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Research Article

Development of sustainable high performance self-compacting concrete incorporating natural and waste pozzolanic materials

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Abstract

High-Performance Concrete (HPC) satisfies specific requirements (such as high strength and permeability, enhanced durability, and low shrinkage) and uniformity standards that exceed those of conventional concrete. Self-Compacting Concrete (SCC) is placed by its weight, as it is sufficiently flowable to navigate through densely reinforced areas and prevent aggregate segregation. To minimize cement usage and the associated CO2 emissions from its production, two blending systems were developed: binary and ternary, including (OPC+CKC, OPC+WMP, OPC+GGBS, OPC+CKC+WMP, and OPC+CKC+GGBS). This study examined and compared the fresh-state properties (slump flow (D (mm), L-box, and segregation resistance tests), mechanical-state properties (unit weight and compressive strength), microstructural characteristics (Scanning Electron Microscopy (SEM)) and durability properties (water absorption and chloride and sulfate resistance) of high-performance self-consolidating concrete (HPSCC) against a reference mix (M0). All HPSCC mixes satisfied EFNARC criteria, with no bleeding or segregation. The optimal ternary mix (70% OPC, 10% CKC, 20% GGBS) achieved a compressive strength of 85.2 MPa at 90 days, lowest water absorption (2.74%), and significant improvement (25.24% and 25.94%) in durability (weight loss) under chloride and sulfate exposure, respectively. SEM analysis confirmed enhanced microstructural density and reduced calcium hydroxide formation. These results highlight the potential of CKC, WMP, and GGBS as effective supplementary materials for producing eco-efficient, durable high-performance self-compacting concrete.

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1. Introduction

Self-Compacting Concrete (SCC) is a highly flowable concrete that consolidates under its own weight without external vibration, filling complex formwork and dense reinforcement while maintaining homogeneity [1]. High-Performance Concrete (HPC) enhances durability and mechanical strength through optimized mix design and curing, offering superior workability and resistance to segregation compared to conventional concrete. Both SCC and HPC are increasingly favored for demanding construction applications due to these engineered advantages [2,3]. Advancements in concrete technology have led to the development of a novel class of concrete known as High-Performance Self-Compacting Concrete (HPSCC)—a material that combines the superior properties of Self-Compacting Concrete (SCC) and High-Performance Concrete (HPC). HPSCC is characterized by its ability to flow under its own weight without the need for vibration, while also delivering exceptional compressive strength and durability. Unlike conventional concrete, HPSCC typically incorporates a higher cement content, superplasticizers, and highly reactive mineral admixtures such as silica fume. This unique composition enables the concrete to completely fill intricate formworks with congested reinforcement, ensuring self-leveling and

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homogeneous placement. As a result, HPSCC offers enhanced mechanical performance and long-term durability, making it ideal for demanding structural applications [4,5].The increasing demand for cement in high-performance self-compacting concrete (HPSCC) necessitates the exploration of alternative materials to reduce cement consumption and enhance sustainability in construction. The use of alternative cementitious materials such as silica fume, ground granulated blast furnace slag, fly ash, metakaolin, limestone powder, and marble powder is highlighted as a means to develop eco-efficient concrete. These materials contribute to a significant reduction in the carbon footprint associated with traditional concrete production, aligning with global efforts to promote environmentally friendly construction practices [6-9].

Metakaolin is an environmentally friendly pozzolanic material produced by calcining kaolin clay at temperatures between 650 and 900 °C. This thermal activation process is notable for producing minimal carbon dioxide emissions, thereby positioning metakaolin as a sustainable alternative in concrete applications. Kavitha et al. [10] emphasized the benefits of incorporating metakaolin (MK) with ordinary Portland cement (OPC) in self-compacting concrete (SCC), particularly in efforts to reduce CO_2 emissions. Furthermore, studies by Melo and Carneiro [11] and Ghoddousi and Saadabadi [12] have demonstrated that metakaolin improves the viscosity of concrete mixtures and significantly enhances early-age strength due to its high pozzolanic reactivity. These properties make metakaolin both an environmentally responsible and technically effective additive in advanced concrete formulations. Ground Granulated Blast Furnace Slag (GGBS) is an industrial by-product resulting from the iron and steel manufacturing process. GGBS is an effective supplementary cementitious material that improves concrete properties. It slows the setting time, minimizes heat generation during hydration, and enhances resistance to sulfate and chloride attacks, making it particularly suitable for marine environments [1,13].

The marble industry has witnessed a significant increase in waste generation over recent decades, largely due to the alkaline nature of marble and its associated production processes. This waste, commonly produced as fine marble powder, poses environmental and health risks when improperly managed. However, the reuse of marble waste in concrete presents a promising sustainable strategy to mitigate its environmental impact [14,15]. Studies such as that by Tennich et al. [16] have shown that incorporating marble waste into self-compacting concrete (SCC) can improve fresh properties by reducing plastic shrinkage. Additionally, the high calcium content in marble dust (MD) contributes to enhanced strength development in hardened SCC [17]. A recent investigation by Djeddou et al. [18] explored the valorization of three local Algerian waste materials—marble powder (MP), ground granulated blast furnace slag (GGBS), and glass fibre-reinforced plastic waste (GFRPW)—as mineral additives in SCC. This study offers valuable insights into optimizing the use of MP, GGBS, and GFRPW in SCC, thereby promoting more sustainable and cost-effective concrete production.

In general, binary and ternary concrete mixes—those that combine two or three cementitious materials—offer significant advantages over mixes containing only Portland cement or blended cement. By using two types of supplementary cementitious materials (SCMs) in a ternary blend, the combined properties of each component can be synergistically optimized. This approach can enhance key performance aspects of concrete, such as early and late-age strength, workability, durability, and cost-effectiveness. Water absorption, which is directly related to a concrete's resistance to water penetration, plays a crucial role in various deterioration mechanisms. Like other engineering properties, concrete's water absorption is strongly influenced by its porosity, which governs the microstructure. Therefore, the absorption capacity depends on the quantity and distribution of pores of different sizes. As porosity decreases, water absorption also tends to reduce. It has been reported that the rate of water absorption in self-compacting high-performance concrete (SCHPC) typically ranges between 3% and 6% [19]. Sulfate ions, which may originate from soil, groundwater, or seawater, are often present alongside other ions such as sodium, potassium, magnesium, and calcium. The impact of sulfates on concrete durability depends on both the chemical form of the sulfate and the environmental conditions to which the concrete is exposed. Sulfate attack compromises durability by reacting with the cement matrix, leaching out calcium ions and replacing them with magnesium or sodium ions. This substitution leads to the formation of expansive sulfate compounds, increasing internal stress and causing microcracking within the concrete [20].The incorporation of pozzolanic materials such as ground granulated blast furnace slag (GGBS), fly ash (FA), metakaolin (MK), and silica fume (SF) as partial replacements for cement has proven effective in enhancing resistance to sulfate attack [21,22]. The impact of chloride on concrete durability, however, remains a debated topic. Gruber et al. [23] studied the effect of high-reactivity metakaolin (HRM) on chloride diffusion in concrete over 365 days. Their findings indicated that increasing HRM content reduced the diffusion coefficients, particularly with longer exposure durations and lower water-to-binder (w/b) ratios. Additionally, the partial replacement of cement with GGBS has shown promise in enhancing concrete's resistance to chloride penetration [24]. Chandru et al. [25] investigated ternary blends of SCC with crushed stone and induction furnace slag, demonstrating that such systems can significantly enhance durability while maintaining workability and compressive strength. Vivek [26] developed self-compacting concrete (SCC) using a ternary blend system. The fresh property test results—including slump flow, T500 time, V-funnel, L-box, and U-box tests—met the criteria established by EFNARC guidelines. However, it was observed that higher levels of cement replacement using metakaolin (MK) and ground granulated blast furnace slag (GGBS) led to a reduction in filling ability and passing ability in the ternary SCC mixes. The optimal performance was achieved when 30% GGBS was blended with either 5% or 15% MK, resulting in improved strength characteristics. Similarly, Chavan et al [27] demonstrated that multi-blended M70-grade concrete incorporating supplementary cementitious materials (SCMs) not only enhances durability but also provides economic advantages by reducing overall life cycle costs. These findings offer valuable insights for engineers and decision-makers seeking to design durable, cost-effective, and sustainable concrete structures.

This study aims to investigate the fresh, mechanical, and durability properties of High-Performance Self-Compacting Concrete (HPSCC) incorporating alternative supplementary cementitious materials such as calcined kaolin clay (CKC), ground granulated blast furnace slag (GGBS), and waste marble powder (WMP). The research also seeks to compare the performance of these mixes with conventional Self-Compacting Concrete (SCC) to evaluate the effectiveness of these materials in enhancing overall concrete performance, reducing cement consumption, and achieving environmental and economic benefits through lower CO_2 emissions and improved structural durability.

2. Materials and Experimental Procedure

This study introduces a novel approach by integrating locally available pozzolanic materials—CKC, WMP, and GGBS—into ternary blends to develop sustainable HPSCC. Unlike previous studies focusing on limited combinations, this work explores the synergistic effects of these materials, particularly ternary mixes such as 10% CKC + 10% WMP and 10% CKC + 20% GGBS, which showed superior strength, durability, and microstructural performance. By maintaining a constant water-to-binder ratio and assessing a broad range of properties, the study provides a holistic evaluation, contributing to the advancement of durable, eco-efficient concrete for modern infrastructure. The flowchart (Fig. 1) outlines the five major stages: preparation of materials, mix design, mixing and casting, fresh tests, and hardened & durability tests.

2.1. Materials

Ordinary Portland Cement (OPC-CEM I) produced by Lafarge, complies with the Iraqi Standard IQS 5 [28] was used. It has a specific gravity of 3.12 and a specific surface area (SSA) of 358 m^2/kg, indicating its quality and suitability for construction applications. The production of Calcined Kaolin Clay (CKC) in this study utilized Iraqi kaolin clay sourced from the Dewekhla region in the Al Ramadi desert. The raw clay was first ground and then thermally activated by calcination in a furnace at approximately 800 °C for two hours, with a controlled heating rate of 5 °C/min. After calcination, the material was allowed to cool gradually to room temperature over a period of 24 hours. This method of thermal treatment is consistent with the procedures reported by Khoman and Owaid [29]. Following calcination, the CKC was further processed using the air blast grinding technique to enhance its fineness, resulting in a high-quality pozzolanic material. Chemical analysis revealed that the combined content of the major oxides—SiO_2, Al_2O_3, and Fe_2O_3—exceeded 70%, thereby meeting the requirements of ASTM C618 [30] for Class N natural pozzolans. Additionally, the specific gravity of CKC was determined to be 2.6, and its specific surface area (SSA) was measured at 1640 m^2/kg, indicating its suitability as a supplementary cementitious material in construction applications.

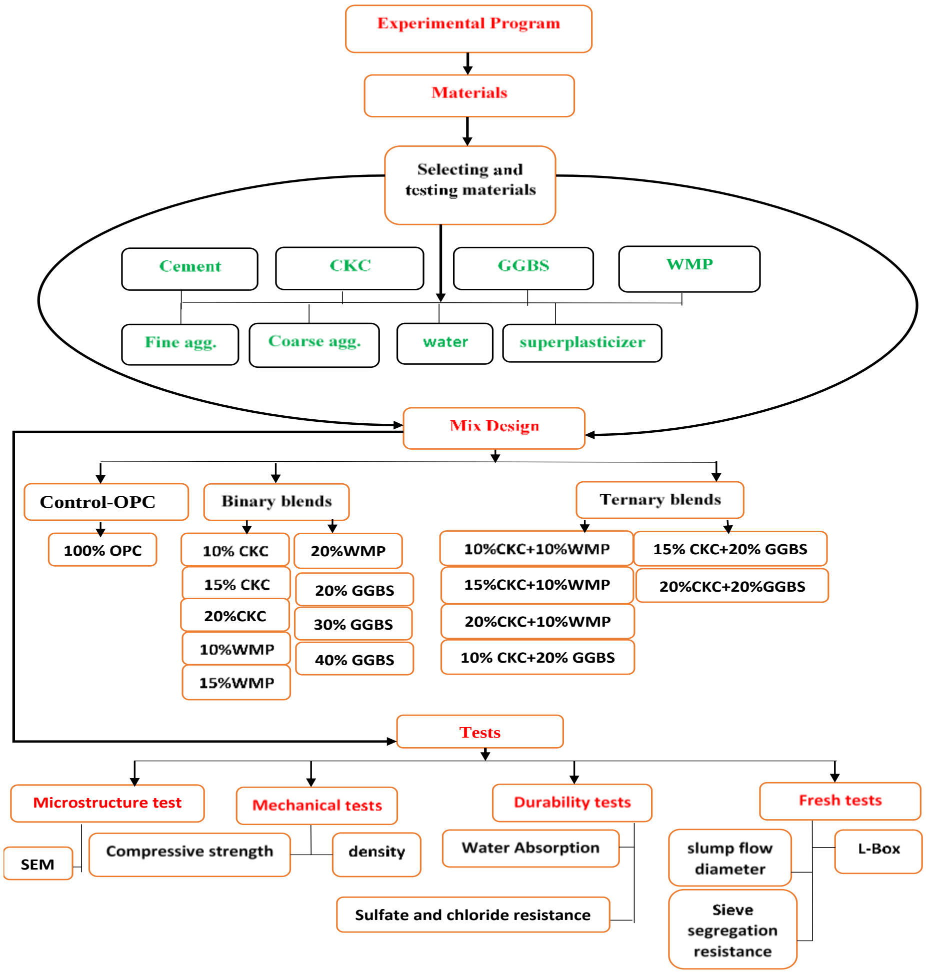


Fig. 1. Flowchart of the experimental procedure

Waste Marble Powder (WMP) sourced from marble masonry operations in Al-Hilla, Iraq. Collected as sludge during the marble cutting process, the WMP is dried before analysis. The findings reveal that WMP contains 85.62% calcium oxide, indicating potential use as a cement substitute due to its cementitious properties. Additionally, the specific gravity of WMP is measured at 2.68, which is slightly lower than that of OPC, while its specific surface area is found to be 569 m^2/kg. Ground granulated blast furnace slag (GGBS) is recognized for its environmental benefits as a by-product in construction. It requires less energy and generates considerably lower carbon dioxide emissions compared to traditional Portland cement [31]. The GGBS studied adheres to ASTM C989 [32] standards, is characterized as a fine white powder, and serves as a partial replacement for cement. With a specific gravity of 2.9 and a specific surface area of 418 m^2/kg, GGBS demonstrates a lower density and higher surface area than OPC, enhancing its utility in sustainable building practices.

The critical factors influencing the production of high-performance self-compacting concrete, specifically the fine aggregate's quantity, grading, and particle shape. The fine aggregate analyzed is local sand from the Al-Ukhaidher region, which satisfies the third grading zone criteria and complies with Iraqi standards IQS 45 [33], having a fineness modulus of 2.52. The coarse aggregate used is crushed and washed gravel from the Al-Nabai'i area, with a maximum size of 10 mm, also meeting relevant Iraqi specifications. SikaViscocrete-180GS is a superplasticizer admixture formulated from polycarboxylic ether, designed specifically for the ready-mix concrete industry. This admixture is based on polycarboxylic ether and is an economical high-range water reducer that enhances early and final strength while maintaining workability. SikaViscocrete-180GS meets the requirements of ASTM C494[34] Type F&G based on dosage.

2.2. Mix Proportions

Table 1 presents the mix proportions of the developed HPSCC mixes in kg/m^3, with a constant w/b ratio of 0.33 and total binder content of 530 kg/m^3. Table 2 compares the actual values of key parameters with EFNARC recommendations [35] to validate compliance. The concrete mixtures were developed using two blending systems—binary and ternary—executed in two distinct phases to evaluate their performance and effectiveness. In the first phase, a control mix was prepared using only ordinary Portland cement (OPC). Subsequently, binary blend systems were developed by partially replacing OPC with 10%, 15%, and 20% of calcined kaolin clay (CKC); 10%, 15%, and 20% of waste marble powder (WMP); and 20%, 30%, and 40% of ground granulated blast furnace slag (GGBS) by mass.

Table 1. Mix proportions of HPSCCs

Mix Num.	Mix Notation	*W/B*	Quantities of ingredients (kg/m3)						
			OPC	CKC	WMP	GGBS	FA	CA	SP
M0	Control-OPC	0.33	530	-	-	-	872	887	10.6
M1	10%CKC	0.33	477	53	-	-	872	887	10.6
M2	15%CKC	0.33	450.5	79.5	-	-	872	887	10.6
M3	20%CKC	0.33	424	106	-	-	872	887	10.6
M4	10%WMP	0.33	477	-	53	-	872	887	10.6
M5	15%WMP	0.33	450.5	-	79.5	-	872	887	10.6
M6	20%WMP	0.33	424	-	106	-	872	887	10.6
M7	20%GGBS	0.33	424	-	-	106	872	887	10.6
M8	30%GGBS	0.33	371	-	-	159	872	887	10.6
M9	40%GGBS	0.33	318	-	-	212	872	887	10.6
M10	10%CKC+ 10%WMP	0.33	424	53	53	-	872	887	10.6
M11	15%CKC+ 10%WMP	0.33	397.5	79.5	53	-	872	887	10.6
M12	20%CKC+ 10%WMP	0.33	371	106	53	-	872	887	10.6
M13	10%CKC+ 20%GGBS	0.33	371	53	-	106	872	887	10.6
M14	15%CKC+ 20%GGBS	0.33	344.5	79.5	-	106	872	887	10.6
M15	20% CKC+ 20%GGBS	0.33	318	106	-	106	872	887	10.6

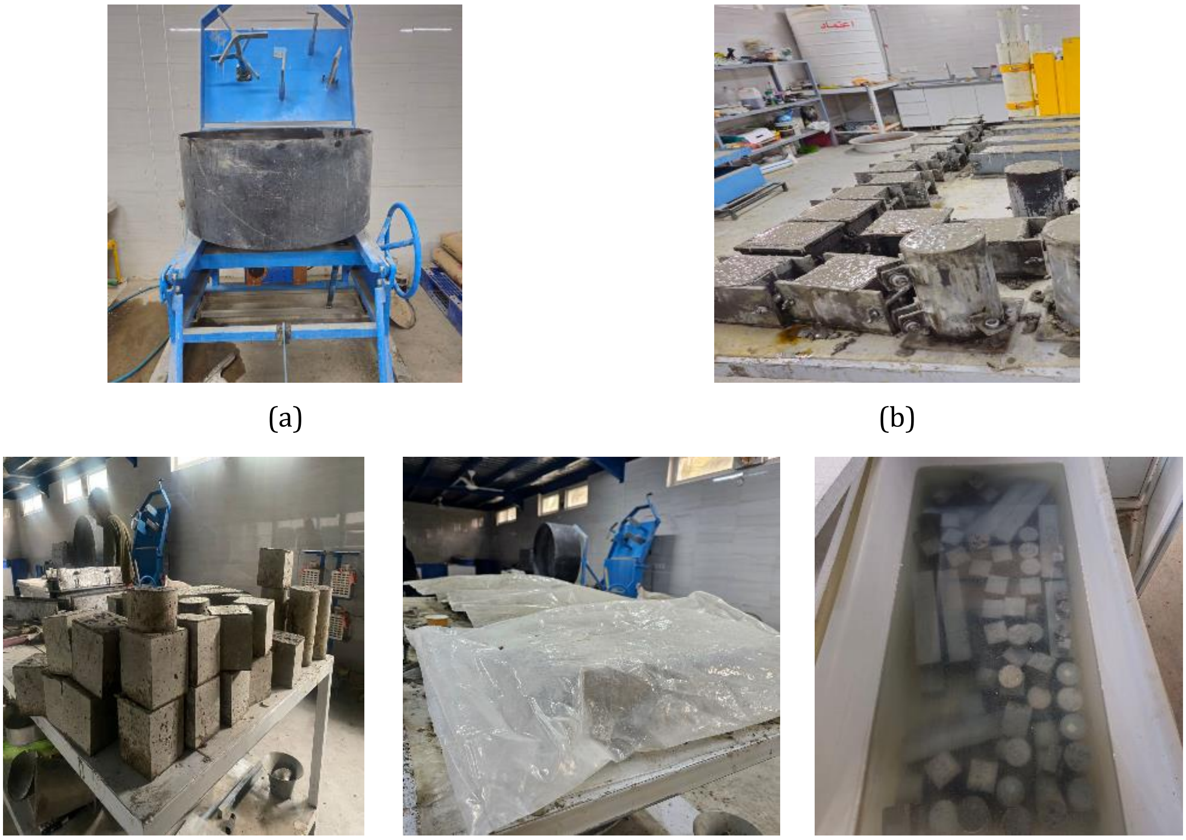
Table 2. Comparison with EFNARC recommendations [35]

Constituent	Typical range by mass (kg/m3)	Values Used in Study	Compliance
Water	150-210	174.9	✓ Compliant
Binder Content	380 – 600 kg/m^3	530 kg/m^3	✓ Compliant
Coarse Aggregate	750-1000	887	✓ Compliant
Fine Aggregate	48 – 55% of total aggregate weight.	49.6%	✓ Compliant

In the second phase, ternary blend systems were formulated using two combinations: OPC + CKC + WMP and OPC + CKC + GGBS. In the first combination, CKC was used at replacement levels of 10%, 15%, and 20%, each combined with a fixed 10% of WMP. In the second combination, CKC was used at 10%, 15%, and 20% replacement levels, each combined with a fixed 20% of GGBS. All replacements were made by mass as partial substitutes for OPC.

2.3. Preparation of Specimen

The process of concrete mixing was conducted within a laboratory setting, adhering to a stringent temperature regulation of 25±2°C, utilizing a horizontal drum mixer apparatus. Subsequent to the mixing process, the freshly prepared concrete was transferred into standardized cube molds, each measuring 100 mm on all sides. In order to facilitate adequate curing, the specimens were enveloped in nylon sheeting and retained in the casting room for a duration of 24 hours prior to their demolding. Following the demolding procedure (Fig.2), the specimens were immersed in a water basin for additional testing at ambient temperature at specified ages.



(a) (b)

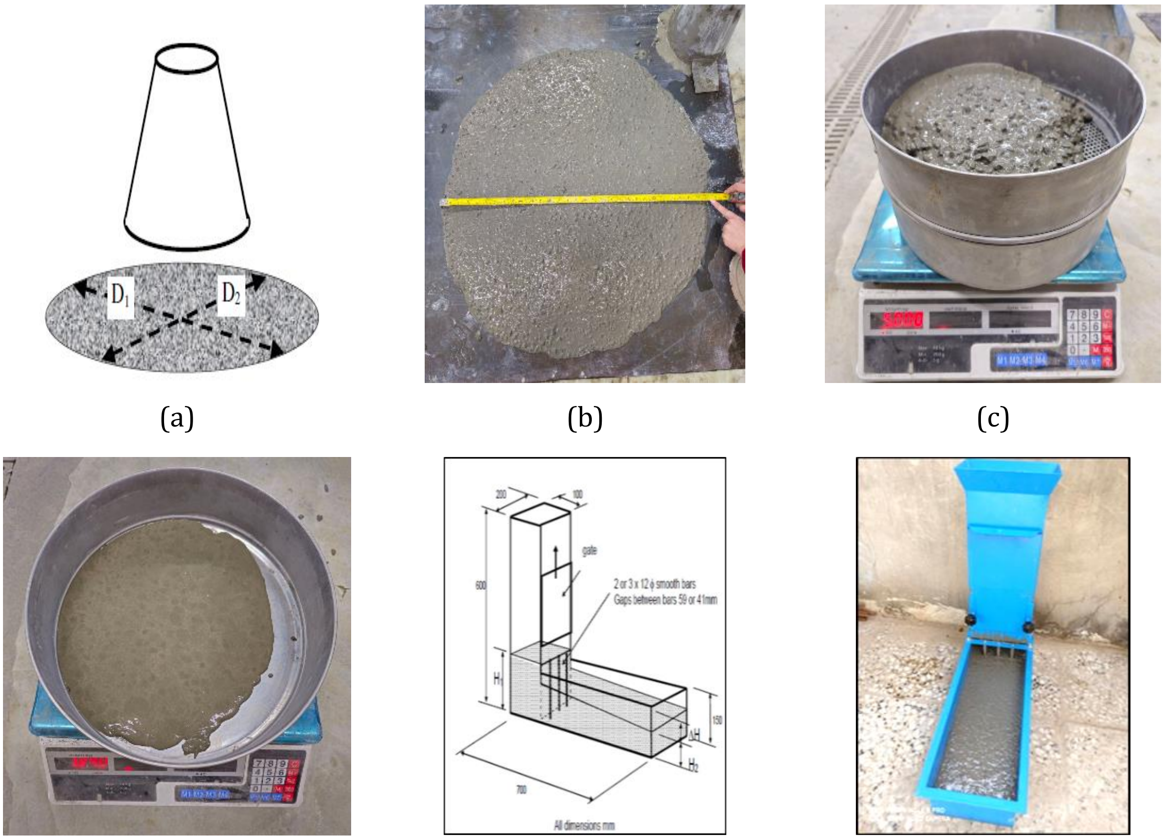
(c) (d) (e)

Fig. 2. (a) Mixing (b-d) casting process and (e) curing of test specimens for HPSCC

2.4. Testing Methods

2.4.1 Fresh Tests

Fresh properties of HPSCC are critical for its performance in construction. According to EFNARC [35], three main properties need evaluation: passing ability, segregation resistance, and filling ability. However, no single test can assess all these characteristics at once. The study utilizes the slump flow measurements to evaluate filling ability Fig. 3(a), sieve segregation resistance for segregation assessment Fig. 3(b), and L-box test for passing ability Fig. 3(c), providing a comprehensive understanding of HPSCC's fresh properties.



(a) (b) (c)

(d) (e) (f)

Fig. 3. (a-b) Slump (c-d) sieve segregation resistance and (e-f) L-box tests for HPSCC

2.4.2 Mechanical Tests

Essential tests for hardened concrete in this study included density measurement, scanning electron microscopy (SEM), and compressive strength evaluation. The density of the concrete was measured in kg/m^3 in accordance with BS 1881: Part 114 [36]. It was determined by calculating the mass-to-volume ratio of standard cube specimens (100 × 100 × 100 mm) prior to compression testing at curing ages of 7 and 28 days.

Fig. 4. Compressive strength test

The compressive strength test was conducted to assess the mechanical performance and structural integrity of the concrete. All procedures followed BS 1881: Part 116 [37], using 100 mm cubic specimens. For each mix, the average compressive strength was calculated based on the results of three specimens tested at 7, 28, and 90 days of curing. A compression testing machine with a capacity of 1900 kN was used to apply load until failure occurred. The compressive strength was then computed by dividing the maximum applied load by the cross-sectional area of the specimen (see Fig. 4).

The microstructure of HPSCC specimens containing blended pozzolanic materials was examined using scanning electron microscopy (SEM). SEM analysis was performed on selected mixes (M1, M4, M7, M10, and M13) that exhibited optimal compressive strength at 28 days, and the results were compared with the reference mix (M0), in accordance with ASTM C1723 [38]. Concrete cube cores were sectioned using a precision saw to obtain specimens measuring 10 × 10 × 10 mm. The SEM examination was conducted using a high-resolution setup with an accelerating voltage of 20 kV (HV: 20 kV) at various magnifications to capture detailed surface morphology and microstructural features.

2.4.3 Durability Tests

The water absorption test was carried out in accordance with ASTM C642 [39] to evaluate the volume of voids in hardened concrete and assess the concrete's resistance to water penetration. The test was conducted on all mixtures at 28 and 90 days (following initial 28-day curing).
Cube specimens measuring 100 × 100 × 100 mm were first oven-dried at 110 ± 5 °C for a minimum of 24 hours until a constant mass was achieved (dry mass A). The specimens were then immersed in tap water for at least 48 hours. Saturation was considered reached when two consecutive mass measurements taken 24 hours apart showed either constant mass or a mass increase of less than 0.5% of the higher value. After immersion, the surface of each specimen was quickly wiped with a damp cloth, and the saturated surface-dry mass (B) was recorded immediately. The percentage of water absorption (WA) was then calculated using the following equation Eq (1):

$$WA\,(\%) \;=\; [(B - A)\,/\,A] \;\times\; 100 \qquad (1)$$

Where, WA: Water absorption, A: Oven-dried mass, B: Saturated surface-dry mass.

This test allowed the determination of the total volume of permeable pores in the concrete, providing a key indicator of its durability performance. Sulfate and chloride ions are among the most aggressive agents affecting the durability of concrete structures. In this study, durability assessment was conducted in two stages.In the first stage, concrete cube specimens (100 × 100 × 100 mm) were submerged separately in 5% sodium sulfate (Na_2SO_4) and 5% sodium chloride (NaCl) solutions for 90 and 180 days, following an initial 28-day period of water curing. As per ASTM C1012 [40], each liter of solution was prepared by dissolving 50 grams of either NaCl or Na_2SO_4 in 900 mL of water, and then diluting with distilled or deionized water to reach a total volume of 1.0 L. The solutions were prepared one day in advance, stored at a controlled temperature of 23 ± 2 °C, and renewed monthly throughout the exposure period.In the second stage, the weight change of the HPSCC specimens was monitored at various ages. After 28 days of moist curing, the initial weight of each specimen was recorded as the reference weight (W_0). The specimens were then exposed to NaCl and Na_2SO_4 solutions separately and reweighed after 90 and 180 days of exposure (denoted as W_i). The cumulative weight change was calculated using the following equation Eq (2):

$$Weight\ Change\,(\%) \;=\; [(W_i - W_0)\,/\,W_0] \;\times\; 100 \qquad (2)$$

Where, W_i: Weight after 90 and 180 days of exposure to NaCl and Na_2SO_4 solutions separately, W_0: Reference weight.

3. Results and Discussion

3.1. Fresh Properties, Results and Discussion

In self-compacting concrete (SCC), powder content plays a crucial role in determining flowability and stability. According to EFNARC [35], the total powder content, including cement and supplementary cementitious materials (SCMs), should generally exceed 380 kg/m^3 to ensure sufficient cohesiveness and viscosity. In this study, the powder content was maintained at 530 kg/m^3 across all mixes, aligning with these recommendations. One of the key parameters influencing the fresh behavior of HPSCC is the particle size distribution of the powder materials. Fine particles, especially those smaller than 125 microns, contribute significantly to the mix's rheological properties. These ultrafine particles fill voids between larger aggregates, leading to improved particle packing density. As a result, internal friction is reduced, enhancing the mixture's flowability. Materials such as Calcined Kaolin Clay (CKC), Waste Marble Powder (WMP), and Ground Granulated Blast Furnace Slag (GGBS) used in this study contained a substantial proportion of particles below 125 μm. For example, CKC, with a specific surface area of 1640 m^2/kg, provided high fineness and reactivity, thereby increasing the mixture's cohesiveness and reducing the risk of segregation. WMP, with its smooth morphology and fine particle structure, acted as a filler that enhanced deformability and helped in achieving high slump flow values. Similarly, the finely ground particles of GGBS contributed to improved lubrication within the paste matrix, facilitating better flow. However, an excessive amount of ultrafine powder can increase water demand and reduce flow [41]. In this study all HPSCC mixtures achieved slump flow diameters ranging from 740 to 845 mm (Fig. 5), corresponding to the SF3 classification according to EFNARC guidelines, with the exception of binary mixtures containing 20% CKC, which fell under the SF2 category.

Consequently, all mixtures were deemed to possess satisfactory consistency and workability from a filling perspective. For the reference mixture (M0), comprising only of ordinary Portland cement (OPC), the slump flow diameter was recorded at 800 mm, whereas the slump flow diameters for mixtures M1, M2, and M3 were 780 mm, 765 mm, and 740 mm, respectively (the minimum flow diameter). It was observed that the inclusion of 10%, 15%, and 20% CKC resulted in a reduction of the flow diameter by 2.5%, 4.37%, and 7.5%, respectively. Notwithstanding the dosage of superplasticizer (SP) being maintained at 2%, the flow diameter experienced a decrement due to the incorporation of CKC. The decline in filling capacity signifies that the addition of up to 20% CKC adversely impacts the consistency of the concrete. This may attribute to CKC's particles size which is can be categorised as an ultra-fine and pozzolanic reactivity produced the internal friction among the grains increased. Therefore, this friction causes a loss of fluidity (deformability) [41,42]. For the mixtures incorporating WMP, M4, M5, and M6, the slump flow diameters were recorded at 805 mm, 810 mm, and 825 mm, respectively. It was observed that in comparison to M0, the increase of the replacement levels of WMP enhances flowability (deformability). This improvement was manifested in the M4, M5, and M6 mixtures, which demonstrated increases in flowability of 0.63%, 1.25%, and 3.13% relative to M0, respectively. This modest enhancement can be primarily attributed to the fine particle size of the marble powder, which facilitates more efficient particle packing and marginally diminishes internal friction within the mixture [43,44].

For the mixtures incorporating Ground Granulated Blast Furnace Slag (GGBS), the formulations M7, M8, and M9 attained slump flow diameters of 820 mm, 835 mm, and 845 mm, respectively, thereby signifying enhanced flow diameters. It was noted that, in contrast to M0, augmenting the levels of GGBS replacement significantly improves flowability (deformability). This enhancement was evident in the M7, M8, and M9 mixtures, which exhibited increases in flowability of 2.5%, 4.37%, and 5.62% in relation to M0, respectively. The fine particles of GGBS serve to occupy the voids present between the aggregate sand and cement, thereby facilitating an improved flow of the concrete mixture, as a reduced quantity of water is necessitated for lubrication, consequently leading to an elevated slump value [45]. Regarding the ternary mixtures (M10, M11, M12, M14, and M15), it was documented that the slump diameter values diminished by 0.63%, 2.5%, 4.37%, 1.87%, and 3.13%, respectively, when compared to M0. Conversely, for M13, the slump flow diameter attained 800 mm, which exhibits equivalent flowability to that of M0, thus preserving the workability of the concrete. In comparison with binary blends inclusive of CKC, the slump diameter value of the ternary blend demonstrated an increase. The prospective utilization of the combinations of CKC + WMP and CKC + GGBS as partial cement replacements within a ternary blending framework yielded satisfactory fresh properties of High-Performance Self-Compacting Concrete (HPSCC). The incorporation of GGBS in the HPSCC mixtures improved the fresh properties and effectively mitigated the reduction in workability associated with the use of CKC. Additionally, the inclusion of WMP in ternary blends further enhanced the workability of HPSCC. These findings reinforce the significant influence of supplementary cementitious materials on the rheological behavior of cementitious systems[46,47].

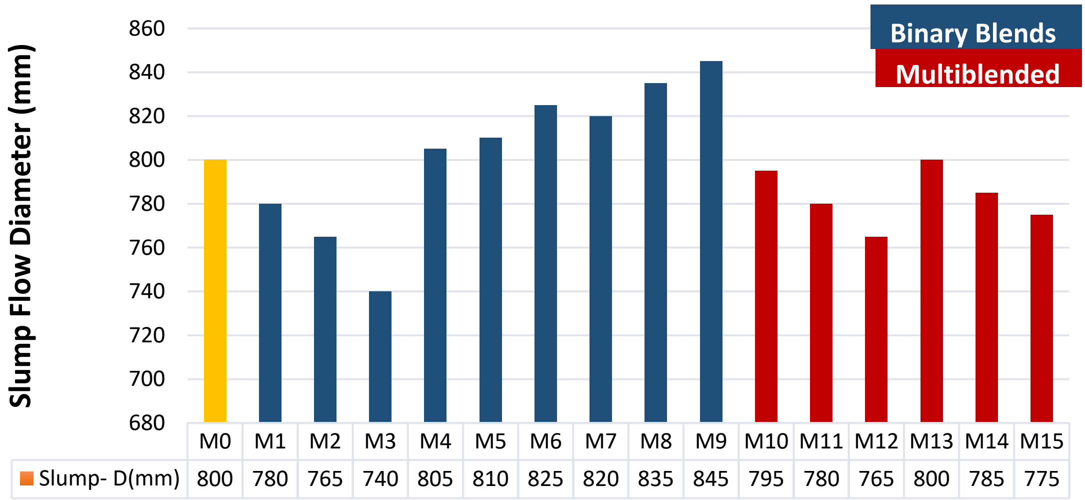


Fig 5. Slump flow diameter results of HPSCCs

The elevated passing ability (PA) value signifies an enhanced capacity for the concrete mixture to facilitate the flow of materials. The PA values recorded range from 0.874 to 0.996(Fig.6), classifying the mixtures within the second category (PA2) as delineated by the standards established by EFNARC [35]. No evidence of segregation or blockage was detected in any of the concrete mixtures analyzed. The PA values determined for mixtures M0, M1, M2, and M3 were 0.948, 0.936, 0.912, and 0.874, respectively. The observed decline in PA is attributed to the incorporation of calcined kaolin clay (CKC), which may adversely affect the passing ability of the mix. It is evident that the integration of CKC results in a diminished passing ability due to a concomitant reduction in fluidity. This phenomenon may be explained by the geometric configuration of the long, hexagonal plates of CKC, which may create impediments within the fresh mixture and augment the frictional forces among the constituent particles. Furthermore, the fine particulate nature of CKC, characterized by a markedly increased surface area capable of water absorption, results in a reduction of free water availability, thereby impairing the flow capability [48]. The passing ability of the mixtures M4, M5, and M6 was determined to be 0.962, 0.976, and 0.980, respectively, demonstrating that the flow as measured by the L-box test improved concomitantly with increasing percentages of waste material powder (WMP). An increase in WMP content correlates with enhanced workability in high-performance self-consolidating concrete (HPSCC), as it increases the free water quantity available to bolster the filling capacity of the concrete matrix. Moreover, the volume of paste relative to the aggregate content is elevated, which effectively diminishes the frictional interactions among the aggregate particles [49].The passing ability of concrete mixtures M7, M8, and M9, which were found to have passing ability scores of 0.984, 0.991, and 0.996, respectively. The results indicate a correlation between the percentage of GGBS in the mixtures and their passing ability, with higher GGBS percentages leading to improved flow characteristics. This enhancement is likely due to the particle size of GGBS, which reduces internal friction, thus improving the fluidity and passability of the mixtures, as noted by [1].

However, for the ternary blend mixes (M10, M13, and M14), the passing ability increased by 0.32%, 1.37%, and 3.90% compared to M0. It is noted that the passing ability of (M11, M12, and M15) decreased by 1.05%, 3.59%, and 2.22% in comparison with M0. In comparison with binary blends containing CKC, the passing ability of the ternary blend mixtures was enhanced. The potential use of the combinations CKC + WMP and CKC + GGBS as partial cement replacements resulted in satisfactory fresh properties of HPSCC. The enhancement in the passing ability of concrete mixtures is attributed to the particle size of GGBS, which reduces internal friction and enhances fluidity.

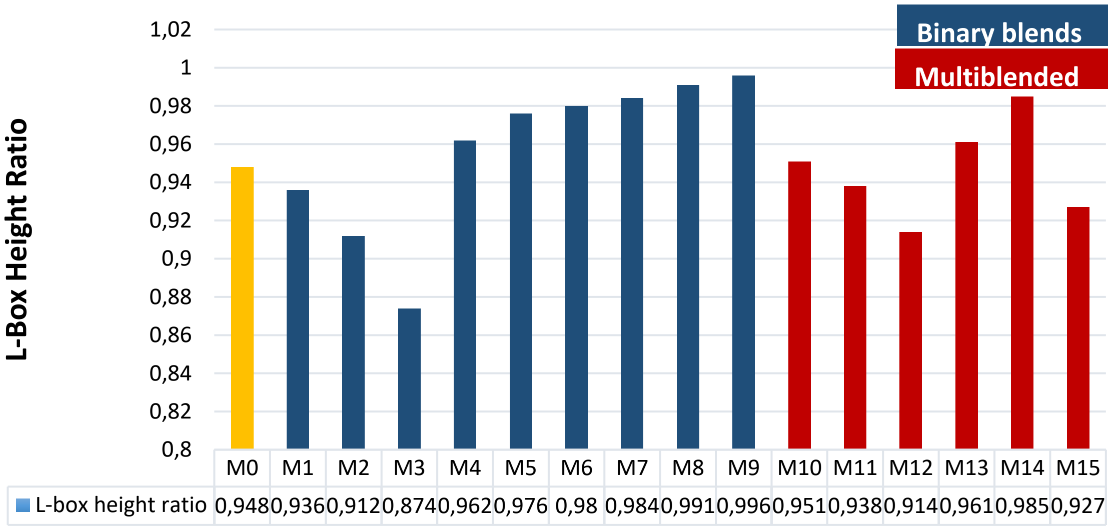


Fig. 6. L-box height ratio results of HPSCCs

The inclusion of WMP further improves the workability of HPSCC by increasing the free water content, thus enhancing filling ability and reducing friction among aggregate particles [1,49]. The segregation ratio exhibited a range spanning from 9.7% to 14.6% (SR2 class) (Fig.7). Analyzing the segregation data allows for the inference that all High-Performance Self- Compacting Concrete (HPSCC) samples possess commendable quality and demonstrate acceptable segregation resistance as per EFNARC [35]. The segregation ratio (SR) values recorded for mixtures M1, M2, and M3 were determined to be 11.3, 10.8, and 9.7, correspondingly. It is evident that the binary mixtures (10% CKC, 15% CKC, and 20% CKC) exhibit superior segregation resistance compared to the control mixture (M0), as the segregation percentage diminishes with an increased proportion of partial replacement. The observed percentage reductions were approximately 7.38%, 11.48%, and 20.49% for the aforementioned binary mixtures, respectively, thereby indicating enhanced resistance to segregation. The ultrafine particles derived from CKC displayed a high level of reactivity, which facilitated hydration and augmented the viscosity of the mixture [41,42].

As the percentages of Waste Marble Powder (WMP) increased (M4, M5, and M6), the segregation ratios escalated by 4.92%, 7.74%, and 9.02%. The elevation of WMP content resulted in a less cohesive concrete mixture, yielding a higher slump flow while concomitantly lowering the flow time. A reduction in cohesiveness leads to an increased separation of mortar, consequently yielding a higher segregation ratio, which indicates that viscosity diminishes with the augmentation of the marble powder ratio [50]. It noted that, the GGBS replacement level increases, the segregation ratio also rises significantly, with the highest increase observed at 40%. Specifically, the segregation ratios increased by 12.3%, 14.75%, and 19.67% for 20%, 30%, and 40% GGBS replacements, respectively, compared to a control mix. Increasing the replacement levels of GGBS up to 40% gives a higher flowability and lower viscosity of concrete, thus resulting in a higher value of segregation ratio [6,51]. Whereas, ternary blend mixes (M10, M11, M12, M14, and M15) have a higher segregation resistance compared with control mix (M0). That is, the segregation ratio decreased by 1.63%, 4.09%,7.38%,0.82%, and 5.74%, respectively in comparison to (M0). But the segregation ratio for (M13) increased by 4.09 % in comparison to (M0). This is a result of the synergistic effect of the reasons explained above; no segregation or blocking phenomena were experimental in the mixes during the test execution [6,41] and [50,51].

Overall, the mixtures exhibit good workability, consistency, and stability, with GGBS and WMP effectively compensating for fluidity reductions caused by CKC. The significant correlation between slump flow diameter and segregation ratio in High- Performance Self-Consolidating Concrete (HPSCC) mixes were shown in Fig 8., with a correlation coefficient of 0.9529. This strong linear relationship suggests that measuring the slump flow can effectively indicate the segregation resistance of HPSCCs, highlighting the importance of slump flow in evaluating the performance of these concrete mixes.

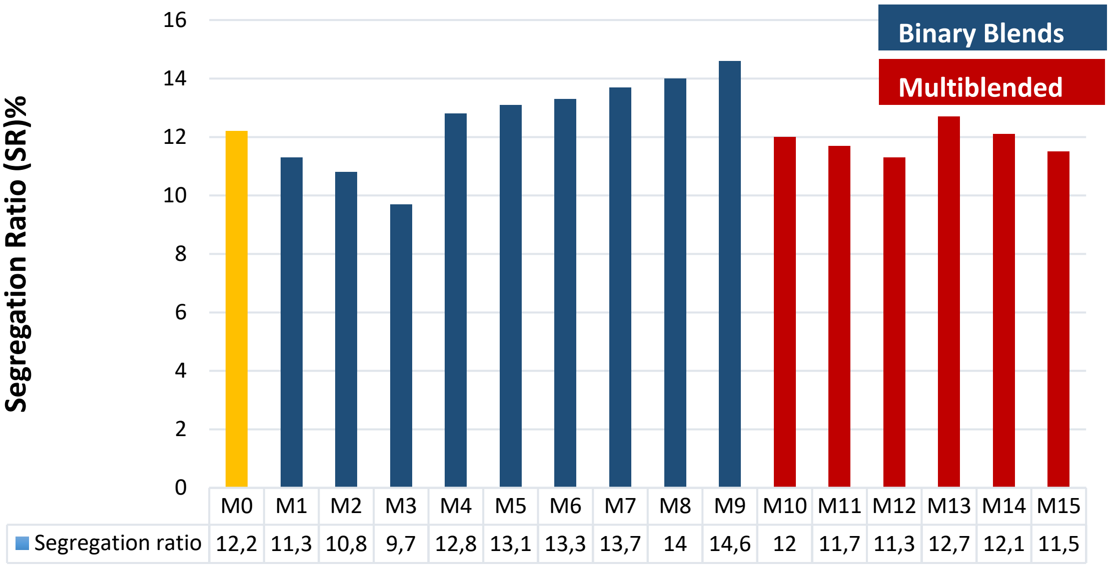


Fig. 7. Segregation ratio results of HPSCCs

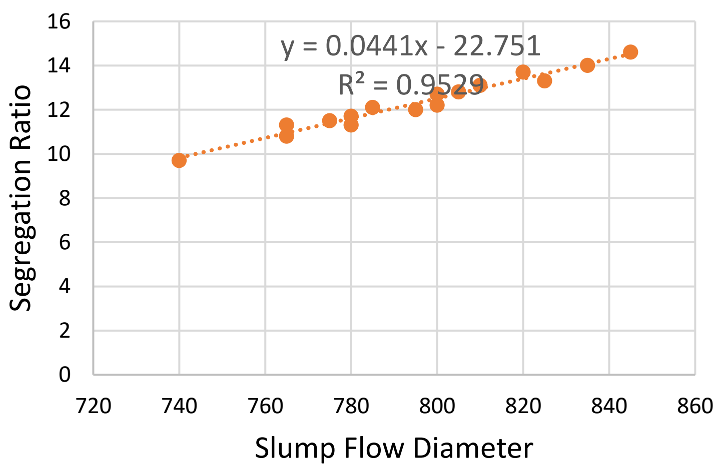


Fig. 8. Relationship between slump flow diameter and segregation ratio of HPSCCs

3.2. Mechanical Properties – Results and Discussion

The self-weight of any structure is completely dependent on the unit weight of the ingredient materials. The HPSCC mixtures density decreased as the pozzolan percentage (CKC, WMP, and GGBS) replacement increased (Fig. 9). The density of all HPSCC mixes increased with curing age. The observed percentage reductions in the density of HPSCCs (M1-M15) were (0.77, 1.06, 1.42, 0.45, 0.77, 1.38, 0.28, 0.61, 1.22, 1.26, 1.47, 1.75, 1.10, 1.34, and 1.59) % at the 28-day respectively, in compared to the control mixture (M0). A further decline in density was noted in ternary mixtures, with the most significant reduction recorded in mixture M12, which comprised 20% CKC and 10% WMP. This phenomenon can be rationalized by the observation that the specific gravity of the pozzolanic materials is lower than that of cement, resulting in a diminished mass per unit volume [50,52]. Therefore, CKC, WMP, and GGBS can be utilized in mortar or concrete as lighter alternatives to cement. The findings are promising in reducing the self-weight of structures on soils with poor bearing capacity to some extent.

The experimental outcomes regarding the compressive strength of the specimens, as depicted in Fig.10, suggest that all concrete formulations generated within the scope of this investigation exhibit high-performance characteristics, with the strength at 28 days varying from 63.7 to approximately 79.2 MPa, and the strength at 90 days ranging from 69.7 to 85.2 MPa. Collectively, the findings elucidate that all high-performance self-compacting concrete (HPSCC) mixtures exhibit a gradual enhancement in compressive strength corresponding with the extended duration of curing. This increment in compressive strength of the specimens is ascribed to the persistent hydration process that engenders novel hydration products within the concrete matrix. The compressive strength of binary blends incorporating CKC (M1, M2, and M3) increased by 10.25%, 7.32%, and 2.26%, respectively, in relation to the control mix (M0) at the 90-day mark.

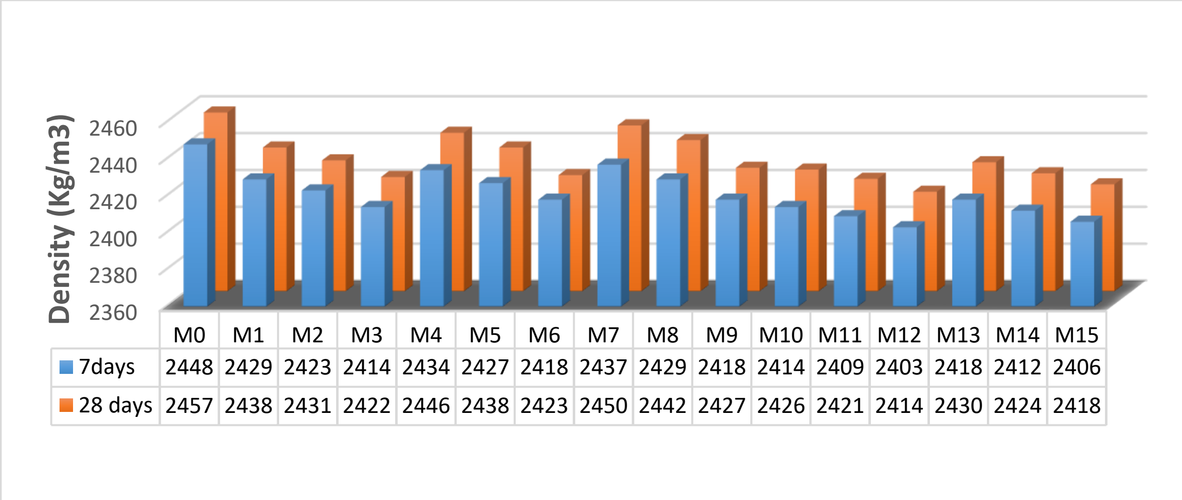
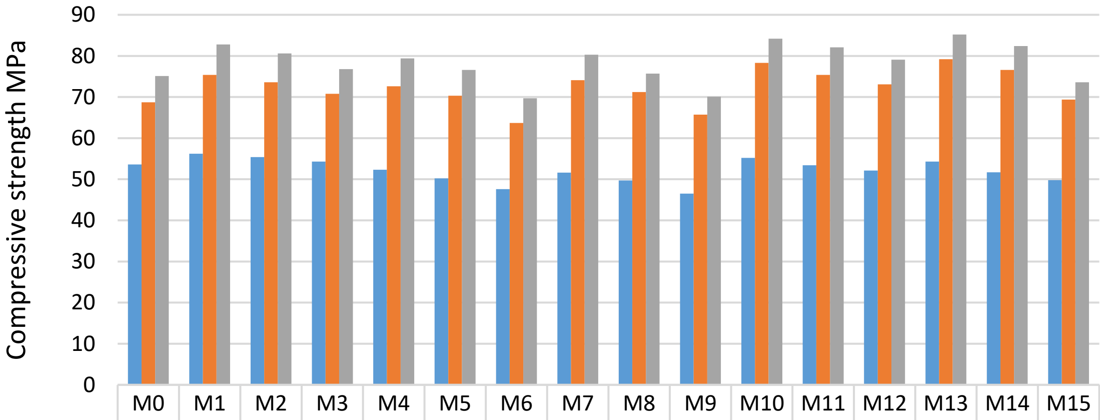


Fig. 9. Density results of HPSCCs

It is significant to note that the compressive strength was maximized in the formulation incorporating 10% CKC (M1), achieving a strength of 82.8 MPa at 90 days. This enhancement can be primarily attributed to the finer particle size of CKC, which augments its reactivity with $Ca(OH)_2$, thereby facilitating the formation of additional calcium silicate hydrate (C–S–H) and(C-A-H), subsequently, superior compressive strength. The reduced particle size of CKC further contributes to this gain in strength [53,54]. However, an increase in CKC content to 15% and 20% precipitates a decline in compressive strength in comparison to the 10% substitution level. This reduction can be elucidated by the clinker dilution effect, which emerges when a portion of the cement is supplanted by CKC. In CKC concrete, the filler effect, the pozzolanic interaction between CKC and calcium hydroxide, and the synergistic influence of mineral admixtures serve to mitigate the dilution effect [53,55]. Concerning binary blends utilizing WMP, mixtures M4 and M5 exhibited compressive strength enhancements of 5.73% and 1.99%, respectively, whereas mixture M6 encountered reductions of 7.19% and 6.66% at 90 days when assessed against the control mix (M0). The data clearly show that the 10% replacement of WMP yields the highest compressive strength of 79.4 at 90 days.

The study investigates the impact of fine particles from WMP on concrete strength, demonstrating a notable improvement in compressive strength due to the filling of micro-pores in the concrete matrix [47]. Increasing the WMP content to 15% and 20% leads to a decline in strength, showing that optimal benefits are realized at or below the 10% mark. In binary blends with GGBS, 20% GGBS blend exhibited the highest compressive strength, reaching 80.3. The chemical reactions between GGBS and calcium hydroxide lead to the formation of additional C-S-H gel compounds, improving overall strength [26,56]. Various ternary mixes demonstrated increased compressive strength at 90 days, with mix M13 exhibiting the highest strength of 85.2 MPa. Conversely, mix M15 experienced a slight decrease in strength. The incorporation of pozzolanic materials, specifically 20% Ground Granulated Blast Furnace Slag (GGBS) and fine particles of calcined Kaolinite Clay (CKC), contributes to strength improvement in high-performance self-compacting concrete.

GGBS serves as a filler, increasing packing density and chemically reacting with calcium hydroxide to form additional crystalline C-S-H gel, which enhances the cohesive transition zone and overall compressive strength (26,46). CKC further aids in sealing micro-pores, thereby enhancing the concrete's durability and strength. It highlights that the combination of CKC and WMP yields higher compressive strength compared to when they are used separately. However, specific mixes, particularly those with 20% CKC and varying percentages of WMP or GGBS, exhibit a reduction in strength, attributed to limited calcium hydroxide availability and slower GGBS reactivity. Increased CKC proportions may also negatively impact strength due to greater surface area [13,47, 51].



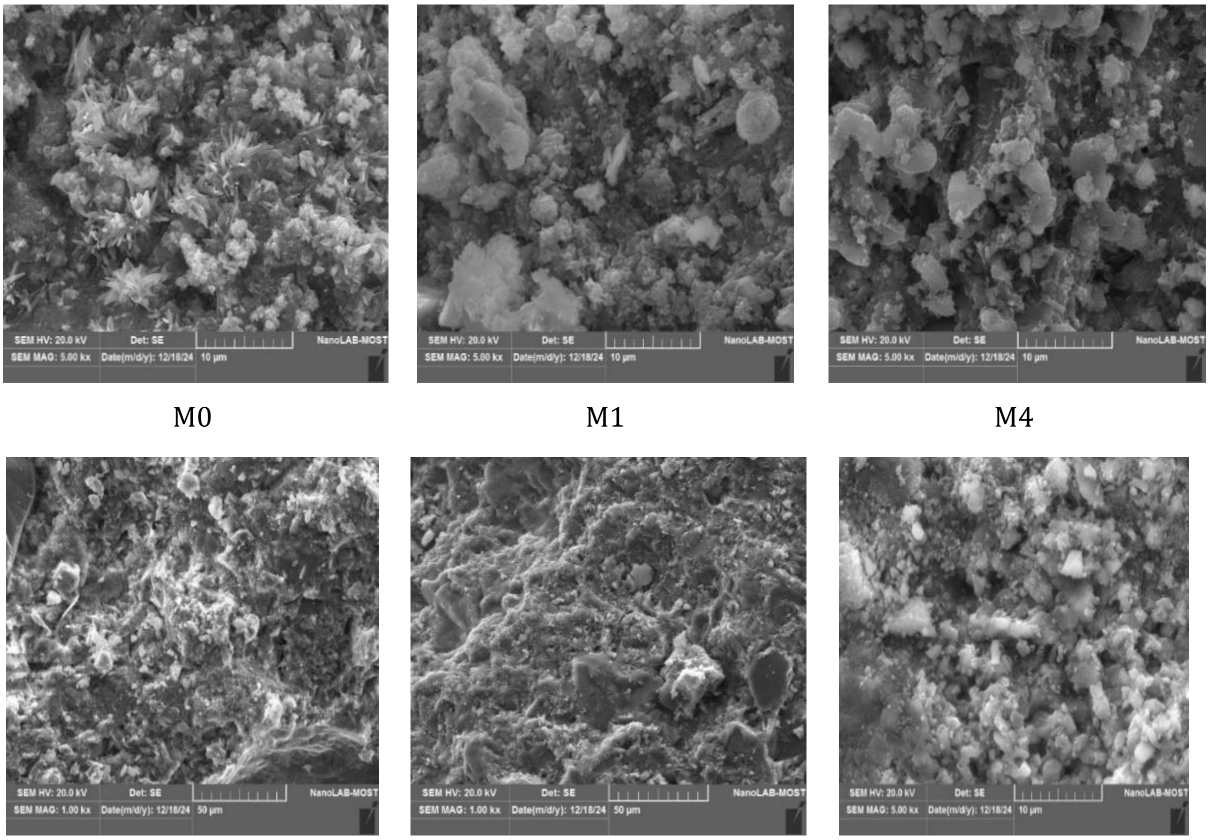
	M0	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15
7 days	53,6	56,2	55,4	54,3	52,3	50,2	47,6	51,6	49,7	46,5	55,2	53,4	52,1	54,3	51,7	49,8
28 days	68,7	75,4	73,6	70,8	72,6	70,3	63,7	74,1	71,2	65,7	78,3	75,4	73,1	79,2	76,6	69,4
90 days	75,1	82,8	80,6	76,8	79,4	76,6	69,7	80,3	75,7	70,1	84,2	82,1	79,1	85,2	82,4	73,6

Fig. 10. Development of compressive strength in HPSCCs

Figure 11 displays the SEM results for concrete mixes M1, M4, M7, M10, and M13, compared to a reference mix (M0), were analyzed to assess their mechanical performance at ambient temperature. These mixes were chosen for their optimal compressive strength after 28 days of curing. The control mix exhibited key hydrated products such as portlandite, ettringite crystals, and C-S-H plates. Notably, the mix with a 10% CKC replacement showed enhanced compressive strength and active pozzolanic reactions, characterized by increased C- S-H and decreased calcium hydroxide, leading to improved cement microstructure. Studies confirm that replacing cement with calcined clay leads to a finer pore network and increased matrix compactness, contributing to enhanced mechanical properties.

Cement-based paste specimens with replaced calcined kaolin clay exhibit a denser and more refined pore structure, which aligns with observed improvements in compressive strength [57]. Similarly, mixes containing marble powder also develop a denser and less porous microstructure compared to conventional cement pastes. The microstructural features of concrete pastes that include amorphous calcium silicate hydrate (C-S-H) and ettringite, which promote complete hydration and efficient void filling. The use of supplementary materials such as GGBS is highlighted for its role in minimizing the size and quantity of calcium hydroxide crystals in the ITZ. This results in a denser ITZ microstructure, enhancing the overall strength and durability of concrete mixes when optimized with calcined clay or GGBS alongside Portland cement [58,59].

Yuksel [60] noted that the microstructure of concrete containing Ground Granulated Blast- furnace Slag (GGBS) is distinct from that of traditional Portland Cement (PC) concrete, primarily due to the unique chemical reactions involving GGBS. The formation of calcium silicate hydrate (C-S-H) compounds is crucial for improving the durability and longevity of concrete, as supported by the findings of [61,62]. Generally, the absence of cracks in the concrete signifies effective mixing and strong bonding among the constituent materials. The ITZ, which develops where different components meet, can be minimized through better mixing and uniform distribution, thereby enhancing the material's integrity. Ternary blends containing 10% CKC and 10% WMP, or 10% CKC and 20% GGBS, demonstrate strong bonding with the cement matrix, as evidenced by the absence of visible cracks. The ITZ, formed by the interaction of various chemical components, is distinctly observed and contributes positively to the concrete strength. This enhancement is attributed to the high reactivity of CKC, whose fine particles react with calcium hydroxide to generate additional C-S-H, further densifying the microstructure. Moreover, the fine particles of WMP and CKC assist in sealing micro-pores, decreasing porosity and improving the binding properties of the mix through chemical hydration reactions [54].



M0 M1 M4

M7 M10 M13

Fig. 11. Scanning Electron Microscopy (SEM) results of HPSCCs

3.3. Durability Properties – Results and Discussion

Water absorption (WA) determines the amount of water absorbed under specified conditions, which indicates the degree of porosity in a material. The characteristics of concrete absorption indirectly represent the porosity.

The average test results for the water absorption of binary blends, and ternary mixes of HPSCCs at 28 and 90 days are illustrated in Fig 12. It could be noted that the water absorption values declined with an increase in the curing period for all blended HPSCCs. This is due to the reduction of pore volume with hydration products. The water absorption of high-quality concrete (high- strength concrete or high-performance concrete) is generally less than 5% [63]. The absorption for binary, and ternary mixes was in the range of 3.04–3.65%, at 28 days, and 2.74–3.34% at 90 days, respectively. So, all HPSCCs could be categorized as "high quality".

Introducing calcined kaolin clay (CKC) in M1 at 10% led to a clear improvement in water absorption, dropping the value to 2.82%, which corresponds to an 9% reduction relative to the control mix (M0) at age 90 days. This improvement is attributed to the pozzolanic reaction between the amorphous silica and alumina of CKC and calcium hydroxide, forming additional C–S–H gel that refines the pore structure. However, increasing the CKC content to 20% (M3, 3.04%) resulted in a gradual loss of efficiency, with reductions of only 1.93%, respectively at age 90 days. Mixes incorporating waste marble powder (WMP) showed variable behavior. At 10% replacement (M4), the absorption decreased to 2.94%, representing a 5.16% improvement. Ground granulated blast furnace slag (GGBS) at 20% (M7) reduced water absorption to 2.91%, yielding a 6.13% improvement at age 90 days. Due to filling ability of GGBS, this slag can reduce porosity in concrete and reduce water absorption. As the replacement increased to 40% (M9, 3.32%), the absorption increased again. GGBS contributes to long-term strength and durability through the latent hydraulic reaction; however, it is known to have low early-age reactivity.The combination of CKC and WMP in M10 (10% each) significantly enhanced performance, reducing absorption to 2.77%, equivalent to a 10.65% reduction at age 90 days. Similarly, mixes with CKC and GGBS displayed favorable behavior: M13 (10% CKC + 20% GGBS) reached 2.74%, achieving the highest reduction (11.61%) in water absorption comparing to control mix(M0). The strong performance of these ternary mixes is due to the synergistic action of fast-reacting CKC and slow-reacting or filler-type SCMs, which enhance early hydration and pore refinement [26,47,64].

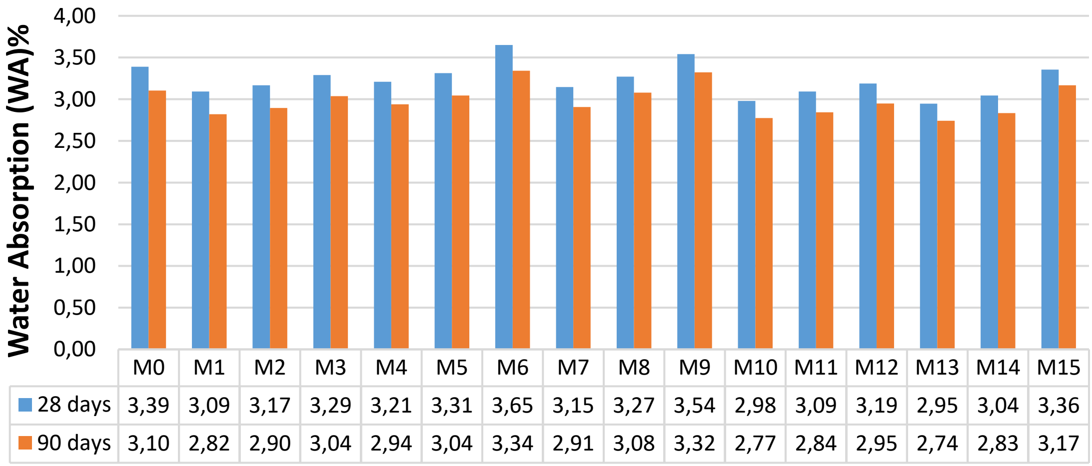
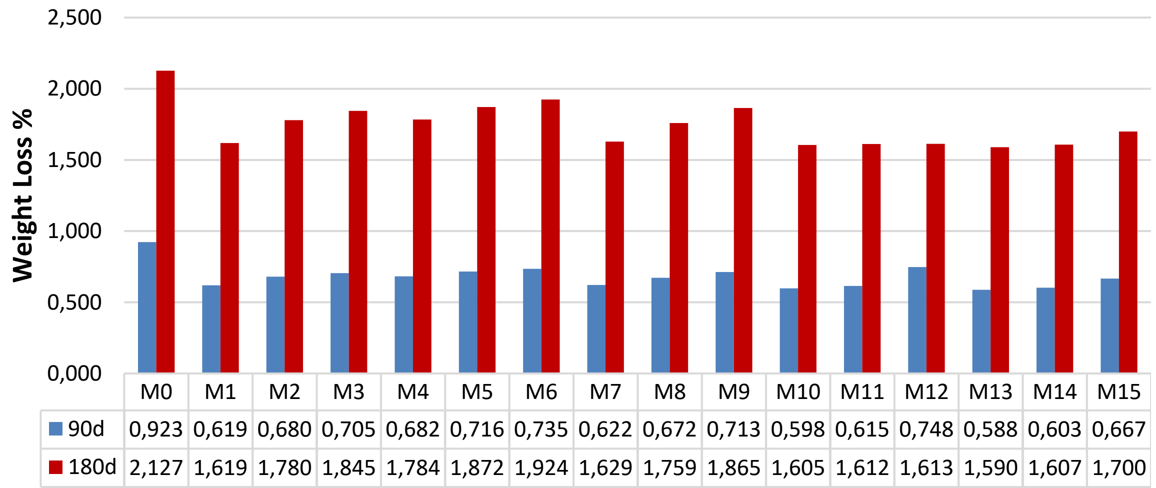


Fig. 12. Water absorption results for binary blends and ternary mixes of HPSCCs

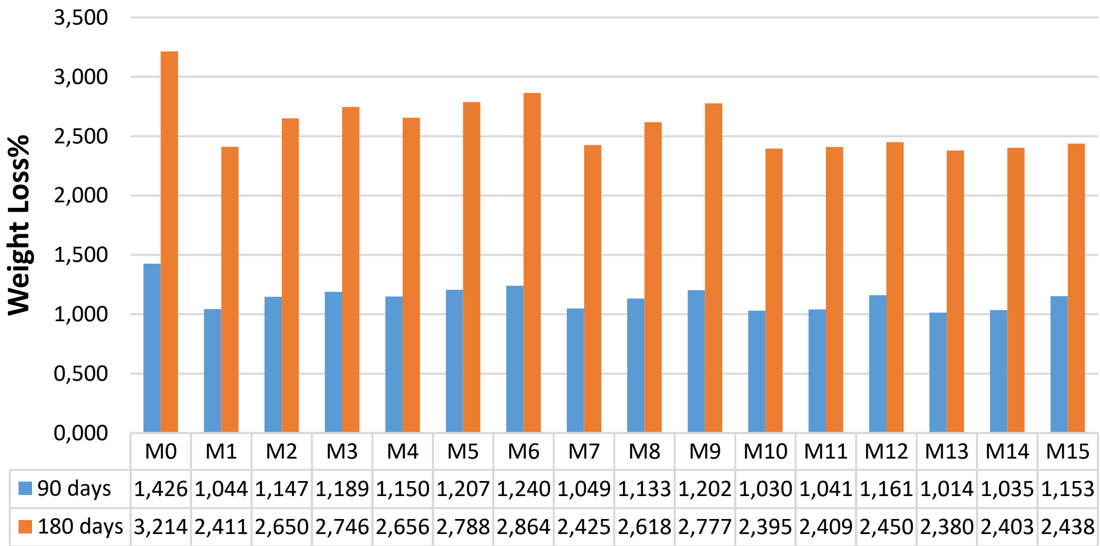
Fig. 13-14 shows the average weight loss of HPSCCs incorporating calcined kaolin clay (CKC), Waste Marble Powder (WMP), and Ground Granulated Blast Furnace Slag (GGBS) in binary, and ternary blend systems, that exposed to solutions of NaCl, and Na_2SO_4, over periods of 90 and 180 days (after 28 days of curing in water). At both 90 and 180 days, the relative weight loss values of the mixes under NaCl exposure indicate a generally milder form of degradation compared to sulfate salts. Mixes containing CKC (M1–M3) exhibited significant improvement, particularly M1, which recorded 23.88% improvement compared to M0 weight loss at 180 days. This indicates that the incorporation of 10% CKC enhanced the internal microstructure by densification through pozzolanic reactions, reducing ingress and crystallization pressure from NaCl [65]. Mixes with WMP (M4–M6) achieved moderate improvement (around 16.13–9.54%), which can be attributed primarily to the filler effect of marble powder, enhancing particle packing but lacking chemical interaction [66]. Meanwhile, GGBS-based mixes (M7–M9) performed similarly to CKC, particularly M7 (23.41% at 180d), due to GGBS's latent hydraulic properties and its ability to reduce portlandite content [67]. Combination of CKC and WMP (M10–M12) showed moderate reduction in weight loss, with M10 achieving 24.54%improvment compared to the control at 180 days. Also combining CKC with GGBS (M13–M15) showed effective reduction in weight loss, with M13 achieving 25.24%improvment compared to the control at 180 days.

Under Na_2SO_4 exposure, the degradation mechanisms intensified due to the chemical reactivity of sulfate ions with aluminate phases in cement, forming expansive ettringite and gypsum. CKC mixes (M1–M3) displayed reduced weight loss ranging from 24.98–14.56% compared to M0 at 90 days, with M1 (24.98% at 90d) showing the best performance. CKC's pozzolanic reaction reduces C_3A reactivity by forming additional C-S-H and C-A-H, thus mitigating ettringite formation (41). WMP mixes (M4–M6) showed slightly inferior performance (17.36–10.89%), confirming their limited chemical action. GGBS mixes (M7– M9) achieved better performance than WMP with 24.54-13.59% improvement than control mix, due to the ability of GGBS to bind Ca^{2+} and lower the availability of calcium hydroxide for gypsum formation [67]. Among the ternary mixes, M13 stood out. M13 showed 25.94%improvment in weight loss at 180 days, compared to control mix (M0), the lowest of all, underscoring the role of combined material functions: CKC's pozzolanic reactivity, and GGBS's chemical stabilization.



	M0	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15
90d	0,923	0,619	0,680	0,705	0,682	0,716	0,735	0,622	0,672	0,713	0,598	0,615	0,748	0,588	0,603	0,667
180d	2,127	1,619	1,780	1,845	1,784	1,872	1,924	1,629	1,759	1,865	1,605	1,612	1,613	1,590	1,607	1,700

Fig. 13. Weight change results for binary blends and ternary mixes of HPSCCs under chloride (NaCl) exposure at various ages



	M0	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15
90 days	1,426	1,044	1,147	1,189	1,150	1,207	1,240	1,049	1,133	1,202	1,030	1,041	1,161	1,014	1,035	1,153
180 days	3,214	2,411	2,650	2,746	2,656	2,788	2,864	2,425	2,618	2,777	2,395	2,409	2,450	2,380	2,403	2,438

Fig. 14. Weight change results for binary blends and ternary mixes of HPSCCs under sulfate (Na2SO4) exposure at various ages

4. Conclusions

This study presents a comprehensive experimental investigation into the design and performance evaluation of Sustainable High-Performance Self-Compacting Concrete (HPSCC) through the incorporation of locally available natural and industrial pozzolanic materials—Calcined Kaolin Clay (CKC), Waste Marble Powder (WMP), and Ground Granulated Blast Furnace Slag (GGBS). The concrete mixtures were developed in both binary and ternary blending systems with the primary objective of enhancing workability, mechanical strength, and durability while minimizing the environmental footprint associated with Ordinary Portland Cement (OPC) usage.

- Slump flow diameters ranged from 740 mm to 845 mm, placing most mixtures within the SF3 class. However, binary mixtures containing 20% CKC were categorized as SF2 due to slightly reduced flowability.
- Passing ability values (L-box ratios) ranged between 0.874 and 0.996, meeting the criteria for PA2 classification with no evidence of blocking or segregation. Segregation resistance

was satisfactory for all mixes, with segregation ratios ranging from 9.7% to 14.6%, which falls within SR2 classification.

- The addition of GGBS and WMP improved flow characteristics and reduced viscosity due to their fine particle size and smooth morphology. In contrast, higher CKC contents slightly reduced flowability, attributed to its high surface area and internal friction. Nonetheless, ternary systems effectively balanced these effects, maintaining high performance in fresh-state behavior.
- Binary blends achieved peak performance at 10% CKC (M1, 82.8 MPa), 10% WMP (M4, 79.4 MPa), and 20% GGBS (M7, 80.3 MPa).
- Ternary blend M13 (10% CKC + 20% GGBS) exhibited the highest compressive strength: 85.2 MPa at 90 days, representing a 13.3% improvement over the control mix. The increase in strength is attributed to the synergistic pozzolanic activity between CKC and GGBS. CKC actively reacts with calcium hydroxide to form additional calcium silicate hydrate (C–S–H), while GGBS contributes to later-age strength through its latent hydraulic properties and refinement of the microstructure.
- Water Absorption: All mixes exhibited absorption values below 5%, classifying them as high-quality concrete. The lowest absorption was observed in M13 (2.74%), achieving the highest reduction (11.61%) compared to reference mix, followed closely by M10 and M1. This indicates improved pore structure due to pozzolanic reactions and filler effects.
- Resistance to Chloride (NaCl): M13 showed 25.24% (highest improvement) in weight loss compared to the control mix at 180 days.M10 also demonstrated significant resistance, reducing degradation by 24.54% at 180d.
- Resistance to Sulfate (Na_2SO_4):M13 again exhibited the best performance, with a 25.94%improvment in weight loss at 180 days, confirming the beneficial synergy of CKC and GGBS.M10 followed closely with comparable improvements (25.48%).
- At both 90 and 180 days, the relative weight loss values of the mixes under NaCl exposure indicate a generally milder form of degradation compared to sulfate salts. These results validate that the ternary blends not only improve strength but also significantly enhance long-term chemical durability under aggressive environments.
- Uniform distribution of hydration products, especially in mixes M1, M7, M10, and M13 with reduced calcium hydroxide ($Ca(OH)_2$) content. Denser and more refined microstructure. Enhanced Interfacial Transition Zone (ITZ) with minimal micro cracks The most compact and homogenous microstructure was observed in M13, confirming the link between microstructural densification and superior mechanical and durability outcomes.

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