Experimental Investigation on the Influence of High Water-to-Binder Ratio on the Properties of Self-Compacting Concrete Incorporating Ceramic Waste Powder as a Cement Replacement

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Abstract
High-performance, sustainable construction materials are urgently needed to reduce CO2 emissions from cement production and to valorize growing volumes of ceramic tile waste; incorporating finely ground ceramic waste powder (CWP) as a partial cement replacement in self-compacting concrete (SCC) offers a promising route to both objectives. However, SCC containing pozzolanic or inert mineral additions frequently requires modified mix proportions and superplasticizer dosages to maintain fresh-state self-compactability, and the effects of elevated water-to-binder (w/b) ratios on the combined fresh and hardened behavior of CWP-blended SCC remain poorly quantified in published literature. This study therefore investigates the influence of water-to-binder ratio and ceramic waste powder replacement level on the fresh and hardened properties of self-compacting concrete. SCC mixes were prepared with water-to-binder ratios of 0.45 and 0.50 and ceramic waste powder replacement levels from 0% to 30% by mass of cement. Fresh properties were assessed using slump flow, T500 time, V-funnel, L-box, and segregation resistance tests, while hardened properties were evaluated through compressive, split tensile, and flexural strength at 7, 28, and 90 days. The results showed that increasing the water-to-binder ratio improved flowability but reduced stability and strength. Moderate ceramic waste powder content, particularly in the range of 5% to 15%, maintained acceptable SCC performance and in some cases improved long-term strength, whereas higher replacement levels caused strength reduction and loss of cohesiveness. These findings support sustainable SCC mix designs that reuse ceramic waste while maintaining performance targets. Overall, this study highlights the potential of ceramic waste powder as a sustainable construction material, provided that the water-to-binder ratio and replacement level are carefully optimized.

Keywords: Self-compacting concrete; ceramic waste powder; water-to-binder ratio; sustainable cement replacement; fresh and hardened properties.

Introduction

The construction industry has seen a significant shift toward the development of advanced cementitious materials, with self-compacting concrete (SCC) representing a major technological advancement due to its high fluidity and ability to consolidate under its own weight without mechanical vibration[1], [2]. While SCC offers numerous advantages—including reduced labor costs, enhanced surface finish, and improved filling capacity in congested reinforcements—it was traditionally associated with a high cement content, which increases both the economic cost and the environmental carbon footprint [1], [3], [4]. In response to global demands for sustainability and the need to manage burgeoning industrial waste, researchers have increasingly investigated the incorporation of recycled materials as partial replacements for cement or natural aggregates in SCC [5]–[7].

Researchers have utilized various forms of industrial and construction waste as supplementary cementitious materials (SCMs) or aggregate replacements. Several studies focused on ceramic waste powder (CWP) or ceramic tile powder (CTP) derived from sanitary ware, floor tiles, and electrical insulators [8]–[11].

Table **1** shows physical and chemical properties of waste powders (fillers) used by the researchers. Specific variations include bone china ceramic waste (BCCW), which was typically ground to a fineness passing 90 µm to serve as a cement substitute [7][12]. Other researchers utilized waste marble powder (WMP) or marble dust, noting its high calcium carbonate ($CaCO_3$) content, often exceeding 90% [1], [4]. Granite cutting waste (GCW) or granite sawing waste (GSW) was frequently employed, characterized by its irregular, angular particle shape and rough surface texture [2], [13], [14]. To mitigate the potential negative effects of these wastes on fresh properties, several authors incorporated other mineral admixtures such as fly ash (FA), silica fume, and ground granulated blast furnace slag (GBFS) to create binary, ternary, or quaternary blends [3], [13], [15], [16]. The binder materials generally included Ordinary Portland Cement (OPC) or Portland Pozzolana Cement (PPC). For aggregate substitution, natural river sand (NRS) and natural coarse aggregates (NCA) were replaced with recycled ceramic aggregates (RCA) or porcelain tile aggregates (PTA). Chemical admixtures, predominantly polycarboxylate-based superplasticizers (SP), were essential across all studies to achieve the required rheological stability [2], [16]–[18].

Table 1 Physical and Chemical Properties of Waste Powders

Material	Physical Properties	Chemical Composition (Major Oxides %)	Description/Morphology
Calcium Carbonate (CC) [16]	SG: 2.72; SSA: 1450 m2/kg;	CaO: 66.4; LOI: 42.4	Light grey color; rough and uneven surface texture.

	Mean Size: 16.6 µm		
Cement Kiln Dust (CKD) [5]	SG: ~3.15 (modified); Fineness: < 50 µm	CaO: 58.7; SiO2: 18.9; LOI: 16.5	Highly alkaline waste; dehydrated and chemically unstable.
Marble Powder (WMP) [19]	SG: 2.7–2.71; SSA: 2160 cm2/g; Absorption: 3.13%	CaCO3: > 90%; CaO: 54.9; LOI: 43.7	Mostly white; angular and relatively rounded shapes.
Bone China Ceramic Waste (BCCW) [7], [20]	SG: 2.07; SSA: 425 m2/kg; Fineness: < 90 µm	SiO2: 38.0–48.0; CaO: 18.0–29.3; Al2O3: 8.3–16.6	High P2O5 content (up to 14%); irregular and rough surface.
Ceramic Waste Powder (CWP) [3], [6], [8], [9]	SG: 2.43–2.65; SSA: 365–555 m2/kg	SiO2: 67.3–72.6; Al2O3: 12.6–19.8	Derived from tiles/sanitary ware; angular and rough surface.
Granite Cutting Waste (GCW) [2], [14], [20]	SG: 2.55–2.57; Absorption: 4.49%; FM: 1.38–1.40	SiO2: 61.4–75.9; Al2O3: 11.9–16.3	Irregular, rugged, and angular nature; non-pozzolanic/inert filler.

Studies suggest that the incorporation of waste powders generally leads to a reduction in the workability of fresh SCC. Evidence indicates that the angular shape and rough surface texture of ceramic and granite particles increase internal friction, necessitating a higher dosage of superplasticizer to maintain a constant slump flow [6], [7], [12], [17]. However, AlArab et al. (2021) and Aly et al. (2019) observed that acceptable SCC properties could be maintained at low replacement levels, typically up to 20% for cement and 40% for fine aggregates. Regarding mechanical performance, conflicting results have been reported based on the type and volume of waste used. Several studies found that compressive and flexural strengths peak at an optimum replacement level—often 10–20% for powders and up to 60% for ceramic tile aggregates—due to the pore-filling effect and synergistic pozzolanic reactions [7], [8], [11], [16], [21]. For instance, Gautam et al. (2022) reported improved strength at 10% replacement of cement with bone china ceramic waste, while Meena et al. (2022) noted optimal performance at 60% replacement of river sand with waste ceramic tiles [7], [22]. Conversely, high replacement rates (exceeding 25–40%) typically lead to a strength decline, attributed to the dilution effect and increased porosity [6], [8]. The inclusion of waste materials also enhance the resistance of SCC to environmental stressors as indicated from the durability findings. Studies suggest that optimum replacement levels lead to higher UPV values and reduced water absorption, indicating a densified microstructure and a more compact ITZ [6], [16], [21], [22]. Additionally, ceramic-modified SCC has demonstrated superior performance when exposed to high temperatures, with RCA-based mixes exhibiting higher residual strength compared to control mixes after fire exposure [11], [17]. In most self-compacting concrete (SCC) formulations, the W/B ratio (water-to-powder/binder) was kept low (typically 0.26 to 0.44) to maintain high fluidity without segregation. The W/C ratio often increases as the percentage of cement replacement grows, as more water was required to maintain consistency for a lower cement content.

The existing literature demonstrates that ceramic waste powder (CWP) can be produced from a wide range of ceramic-based waste materials, each exhibiting distinct physical, mineralogical, and chemical characteristics. Based on their chemical composition, CWP may be broadly categorized into two groups: (i) calcium-rich materials, including marble powder, bone china ceramic waste (BCCW), and granite waste, which contain relatively high CaO contents, and (ii) aluminosilicate-rich materials, such as ceramic tile waste and sanitary ware waste, which are characterized by comparatively low CaO and high SiO_2 and Al_2O_3 contents. Although considerable research has been devoted to calcium-rich ceramic wastes, studies investigating the performance of low-calcium aluminosilicate ceramic waste powders remain relatively limited. Existing research indicates that ceramic waste materials can serve as sustainable alternatives to cement and natural aggregates in self-compacting concrete (SCC), provided that their replacement levels are appropriately optimized to maintain the required fresh and hardened properties. Nevertheless, several critical knowledge gaps persist. Long-term durability performance has not been comprehensively established, while the synergistic effects of incorporating multiple waste streams in hybrid SCC systems remain insufficiently explored. Furthermore, the significant variability in the chemical and mineralogical composition of ceramic wastes originating from different manufacturing processes and geographical regions presents challenges for ensuring consistent concrete performance, highlighting the need for more reliable predictive models and mix design methodologies. These limitations underscore the necessity for further research aimed at developing region-specific SCC formulations capable of maximizing waste utilization without compromising structural performance and durability. Accordingly, the present study investigates the engineering performance of self-compacting concrete incorporating ceramic waste powder obtained from the Morbi ceramic manufacturing cluster in Gujarat, India, one of the largest ceramic production hubs in the world. Owing to the relatively high water absorption characteristics of ceramic-based materials, particular emphasis was placed on evaluating the combined influence of increased water-to-binder ratios and partial cement replacement with ceramic waste powder on the fresh, mechanical, durability, and microstructural properties of SCC. This work addresses the collective challenge of reducing environmental impact while maintaining or enhancing the mechanical and durability performance of modern concrete structures.

Materials and Methods

Research design

The present study investigates the effect of high water-to-binder ratio on the fresh, mechanical, and durability properties of self-compacting concrete incorporating ceramic waste powder as a partial replacement of cement. The experimental program was designed to examine the interaction between two principal variables: water-to-binder ratio and ceramic waste powder replacement level. A control mix without ceramic waste powder was prepared to serve as the reference composition, and all experimental results are compared against it to determine the net influence of the waste powder addition.

Materials

Commercially available 53-grade Ordinary Portland Cement (OPC) as prescribed by the IS 12269 (1987) standard was used as the primary binder. The cement has a characteristic grey colour, a specific gravity of about 3.15, a Blaine fineness of approximately 2250 cm^2/g, and a mean particle size below 90 μm, all of which influence its reactivity and contribution to strength development. Ceramic waste powder was produced from discarded ceramic tile waste through cleaning, crushing, grinding, and sieving to obtain a fine powder suitable for use as a cementitious replacement material. Fine aggregate and coarse aggregate were used in saturated surface dry condition, while potable water was used for mixing and curing. A lightish brown Viscosity Modifying Admixture (VMA), having specific gravity of 1.08 was incorporated to achieve the flowability required for self-compacting concrete.

Table **2** shows the Chemical composition of cement and CWP used in this study.

Table 2 Physical and chemical composition of cement and CWP

Parameter	OPC (53 grade)	CWP
Density (g/cm3)	3.15	2.08
Specific Surface Area (cm2/g)	2960	3620
CaO	72.96	1.98
SiO2	12.58	72.46
Al2O3	8.32	17.69
MgO	3.20	2.16
K2O	1.89	0.75
SO3	0.12	0.13
Fe2O3	-	1.59
ZrO2	-	1.17
Na2O	-	1.37
LOI	3.5	0.20

Mix proportioning

The SCC mixtures were proportioned by maintaining a constant total binder content while varying both the water-to-binder ratio and the percentage of cement replaced by ceramic waste powder. The experimental matrix included water-to-binder ratios of 0.45 and 0.50, together with ceramic waste powder replacement levels of 0%, 5%, 10%, 15%, 20%, 25%, and 30% by mass of cement. The mix with 0% replacement was taken as the control mix. From the pilot studies, VMA dosage was adjusted to obtain the desired SCC consistency while avoiding segregation and excessive bleeding. Trial mixes were prepared so that the fresh-state parameters satisfy accepted SCC workability limits before final specimen casting. The cement content was fixed at 450 kg/m3, VMA was used at 0.8% weight of binder, coarse aggregate content was fixed to 800 kg/m3 and fine aggregate content was fixed to 890 kg/m3.

Table **3** shows mix proportions of all 14 mixes used in this research.

Table 3 Mix proportions of SCC mixes used for the experimental work

<table>
<tr><th></th><th>ID</th><th>Water to binder ratio</th><th>CWP (%)</th><th>Cement (kg/m3)</th><th>CWP (kg/m3)</th><th>Water (kg/m3)</th></tr>
<tr><td rowspan="7">Series-01</td><td>W1C00</td><td rowspan="7">0.45</td><td>0</td><td>450.0</td><td>0.0</td><td rowspan="7">202.5</td></tr>
<tr><td>W1C05</td><td>5</td><td>427.5</td><td>22.5</td></tr>
<tr><td>W1C10</td><td>10</td><td>405.0</td><td>45.0</td></tr>
<tr><td>W1C15</td><td>15</td><td>382.5</td><td>67.5</td></tr>
<tr><td>W1C20</td><td>20</td><td>360.0</td><td>90.0</td></tr>
<tr><td>W1C25</td><td>25</td><td>337.5</td><td>112.5</td></tr>
<tr><td>W1C30</td><td>30</td><td>315.0</td><td>135.0</td></tr>
<tr><td>Series-02</td><td>W2C00</td><td>0.5</td><td>0</td><td>450.0</td><td>0.0</td><td>225</td></tr>
</table>

	W2C05		5	427.5	22.5	
	W2C10		10	405.0	45.0	
	W2C15		15	382.5	67.5	
	W2C20		20	360.0	90.0	
	W2C25		25	337.5	112.5	
	W2C30		30	315.0	135.0	

Test Procedure

Fresh properties were evaluated immediately after mixing using standard SCC tests as per the EFNARC guidelines. Slump flow and T500 time were measured to assess filling ability and viscosity. V-funnel testing was conducted to determine flow time and resistance to movement, while L-box testing was used to measure passing ability through reinforcement-like obstructions. Segregation resistance was assessed by sieve segregation test. After confirmation of satisfactory fresh behavior, specimens were cast into standard molds for hardened testing. The concrete was placed into molds without vibration, as required for SCC, and allowed to flow and self-consolidate under its own weight. The specimens were covered immediately after casting to minimize moisture loss and demolded after 24 hours. They were then cured in water until the selected test ages. All specimens, including the control mix, were subjected to the same curing regime so that variations in performance can be attributed to mixture composition rather than curing differences. The curing procedure was kept constant throughout the study to preserve comparability among the mixes.

The mechanical properties of these mixes such as compressive strength, split tensile strength, and flexural strength adopting the test procedures prescribed in IS codes through experiments on standard specimens were studied. Strength tests were conducted at multiple ages in order to capture early-age and later-age development. The influence of the high water-to-binder ratio was analyzed carefully because excessive water can enhance flowability but may also increase porosity after hardening. Accordingly, the study examines whether ceramic waste powder can partly offset the negative effect of high water content through filler action, particle packing, or delayed pozzolanic contribution. Results were presented relative to the control mix so that the performance of each replacement level can be clearly interpreted.

Results and Discussion

Fresh-state performance of self-compacting concrete

The fresh-state results indicated that the behavior of self-compacting concrete incorporating ceramic waste powder was strongly governed by the combined influence of water-to-binder ratio and replacement level. These results are shown in
Table **4**. For the mixtures with w/b ratio of 0.45, slump flow was in a range of 740 mm to 775 mm, corresponding to the upper SF2 and lower SF3 classes. The highest flow values (770–775 mm) were obtained at 10–15% CWP, whereas further increase in CWP content leads to a gradual reduction. At a w/b ratio of 0.5, all mixes exhibited higher slump flow values ranging from 775 mm to 830 mm, placing them predominantly in the SF3 class (>760 mm). The maximum value (≈830 mm) is achieved at 15–20% CWP, followed by a decrease at higher replacement levels. Overall, an increase in w/b ratio lead to a consistent increase in slump flow, and optimum performance was observed at moderate CWP replacement levels (10–20%). This trend was consistent with the known behavior of SCC containing ceramic-derived fines, where the increased surface area of the powder influences water demand and rheological response.

Table 4 Fresh-state properties of all SCC mixtures.

MIX ID	w/b	CWP (%)	Slump flow (mm)	T500 (s)	V-Funnel (s)	L-Box (H2/H1)	Segregation (%)
W1C00	0.45	0	755	3.5	8.3	0.94	14.8
W1C05	0.45	5	770	3.3	7.9	0.96	13.6
W1C10	0.45	10	775	2.8	7.8	0.97	11.2
W1C15	0.45	15	770	2.8	7.6	0.95	11.2
W1C20	0.45	20	765	3.3	9.2	0.85	11.2
W1C25	0.45	25	750	4	10.4	0.84	10.8
W1C30	0.45	30	740	5	12.3	0.83	10.4
W2C00	0.5	0	810	2.8	7.9	0.96	18.5
W2C05	0.5	5	820	2.5	7.7	0.98	18
W2C10	0.5	10	825	2.4	7.7	0.98	16.8
W2C15	0.5	15	830	2.3	7.3	0.99	13.6

W2C20	0.5	20	830	3.2	8.4	0.93	13
W2C25	0.5	25	800	3.6	9.8	0.87	12.6
W2C30	0.5	30	775	3.9	13.4	0.86	12.2

The slump flow results showed that an increase in ceramic waste powder content beyond the optimum range caused a reduction in the free-flowing capacity of the concrete. This behavior may be attributed to the angular texture and high fineness of the ceramic particles, which increase internal friction and require a greater volume of free water or superplasticizer to maintain equivalent consistency. In contrast, mixtures with moderate replacement levels demonstrated stable flow, indicating that limited incorporation of ceramic waste powder can contribute to powder packing and cohesiveness without significantly impairing the filling ability of SCC.

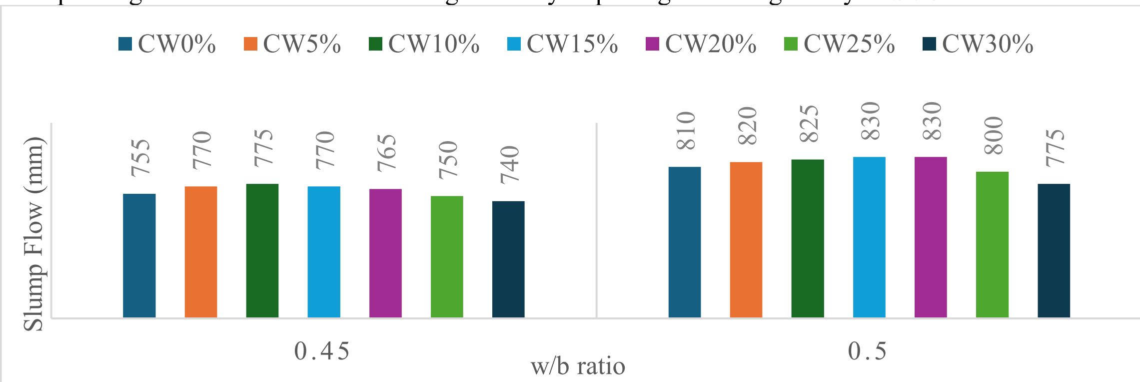

Figure 1 Slump flow of SCC mixes

The T500 flow time and V-funnel results further confirmed the influence of ceramic waste powder on the viscosity characteristics of the mixtures. For w/b of 0.45, the T500 time reduces overall, ranging from 2.8 s to 5.0 s. The minimum values (2.8 s) are observed at 10% and 15% CWP, while the maximum value (5.0 s) occurs at 30% replacement. At a higher w/b ratio of 0.5, the T500 values further decrease, ranging between 2.3 s and 3.9 s. The lowest value (2.3 s) is recorded at 15% CWP, whereas the highest value (3.9 s) corresponds to 30% CWP. Across all w/b ratios, T500 values initially decrease with increasing CWP content up to 10–15%, and subsequently increase at higher replacement levels (20–30%). Additionally, increasing the w/b ratio consistently reduces the T500 time, indicating faster flow. All measured T500 values fall within the acceptable range of 2–5 seconds as recommended by EFNARC (2005), confirming the suitability of the mixes for SCC applications. An increase in T500 time with increasing replacement level suggested that the flow became slower and more viscous.

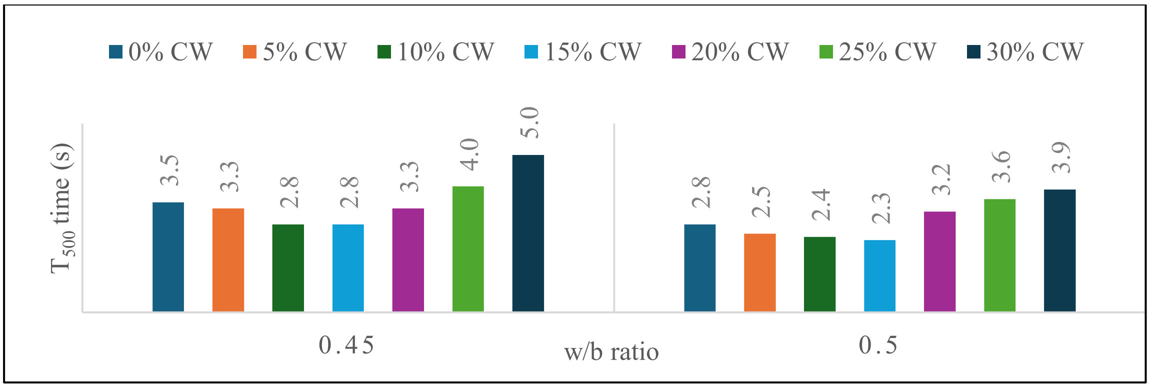

Figure 2 T500 time of SCC mixes

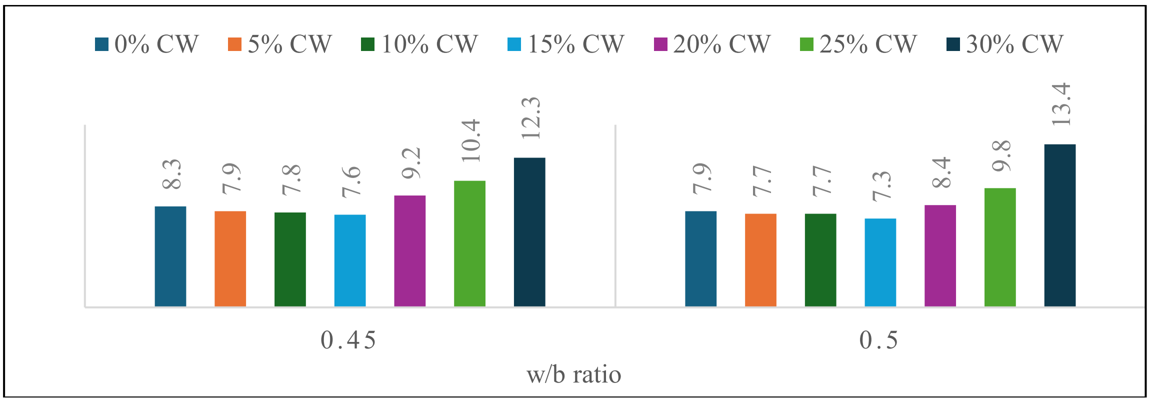

Figure 3 V-Funnel Time of SCC mixes.

The V-funnel test results of SCC incorporating CWP exhibit a systematic variation with CWP replacement levels (0–30%) and water–binder (w/b) ratios (0.45, and 0.5). For mixes with w/b of 0.45, the V-funnel time lies between 7.6 s and 12.3 s. The minimum value (7.6 s) is observed at 15% CWP, while the maximum (12.3 s) occurs at 30% replacement. Intermediate values show a decreasing trend up to 15% replacement, followed by an increase. At a w/b ratio of 0.5, the V-funnel time further reduces, ranging from 7.3 s to 13.4 s. The lowest value (7.3 s) is recorded at 15% CWP, whereas the highest value (13.4 s) corresponds to 30% CWP. Across both w/b ratios, V-funnel time decreases with increasing CWP content up to 10–15%, and subsequently increases at higher replacement levels (20–30%). Additionally, increasing the w/b ratio consistently reduces V-funnel time, indicating enhanced flowability. Most mixtures fall within the acceptable VF1 (≤8 s) and VF2 (9–25 s) classes as per EFNARC (2005), confirming the suitability of the mixes for SCC. Similarly, V-funnel time tended to rise for mixtures with high powder incorporation, indicating increased resistance to deformation. These observations suggest that although ceramic waste powder can improve mix stability by increasing the fines content, excessive replacement may reduce the ease of movement of the paste phase and thereby impair fresh-state performance.

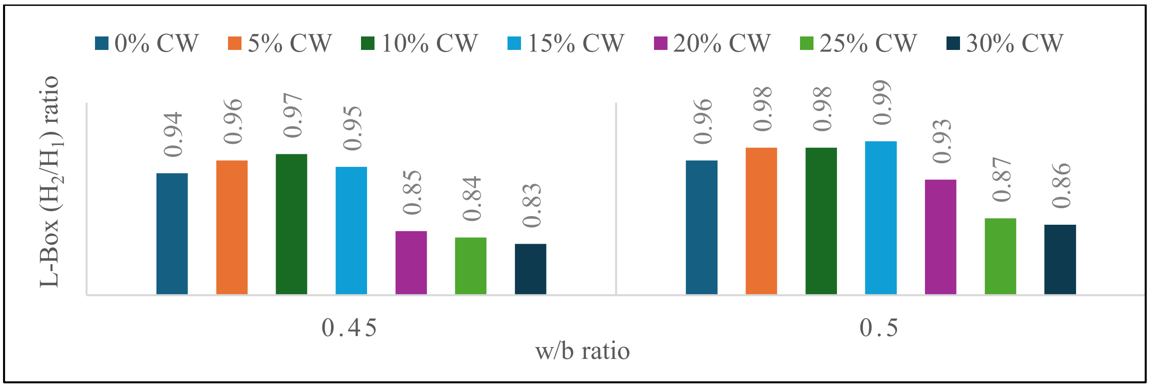

Figure 4 L-Box (H2/H1) ratio of SCC mixes.

The L-box test results of SCC mixes demonstrate variation in passing ability (H_2/H_1 ratio) with respect to CWP replacement levels (0–30%) and water–binder (w/b) ratios (0.45, and 0.5). The L-box ratio values range from 0.83 to 0.99 across all mixtures. For w/b of 0.45, the L-box ratio ranges from 0.83 to 0.97. The highest value (0.97) is observed at 10% CWP, while the lowest (0.83) occurs at 30% replacement. Intermediate values show an increasing trend up to 10–15% replacement, followed by a gradual decline. At a w/b ratio of 0.5, the L-box ratio further increases, ranging between 0.86 and 0.99. The maximum value (0.99) is recorded at 15% CWP, whereas the minimum value (0.86) corresponds to 30% CWP. Across all w/b ratios, the L-box ratio increases with CWP content up to 10–15%, and decreases at higher replacement levels (20–30%). Additionally, increasing the w/b ratio results in higher L-box ratios, indicating improved passing ability. All mixes exhibit L-box ratios greater than 0.80, satisfying EFNARC (2005) criteria for SCC passing ability, with most mixtures falling within the recommended range of 0.80–1.00. Mixtures with moderate ceramic waste powder content generally maintained acceptable blocking ratios, whereas high replacement levels caused a reduction in passing ability due to increased cohesiveness and resistance to flow through confined spaces. This finding was important because SCC must not only spread under its own weight but also pass through congestion without blocking.

The sieve segregation resistance results present the variation of segregation resistance (%). At a w/b ratio of 0.45, a similar decreasing trend was observed, with segregation reducing from 14.8% (0% CWP) to 10.4% (30% CWP). The intermediate values were 13.6% (5%), 11.2% (10%), 11.2% (15%), 11.2% (20%), and 10.8% (25%), indicating a plateau between 10–20% replacement before further reduction. For the highest w/b ratio of 0.5, segregation values were consistently higher across all replacement levels, ranging from 18.4% (0% CWP) to 12.2% (30% CWP). The reduction trend remained monotonic: 18.0% (5%), 16.8% (10%), 14.6% (15%), 13.0% (20%), and 12.6% (25%). Across all mixtures, increasing w/b ratio resulted in higher segregation values, while increasing CWP replacement led to a systematic reduction in segregation. Based on EFNARC (2005) guidelines, mixtures with segregation values ≤20% are considered acceptable for SCC. Accordingly, all mixes satisfied the stability requirement.

Therefore, the fresh-state results suggest that the use of ceramic waste powder was beneficial only within a controlled replacement range, beyond which the self-compacting nature of the concrete begins to deteriorate. Overall, the fresh-state behavior demonstrates that the successful use of ceramic waste powder in SCC depends on balancing the beneficial filler effect against the adverse increase in water demand. The findings indicate that high water-to-binder ratio alone does not guarantee satisfactory SCC performance, because excessive water can increase slump flow while simultaneously promoting segregation or loss of cohesion. Thus, the fresh-state optimum must be defined not by a single test result, but by a combined assessment of filling ability, viscosity, passing ability, and segregation resistance.

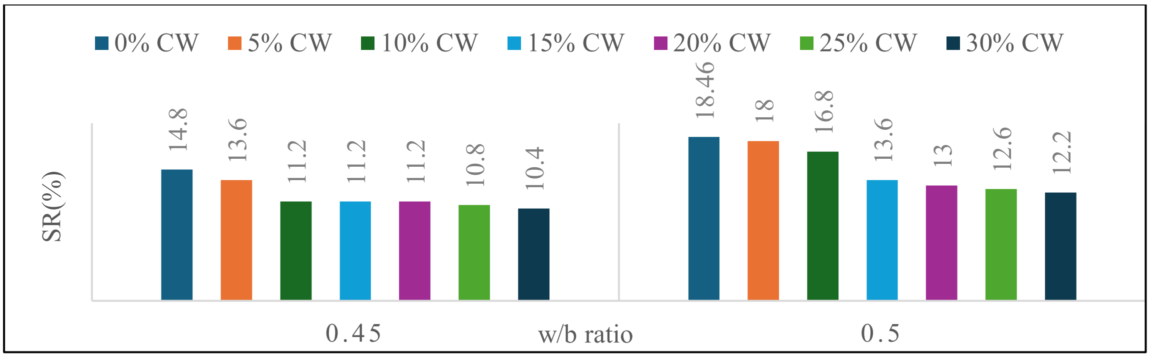

Figure 5 Segregation Resistance (SR %) of SCC mixes.

The influence of water-to-binder ratio was clearly reflected in the workability response of the SCC mixtures. As the water-to-binder ratio increased, slump flow generally increased and the mixtures appeared more fluid. However, this increase in spread was not always accompanied by improved stability. At higher water-to-binder ratios, certain mixtures showed a tendency toward segregation and paste instability, indicating that excessive mixing water may reduce the cohesiveness needed for uniform self-compaction. At relatively moderate high water-to-binder ratios, the presence of ceramic waste powder appeared to improve the stability of the fresh matrix by increasing the overall powder content. In this range, the ceramic particles acted as micro-fillers and improved the internal structure of the paste, thereby assisting in the maintenance of SCC consistency. However, once the water-to-binder ratio became too high, the beneficial effect of added fines was no longer sufficient to counteract the increase in free water. As a result, mixtures at the upper end of the water-to-binder range showed inferior stability despite apparently satisfactory spread values.

These results highlight the main technical challenge addressed in the present study. In SCC, workability and stability must be achieved simultaneously, and the use of ceramic waste powder under high water-to-binder ratio conditions creates a narrow balance between the two. The findings therefore show that high water content should not be treated as a simple means of improving flowability, since it may compromise fresh homogeneity and later hardened performance.

Compressive strength development

The compressive strength results demonstrated that the incorporation of ceramic waste powder influenced both the rate and magnitude of strength development. The compressive strength results of SCC mixes containing ceramic waste powder (CWP) as cement replacement (0–30%) with different water–binder ratio (0.4, 0.45, 0.5), and curing age (7, 28, and 90 days) is shown in

Table **5**. At a w/b ratio of 0.45, the 7-day strength decreased from 21.64 MPa (0% CWP) to 15.58 MPa (30% CWP). The 28-day strength varied between 32.46 MPa (control) and 25.32 MPa (30% CWP). At 90 days, the strength increased with curing time, with a peak of 44.40 MPa at 10% CWP, followed by 43.20 MPa at 5% CWP, while the lowest value of 32.80 MPa was observed at 30% replacement. At the highest w/b ratio of 0.5, compressive strengths were consistently lower across all curing ages. The 7-day strength ranged from 19.72 MPa (control) to 13.41 MPa (30% CWP). The 28-day strength varied from 29.58 MPa to 22.48 MPa, while the 90-day strength ranged between 36.60 MPa (control) and 29.28 MPa (30% CWP). A marginal increase was observed at 10–15% CWP, but no significant enhancement beyond the control mix was noted.

Table 5 Hardened properties of the SCC mixes.

Mix ID	w/b ratio	CWP (%)	Avg. Compressive Strength (MPa)			Avg. Split Tensile Strength (MPa)			Avg. Flexural Strength (MPa)
			7 day	28 day	90 day	7 day	28 day	90 day	28 day
W1C00	0.45	0	21.64	32.46	40	2.47	3.03	3.73	5.32
W1C05	0.45	5	19.25	29.76	43.2	2.28	2.73	3.28	6.08
W1C10	0.45	10	18.98	29.66	44.4	2.3	2.72	3.21	4.97
W1C15	0.45	15	18.18	30.02	40.8	2.33	2.75	3.21	5.27
W1C20	0.45	20	17.53	28.89	37.6	2.32	2.74	3.2	4.84
W1C25	0.45	25	16.88	26.78	36.6	2.28	2.66	3.11	4.5
W1C30	0.45	30	15.58	25.32	32.8	2.21	2.59	3.02	4.17
W2C00	0.5	0	19.72	29.58	36.6	2.1	2.58	3.17	5.98
W2C05	0.5	5	15.91	25.39	34.62	1.88	2.17	2.51	5.45
W2C10	0.5	10	15.98	25.5	36.09	1.93	2.19	2.52	4.02
W2C15	0.5	15	16.36	26.11	34.73	1.97	2.23	2.58	4.8
W2C20	0.5	20	15.58	25.53	33.96	1.91	2.18	2.52	4.87

W2C25	0.5	25	15.05	23.96	33.19	1.86	2.09	2.41	4.77
W2C30	0.5	30	13.41	22.48	29.28	1.82	2.06	2.36	4.72

Overall, compressive strength decreased with increasing w/b ratio and higher CWP replacement levels (>15%), while moderate replacement levels (5–10% CWP) showed comparable or improved long-term strength. Strength gain from 7 to 90 days was evident across all mixes, indicating continued hydration and microstructural densification. In general, mixtures containing moderate replacement levels exhibited strength values that were comparable to, or only slightly lower than, those of the control mix, whereas mixtures with excessive replacement showed a distinct reduction in compressive strength. This pattern was widely reported in ceramic waste-based cementitious systems and was usually attributed to the balance between beneficial filler action and adverse cement dilution. At early curing ages, the reduction in strength at higher replacement levels may be explained by the lower amount of Portland cement available for hydration. Since ceramic waste powder does not contribute to clinker hydration in the same manner as cement, excessive replacement reduces the amount of primary calcium silicate hydrate formed during the early period. At later ages, however, some recovery in strength may occur where the ceramic waste powder possesses sufficient fineness and reactive silica or alumina content, allowing limited pozzolanic interaction and matrix densification.

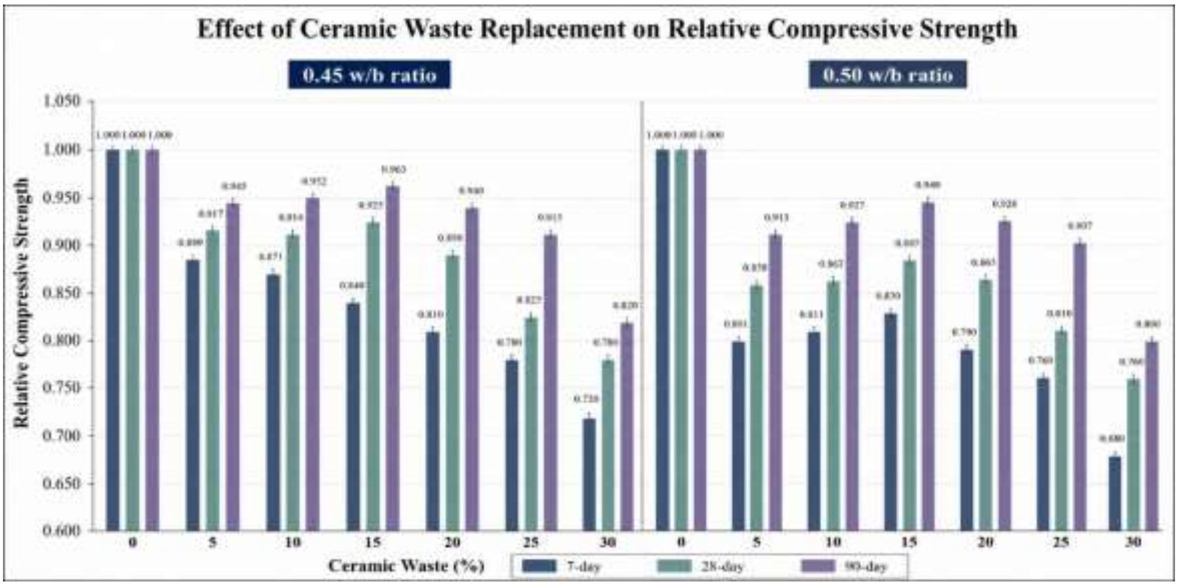

Figure 6 Compressive Strength

The relative strength of each mix with reference to control mix at each w/b ratio is shown in Figure 6. The variation of relative compressive strength of SCC with CWP exhibits a consistent trend. At w/b of 0.45, the strength varies between 0.742 and 1.000, with all mixes showing values below or close to the control, and a continuous reduction beyond 10–15% replacement. At w/b of 0.5, the reduction is more pronounced, with strength values ranging from 0.680 to 1.000, and significant decreases observed at higher replacement levels (≥20%). Across both w/b ratios, compressive strength increases with curing age, with 90-day values consistently higher than 28-day and 7-day values, indicating continued strength development. The influence of increasing w/b ratio is clearly reflected in reduced strength across all replacement levels.The influence of high water-to-binder ratio was also pronounced in the compressive strength response. Although increased water content may assist fresh-state mobility, it generally produces a more porous hardened matrix once the excess water evaporates. Accordingly, mixes cast at higher water-to-binder ratios showed lower compressive strength compared with corresponding mixes at lower water-to-binder ratios. This indicates that the effect of ceramic waste powder should not be interpreted in isolation, because the beneficial filler effect can be overwhelmed by the detrimental increase in capillary porosity created by excessive water. The optimum compressive-strength response was therefore expected at a moderate ceramic waste powder replacement level combined with a controlled high water-to-binder ratio. In this condition, the powder content was sufficient to improve particle packing and paste cohesion, while the amount of cement retained in the system remains adequate to sustain hydration and strength development. Beyond this optimum region, the combined influence of dilution and porosity causes a measurable decline in load-bearing capacity.

Split tensile and flexural strength

The split tensile and flexural strength results followed the general pattern observed in compression, but these properties appeared to be more sensitive to changes in microstructural continuity. The split tensile strength relative to the control mix are shown in Figure 7. For w/b of 0.45, the 7-day strength ranged from 2.47 MPa (0% CWP) to 2.21 MPa (30% CWP). At 28 days, values decreased from 3.03 MPa to 2.59 MPa, while 90-day strength reduced from 3.73 MPa (control) to 3.02 MPa (30% CWP). The intermediate replacement levels (10–20%) exhibited relatively stable values, with 28-day strength in the range of 2.72–2.75 MPa and 90-day strength between 3.20–3.21 MPa. At the highest w/b ratio of 0.5, tensile strengths were consistently lower. The 7-day strength decreased from 2.10 MPa (control) to 1.82 MPa (30% CWP). The 28-day strength ranged from 2.58 MPa to 2.06 MPa, while the 90-day strength varied between 3.17 MPa and 2.36 MPa. Slight increases were observed at 10–15% CWP, but no values exceeded those of the control mix. At lower replacement levels (5–10% CWP), the relatively small reduction in tensile strength suggests that the filler effect and improved particle packing compensate for the reduction in cement content. However, as the replacement level increases beyond 15–20%, the dilution of cementitious phases becomes dominant. Since ceramic waste powder exhibits limited pozzolanic reactivity compared to conventional supplementary cementitious materials, the formation of C–S–H gel is reduced, leading to a weaker and brittle matrix. Tensile strength, being highly sensitive to microcrack propagation, is adversely affected by this reduction in binding phases.

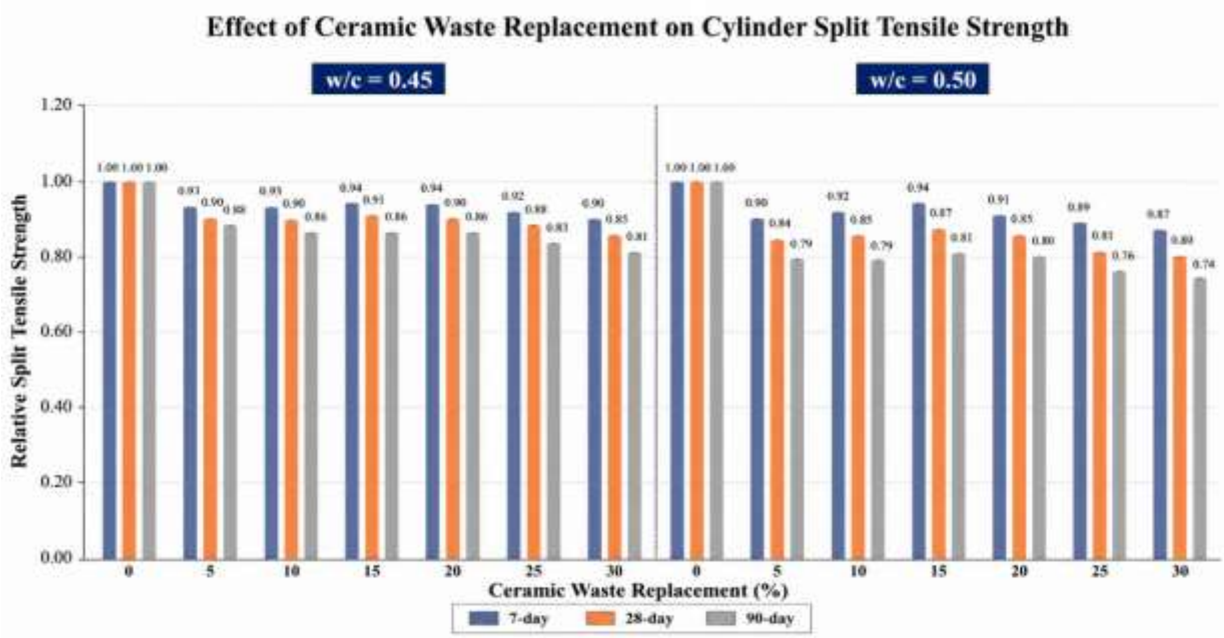

Figure 7 Split tensile strength

The 28-day flexural strength (f_r) of SCC mixes evaluated with CWP is reported in
Table **5**. For w/b of 0.45, the strength increased from 5.32 MPa (control) to 6.08 MPa at 5% CWP, then decreased progressively to 4.17 MPa at 30%. At w/b of 0.5, the control mix exhibited 5.98 MPa, with a general reduction to 4.02 MPa at 10% CWP, followed by slight recovery and stabilization within 4.72–4.87 MPa for higher replacements. Overall, the flexural strength ranged between 4.02 MPa and 6.17 MPa, with peak values observed at low to moderate replacement levels depending on w/b ratio. The variation in flexural strength is governed by the combined effects of particle packing, microcrack resistance, and matrix continuity. At lower replacement levels (5–10% CWP), the improvement in flexural strength, at w/b of 0.45, can be attributed to the filler effect, which enhances packing density and reduces microvoids, thereby improving resistance to crack initiation and propagation. The fine and angular nature of CWP contributes to improved inter-particle friction and bond strength within the matrix. However, beyond this optimum range, the dilution of cementitious content reduces the formation of C–S–H gel, weakening the matrix and leading to reduced flexural capacity. Increased w/b ratio further reduces flexural strength due to higher porosity and weaker ITZ, consistent with SCC behavior. Overall, an optimum CWP range of 5–10% is identified for maintaining flexural performance while ensuring adequate SCC stability.

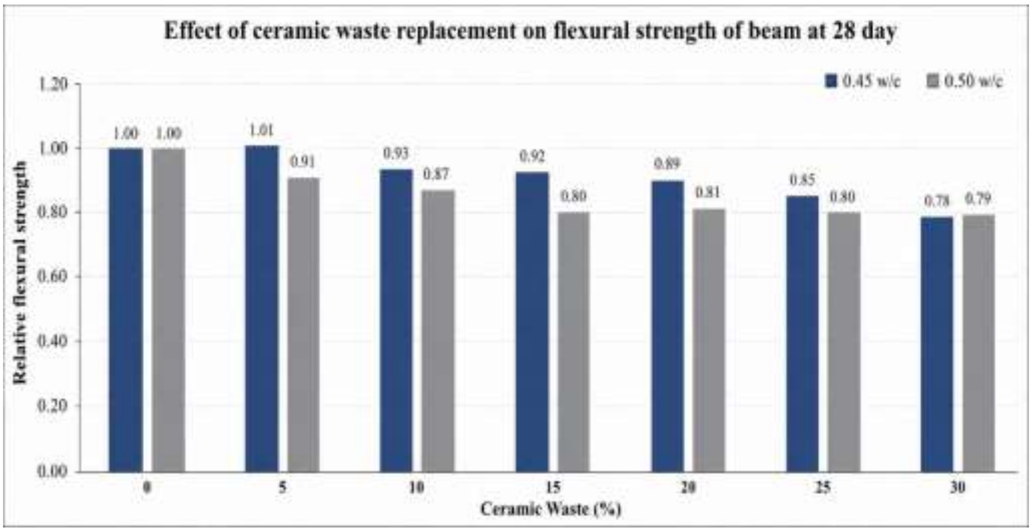

Figure 8 Flexural strength

The most important outcome of the present study was the identification of how high water-to-binder ratio modifies the effect of ceramic waste powder in self-compacting concrete. The results show that ceramic waste powder can be beneficial only when the water-to-binder ratio remains within a controlled upper range. At moderate levels, the powder assists in maintaining cohesiveness and contributes to matrix refinement. At excessive levels, however, the increase in free water creates a porous hardened structure that dominates the overall behavior and reduces both strength and durability. This finding confirms that the role of ceramic waste powder in SCC was not independent of mixture water content. A replacement level that appears suitable at one water-to-binder ratio may become ineffective or even detrimental at another. Accordingly, the paper contributes to the field by showing that the practical use of ceramic waste powder in SCC should be evaluated through a coupled mix-design approach rather than through replacement percentage alone. The study therefore provides a more realistic understanding of SCC design for sustainable construction. Instead of assuming that ceramic waste powder will always improve performance, the results indicate that its value lies in careful proportioning. This conclusion was particularly relevant for large-scale implementation, where slight changes in water content can produce substantial variation in workability, stability, and service-life behavior. In comparison with prior SCC-related work, the present study offers added significance by explicitly focusing on elevated water-to-binder ratio, which was often mentioned as an influential variable but less frequently isolated as the core research factor.

Conclusions

Ceramic waste powder is a feasible partial cement replacement material for self-compacting concrete, but its effectiveness depends on both replacement percentage and water-to-binder ratio. Thus it also satisfies the higher powder requirements in SCC without increasing cement content.

Ceramic waste powder replacement in the range of 5-15%, preserved the fresh-state requirements of SCC, whereas higher dosages reduced filling ability and passing ability due to increased powder fineness and water demand.

The water-to-binder ratio of 0.5 improved the apparent flowability of the mixtures, but excessive values impaired stability and negatively influenced hardened performance.

The compressive, tensile, and flexural strengths of SCC were best maintained at moderate ceramic waste powder replacement levels (5-15%), while excessive replacement produced a clear dilution effect and reduced binder efficiency.

The optimum mixture should therefore be selected on the basis of combined fresh and mechanical criteria rather than compressive strength alone.

Overall, the study demonstrates the potential of ceramic tile waste powder to support sustainable SCC production through partial cement replacement, provided that mixture proportioning is carefully optimized.

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