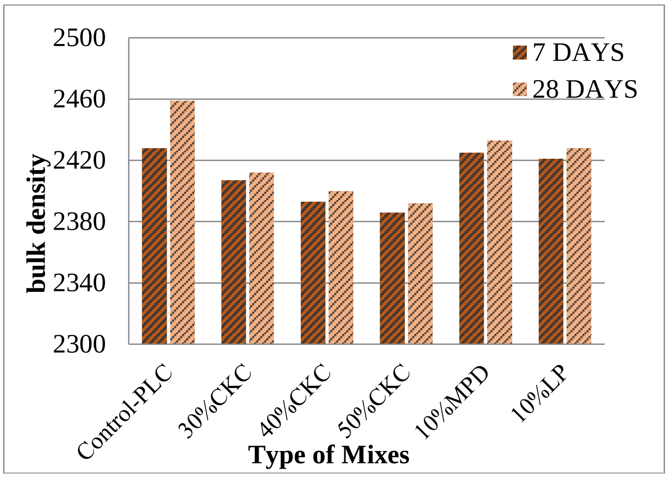

Figure 10. Bulk densities of binary blended SCC mixes

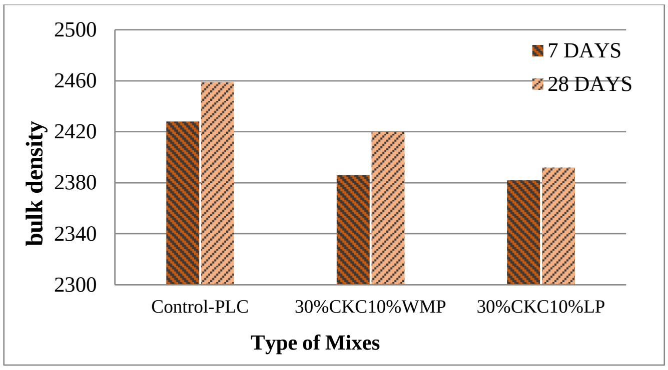

Figure 11. Bulk densities of ternary blended SCC mixes

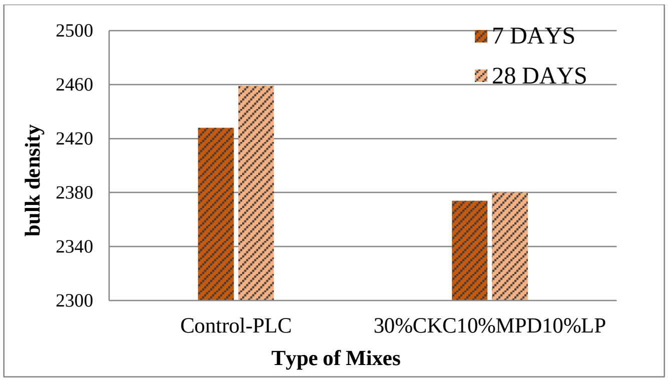

Figure 12. Bulk densities of quarterly blended SCC mixes

Figure 13 illustrates that a higher percentage of CKC substitution for cement corresponds to a lower compressive strength. Figure 13 shows that compared to the values of the reference mixture, the compressive strength in the binary mixtures (10%WMP and 10%LP) has a higher compressive strength. At ages 7, 28, and 56 days, the increase ratios for these mixtures were (12.3, 13.8 and 10.44, 13.2 and 9.12, 12.38 at 7, 28 and 56 age respectively. Among the various mixes, the most significant reduction in compressive strength between 7 and 28 days was observed for the 30% CKC replacement as showen Figures 14 and 15. This decrease could stem from either the micro-filling effect of water or the pozzolanic impact of CKC containing ($Ca(OH)_2$). However, due to insufficient CKC to counterbalance the adverse impact of low cement content on compressive strength, the pozzolanic reaction did not yield an immediate strength increase during the initial curing phases. It has been found that incorporating 10% WMP and 10% LP as substitutes for cement in the binary blended SCC mixture leads to an overall enhancement in compressive strength.

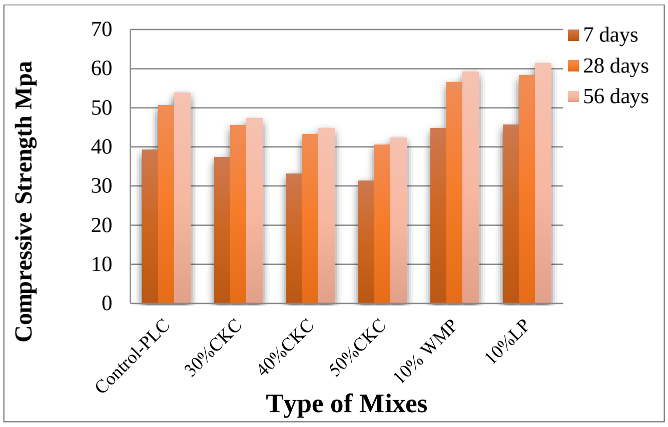

Figure 13. Binary mixture compressive strength values at 7, 28, and 56 days

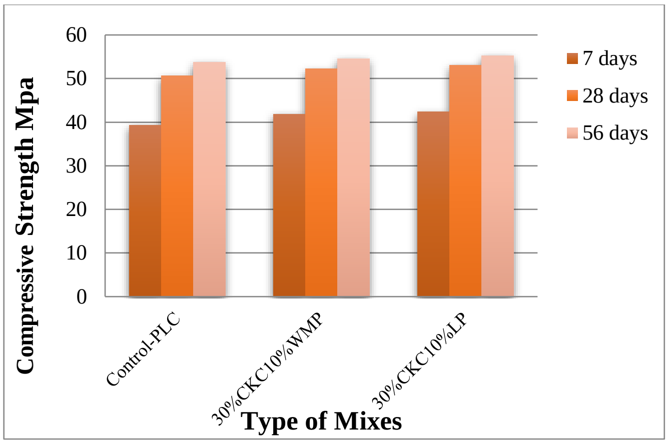

Figure 14. Ternary mixture compressive strength values at 7, 28, and 56 days

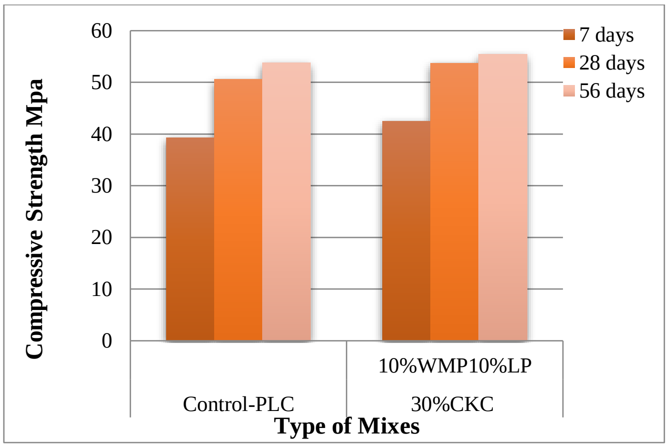

Figure 15. Quarterly mixture compressive strength values at 7, 28, and 56 days

Consequently, 10% WMP and 10% LP exhibited superior compressive strength across all age periods compared to other replacement components. This improvement arises from the interaction of waste products with tricalcium silicate (C3S) and tricalcium aluminate (C3A) during the early hydration process, forming calcium carboaluminates and C-S-H. Upon comparing the compressive strength of ternary blends at 7 and 28 days of age with that of binary blends and mixes containing 30% CKC and 10% WMP, the performance of the former proves to be superior. Consequently, CKC plays a crucial role in enhancing the bond between cement paste and aggregate particles, leading to a robust microstructure in the ITZ (interfacial transition zone). The physical and chemical benefits of CKC contribute to improving the paste matrix. These findings align with prior studies [26, 27].

10% WMP and 10%LP are added to ternary combinations. 30% CKC, 10% WMP and 30% CKC 10% LP For ages 7, 28, and 56 days enhances the compressive strength by approximately 10.6, 10.7 and 10.3, 10.8 and 10.1 and 10.5 respectively.

Adding 10%WMP and 10%LP to quarterly mixtures 30%CKC 10%WMP 10%LP increases the compressive strength by about 8.14%, 6.12% and 2.98% for ages 7, 28, and 56 days, respectively. Thus, incorporating limestone powder (LP) in blended cement benefited the compressive strength development of ternary and quarterly blended SCC.

3.4 Splitting tensile strength

Self-compacting concrete's splitting tensile strength as a result specimens shown in Figure 16. The splitting tensile strength of binary mixture 10WMP and 10LP increased at 7 and 28 days, Where the increase rate was 11.47 and 13.69% at seven days, 10.9% and 14.09% at 28 days, respectively, compared to the control-PLC mixture while in the mix with 30%CKC, 40%CKC and 50%CKC the tensile strength is low when compared to (Portland limestone cement) control –PLC value. The reductions were approximately 7.06%, 15.92%, and 19.42% at seven days; 8.77%, 13.03% and 15.42% at 28, respectively; this is caused by pozzolanic reactions and the ability of CKC to fill small spaces after reacting with C.H. to produce additional C-S-H. By reducing the porosity of the concrete through this procedure and enhancing its microstructure in the ITZ and paste cement matrix, tensile strength is raised. In addition, the calcined kaolin clay's colossal surface area also increases the reaction. These findings are consistent with earlier research [28, 29].

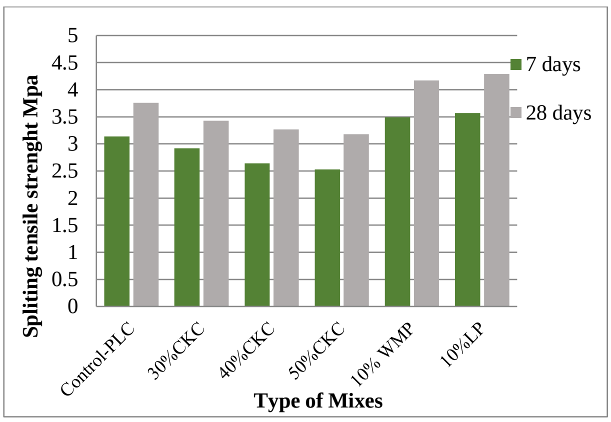

Figure 16. Binary mix values for splitting tensile strength at 7 and 28 days

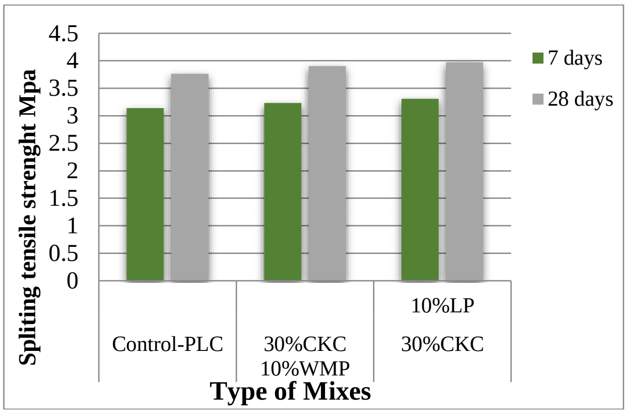

Figure 17. Ternary mix values for splitting tensile strength at 7 and 28 days

In Figure 17, ternary mixtures containing 30%CKC 10%WMP and 30%CKC 10%LP perform better than binary blends of 30%CKC and the control blend of 100%OPC at 7 and 28 days. Generally, the splitting tensile strength for all types of binary and ternary blends SCC mixes cured of 3 to 90 days was in the range of 7.4-7.92% of their respective compressive strengths, which is less than the outcomes of concretes of average strength, which range from about 8% to 10% [24].

3.5 Relationship between splitting tensile strength and compressive strength

The compressive strength and splitting tensile strengths of self-compacting concrete are shown in all possible combinations in Figure 18. This relationship was discovered for splitting tensile strength, which ranged from 2.53 to 4.61 MPa, and compressive strength, which varied from 22.3 to 63.2 MPa. The best-fit curve's R2, which gauges the strength of a relationship, was 0.975. Eq. (1) illustrates this relationship, which was determined for both ages (7 and 28 days) from concrete. These findings are consistent with those of the earlier investigation [30]. Fsp= 0.1237 fcu$^{0.8797}$.

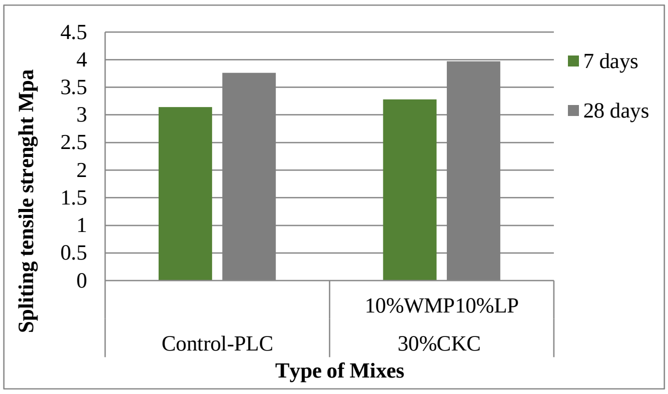

Figure 18. Quarterly mix values for splitting tensile strength at 7 and 28 days

3.6 Ultrasonic pulse velocity

Before testing (7, 28, and 56 days), UPV was recorded for all cube specimens for each concrete mix. The compressive strengths of the cubes were then measured after being crushed. The tests on binary Ternary and Quarterly mixes created by combining cement concrete with various (CKC, WMP and LP) proportions yielded results that are analyzed and discussed below. Figure 19 describes the UPV of SCC containing forvarious (calcined kaolin clay CKC, waste marble powder (WMP) and Limestone powder (LP) replacements of (30% CKC, 40% CKC, 50% CKC 10%WMP, 10%LP, 30%CKC 10%WMP, 10%CKC 10%LP and 30%CKC 10%WMP 10%LP) by weight of cement and 7, 28-, and 56-days curing periods. The UPV values changed from 3908 to 4863 m/s for 28 to 90 days, respectively, as shown in Figure 19.

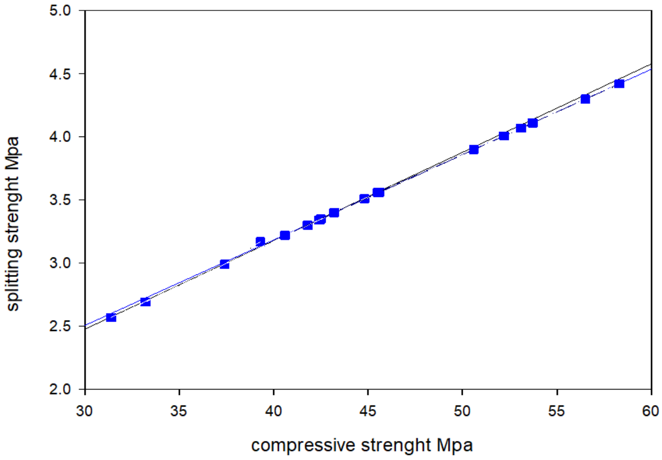

Figure 19. Relationship between compressive strength and splitting tensile strength at various days

In comparison to the control-PLC mixture, the inclusion of 10%WMP and 10%LP in the binary blended increased the UPV by 2.17% and 6.07% at seven days, 0.45% and 3.11 %at 28 days, 0.65 and 2.1%at 56 days, respectively compared to the control-PLC mixture. The mix of 10% LP exhibited the highest UPV of all ages (early and long-term). The increase in UPV of ternary blends SCC mixes (30%CKC 10%WMP, and 30%CKC 10%LP) were (1.02 and 1.28) %, (0.66 and 1.01) %, and (0.33 and 0.56) % of the ages 7, 28, and 56 days, respectively, compared with SCC control mix. As we saw from these percentages, all mixes had UPV higher than the control mix at all ages.

The increase in UPV for quaternary blends of SCC mixes (30%CKC 10%WMP 10%LP) was (6.2% (1.17%), (2.86%), and at the ages of 7, 28, and 56 days, respectively, compared with the SCC control mix (without CKC, WMP, and LP). These findings could be attributed to the hybrid use of WMP and LP particles in the mixed blended CKC being more effective than the single use of waste marble powder WMP or limestone powder LP particles due to the combined effect of WMP and LP, which both contribute to increasing or accelerating pozzolanic reactions, resulting in the consumption of $Ca(OH)_2$ and the formation of an "additional" C–S–H gel and filling the voids between cement grains. Also, WPM and LP make the matrix homogenous and compact, improving the concrete microstructure. Similar trends were also stated by other researchers [31].

3.7 Effect of calcined kaolin clay, WMP and LP on quality of SCC through UPV values

According to the (IS 13311: Part 1, 1992) [16], the degree of compactness, or ultrasonic pulse velocity (UPV), has a significant impact. The number of voids or pores in the concrete matrix, the mix ratio, how the concrete is placed and cured, the concrete's temperature and moisture content, etc. If the concrete matrix has enough homogeneity, uniformity, and packing density, the UPV values will be higher. During all combinations, the measured UPV ranged from 3908 to 4698 m/s during 7, 28, and 56 days., respectively, as shown in Figure 20, m/s from 7 to 56 days of age. According to IS 13311: Part 1 [16], all SCCs were found to have good and excellent quality, as shown in Table 3.

Table 3. The Effect of calcined kaolin clay, WMP, and WMP, andality of SCC

Type of Mixes	Ultrasonic Pulse Velocity (m ⁄s) Time (days)		
	7	28	56
Control-PLC	Good	Excellent	Excellent
30%CKC	Good	Good	Good
40%CKC	Good	Good	Good
50%CKC	Good	Good	Good
10%WMP	Good	Excellent	Excellent
10%LP	Good	Excellent	Excellent
30%CKC 10%WMP	Good	Excellent	Excellent
30%CKC 10%LP	Good	Good	Excellent
30%CKC 10%WMP 10%LP	Good	Excellent	Excellent

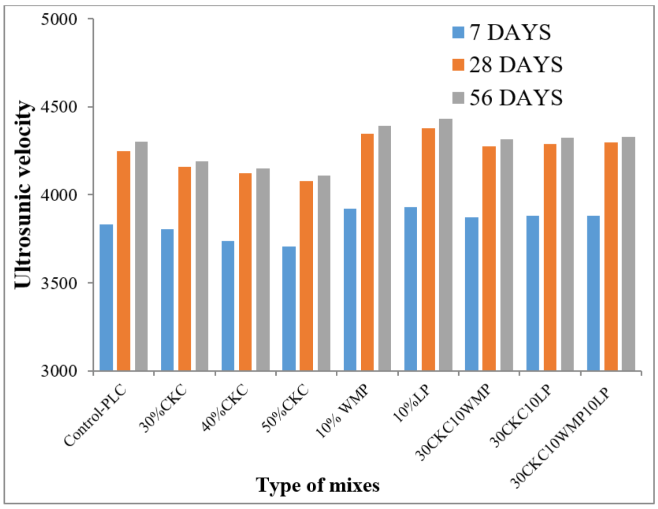

Figure 20. Ultrasonic pulse velocity values for control, binary ternary and quarterly blended SCCs mixtures incorporating CKC, WMP, and LP at various ages

4. CONCLUSION

The present study investigated the performance of self-compacting concrete (SCC) incorporating waste materials, namely Waste Marble Powder (WMP) and Limestone Powder (LP), as well as Calcined Kaolin Clay (CKC) as binary and ternary binders. The following key conclusions can be drawn:

1- Binary and ternary blends of waste materials (WMP and LP) with CKC demonstrated successful utilization in the production of self-compacting concrete.
2- Regarding fresh characteristics, the substitution of CKC decreased the slump flow diameter, while replacing WMP and LP in binary blend mixtures increased the slump flow value. Fresh properties were adversely affected by the partial replacement of CKC in binary blends. Ternary blends exhibited more significant effects than binary

mixtures, with increased V-funnel time but a continuous decrease in slump flow value. Long, hexagonal plate-shaped CKC particles likely contributed to these results by obstructing the fresh mixture and increasing friction between particles. The irregular or plate-like shape of M.K. particles may have also contributed to reduced slump flow diameter due to decreased mixture expandability. Additionally, the calcined pozzolanic materials' fineness and higher surface area played a role in these observations.

3- The density of binary, ternary, and quarterly SCC combinations, including up to 30% CKC, 10% WMP and 10% LP, generally decreased compared to control SCC at all ages. The binary blend and ternary mix with 30% CKC demonstrated the lowest bulk densities. The lower specific gravity of the pozzolanic materials (CKC) and waste materials (WMP and LP) compared to cement contributed to this trend.

4- Binary blended SCC mixes with 10% WMP and 10% LP exhibited improved compressive strengths at all ages, with the most significant impact observed at early curing ages due to the pozzolanic activity of LP. However, the mixture with 30% CKC showed a significant decrease in compressive strength compared to other combinations. Ternary mixes containing 30% CKC with 10% WMP and 30% CKC with 10% LP outperformed binary blends with 30% CKC and control Portland Limestone Cement (PLC) mix in terms of compressive strength.

5- Splitting Tensile Strength (STS) of SCC mixes generally followed a similar trend to compressive strength, albeit with a slower growth rate. A high volume of CKC resulted in lower levels of $Ca(OH)_2$ generation, which in turn affected the production of C-S-H gel and the density of the interfacial transition zone. As reported in previous studies, this factor influenced tensile strength to a greater extent than compressive strength.

6- The laboratory examination results (Ultrasonic Pulse Velocity - UPV) were consistent with those of the laboratory examination (Flexural Strength - F.C.), although the improvement observed in binary mixtures with 10% LP was slightly less compared to other mixtures. Overall, the SCCs incorporating the aforementioned binary mixtures, particularly with a 10% LP content, demonstrated good to excellent quality.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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NOMENCLATURE

Abbreviations

SCC	Self-compacting Concrete
S.P.	Superplasticizers
VMA	Viscosity-modifying additives
CKC	Calcined Kaolin Clay
MP	Marble Powder
MS	Marble Sand
SL	Self-Compacting Limestone
PLC	Portland Limestone Cement
P.C.	Portland Cement
WMP	Waste Marble Powder
LP	Limestone Powder
IQS	Iraqi Standard