



Sustainable High-performance Self-compacting Concrete with Multi Blended of Materials Powders: Fresh and Hardened Properties

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PAPER INFO

Paper history:

Received 09 May 2025
Received in revised form 23 May 2025
Accepted 07 June 2025

Keywords:

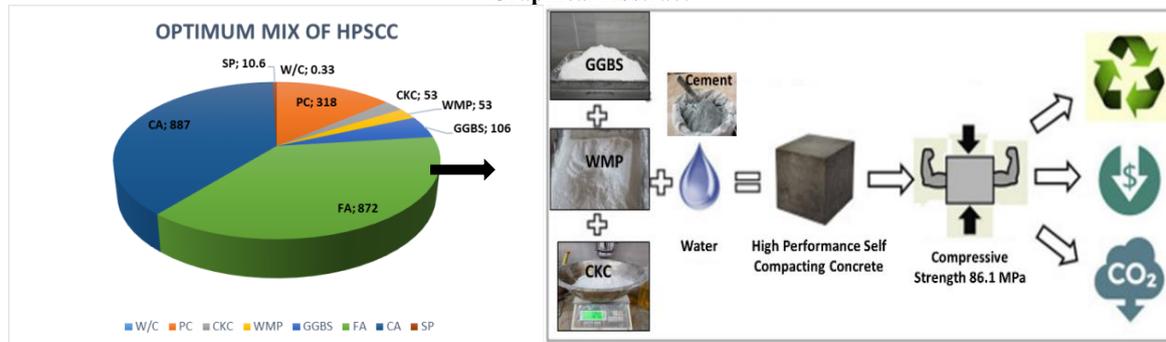
High-performance Self-consolidating Concrete
Calcined Kaolin Clay
Waste Marble Powder
Fresh-state Properties
Hardened-State Properties
Ground Granulated Blast Furnace Slag

ABSTRACT

High-performance self-consolidating concrete represents a significant advancement in construction technology. This study examined and compared the fresh-state properties (slump flow (D (mm), V-Funnel flow time, and L-box tests), hardened-state properties (unit weight and compressive strength), and microstructure characteristics (Scanning Electron Microscopy (SEM)) of high-performance self-consolidating concrete (HPSCC) with a reference mix (M0) as the control mix containing only Ordinary Portland Cement (OPC) without pozzolanic substitutions. Two blend systems were developed in this study: a binary blend system and a quaternary blend system, which included (OPC+CKC, OPC+WMP, OPC+GGBS, and OPC+CKC+WMP+GGBS). The results for the fresh properties of all HPSCC mixtures fell within the acceptable ranges set by EFNARC, with no segregation or bleeding observed, and all HPSCC mixtures demonstrated superior performance than the control mixture. From this study, it can be concluded that using 60% OPC + 10% CKC + 10% WMP + 20% GGBS yielded improved fresh, compressive strength and denser microstructure compared to control mix (M0), making it suitable for use as HPSCC. By cutting clinker content 40 %, the optimal quaternary blend lowers the binder's embodied CO₂ by roughly 30 %, offering a tangible environmental benefit while still achieving a 90-day compressive strength of 86.1 MPa.

doi: 10.5829/ije.2026.39.05b.05

Graphical Abstract



NOMENCLATURE

OPC	Ordinary Portland cement	W/B	Water to binder ratio
CKC	Calcined kaolin clay	SP	Superplasticizer
GGBS	Ground granulated blast furnace slag	FA	Fine aggregate
WMP	Waste marble powder	CA	Coarse aggregate

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Please cite this article as: Khoman RK, Owaid HM. Sustainable High-performance Self-compacting Concrete with Multi Blended of Materials Powders: Fresh and Hardened Properties. International Journal of Engineering, Transactions B: Applications. 2026;39(05):1101-14.

1. INTRODUCTION

Self-compacting concrete (SCC) is a modern type of concrete known for its capability to flow and self-consolidate under its own weight, eliminating the necessity for mechanical vibration. It can fill formwork with heavy reinforcement while maintaining consistent homogeneity, preventing any migration or separation of its large components (1). The use of SCC addresses the problem of unskilled labor in construction, particularly in underwater concreting and heavily reinforced structures. The necessity for vibration is obviated, construction timelines are expedited, labor expenditures are diminished, and noise pollution is curtailed (2, 3). SCC is distinguished by a substantial amount of cement, a minimal quantity of coarse aggregates, and the incorporation of superplasticizers to reduce the water-to-binder ratio. High-performance concrete (HPC) is delineated as concrete that is meticulously formulated, mixed, placed, consolidated, and cured to attain elevated strength and diminished transport properties, thereby ensuring enhanced durability. It demonstrates remarkable resistance to segregation (4). The demand for HPC has experienced a consistent upward trajectory owing to its remarkable mechanical and durability attributes (5, 6). HPC can be engineered to manifest elevated workability, mechanical properties, and improved durability (7, 8). Innovations in concrete technology have culminated in the advent of a novel generation of concrete predicated on the principles of SCC and HPC, which is designated as High Performance Self-Compacting Concrete (HPSCC).

HPSCC is described as a type of SCC that exhibits great compressive strength and enhanced durability. Unlike conventional concrete, the mix design of HPSCC is characterized by higher cement content, the use of superplasticizers, and the incorporation of reactive materials like silica fume. As a result, HPSCC can effectively fill forms containing densely packed steel reinforcement and achieves self-leveling without the need for mechanical compaction, leading to exceptional strength and durability (9, 10). Due to the significant demand for cement in HPSCC production, it is essential to utilize alternative materials to partially replace cement, contributing to environmentally sustainable construction practices by reducing the carbon footprint. Currently, supplementary cementitious materials e.g. ground granulated blast furnace slag (GGBS), fly ash, silica fume, metakaolin (MK), marble powder, and limestone powder are increasingly employed in the development of next-generation concrete that is both eco-efficient and environmentally friendly (2, 3, 11-14). Metakaolin, a fine, white, and environmentally benign material, is derived from kaolin clay via a CO₂-free calcination process at 650–900 °C. This abundant natural mineral, primarily composed of silicate (SiO₂ 50–55%) and

aluminate (Al₂O₃ 40–45%), along with minor oxides (Fe₂O₃, TiO₂, CaO, MgO), offers a sustainable alternative to cement. Research studies conducted by Vejmelková et al. (15) and Kavitha et al. (16) have evaluated the effects of metakaolin and ordinary Portland cement (OPC) on SCC by measuring CO₂ emissions, and have shown that metakaolin provides environmental benefits during its production. Additionally, metakaolin can enhance early-age concrete strength and more effectively fill the pores of the cement paste compared to other fillers. Its incorporation in concrete enhances the mixture's viscosity (17) and accelerates early strength gain owing to its higher pozzolanic reactivity at early-ages (18). In contrast, GGBS is derived from the steel and iron production. It is a non-metallic product mainly composed of aluminosilicates and calcium silicates along with other bases, and is formed in a molten state alongside iron during the blast furnace process (1). GGBS exhibits a chemical structure similar to that of cement and relatively consistent properties. Annually, approximately 250 million tons of GGBS are produced worldwide, of which only 90 million tons are utilized in concrete production (19). GGBS can enhance the hardened and fresh properties of SCC and supports sustainable construction practices. It delays the setting time of concrete, causing strength development over a longer period (20).

Studies have shown that GGBS increases workability and reduces water demand owing to the greater water absorption capacity of its smoother, glossier particles compared to cement particles. Concrete incorporating GGBS exhibits superior ultimate strength in comparison to that produced with Portland cement (PC), owing to an increased formation of strength-enhancing calcium silicate hydrates (CSHs) and a reduction in free lime content, that is not strength-enhancing. Marble waste, on the other hand, is regarded as a severely contaminating type of industrial byproduct, presenting substantial environmental and health hazards (21). The disposal of marble industry waste, which mainly involves of fine-powder, presents numerous environmental challenges (22). Nevertheless, these waste materials offer potential for beneficial and commercial application in improving SCC properties (23, 24). Marble waste is generated during both the early stages of mining and the various machining stages (cutting, polishing, and finishing) (25). According to Tennich et al. (26), marble waste improves the fresh properties of concrete via decreasing plastic contraction. Moreover, the higher calcium content of marble dust (MD) enhances the SCC hardened properties (27).

Few studies in the literature have examined HPSCC and its optimization. However, there is a lack of comprehensive investigations addressing the comparative effects of combining natural and waste-based pozzolanic materials in multi-blend systems for

HPSCC, particularly regarding their role in enhancing mechanical and durability properties under sustainable construction frameworks. HPSCC shows significant promise for a wide range of applications and structural uses. However, realizing this potential necessitates a thorough evaluation of its performance prior to widespread implementation in the construction industry. Existing research highlights developments in both the hardened and fresh properties of HPSCC mixtures achieved through the incorporation of CKC, GGBS, and WMP in binary and quaternary blend systems. Based on this context, the present study offers a thorough analysis of the overall properties of HPSCC and to compare these properties with those of conventional SCC.

2. EXPERIMENTAL PROGRAM

Constituent materials, mix proportion, specimens preparation, and tests are described in detail as follows:

2. 1. Materials All HPSCC mixes used locally sourced Ordinary Portland Cement (OPC)-CEM I from Lafarge, conforming to Iraqi Standard (28), with a specific gravity of 3.12 and a specific surface area (SSA) of 358 m²/kg. Tables 1 and 2 present chemical and physical properties of CKC, WMP and GGBS. Calcined kaolin clay (CKC) was produced by calcining kaolin clay from the Dewekhla region (Al Ramadi desert) at 800 ± 20 °C for 2 hours (heating rate: 5 °C/min), followed by slow cooling at room temperature over 24 hours (29). Following this, the CKC was ground via the air blast method to obtain a reactive material with greater fineness. The CKC's major oxide content (SiO₂ + Al₂O₃ + Fe₂O₃) exceeded 70%, meeting the minimum requirement for Class "N" pozzolans (30). Waste marble powder (WMP), a by-product of marble masonry, served as a supplementary cementitious material. Sludge collected from companies in Al-Hilla city (Iraq) was utilized as WMP industrial waste in this work. This material is produced as a waste by-product during the cutting and shaping of marble. The material contains a high percentage of CaO (85.62%), which is comparable to that of cement, potentially imparting cementing properties to WMP. GGBS is a highly sustainable construction material, offering significant ecological benefits by utilizing a by-product. GGBS production is significantly more energy-efficient and generates substantially fewer CO₂ emissions than PC production (31). GGBS exhibits hydration characteristics similar to those of PC and is ground to a fine cement-like consistency. The GGBS used in this study aligns with ASTM standards (32). It is in the form of a white powder and is incorporated into the mixtures as a partial replacement for cement. Locally sourced sand from the Al-Ukhaidher region served as the fine aggregate, meeting Iraqi standards and falling within the third

gradient zone (28), and has a fineness modulus of (2.52). Coarse aggregate consisted of crushed and washed gravel (10 mm maximum size) sourced from Al-Nabai'i and meeting Iraqi standard specifications (28). A high-performance superplasticizer concrete admixture (SikaViscocrete-180GS) was employed; it is based on polycarboxylic ether, serves as an economical high-range water reducer, enhances early and final strength, and maintains workability, specifically developed for the ready-mix concrete industry and suitable for hot weather conditions. This admixture was utilized to achieve the preferred flowability of HPSCC. SikaViscocrete-180GS complies with the requirements of Type F&G upon dosage (33).

2. 2. Mixture Proportions A total of 13 mixtures (Table 3) were meticulously formulated and cast with a water to binder ratio (w/b) of 0.33, accompanied by a comprehensive binder content of 530 kg/m³. The dosages of the superplasticizer were set at 2% by mass of the cementitious material to meet the performance requirements of SCC as per EFNARC (34). This work developed two blending systems: binary and quaternary, executed in a two-stage process. In the initial stage, the control mix was created using only OPC as the binder, while the other mixtures incorporated binary blend

TABLE 1. Chemical Compositions of CKC, GGBS and WMP

Chemical composition (%)	CKC	GGBS	WMP
SiO ₂	54.7	34.40	1.51
Al ₂ O ₃	37.4	13.26	0.84
Fe ₂ O ₃	1.72	0.43	0.44
CaO	0.84	39.94	85.62
MgO	0.42	8.82	0.54
Na ₂ O	0.37	0.38	1.17
K ₂ O	0.54	0.59	0.08
SO ₃	0.13	0.3	0.61
P ₂ O ₅	0.29	-	0.28
TiO ₂	0.68	0.94	-
MnO	-	0.29	-
Loss on ignition (LOI)	2.91	0.2	8.31

TABLE 2. Physical Properties and Strength Activity Index (SAI) of CKC of CKC, GGBS and WMP

Property	CKC	GGBS	WMP
Specific gravity	2.6	2.9	2.68
Fineness, m ² /kg	1640	418	569
(SAI%), at 7 days	85	98	82
(SAI%), at 28 days	94	117	92

systems (OPC + CKC, OPC + WMP, and OPC + GGBS) where OPC was replaced by 10%, 15%, and 20% of CKC, 10%, 15%, and 20% of WMP, and 20%, 30%, and 40% of GGBS (by mass). The selection of replacement levels was based on previous studies indicating this range as optimal for balancing workability, pozzolanic reactivity, and compressive strength development in SCC. In the subsequent phase, pertaining to the quaternary systems (OPC+CKC+WMP+GGBS), the substitution ratios for CKC were established at (10%, 15%, and 20%) with optimum replacement ratio of WMP and GGBS (10% WMP + 20% GGBS) serving as a partial replacement of the binder (by mass).

2. 3. Preparation of Specimen All materials were used in their processed powder form, not raw. The consistency of the blended powders was ensured by first thoroughly mixing the pozzolanic materials (CKC, WMP, and GGBS) with the OPC to achieve a uniform blend before adding them to the aggregates. The powders were stored in sealed, dry conditions to prevent moisture absorption and maintain their physical properties. All materials used were in processed, finely ground form to enhance reactivity and ensure homogeneity in the concrete mix. The concrete mixtures were prepared for approximately 5 minutes with a rotating planetary mixer yielding a uniform slurry without any sign of agglomeration or segregation. Following the mixing process, tests were performed to assess the characteristics of fresh concrete, after which the mixtures were cast into specimens using standard 100 mm³ cube molds, as illustrated in Figure 1. Following the casting process, the specimens were covered with nylon sheets to maintain a humid environment. These specimens were then stored

in a controlled environment within the casting room, maintained at a constant temperature of $25 \pm 2^\circ\text{C}$, for a period of 24 hours. After this initial curing period, the molds were removed from the specimens. Subsequently, to ensure proper curing and preparation for subsequent testing, the specimens were immersed in a water basin at room temperature until the required testing ages were reached.

2. 4. Tests of Fresh Concrete In accordance with EFNARC (34) guidelines, the combination of slump flow, V-funnel, and L-box tests effectively evaluates the key fresh properties of self-compacting concrete—deformability, flowability, and passing ability, respectively. While other tests such as the J-ring provide additional insights, they often overlap in purpose with the L-box and slump flow tests. Thus, selecting these three standard EFNARC tests ensures comprehensive assessment of SCC fresh behavior with efficiency and reliability, avoiding redundant testing.

2. 5. Tests on Hardened Concrete Hardened concrete was evaluated through tests including unit weight (density), compressive strength, and Scanning Electron Microscopy (SEM) analysis. Concrete density (kg/m^3) was determined as mass per unit volume (35). To determine the density, the dimensions and weights of concrete cubes, specifically those measuring $100 \times 100 \times 100$ mm, were meticulously recorded prior to the execution of compressive strength assessments at curing intervals of 7 and 28 days. Compressive strength testing, performed according to relevant standards, is a widely accepted measure of concrete's mechanical performance

TABLE 3. Mixes Proportions of HPSCCs

Mix. no	Mix Notation	W/B	Quantities of ingredients (kg/m ³)						
			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+20%GGBS	0.33	318	53	53	106	872	887	10.6
M11	15%CKC+10%WMP+20%GGBS	0.33	291.5	79.5	53	106	872	887	10.6
M12	20%CKC+10%WMP+20%GGBS	0.33	265	106	53	106	872	887	10.6



Figure 1. HPSCC Specimen Preparation: Mixing, Casting, and Curing



Figure 2. Flowability Testing of HPSCC (Slump Flow, V-Funnel, and L-Box Tests)

and overall quality (36). For each mixture and curing age (7, 28, and 90 days), the mean compressive strength has been calculated from three cube specimens with dimensions of $100 \times 100 \times 100$ mm. Throughout the testing procedure, each specimen was subjected to a progressively increasing load in a compression apparatus with a maximum capacity of 1900 kN (refer to Figure 3) until the point of failure was reached. The Strength was calculated as the maximum load divided by the cross-sectional area.

The microstructure of HPSCC specimens that incorporated blended materials powders was analyzed using Scanning Electron Microscopy (SEM). SEM was conducted on mixes (M1, M4, M7, and M10) and compared with the reference mix (M0). Samples for SEM examination were prepared following the methodology outlined according to ASTM (37). The samples were reduced in size using a saw, with $10 \times 10 \times 10$ mm pieces selected from concrete cube cores that exhibited optimal

compressive strength at 28 days. The SEM apparatus was set to HV: 20 KV with various magnification factors and high resolution.



Figure 3. Compressive strength test

3. RESULTS AND DISCUSSION

The test consequences for all mixes were reviewed and discussed in both the fresh and hardened states as follows:

3.1. Fresh Results Table 4 summarizes the fresh-state test results (slump flow, V-funnel, and L-box). The slump flow test assesses the flowability of freshly mixed concrete without confinement. A larger slump-flow diameter corresponds to greater flowability (or deformability) of the mixture. The outcomes of the testing demonstrate that the fresh characteristics of the manufactured concrete meet acceptance criteria, as illustrated in Figure 4. All concrete mixes met the SF3 class in terms of slump flow, except for the binary mixtures containing 20% CKC, which fell within the SF2 class. Therefore, all the mixes were assumed to have acceptable rheological consistency / uniformity of flow from the filling perspective. It was noted that the presence of 10%, 15%, and 20% of CKC reduced the flow diameter by 2.5%, 4.37%, and 7.5%, respectively. Even though the dosage of SP is 2%, the flow diameter decreased because of the inclusion of CKC. This is likely due to the particle size of CKC, which could be categorized as ultra-fine, and its pozzolanic reactivity, which increased the inter-granular friction. As a result, the elevated friction leads to diminished fluidity (deformability), whereas higher replacement levels of WMP contribute to enhanced flowability (deformability). This improvement is demonstrated by the M4, M5, and M6 mixes, which showed an increase in flowability by 0.63%, 1.25%, and 3.13% compared to M0, respectively. The fine particle size of the marble powder is the main

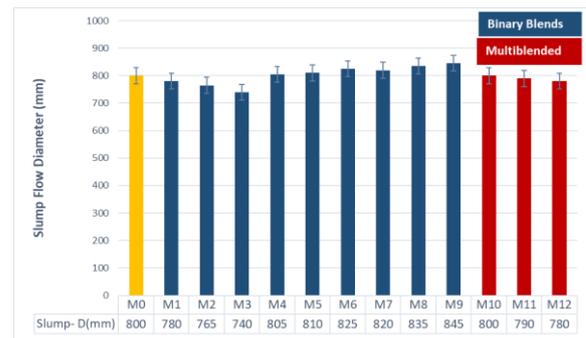


Figure 4. Slump flow diameter results of HPSCCs

reason for this modest improvement, as it leads to denser packing and reduced inter-particle friction (38-40). Additionally, escalating the replacement ratios of GGBS further enhances the mix flowability. This escalation is evidenced by M7, M8, and M9 mixes which increased flowability by 2.5%, 4.37%, and 5.62% in comparison with M0, respectively. The escalation in slump value is because of GGBS's fine, smooth particles. The fine GGBS particles occupy the spaces between the cement and aggregate sand, facilitating improved flow of cement concrete as less water is required for lubrication, resulting in an increased slump value (41). For the multiblenDED mixes (M11 and M12), it was observed that the slump diameter value decreased by 1.25% and 2.5%, respectively, compared to M0. In contrast, for M10, the slump flow diameter reached 800 mm, which has the same flowability as M0, thereby maintaining the workability of the concrete. When compared to binary blends with CKC, the slump diameter value of the multiblenDED mixes increased. Utilizing a quaternary blend of CKC, WMP, and GGBS as a partial cement replacement resulted in acceptable fresh-properties for HPSCC. Addition of GGBS to the HPSCC mixtures bettered the fresh characteristics and effectively offset the negative impact of CKC on these properties. These findings provide further evidence of the significant influence that supplementary cement-based materials exert on the rheology of cement-based systems (42). The V-funnel test assessed the HPSCC filling ability (inversely related to viscosity). Longer flow times indicate lower filling ability and higher viscosity. Observed flow times ranged from 5.3 to 9.7 seconds (see Figure 5). Consequently, all the mixes were classified into the VF1 class, except for the 20% CKC, which was classified into the VF2 class according to EFNARC. The V-funnel time for the control mixture M0 was 6.2 s, and it escalated for M3, which reached 9.7 s (the highest funnel time). The reduction in filling ability may be attributed to two factors: the particle size and the increased yield strength of CKC (43). Ultrafine CKC particles, due to their high reactivity, augmented mixture viscosity and accelerated hydration. The V-funnel times

TABLE 4. Fresh-State Test Results of HPSCCs

Mix.no	Slump flow D(mm)	V-funnel Time(s)	PA
M0	800	6.2	0.948
M1	780	7.5	0.936
M2	765	8.1	0.912
M3	740	9.7	0.874
M4	805	6.5	0.962
M5	810	5.9	0.976
M6	825	5.6	0.98
M7	820	6	0.984
M8	835	5.7	0.991
M9	845	5.3	0.996
M10	800	6.8	0.963
M11	790	7	0.954
M12	780	7.5	0.942

for mixtures M4, M5, M6, M7, M8, and M9 were 6.5 s, 5.9 s, 5.6 s, 6.0 s, 5.7 s, and 5.3 s, respectively. The V-funnel time decreased with escalating waste marble powder quantity, indicating that viscosity diminishes with a higher marble powder ratio. This occurred because of the augmentation of the fines ratio and surface area. The lowest funnel time was recorded for M9, which was 5.3 s. It was detected that escalating the replacement amount of GGBS to a maximum of 40% can enhance the filling capacity by reducing the time required for filling. GGBS possesses larger particle sizes than CKC, which helps to decrease surface area and reactivity, thereby enhancing the concrete's flowability. Additionally, GGBS exhibits reduced yield strength because of reduced internal forces within the mixture, which contributes to increased fluidity of the concrete (1, 19). However, for multiblended mixes, the funnel time ranged from 6.8 to 7.5 seconds, indicating an increase compared to M0. The prospective application of an amalgamation of CKC, WMP, and GGBS as partial cement replacements in a quaternary blend can yield satisfactory fresh properties of HPSCC. These consequences further underscore the significant impact of supplementary cement-based substances on the rheology of cement-based systems (42). An L-box test was performed to evaluate the HPSCC's passing capacity.

The results of the passing ability (PA) produced ranged between 0.874 and 0.996 (see Figure 6), categorizing it as class two (PA2) within the satisfactory limits specified according to ASTM (34). All of the mixtures demonstrated homogeneous characteristics, with no observable segregation or blocking. The PA values measured for M0, M1, M2, and M3 were 0.948, 0.936, 0.912, and 0.874, respectively. The observed decline is because of the inclusion of CKC, which can diminish the passing ability because of reduced fluidity. This may be due to the long, hexagonal shape of the calcined kaolin clay particles being shaped and sized in such a way as to create obstructions within the fresh mixture and escalate inter-particle friction (43). The passing ability produced by mixtures M4, M5, and M6 was 0.962, 0.976, and 0.980, respectively, indicating that the L-box flow escalated with increasing WMP percentages. The higher WMP content improves HPSCC workability by increasing free water, thus enhancing the concrete's filling ability (44, 45). The passing ability for mixtures M7, M8, and M9 was 0.984, 0.991, and 0.996 (the highest passing ability), respectively, demonstrating that the L-box flow escalated with higher percentages of GGBS. The enhanced passing ability may be ascribed to the particle size of GGBS, which positively affects the reduction of internal friction, thereby contributing to enhanced fluidity and passability (1, 19). However, for multiblended mixes (M10 and M11), the passing ability (PA) was increased by 1.58% and 0.63% compared to M0. It is noted that the passing ability of (M12) decreased

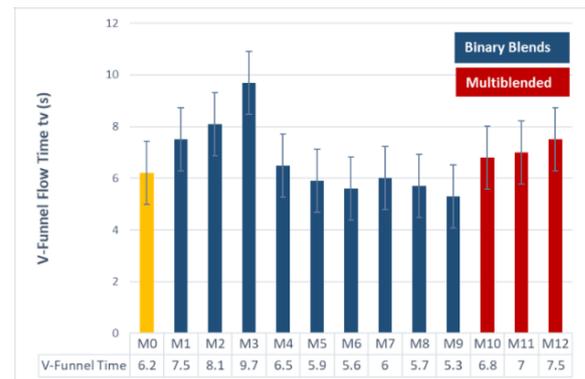


Figure 5. V-Funnel flow time results of HPSCCs

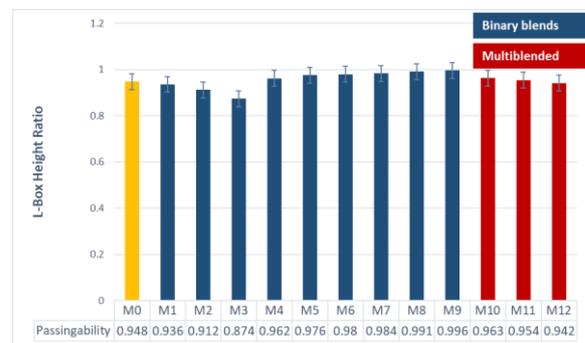


Figure 6. L-box height ratio results of HPSCCs

by 0.63% in comparison with M0. The incorporation of CKC, WMP, and GGBS as partial replacements for cement in a quaternary blend establishes promising fresh properties for HPSCC. In summary, all mixtures exhibited satisfactory workability, stability, and consistency.

3. 2. Hardened Results The self-weight of any structure is entirely dependent on the unit weight of the constituent materials. Therefore, it is a significant parameter for mortar or concrete. The HPSCC mixtures density reduced with increasing pozzolan (CKC, WMP, and GGBS) replacement (see Figure 7). The density of all HPSCC mixes increased with curing age. The percentage decrease in density of HPSCCs (M1-M12) was (0.77, 1.06, 1.42, 0.45, 0.77, 1.38, 0.28, 0.61, 1.22, 1.42, 1.71, and 2.04) % at 28 days, respectively, in comparison with the control mixture (M0). The density diminished further in multi-blended mixes, with the most significant reduction observed in mixture M12 (20% CKC, 10% WMP, 20% GGBS). This outcome can be ascribed to the reduced specific gravity of the pozzolans relative to cement, resulting in a decreased mass per unit volume (19). Thus, CKC, WMP, and GGBS can be used in mortar or concrete as lighter alternatives to cement. The results are promising in decreasing the self-weight of the structure on soils with poor bearing capacity to some

extent. “Table 5 summarizes the development of compressive strength at 7, 28, and 90 days for binary and multiblened mixes using CKC, WMP, and GGBS respectively.” The compressive strength results show that all the concretes samples produced within this investigated study exhibit high performance, with the 28-day compressive strength ranges from 63.7 MPa to approximately 81.2 MPa, while the 90-day compressive strength fell within the range of 69.7 to 86.1 MPa. “CKC, owing to its fine particle size and high contents of reactive SiO₂ and Al₂O₃, offers an extensive specific surface area that accelerates the formation of calcium silicate hydrate (C–S–H) gel, resulting in a noticeable gain in early-age strength. By contrast, GGBS—although similarly rich in silica and alumina—possesses a coarser granulometry, which lowers its effective surface area and slows its initial dissolution. The reduced reaction rate extends the setting time and, consequently, suppresses 7-day compressive strength. However, once hydration progresses, the latent hydraulic activity of GGBS becomes dominant; additional C–S–H and C–A–S–H

phases precipitate, progressively densifying the microstructure. This delayed but sustained reaction produces the marked strength increments measured at 28 and 90 days, ultimately allowing the GGBS-containing mixes to surpass the control concrete. The primary benefits of WMP—better particle packing and dilution of the cement matrix—are realised gradually, so any strength enhancement becomes more evident at later ages once the denser microstructure compensates for the initial lack of chemical reactivity.” It is worth noting that our findings are in line with those of (46, 47). The observed increase in compressive strength beyond 28 days results from a combination of ongoing hydration of the cementitious materials and pozzolanic reactions of the supplementary powders (CKC, WMP, and GGBS). While OPC hydration continues at a slower rate after 28 days, the pozzolanic materials contribute significantly by reacting with calcium hydroxide (CH) released during cement hydration to form additional calcium silicate hydrate (C–S–H) gel. This secondary C–S–H formation densifies the microstructure, reducing porosity and enhancing mechanical strength over time. Specifically, CKC and GGBS exhibit notable pozzolanic and latent hydraulic activity, respectively, which drives the substantial strength improvements observed at 28 and 90 days. WMP acts primarily as a microfiller, contributing mainly to physical densification rather than chemical reaction.

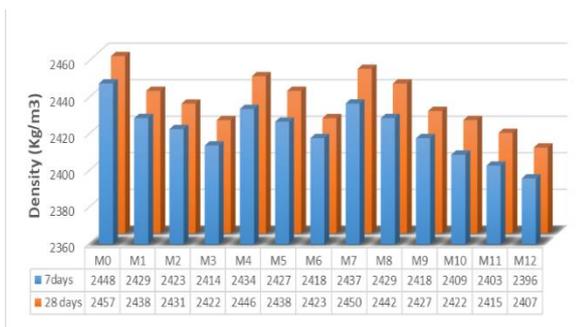


Figure 7. Density results of HPSCCs

TABLE 5. Compressive Strength Results of HPSCCs

Mix.no	7days	28days	90days
M0	53.6	68.7	75.1
M1	56.2	75.4	82.8
M2	55.4	73.6	80.6
M3	54.3	70.8	76.8
M4	52.3	72.6	79.4
M5	50.2	70.3	76.6
M6	47.6	63.7	69.7
M7	51.6	74.1	80.3
M8	49.7	71.2	75.7
M9	46.5	65.7	70.1
M10	55.3	81.2	86.1
M11	52.7	78.7	82.8
M12	50.6	65.2	69.2

Figures 8, 9, 10 and 11 show the development of compressive strength at 7, 28, and 90 days for binary mixes using CKC, WMP, and GGBS and multiblened mixes, respectively in comparison to control concrete (M0). At 90 days, the compressive strength of binary blends containing CKC (M1, M2, and M3) increased by 10.25%, 7.32%, and 2.26%, respectively, relative to the control mix (M0). It is evident that the compressive strength was highest for the 10% CKC (M1) mixture, achieving a strength of 82.8 at 90 days. This demonstrates that the optimal compressive strength was accomplished at a 10% CKC replacement level. This enhancement is ascribed to the increased fineness of CKC, promotes a more significant reaction with Ca(OH)₂, causing the development of further C–S–H and therefore increasing the compressive strength. Furthermore, the miniaturization of CKC particles also increases the compressive strength (48). The reduction in compressive strength for 15% CKC and 20% CKC, compared to 10% CKC, can be explained by the clinker dilution impact. The dilution influence, resulting from substituting part of the cement with CKC, is offset in CKC concrete by the filler influence, the pozzolanic reaction of CKC with calcium hydroxide, and the synergistic influence of the mineral admixture (48). The compressive strength of binary blends with WMP (M4 and M5) increased by (5.73% and 1.99%), while the compressive strength of (M6) diminished by (7.19% and 6.66%) at 90 days of age

versus the control mix (M0). The data indicate that the compressive strength was highest for the 10% WMP (M4) mixture, achieving strengths of 79.4 at 90 days. When the replacement level of WMP reaches 15% and 20%, the compressive strength starts to decrease, suggesting that the optimal limit for WMP replacement is 10%, beyond which the gains in strength are minimal or negative. The fine particles of WMP occupy the microvoids of the concrete matrix, leading to a denser microstructure in the HPSCC mix. This leads to enhanced mechanical properties in HPSCC mixes. In addition, marble powder decreases the porosity of the concrete mix and improves binding properties as a result of the chemical hydration of calcite and tricalcium aluminates (49). Furthermore, the compressive strength of binary blends with GGBS (M7 and M8) increased by (6.92% and 0.8%), while the compressive strength of (M9) decreased by (6.66%) at 90 days relative to the control mix (M0). Notably, the 20% GGBS (M7) blend achieved the highest compressive strength of 80.3 MPa at 90 days. The escalation in compressive strength of mix 7 can be ascribed to the incorporation of an optimal 20% GGBS content. The existence of calcium oxide and silicon dioxide in GGBS enables their reaction with calcium hydroxide, likely causing the establishment of supplementary crystalline calcium-silicate-hydrate gel.

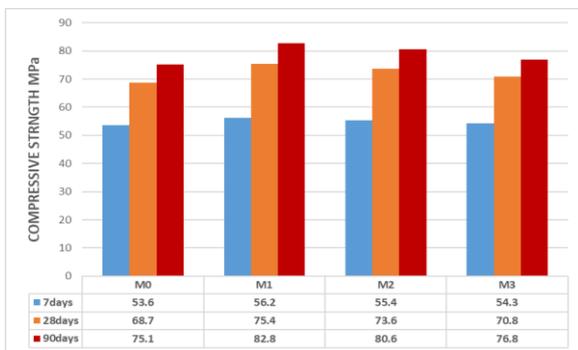


Figure 8. Compressive strength development results of HPSCCs with CKC blends

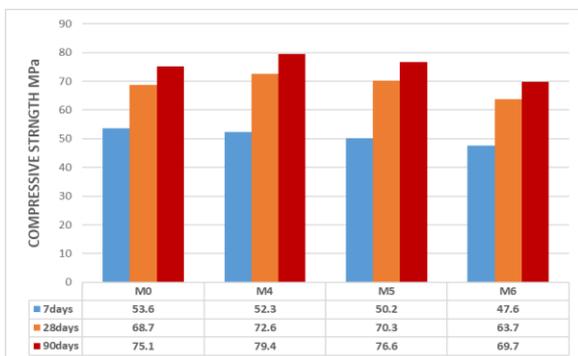


Figure 9. Compressive strength development results of HPSCCs with WMP blends

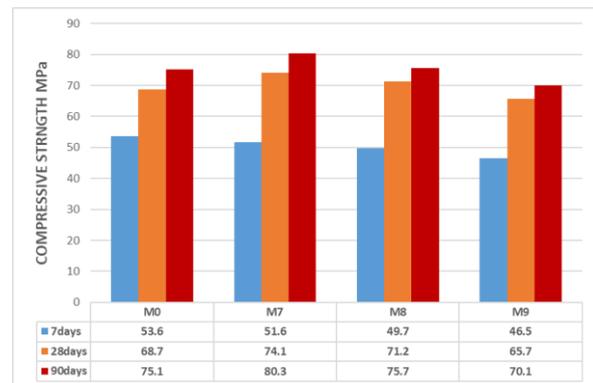


Figure 10. Compressive strength development results of HPSCCs with GGBS blends

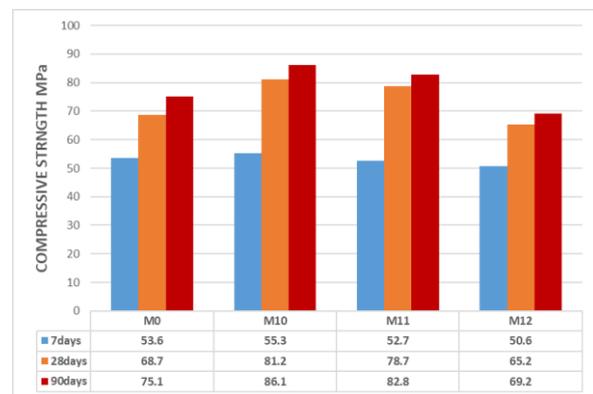


Figure 11. Compressive strength development results of HPSCCs with Multibleneded mixes

These crystalline compounds are responsible for the improvement in strength properties (50). The compressive strength of multibleneded mixes M10 and M11 increased by 14.65% and 10.25%, respectively, while the compressive strength of M12 decreased by 7.86% at 90 days of age in comparison with the control mix (M0). The maximum compressive strength was accomplished for the mix containing 10% CKC, 10% WMP, and 20% GGBS (M10), reaching a strength of 86.1 at 90 days. The observed enhancement can be ascribed to the synergy action of the pozzolans, wherein the optimal 20% GGBS content provided a notable filler or packing effect. The existence of calcium oxide and silicon dioxide in GGBS allows them to react with calcium hydroxide, which may result in the establishment of supplementary crystalline C-S-H gel. The inclusion of 20% CKC, 10% WMP, and 20% GGBS in the M12 mix gave rise to a marked lowering of compressive strength. This is because of the reduced supply of calcium hydroxide from OPC and the low reactivity of GGBS. “SEM analysis was conducted using a Hitachi TM4000Plus tabletop scanning electron microscope (Hitachi High-Tech Corp., Japan). The instrument

operated at an accelerating voltage of 20 kV under high vacuum conditions. Concrete specimens (10 mm × 10 mm × 10 mm) were dried and gold-coated prior to imaging.” Figure 12 displays SEM images of different mixes, namely, M1, M4, M7, and M10, compared with the reference mix (M0) at ambient temperature. The mixes were selected based on their mechanical performance, specifically those with optimum strength at 28 days of age. The SEM analysis revealed that the presence of needles of ettringite (on a micron scale), thin hexagonal plates of portlandite (calcium hydroxide), and C-S-H plates as the main hydrated products in the control specimens. Due to the increased compressive strength from 10% CKC replacement, the SEM presented in Figure 9 shows pozzolanic reactions and gel development during cement hydration, with significant increases in C-S-H and decreases in $\text{Ca}(\text{OH})_2$. Consequently, the microstructures of the cement have been enhanced because of the reaction between the active calcined kaolin clay and $\text{Ca}(\text{OH})_2$ in the cement paste. Cement-based paste specimens with replaced calcined kaolin clay exhibited a more compact and denser pore structure (48). These findings are fully consistent with the compressive strength results. Clearly, the cement-marble powder paste specimens showed higher density and lower porosity than cement paste specimens. In this phase, the microstructure of the pastes consists of amorphous C-S-H particles, while Ettringite (E) needles are found within the pores, indicating that the paste is completely hydrated and all voids have been filled. Furthermore, with an increased amount of MP, the resulting SCC becomes denser and less porous (49). In contrast to the control concrete, pores are scarce in the 20% GGBS concrete. This effect is due to GGBS, which

significantly decreases both the amount and average size and amount of $\text{Ca}(\text{OH})_2$ crystals in the aggregate-mortar Interfacial Transition Zone (ITZ), thereby making the microstructure of the ITZ denser. These influences contribute to the great strength of concrete when an optimal amount of GGBS is used alongside PC (50, 51). Yuksel (52) noted that the micro-structure of concrete containing GGBS differs from that of PC concretes owing to further reactions involving GGBS. Generally, the cracks absence denotes effective mixing and strong bonding among the materials. In concrete, an ITZ forms where two distinct components meet. Thus, ITZ can be minimized through enhanced mixing and uniform distribution. It is concluded that a multi-blend of 10% CKC, 10% WMP, and 20% GGBS offers good bonding with cement. The lack of cracks indicates that the mixture composition and amounts are appropriate. The ITZ, resulting from the combination of various chemical elements, is obviously visible and represents a positive advancement in concrete strength. “Although EDS analysis was not conducted in this study, a qualitative porosity assessment was carried out using grayscale contrast in SEM images. The images of quaternary blends (e.g., Mix M12) showed significantly denser matrices and fewer pores compared to the control mix (M0), indicating enhanced microstructure due to synergistic pozzolanic action.”

4. COST AND ENERGY PERSPECTIVE

Replacing 40% of the binder with CKC, WMP, and GGBS lowers clinker content and therefore both energy demand and cost:

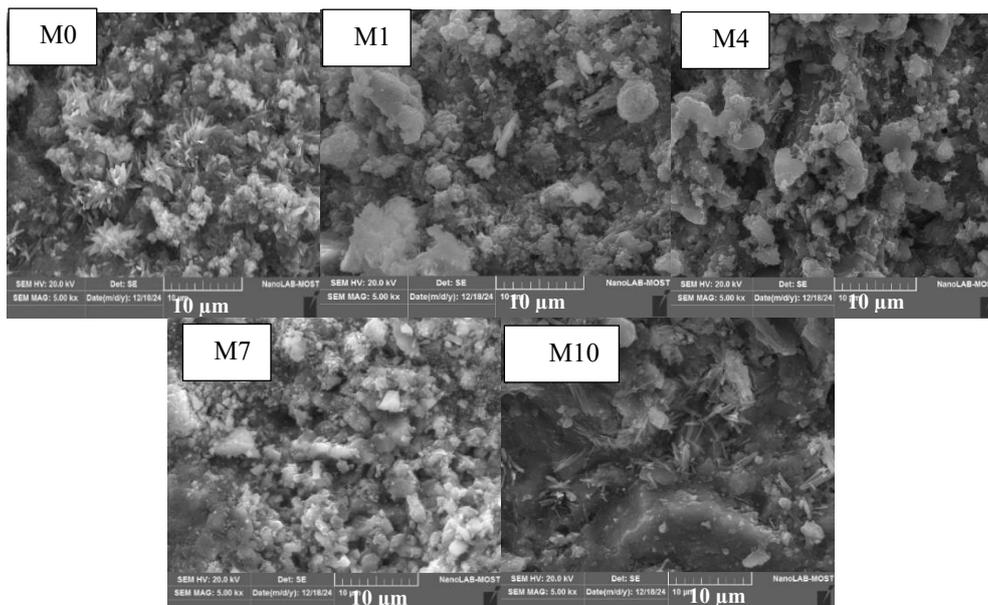


Figure 12. Scanning electron microscopy(SEM) results of HPSCCs at scale bars (10 μm) to assist with pore structure comparison

4. 1. ENERGY Producing 1 t of OPC clinker consumes ≈ 3.3 GJ and emits ≈ 850 kg CO₂. CKC is calcined at ~ 800 °C (≈ 1.8 GJ t⁻¹), GGBS is a by-product requiring only grinding (≈ 0.4 GJ t⁻¹), and WMP is simply milled waste (≈ 0.2 GJ t⁻¹). Weighted for a 60 % OPC + 40 % blend, the embodied energy is cut by about 28–30 % relative to 100 % OPC.

4. 2. COST In most markets GGBS and WMP are 30–50 % cheaper than OPC; CKC is close to parity. Using the same 60/40 proportion typically reduces binder cost by **10–15 %**. Any minor increase in grinding or transport is outweighed by the saving in clinker.

4. 3. SCALABILITY All three powders are already produced at industrial scale (GGBS) or can be scaled through existing calcination/grinding lines (CKC, WMP). No specialized equipment beyond additional silos and dosing screws is needed, so commercial SCC batching plants can adopt the blend with minimal capital expenditure. Thus, at scale the quaternary blend offers a tangible economic advantage while cutting embodied energy and CO₂—making it more sustainable than standard OPC-based SCC.

5. CONCLUSIONS

1. Increased cement usage results in higher carbon dioxide emissions, which subsequently cause detrimental environmental impacts. Utilizing blended pozzolanic materials (CKC, GGBS, and WMP together) up to 50% as partial cementitious replacements in concrete can mitigate these effects.
2. Slump flow diameters measured between 740 and 845 mm. Consequently, all concrete mixes met the SF3 class in terms of slump flow, except for the binary mixtures containing 20% CKC, which fell within the SF2 class according to EFNARC. Therefore, all mixes were considered to have acceptable rheological consistency / uniformity of flow from a filling perspective.
3. The V-funnel flow times (in seconds) ranged from 5.3 to 9.7. Accordingly, all mixes could be classified into the VF1 class, except for the 20% CKC mix, which was classified into the VF2 class based on EFNARC.
4. The results of the produced PA range from 0.874 to 0.996, which is categorized as class two (PA2) (within the EFNARC-recommended range). No segregation or blocking was noticed in any of the mixes.
5. Despite a reduction in certain fresh properties observed with CKC as a cement replacement in HPSCC, the resulting mixtures still met the requirements for SCC.
6. The addition of WMP and GGBS to the HPSCC mixes enhanced the fresh-state properties and mitigated the negative effects of CKC on these properties.

7. The use of CKC, WMP, and GGBS in a quaternary blend as partial cement replacements demonstrated the potential to achieve satisfactory fresh properties in HPSCC at replacement levels up to 50%.

8. The density of the HPSCC mixtures diminished with increasing pozzolan content (CKC, WMP, and GGBS) replacement increased, with the highest reduction in density observed for mixtures containing 20% CKC, 10% WMP, and 20% GGBS.

9. The HPSCC compressive strength outcomes confirm that all the concretes manufactured in this work are of high performance, with 28-day strength varying between 63.7 and approximately 81.2 MPa, and 90-day strength varying between 69.7 and 86.1 MPa.

10. For binary blends, the optimal replacement level was 10% CKC, 10% WMP, and 20% GGBS to achieve higher compressive strength.

11. The maximum compressive strength was attained with 10% CKC + 10% WMP + 20% GGBS (M10), reaching a strength of 86.1 at 90 days. The improvement in strength is attributed to the synergistic interaction between the filler effect, enhanced pozzolanic reactivity, and enhanced particle packing of the supplementary cementitious materials.

12. The quaternary blend exhibited a visibly denser microstructure; this is clearly illustrated in SEM image M10, where the pore network is markedly finer and less connected than in the reference mix, aligning with the observed strength gains.

13. The blended powders caused only subtle aesthetic changes. GGBS and CKC imparted a slightly darker grey tone than plain OPC, while the light-coloured WMP helped keep the hue balanced; overall, the hardened concrete retained a uniform medium-grey shade. Surface texture and finish quality (slump-flow-derived smoothness, absence of bleed lines) were indistinguishable from the reference SCC, so the mix remains suitable for exposed or architectural applications that demand consistent colour and a smooth, defect-free finish.

6. FUTURE WORK

Future research should focus on the long-term durability of the developed concrete mixtures under various environmental conditions, including freeze-thaw cycles and chemical exposure. Investigating the thermal cycling behavior and its impact on microstructure and mechanical properties would provide valuable insights for broader applications. Future work will incorporate EDS or image-based porosity quantification to provide more robust microstructural validation. Additionally, exploring the use of these sustainable concrete formulations in prefabricated structural elements could

help optimize production processes and enhance performance in industrial construction settings.

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Persian Abstract

چکیده

بتن خودتراکم با عملکرد بالا، پیشرفت قابل توجهی در فناوری ساخت و ساز محسوب می‌شود. این مطالعه به بررسی و مقایسه خواص حالت تازه جریان اسلامپ (mm) D، زمان جریان قیف V و آزمایش‌های جعبه L، خواص حالت سخت شده (وزن واحد و مقاومت فشاری) و ویژگی‌های ریزساختار (میکروسکوپ الکترونی روبشی (SEM) بتن خودتراکم با عملکرد بالا (HPSCC) با یک مخلوط مرجع (M0) به عنوان مخلوط کنترلی حاوی فقط OPC بدون جایگزینی پوزولانی پرداخت. دو سیستم ترکیبی در این مطالعه توسعه داده شد: یک سیستم ترکیبی دوتایی و یک سیستم ترکیبی چهارتایی که شامل (OPC+GGBS، OPC+WMP، OPC+CKC) و (OPC+CKC+WMP+GGBS) بود. نتایج مربوط به خواص تازه همه مخلوط‌های HPSCC در محدوده قابل قبول تعیین شده توسط EFNARC قرار گرفت، بدون اینکه جداشدگی یا آب انداختن مشاهده شود، و همه مخلوط‌های HPSCC عملکرد بهتری نسبت به مخلوط کنترلی نشان دادند. از این مطالعه می‌توان نتیجه گرفت که استفاده از ۶۰٪ OPC + 10% CKC + 10% WMP + 20% GGBS در مقایسه با مخلوط کنترلی (M0) مقاومت فشاری تازه بهبود یافته و ریزساختار متراکم‌تری را ارائه داد که آن را برای استفاده به عنوان HPSCC مناسب می‌کند. حداکثر مقاومت فشاری در ۹۰ روز به ۸۵.۲ مگاپاسکال رسید. تجزیه و تحلیل هزینه نشان می‌دهد که خاک رس کائولن کلسینه شده و ضایعات صنعتی می‌توانند به عنوان مواد سبز امیدوارکننده عمل کنند. با کاهش محتوای OPC از طریق جایگزینی جزئی با WMP، CKC و GGBS، این مطالعه به کاهش قابل توجه انتشار CO₂ مرتبط با تولید سیمان کمک می‌کند و شیوه‌های ساخت و ساز پایدارتری را ترویج می‌دهد.
