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ORIGINAL ARTICLE

Optimizing ceramic waste powder ratios for cost and CO_2 emission reduction in high-strength concrete to enhance efficiency and sustainability

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Abstract: Ceramic waste abundant in construction, is typically landfilled due to its brittleness but emerges as a promising cement substitute because of its unique chemical constitution. This investigation aims to expand the utilization of ceramic waste, exceptionally eco-friendly sanitary ceramic waste powder (SCWP) and tiles ceramic waste powder (TCWP), as a substitute for cement to produce sustainable HSC. Eleven HSC mixes incorporating ceramic waste at up to 50% were examined, assessing mechanical properties as compressive, splitting tensile, and flexural strength alongside elasticity modulus. Additionally, durability factors were conducted, including chloride penetration resistance, Sorptivity coefficient, microstructure analysis, and EDX tests. Economic and environmental evaluations encompassed cost analysis, CO2 emissions, and energy consumption. Results demonstrate that incorporating up to 50% of ceramic waste does not compromise concrete's compressive strength, exceeding 60 MPa targets. Relative tensile strength, flexural strength, and modulus of elasticity showed enhancement, notably with 40% TCWP. After 28-day curing, chloride ion penetration decreased by 6.16% compared to conventional mixes with 30% SCWP and TCWP. Economic and environmental analyses revealed significant reductions in CO2 emissions, energy consumption, and the binder OPC/ CWP cost by more than 47 %, 39 %, and 34.9 %, respectively, with 50% SCWP and TCWP. Ceramic waste proves viable as a binder material in sustainable HSC up to 40%, offering cost reductions.

Keywords: Sustainable high strength concrete, ground ceramic powder, Sanitary ceramic powder, CO_2 emission; durability, compressive strength.

1 Introduction

The global populace has recently encountered significant hurdles concerning properly disposing of generated waste and materials recycling, with no clear final destination. Considerable attention has been directed towards addressing these challenges. For instance, data indicates that the worldwide manufacture of ceramic tiles amounted to approximately 13.70 billion square meters [1]. It is noteworthy that a substantial proportion, approximately 30%, of materials within the ceramic industry are rendered waste. In Brazil, ceramics contribute to about 10% of production loss [2]. Unfortunately, a significant portion of this waste is often disposed of improperly, leading to environmental contamination. However, it is imperative to recognize that such waste can potentially serve as valuable

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raw material, offering solutions to numerous industrial dilemmas [3, 4]. The Portland cement production process is responsible for approximately 5% of the primary greenhouse gas emissions worldwide, specifically carbon dioxide (CO_2) [5, 6]. Although there is a growing need for concrete, which is tied to both rapid global development and the expansion of the construction sector, cement is still the most important and costly factor of concrete mixtures. A sustainable method for reducing the negative effects of cement production on the climate and making sustainable concrete is a partial or complete replacement of cement [7, 8]. Waste materials from the ceramic industry's production range from 15% to 30%. Consequently, waste materials from the ceramic industry's production range from 15% to 30%. As a consequence of processing ceramics, ceramic waste is created. These wastes bring pollution of the groundwater, air, and land. Right now, this refuse is not being recycled in any way [9]. There are several applications for ceramic waste recycling, such as thermal performance, infiltration, cement additives, construction materials, and desulfurization methods [10, 11]. Furthermore, as well as in polymer-based composites, mortar, concrete additives, and clay-based materials [12]. Additionally, many experimental studies show that materials similar to concrete with the addition of ceramic waste have excellent workability and strength qualities similar to those of conventional material [13, 14]. The studies examined the probable use of ceramic waste powder (CWP) as an incomplete substitute for OPC in concrete compositions characterized by different cement contents. Mohsen Ebrahimi conducted an experimental study to assess the effect of CWP as a replacement for binders in both OPC and lime-based stonework mortars. The study encompassed replacement rates ranging from 0% to 60% for cement mortars and 0% to 80% for lime-based mortars, with specimens subjected to moist curing for up to 90 days. Results indicated that the compressive and tensile strengths of OPC mortars incorporating CWP exhibited no expressive adverse effects up to a 50% substitution rate, with improvements observed particularly in the substitution range of 10% to 20% [15]. Le L et al. explored pertinent properties of concrete infused with CWP as a cement substitute. Their findings revealed that water absorption and compressive strength variations remained within standard tolerances when 20% CWP replaced OPC [16]. Dima M. Kannan et al. the evaluation of HPC mixtures using 10–40% CWP as a mass substitute for OPC [7]. HPC mixtures were the subject of mechanical, durability, and microstructural studies. Concrete that uses CWP as a significant substitution for OPC has been shown to have great strength and excellent durability. Microstructure studies revealed that compared to cement without CWP, adding CWP had no appreciable impact on cement hydration. The performance increase is because the reference mixture's low water/cement ratio allowed CWP to produce dense packing particles. Irassar et al. [17]. Investigated the use of CWP as pozzolanic materials and found that adding CWP to OPC mimics hydration by increasing the system's effective water-to-cement ratio. Although it was asserted that excellent pozzolanic action was seen at 28 d, no pozzolan activity was seen at young periods with replacement between 8 and 40%. The effects of using tile ceramic waste powder (TCWP) to replace OPC in concrete or mortar have been studied [18–20]. The results show that using no more than 30% TCWP has no negative effects on the mechanical properties of concrete and using 15% ceramic waste to replace OPC in mortar-produced with comparable strength to OPC control for up to 56 days and greater strength at 90 days. The cementitious system mixed with TCWP created a lot of calcium silicate hydrate gel (C-S-H gel) because TCWP can change with CH for 28 days. The findings indicate that HPC incorporating CWP exhibits elevated strength and commendable durability. However, it was observed that including CWP reduces chloride ion permeability [21, 22]. Hoppe Filho et al. [23] assessed the blended mortar's mechanical and microstructure attributes, wherein 30% of OPC was substituted with CWP. Their analysis revealed a potential decrease in compressive strength of up to 16% after 182 days. Nevertheless, SEM examinations highlighted a denser structure attributed to the pozzolanic responsiveness of CWP, consequently leading to diminished chloride ion penetration and improved durability [24].The pozzolanic activity gradually progressed, declining early-age compressive strength [25]. Additionally, Al Arab et al. [26] corroborated the pozzolanic response of CWP in OPC-slag mortar compositions. Additionally, ground ceramics were utilized to substitute 10–40% of OPC in the production of HPC. The studies that have already been conducted primarily concentrated on how ceramic waste affected the characteristics of HPC [21]. Defalla R et al. [27] demonstrated that replacing ceramic waste aggregates can enhance the properties of concrete, particularly with a 10% substitution of the original material. Studies on using TCWP as a cementitious component for high-strength concrete are still scarce. The CWP, on the other hand, is incredibly resilient to physical, chemical, and biological deterioration. Ceramic manufacturers are burdened with locating an appropriate remedy for ceramic degradation because the amount of CW is rising daily. For instance, by substituting a small quantity of crushed vitrified soil aggregates for broken stone coarse aggregates, the modulus of elasticity of HSC has been enhanced. Compressive strength stayed constant when CW was used instead of typical crushed stone coarse aggregates [28]. The administration of raw resources and the reusing of industrial waste depend on the characteristics of CW as aggregate. Most earlier studies [29, 30] concentrated on fine and coarse aggregates or a separate cementitious plan involving refuse sanitaryware, earthenware, tile, and electrical insulators. Due to their characteristics and to preserve the ecosystem and manage resources, waste materials from buildings and explosions have been reused as aggregates through the past few contracts. Concrete from these waste products showed several improvements [31, 32].

Recent research highlights ceramic tile powder particles as cost-effective waste materials with the potential to address solid waste disposal challenges while mitigating environmental contamination [33]. Leveraging ceramic waste presents a promising avenue for advancing waste-recycling efforts and bolstering environmental conservation[34]. International standards have increasingly advocated utilizing industrial waste, including ceramic waste, in cement production due to its beneficial attributes in science, technology, and environmental sustainability, particularly in terms of durability [35]. Consequently, numerous studies have shown cased that tailored combinations of diverse ceramic waste types hold promise for generating eco-friendly building materials and fostering environmentally conscious practices within the construction domain [36]. Such strategies yield positive environmental outcomes and play a pivotal role in sustainable improvement, a critical aspect of the construction industry [36]. These initiatives reduce energy consumption and CO_2 emissions connected with binder manufacturing while mitigating landscape depletion linked to industrial binder and aggregate production. Thus, they curtail the carbon footprint from mining activities that often damage landscapes and river ecosystems [37, 38]. Considering that the energy impact of producing 1 Kg of OPC clinker is about 850 k/cal and cement constitutes over 45% of concrete costs, integrating industrial or byproducts in place of OPC in concrete formulations yields significant environmental and energy savings advantages [35, 39]. Furthermore, such practices can substantially reduce concrete costs [35]. The prime cause of HSC's high price is one of its components (i.e., cement). Cementitious materials are widely used in HSC, being over 500 kg/m^3 compared to traditional concrete, about 350 kg/m^3. This leads to high costs, increased CO_2 emissions, climate change, and global warming by Amin et al. 2022 [40, 41]. Thus, increased efforts are required to improve environmentally friendly micromaterials and decrease the greenhouse influence with low prices.

1.1 Research Significance

Based on an initial literature survey, there remains a notable gap in the literature concerning a comprehensive investigation into HSC production involving the simultaneous incorporation of SCWP and TCWP. Additionally, numerous papers address various experimental studies and analyses about the synthesis of CWP, characterization, and integration into building materials at reduced ratios without comprehensively studying economic and environmental. Unfortunately, using such weak ratios significantly diminishes its effectiveness, limiting the advantages of SCWP and TCWP in concrete. Therefore, this study aims to expand the utilization of CWP, specifically eco-friendly SCWP and TCWP, as a substitute for OPC in producing sustainable HSC. This not only aids in reducing HSC production costs but also decreases CO_2 emissions and energy consumption. In this context, the current work addresses gaps in prior studies, such as the limited application ratio of SCWP and TCWP, which has resulted in considerable enhancements in the mechanical characteristics of HSC. Moreover, this study employs a distinctive strategy to extract essential Si from SCWP and TCWP. This study substituted cement with substantial proportions of these materials, up to 50% SCWP and 50% TCWP for microparticles. So, a comprehensive investigation was conducted, including an in-depth examination of performance characteristics, physical and mechanical behaviors, and long-term durability. Additionally, it applies to sustainable building practices with more economic return. The mechanical and durability characteristics of HSC mixtures were assessed through a comprehensive battery of standardized tests. These included tests for compressive, flexural strength, splitting tensile, and modulus of elasticity, chloride penetration resistance, Sorptivity Coefficient, Microstructure SEM analysis, and the EDX test. Finally, an economic and environmental study was conducted, these included cost analysis, CO_2 emissions, and energy consumption of all mixers. Thus, this study provides an in-depth exploration of the benefits and potential of reusing two different types of ceramic waste. It thoroughly examines the research background, processing techniques, material properties, microstructural studies, and the economic and environmental advantages of using these materials.

2 Experimental works

2.1 Materials

2.1.1 Cementitious materials

The cementitious materials were OPC (CEM I 52.5), utilized as the primary cementitious material. Portland cement properties were determined according to BSEN197/1 2011 [42] an ES 4756/1 2013 [43]. **Table 1** illustrates the physical and chemical characteristics of CEM I.

Table 1. Characteristics of cementitious materials, sanitary and tiles ceramic waste powder

Properties	CEM I	Silica fume	SCWP	TCWP
Physical				
Specific gravity	3.15	2.14	2.36	2.37
Specific area cm^2/gm	3520	19345	5480	5295
Color	Grey	Light Grey	White	White
Chemical compositions (%)				
SiO_2	22.25	98.73	72.75	71.69
CaO	60.72	0.25	0.67	1.16
Al_2O_3	5.73	0.28	19.25	17.55
Fe_2O_3	3.69	0.41	1.06	3.27
SO_3	2.45	0.04	1.85	2.95
MgO	2.67	0.07	0.57	2.48
K_2O	0.80	0.20	2.31	0.31
Na_2O	0.73	0.02	1.02	0.15
Loss on Ignition (LOI)	0.96	-	0.52	0.44

Silica fume (SF) consumed in this study was sourced from Sika company based in Egypt. The characteristics of the SF are detailed in **Table 1.** The SF employed can be classified as high-silica materials, meeting the specifications outlined in ASTM C1240 standard [44].

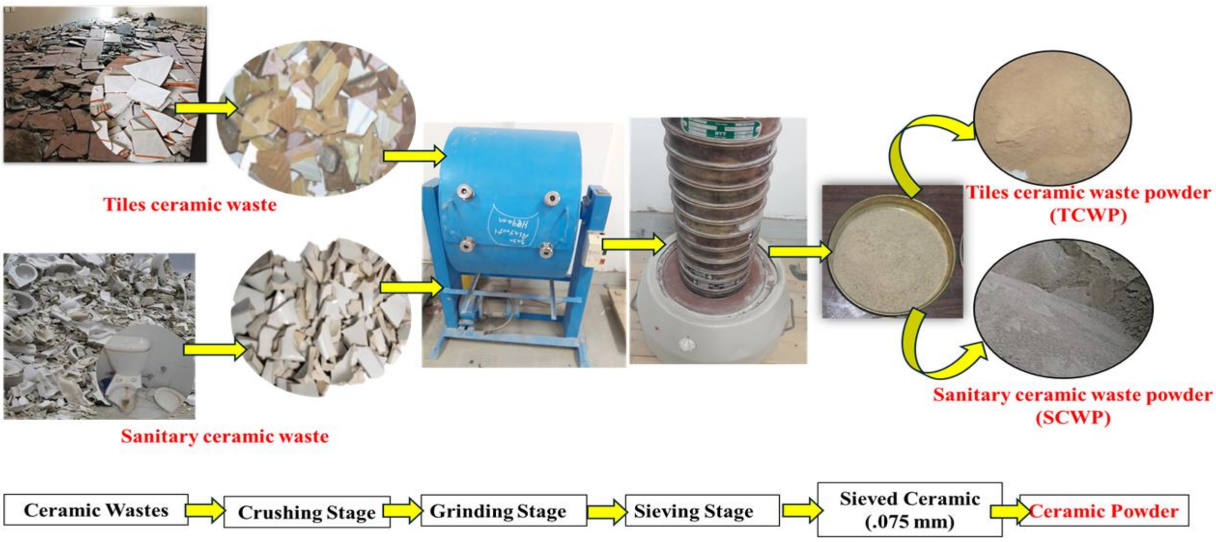

Fig. 1. The process for producing SCWP and TCWP from ceramic waste.

Ceramic wastes, predominantly comprising sanitary and tiles ceramic waste of various colors, were sourced from construction sites in New Mansoura City, Egypt, as depicted in **Fig 1.** Subsequently, these wastes were crushed using a jawbone crusher machine to produce ceramic waste powder (CWP). The SEM and EDX properties of SCWP and TCWP from ceramic waste are illustrated in **Fig 2. Fig 2 a**.

shows a chemical analysis of SCWP and indicates that Si is 27.80 %, while Al is 12.16 %, the main active component of pozzolanic material. The SEM image shows that the particles are generally well milled, having sizes between 4.4 and 6.4 µ and mostly irregular shapes, increasing the material's reactive surface. These morphological features bring out the required compatibility with cement, making it appropriate for partial replacement with several durability and mechanical benefits to concrete. As shown in **Fig 2 a**., the chemical composition of TCWP highlights a Si content of 23.21% and Al of 9.20%, which are key components for pozzolanic activity, though their proportions are lower than SCWP. The material also contains a notable CaO content of 7.25%, which can contribute to cementitious reactions. The SEM image reveals particles with a slightly larger size range (2.6–8.3 µ) and irregular morphology. While the increased calcium content suggests potential for partial self-cementitious behaviour, the particle morphology still ensures sufficient surface area for pozzolanic reactions, making TCWP a viable partial cement replacement for improving concrete properties. The physical and chemical properties of sanitary ceramic waste powder (SCWP) and tiles ceramic waste powder (TCWP) are detailed in **Table 1**. In this study, CWP served as a partial substitution for cement in the experimental investigation.

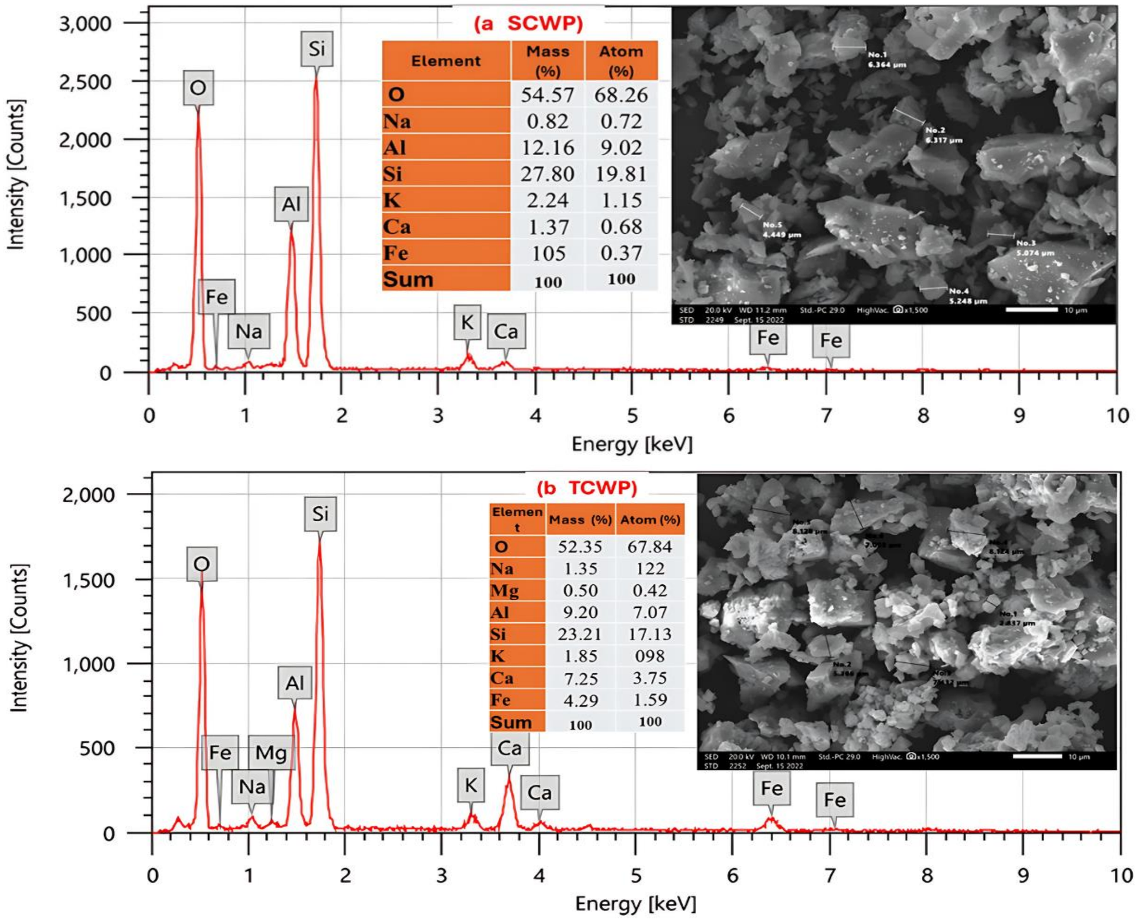

Fig. 2. The SEM and EDX properties of SCWP and TCWP from ceramic waste.

2.1.2 Aggregates

The coarse aggregate comprised ordinary crushed stone, specifically dolomite, with a maximum minimal size of (19 mm). Its specific gravity was (2.68), with an absorption rate of (0.94%). The fine aggregate of normal sand was utilized, possessing a fineness modulus and specific gravity of 2.44 and 2.65, respectively. The characteristics of sand and crushed aggregates were assessed per ECP 203-2017 [45] and ASTM C33/C33M-18 [46]. Details regarding the characteristics of sand and dolomite can be found in **Table 2. Fig. 3** shows the grading curve of the aggregates used.

Table 2. Physical-mechanical properties of aggregates

Chemical composition	Sand	Dolomite
Specific gravity	2.65	2.68
Unit weight (kg/m³)	1680	1665
Water absorption (%)	0.77	0.94
Clay and fine materials (%)	0.46	0.75
Impact value (%)	-	11.6
Crushing value (%)	-	13.1
Los Angeles abrasion loss (%)	-	15.3

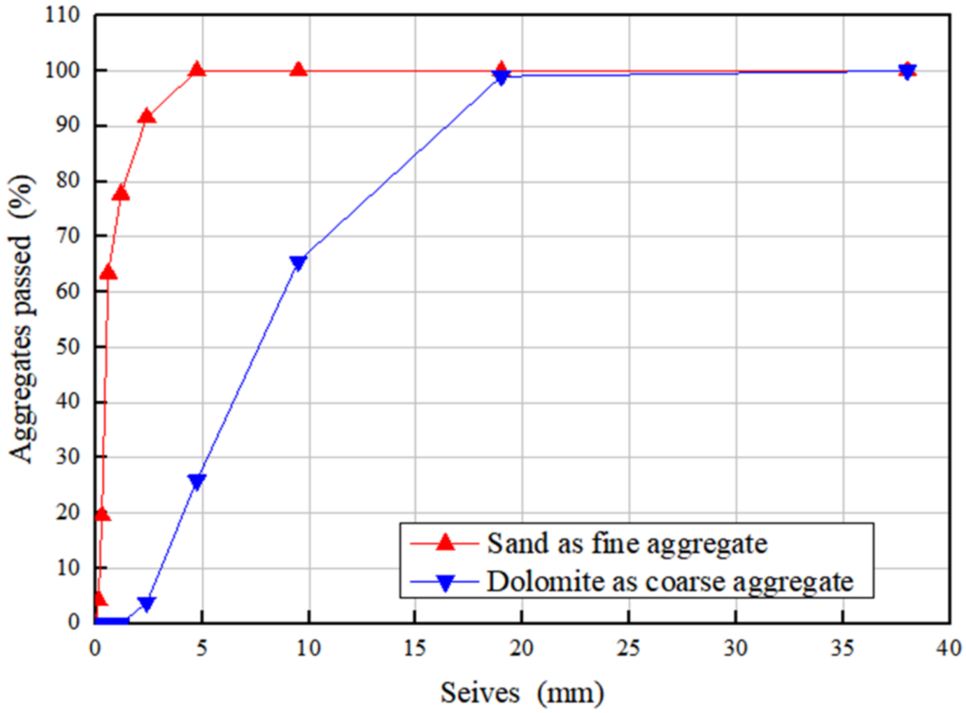

Fig. 3. Grading curve of aggregates

2.1.3 Superplasticizer

In this experimental study, superplasticizer (SP) was utilized as a high-range water-decreasing admixture. SP content of 3.0% of cementitious materials was admixed in HSC blends. The SP utilized met the specified standards, with a clear liquid color and a specific gravity of 1.1, per ASTM C 494/C 49M-17 Type G [45].

2.2 Mix Proportion

The reference mixture included only 1 sand to 1.5 dolomite with a cement content of about 500 kg/m^3, silica fume of about 75 kg/m^3 by 15% by weight of cement (without replacement ceramic waste powder) to complete a slump rate of 10 cm, and a compressive strength of about 60 MPa. SCWP and TCWP were replaced 10, 20, 30, 40, and 50% by weight of cement in HSC mixes, as replacements were prepared with a consistent water/binder ratio (w/b) of 0.23, ensuring uniformity across all mixtures. The constituent materials were placed into the mixer at the mixing stage and blended for approximately 5 minutes. Following 24 hours, the prepared samples were eradicated from their molds and repositioned in a curing room preserved at a constant temperature of 24±2 ℃ by ASTM C192 [46], as shown in **Fig. 4a**. Subsequently, these samples underwent water curing until the designated testing ages. **Table 3** shows the mix q for various HSC mixes. CEM stands for cement in the mixture, and a number beside CEM shows the percentage of cement in the combination. SCWP is short for Sanitary Ceramic Waste Powder, and TCWP is for Tiles Ceramic Waste Powder. The numbers after SCWP or TCWP show the proportion of such waste materials partially replacing cement in the mixture.

Table 3. Proportions of HSC mixtures

Mixture ID	CEM I (%)	Aggregates Sand (%)	Aggregates Dolomite (%)	Silica fume (%/CEM)	Sanitary ceramic waste (%/CEM)	Ground ceramic waste (%/CEM)	SP (%/CEM)	W/b
CEM 100	100	40	60	15	0	0	3	0.23
CEM 90-SCWP10	90	40	60	15	10	0	3	0.23
CEM 80-SCWP20	80	40	60	15	20	0	3	0.23
CEM 70-SCWP30	70	40	60	15	30	0	3	0.23
CEM 60-SCWP40	60	40	60	15	40	0	3	0.23
CEM 50-SCWP50	50	40	60	15	50	0	3	0.23
CEM 90-TCWP10	90	40	60	15	0	10	3	0.23
CEM 80-TCWP20	80	40	60	15	0	20	3	0.23
CEM 70-TCWP30	70	40	60	15	0	30	3	0.23
CEM 60-TCWP40	60	40	60	15	0	40	3	0.23
CEM 50-TCWP50	50	40	60	15	0	50	3	0.23

2.3 Test procedures

Workability assessment for the HSC mixes was conducted through the slump test, following the procedures charted in ASTM C 143 [47] and BS EN 12350-2:2009 [48]. Compressive strength testing was worked on cubic samples (100 mm) after 1, 7, 28, and 91 days, adhering to BS EN 12390-3 [49]. Splitting tensile strength (TS) assessment was functioned on cylindrical specimens 150 mm ×300 mm at 28 days under ASTM C 496 [50]. Flexural strength (FS) tests were performed on HSC beams with dimensions of (100 mm, ×100 mm ×500 mm) at 28 days, as outlined in ASTM C 78 [51]. Modulus of elasticity testing was performed on cylindrical specimens (150×300 mm) at 28 days, as outlined in ASTM C 469 [52]. The mean value of three trials was recorded as the strength rate at all testing ages, as shown in **Fig.4b**. Additionally, the resistance to chloride penetration was evaluated using tests conforming to ASTM C 1202-17 [53]. Disc samples (100 mm) in diameter and (50 mm) in thickness were employed for this purpose. The sorptivity test, indicating the water absorption ratios, was conducted according to the procedure outlined in ASTM C1585-13 [54], utilizing standard test samples measurement (100 mm) in diameter and (50 mm) in length.

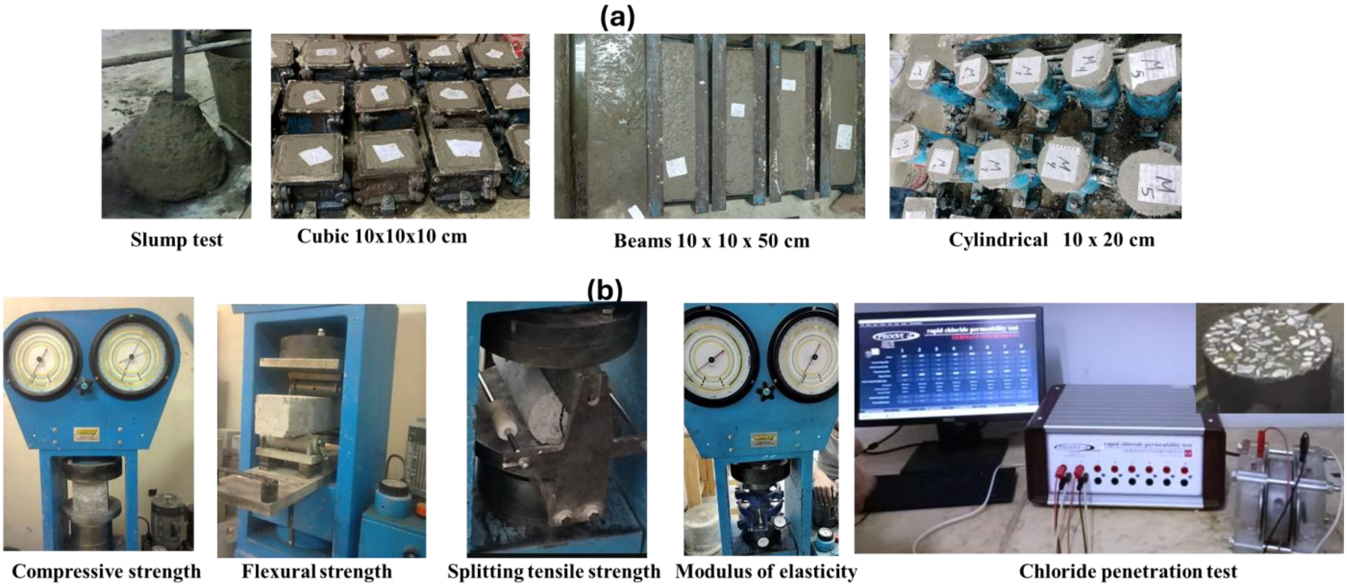

Fig. 4. a) Fresh test and casting concrete in models; b) Hardened test of specimens.

2.4 Economic and Environmental Study

In this investigation, the environmental benefits and sustainability of HSC were examined by evaluating the full spectrum of production costs, CO_2 emissions, and energy consumption associated with OPC, SCWP, and TCWP. The estimated data, as detailed by Mostafa S. et al. [1], is summarized in **Table 4.** The OPC exhibited an energy expenditure of 5.13 GJ/ ton, whereas SCWP and TCWP demonstrated lower energy requirements at 1.12 and 1.13 GJ/ ton, respectively. Regarding CO_2 emissions, OPC displayed a notably higher release of greenhouse gases at 0.904 ton/ton compared to the significantly lower emission rate associated with CWP at 0.045 ton/ton [1]. Furthermore, the production cost analysis revealed stark differences, with OPC recording the highest cost at $44 per ton, while SCWP and TCWP incurred lower costs of $12.46 and $12.35 per ton, respectively. **Table 5** delineates the individual costs of raw materials, as well as the expenses involved in SCWP and TCWP production, including grinding and sieving processes, based on market prices in Egypt. Additionally, the table presents the costs of various HSC mixtures per cubic meter, considering different combinations of binders, such as cement with and without SCWP and TCWP (i.e., cost of P.O /RHA ($/m^3)). Reducing the OPC content of the HSC samples was imperative to curtail energy consumption and production costs, thereby enhancing greenhouse gas emissions and overall product sustainability.

Table 4. Energy consumption, cost of production, and CO_2 emission for SCWP, TCWP, and OPC [1]

Cementitious materials	Energy consumption (GJ/ton)	Cost ($/ton)	CO_2 (ton/ton)
OPC	5.13	44	0.904
SCWP	1.13	12.46	0.046
TCWP	1.12	12.35	0.045

Table 5. Proportions of HSC mixtures kg/m^3

Mixture ID	CEM I	Sand	Dolomite	Silica fume	Sanitary ceramic waste	Ground ceramic waste	SP	Water	*Cost of OPC /CWP ($ /m^3)
CEM 100	500	702.5	1053.8	75	0	0	17.25	132.25	22.0
CEM 90-SCWP10	450	695.3	1043.0	75	50	0	17.25	132.25	20.5
CEM 80-SCWP20	400	689.7	1034.6	75	100	0	17.25	132.25	18.9
CEM 70-SCWP30	350	684.0	1026.0	75	150	0	17.25	132.25	17.4
CEM 60-SCWP40	300	678.4	1017.6	75	200	0	17.25	132.25	15.9
CEM 50-SCWP50	250	672.7	1009.1	75	250	0	17.25	132.25	14.3
CEM 90-TCWP10	450	695.3	1043.0	75	0	50	17.25	132.25	20.5
CEM 80-TCWP20	400	689.7	1034.6	75	0	100	17.25	132.25	18.9
CEM 70-TCWP30	350	684.0	1026.0	75	0	150	17.25	132.25	17.4
CEM 60-TCWP40	300	678.4	1017.6	75	0	200	17.25	132.25	15.8
CEM 50-TCWP50	250	672.7	1009.1	75	0	250	17.25	132.25	14.3
*Cost of material ($/kg)	0.044	2.660 $/m^3	4.433 $/m^3	1.077	0.013	0.013	1.830	0.003	

3 Results and Discussion

Table 6 displays the test outcomes for slump by (mm), compressive strength by MPa (CS), splitting tensile strength by MPa (TS), flexural strength by MPa (FS), and modulus of elasticity by GPa (Ec).

3.1 Fresh Properties (Slump Test)

The concrete mixture underwent a slump test inspection before a cube mold was placed to cure. According to BS EN 12350-2:2009 [48], the concrete mixture underwent a slump test. The slump rates are displayed in Table 6 and **Fig. 5.** The Ref. mixture (CEM 100) showed about 118 mm of slump value. Slump values for mixtures containing SCWP exhibit a decrease with an increase in SCWP percentage. The 2.5%, 5.1%, 9.3%, 15.3%, and 21.2% reduction ratios for SCWP 10, 20, 30, 40, and 50%, respectively, contrasted to the conventional mix (CEM 100), indicate a notable impact on workability. The reduction in slump is attributed to the particular surface area of SCWP exceeding that of cement. This elevated surface area leads to increased water absorption by SCWP, affecting particle lubrication and subsequently diminishing the flowability of the concrete [55]. On the other hand, the slump values for mixtures containing TCWP also demonstrate a reducing leaning with an improvement in TCWP percentage. However, the reduction ratios (0.0%, 3.4%, 6.8%, 11.0%, and 16.9% for TCWP 10%, 20%, 30%, 40%, and 50%) are comparatively lower than those observed for SCWP as shown in **Fig. 5.** The reduction in slump values indicates the impact of TCWP on concrete workability. TCWP, originating from tile production waste, introduces fine particles with specific surface characteristics. Similar to SCWP, TCWP absorbs water, affecting lubrication between particles. The reduction in slump values is explained by the competition for water between cement and TCWP particles during hydration [56]. Both SCWP and TCWP exhibit a similar trend, with higher replacement percentages leading to more pronounced reductions in slump values. When comparing equivalent replacement levels, such as CEM 90-SCWP50 (i.e., 93 mm with a 21.2% decrease) and CEM 90-TCWP50 (i.e., 98 mm with a 16.9% decrease), TCWP tends to have a slightly higher slump. This difference may be attributed to particle size and shape variations, influencing ceramic waste powders' water demand and lubrication characteristics. These results align with findings from previous studies [55–57].

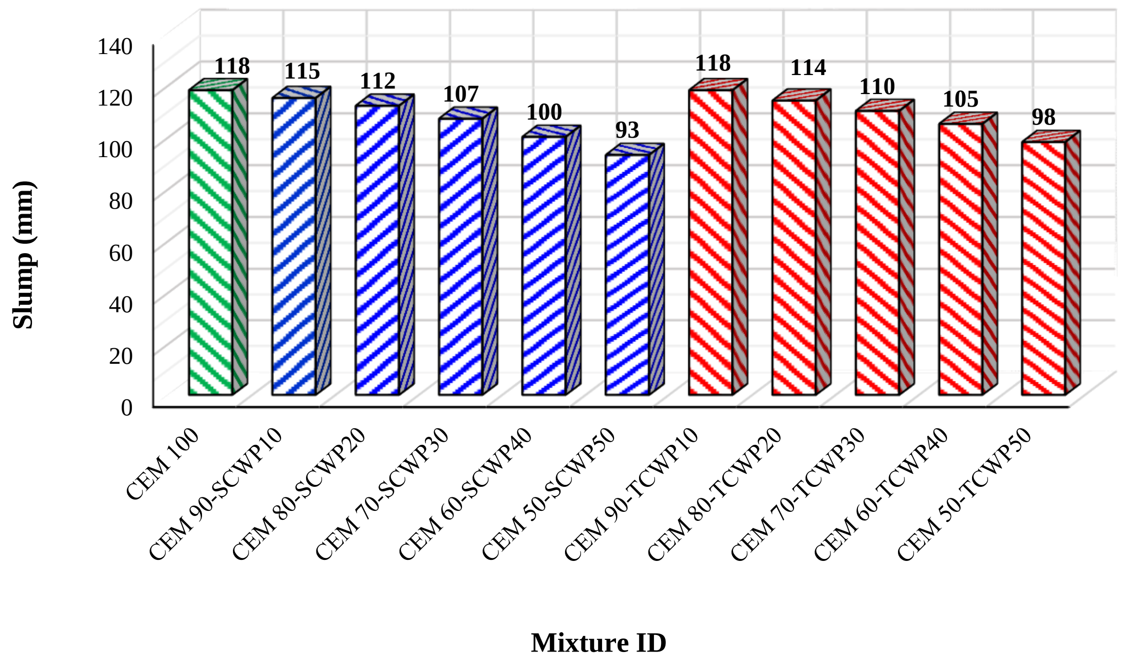

Fig. 5. Slump flow of HSC mixes with and without CWP

Table 6. The hardened properties and fresh properties of HSC combinations

Mixture ID	Slump (mm)	Compressive Strength (MPa)				Splitting Tensile Strength (MPa)	Flexural Strength (MPa)	Modulus of Elasticity (GPa)
		1 day	7 days	28 days	91 days	28 days	28 days	28 days
Mix without CWP	118	34	68.1	88.5	98.2	7.6	11.9	41.09
CEM 90-SCWP10	115	30.6	64	84.3	96.3	7.55	11.8	40.7
CEM 80-SCWP20	112	28.8	59.2	78	89.1	7.1	11	39.18
CEM 70-SCWP30	107	26.7	55.4	72.9	83.3	6.7	10.4	38.01
CEM 60-SCWP40	100	24.5	50.5	66.5	76.1	6.2	9.6	36.35
CEM 50-SCWP50	93	22.6	46.6	62.2	71.2	5.8	8.9	34.92
CEM 90-TCWP10	118	29.95	62.35	82.2	93.4	7.4	11.5	40.1
CEM 80-TCWP20	114	27.75	57.75	76.1	86.5	6.9	10.7	38.66
CEM 70-TCWP30	110	25.75	53.55	70.5	80.2	6.5	10	37.29
CEM 60-TCWP40	105	23.35	48.45	64.9	72.7	6.0	9.2	35.55
CEM 50-TCWP50	98	21.45	44.55	61	68.2	5.6	8.5	34.11

3.2 Mechanical properties

3.2.1 Compressive Strength (CS)

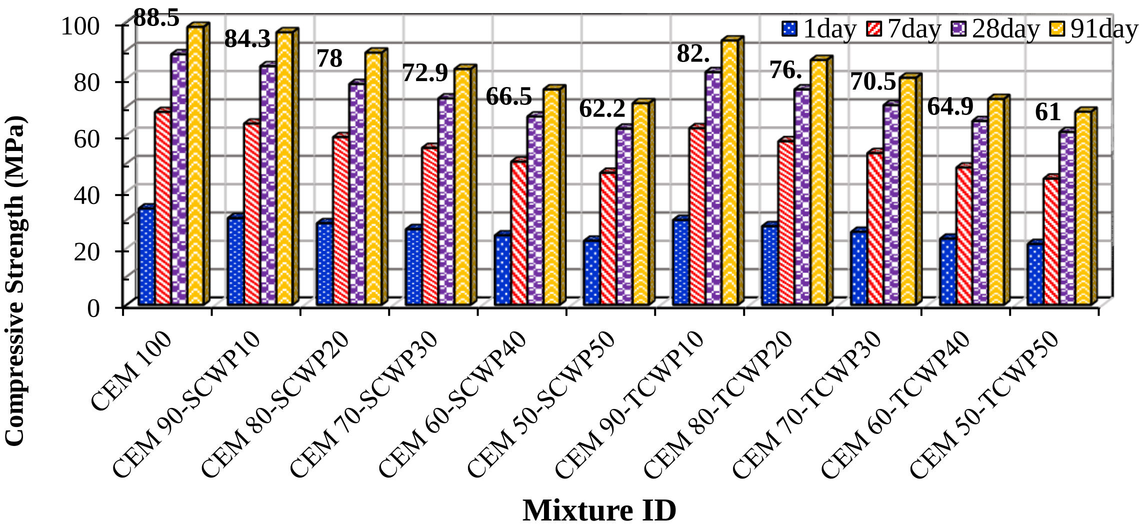

Fig. 6. Compressive Strength (MPa) of HSC samples with and without SCWP and TCWP

Table 6 and **Fig. 6** present the compressive strength (CS) outcomes on high-strength concrete cubes prepared by partially substituting Portland cement with SCWP and TCWP. An analysis of the CS of the cubes shows that it generally increases with curing age for replacement percentages up to 50%. Notably, the control mix displayed the highest strength values at early ages, recording 34 MPa and 68.1 MPa at 1 and 7 days, respectively. However, as the replacement percentage of SCWP and TCWP increased, a decrease in CS at 1 and 7 days was observed. This decrease is more pronounced during the initial curing phases and diminishes with more curing durations at 28. The compressive strength decreased at 7-day to 64, 59.2, 55.4, 50.5, and 46.6 MPa by 6, 13.1, 18.6, 25.8, and 31.6% for SCWP10, SCWP20, SCWP30, SCWP40, and SCWP50, respectively. The 28th-day CS varied between 84.3 and 62.2 MPa, decreasing about 4.7% to 29.7% for the same SCWP ratios. The reduction in strength observed can be linked to the oxide composition of Portland cement upon including SCWP. This decrease in early CS primarily stems from the incomplete pozzolanic response within the concrete and the hindrance of C–S–H gel growth by constituents present in SCWP powder during the initial stages [58]. These findings align with previous literature regarding the addition of ceramic waste [59]. Additionally, it is noted that during early curing stages, pozzolans primarily function as fillers and do not undergo pozzolanic reactions; this is consistent with prior research [59, 60]. However, The CS progressively approached those of the reference concrete with prolonged curing at 91 days of curing, particularly in samples containing up to 10 and 20% SCWP waste (reaching approximately 96.3 and 89.1 MPa). This enhancement in strength rates can be credited to the pozzolanic response of SCWP. The SCWP particles were nucleation sites for OPC grains and hydration products, leading to a denser SEM and compact packing [59, 60]. Conversely, the mixtures incorporating TCWP as a cement substitute exhibit slightly smaller CS than those containing SCWP at equivalent substitution ratios (i.e., 10, 20, 30, 40, and 50% TCWP) [35, 59]. As depicted in **Fig. 5**, there is a similarity in the CS outcomes achieved with up to 50% TCWP waste substitution compared to SCWP at equivalent ratios across all curing durations. Specifically, the compressive strength decreases at 28 days to 82.2, 76.1, 70.5, 64.9, and 61 MPa, representing reductions of 7.1%, 14.0%, 20.3%, 26.7%, and 31.1%, respectively, contrasted to the conventional mix, for substitution levels of 10, 20, 30, 40, and 50% TCWP. The CS at 90 days ranged from 93.4 to 68.2 MPa, declining by approximately 4.9% to 30.5% for the same TCWP ratios of 10% and 50%, respectively. Considering that the two ceramic waste materials employed in this study exhibited comparable particle size distributions and similar contents of SiO_2 + Al_2O_3 + Fe_2O_3 (as outlined in Section 2.1), the observed results primarily stem from the pozzolanic responsiveness of the amorphous stages generated throughout their production operations. Furthermore, the contribution of ceramic waste to early strength primarily hinged on its microfilming capacity, given that the particle sizes of SCWP and TCWP rated from 5 to 10 µm (as outlined in Section 2.1, **Fig. 2**). This increase in strength can be credited to the heavy effect of TCWP, resulting in a denser microstructure than SCWP samples. As illustrated in **Fig. 5**, all concrete incorporating up to 50% of both ceramic wastes (SCWP, TCWP) met the stipulations outlined in UNE EN 450–1 for fly ash (UNE, 2014) [61]. Moreover, these attained values surpassed the targeted strength of 60 MPa [56]. However, the compressive strength values exceeded 30% and 4% after 28 days and over 39% and 19% at 90 curing days for 30% and 50% SCWP, respectively. Similarly, the compressive strength values surpassed 18% and 2% after 28 days and over 34% and 14% at 90 curing days for 30% and 50% TCWP, respectively. Hence, ceramic waste demonstrates its potential as a binder material, slightly adversely impacting the concrete's mechanical properties [35]. These findings are consistent with prior research on utilizing CWP as a substitute for cement, as reported by references [55, 62–64].

3.2.2 The splitting tensile strength (TS)

After 28 days of curing, cylindrical specimens' splitting tensile strength (TS) measuring 15× 30 cm was assessed [50]. The experimental findings indicate that substituting cement with 10% to 30% SCWP particles developed a marginal reduction in the concrete's tensile strength. When 10%, 20%, and 30% SCWP were used, the Ts values of the mixes reduced to 7.55, 7.1, and 6.7MPa (0.8%. 7.6%, and 12.6% decreases) relative to the control mix (i.e., 7.6 MPa). As depicted in **Fig. 7**, the TS shows a clear downward tendency, with the rising content of SCWP up to 40% and 50%. An approximately 18% and 23.8% reduction in TS was noted for samples with 40% and 50% SCWP, respectively, analogized to the control sample. The relative TS relationship to compressive strength improved somewhat at 4.29% to 8.58% for specimens at 10 to 50% SCWP, respectively. The marginal decline in TS can be credited to the pozzolanic response between the CWP and the calcium hydroxide represented in the concrete[32, 65]. **Fig. 7** illuminated a comparable pattern in the TS of mixes incorporating TCWP as a cementitious material. The Ts decreased with a higher TCWP content in HSC, up to 50%, compared to a 50% SCWP substitution [66]. At 28 days of curing time, the TS value of TCWP mixed by 10, 20, 30, 40, and 50% TCWP was recorded as 7.4, 6.9, 6.5, 6.0, and 5.6MPa (2.6%, 9.2%, 14.5%. 21.1% and 26.3%decrease) respectively, compared to7.6 for CEM100. Besides, the relative TS relationship to compressive strength improved somewhat, at 4.83%, 5.58, 7.36, 7.66, and 6.9% for specimens with 10, 20, 30, 40, and 50% TCWP, respectively. These results from the tensile strength tests align with those reported in previous studies [65, 67].

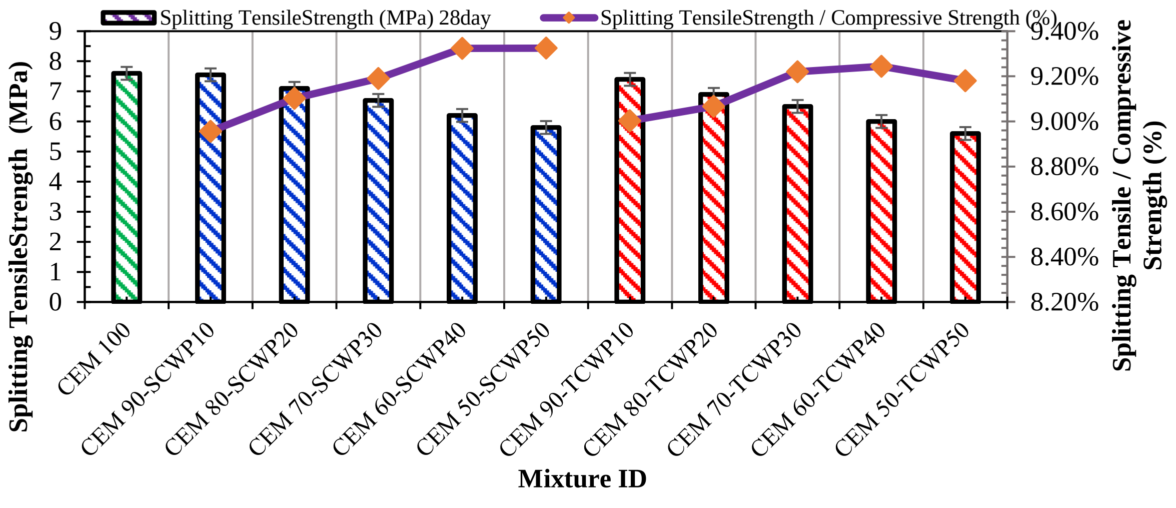

Fig. 7. Splitting Tensile Strength (MPa) and Splitting Tensile / Compressive Strength (%) of HSC samples with and without SCWP and TCWP

3.2.3 The flexural strength (FS)

Specimen prisms subjected to a 28-day curing time underwent a flexural strength (FS) test ASTM C 78 [51], wherein varying proportions of SWCP and TWCP were employed as substitutes for cement. The replacement percentages for cement by either SWCP or TWCP remained constant at 10%, 20%, 30%, 40%, and 50%. The strength of each substitution level was determined based on the mean of three samples representing that specific level. The FS outcomes are graphically presented in **Fig. 8**. The results indicated that the FS of the Ref. mix reached 11.9 MPa. However, FS exhibited a decline of 0.8%, 7.6%, and 12.6% for 10%, 20%, and 30% SWCP, followed by a more substantial decrease of

19.3% and 25.2% for 40% and 50% SWCP, respectively, related to the conventional mix. The reduction in FS is attributed to the increasing substitution of OPC with CWP, which can be attributed to various factors. These include alterations in concrete microstructure, diminished cementitious material content, and modifications in the hydration procedure [65, 68]. The relationship between FS /CS showed a modest improvement, ranging from 4.1% and 7.36% for specimens with 10% to 40% SCWP, respectively. Conversely, with 10%, 20%, and 30% cement substitution by TWCP, there was a decrease in flexural strength of 3.4%, 10.1%, and 16.0%, respectively, associated with the Ref. mix. Similarly, 40% and 50% TWCP replacements led to a more substantial decline in flexural strength values by approximately 22.7% and 28.6%, respectively, compared to the conventional mix. Additionally, the relationship between FS and compressive strength displayed a marginal improvement, ranging from 4.05% to 5.42%, for specimens with 10% to 40% TCWP, respectively, although lower than TWCP specimens. The observed decrease in FS in SWCP or TWCP mixes may be attributed to an extravagance of CWP. This could lead to decreased workability and heightened porosity in the concrete, ultimately resulting in a decline in strength. However, it is crucial to exercise caution and carefully manage the replacement levels to prevent any detrimental impacts on the overall strength and workability of the concrete mixture [65]. These findings align with previous research studies [65, 69].

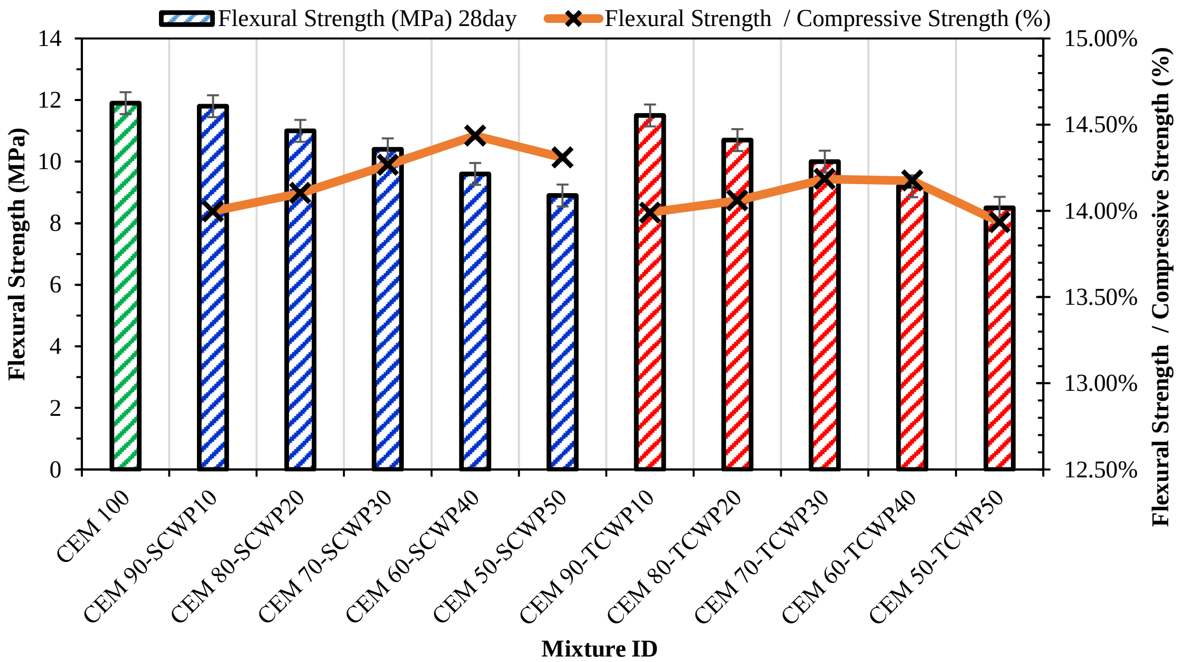

Fig. 8. Flexural Strength (MPa) and Flexural/ Compressive Strength (%) of HSC samples with and without SCWP and TCWP

3.2.4 Modulus of elasticity (Ec)

This part briefly explains the influences of SWCP and TWCP on the modulus of elasticity (Ec) of HSC samples. **Fig. 9** illustrates the Ec of HSC mixes alongside the variations in the ratio of SWCP and TWCP. It is observed that the Ec experiences slight reductions as the ratio of SWCP increases compared to Ref. mixtures. According to **Fig. 9**, the Ec values decreased by 0.9%, 4.6%, 7.5%, 11.5%, and 15.0% for SWCP substitution ratios of 10, 20, 30, 40, and 50% of cement content, respectively, contrasted to conventional concrete mix. The results align with the analyses by Al Arab et al. [26] and Sabbrojjaman et al. [66], which also noted a decrease in the Ec as the content of SWCP increases. Furthermore, concrete containing TWCP reduces the Ec due to the high ratio of TWCP and its strength decreasing. The Ec values decreased by 2.4%, 5.9%, 9.2%, 13.5%, and 17.0% for TWCP substitution ratios of 10%, 20, 30, 40, and 50% of cement content, respectively, contrasted to the conventional concrete mix. Moreover, the decline in the Ec was enriched with higher replacement rates, suggesting a more pronounced effect with larger quantities of waste. Conversely, the Ec rates decreased with rising SWCP ceramic contents, aligning with the reduced strength findings and activity indices noted at lower curing duration. The presence of a porous microstructure and weaker binding at the interfacial transition zone (ITZ) in SWCP and TWCP mixes would likely contribute to a lower EC. Finally, the relative EC relationship to compressive strength was found to improve somewhat at 48.3%, 50.2%, 52.1%, 54.7%, and 56.1% for specimens for 10, 20, 30, 40, and 50% TCWP, respectively, contrasted to 46.4% for a conventional mix. These findings are consistent with the research [68–70].

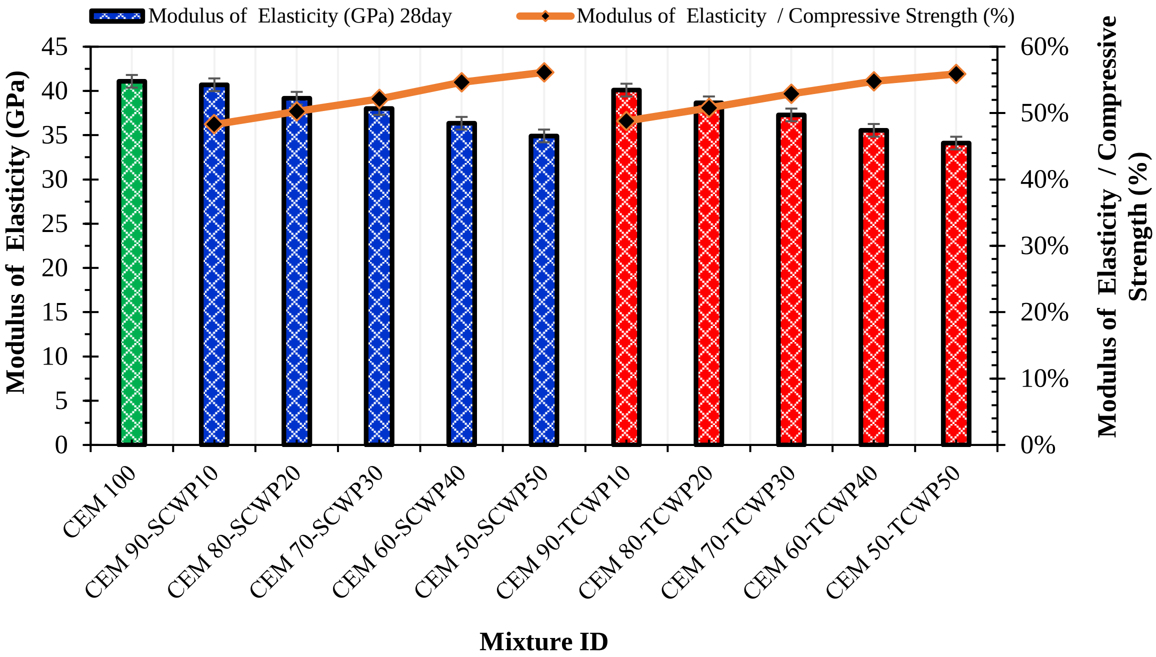

Fig. 9. Modulus of elasticity (GPa) and Modulus of Elasticity / Compressive Strength (%) of HSC samples with and without CWP

3.3 Transition Properties of HSC (Physical properties)

3.3.1 Chloride Penetration Resistance

Table 7. Physical properties of strength concrete mixtures

Mixture ID	Chloride Permeability (CPR) (Columb) 28 days	Sorptivity Coefficient ($mm/s^{0.5}$) 28 days
CEM 100	1575	0.155
CEM 90-SCWP10	1508	0.127
CEM 80-SCWP20	1450	0.115
CEM 70-SCWP30	1432	0.108
CEM 60-SCWP40	1475	0.119
CEM 50-SCWP50	1532	0.135
CEM 90-TCWP10	1540	0.138
CEM 80-TCWP20	1500	0.125
CEM 70-TCWP30	1478	0.119
CEM 60-TCWP40	1523	0.130
CEM 50-TCWP50	1566	0.145

The Chloride Penetration Resistance (CPR) values served as concrete durability indication of chloride-induced corrosion and resistance to chloride ion penetration. Incorporating finely scrunched SCWP and TCWP as cement substitutes positively influenced the CPR in concrete mixes with up to 50% substitute levels. The 28-day test outcomes of all SCWP and TCWP combinations explained a notable reduction in the full passed custody, as shown in **Table 7** and **Fig. 10**. The coefficient of variation (COV) of outcomes ran from 2.86% for the 10%- 50% SCWP mixtures to 2.15% for the 10%-50% TCWP mixtures. After a 28-day curing time age, the CPR rates for the 10%-50% SCWP mixture were 1508, 1450, 1432, 1475, and 1532 coulombs for the 10%, 20%, 30%, 40%, and 50% SCWP substitution ranks, respectively. The chloride ion penetration of mixtures incorporating SCWP decreased by 4.25%, 7.94%, 9.08%, 6.35%, and 2.73% concerning the conventional mixture for mixing 10%, 20%, 30%, 40%, and 50% SCWP, respectively. This reduction in chloride ion penetration could be attributed to the SEM compression and enhancement of the pore structure facilitated by the fine elements of CWP, along with its pozzolanic achieve. Similar results have been found in other studies [59, 71]. Incorporating high substitute levels of SCWP (i.e., ≥30%) resulted in a shift in the combinations CPR class from 9.08% for 30% SCWP to 6.35% and 2.73% for 40 and 50%SCWP, respectively. This could be due to the low pozzolanic response of enormous proportions, making them inactive materials within the mixture. The quantity and type of pozzolan utilized, particle size, and environmental temperature and humidity influence this phenomenon [55]. Mixtures with 10% to 50% replacement were rated as (Low)for CPR according to ASTM C1202's classification [53]. Similarly, the overall passed charge results for the TCWP mixtures indicated a decrease proportional to the CWP content, suggesting an enhancement in resistance to CPR. After a 28-day curing time, CPR decreased by 6.16% compared to the conventional mixture when 30% TCWP was utilized. Incorporating high substitute levels of TCWP (i.e., ≥30%) resulted in a shift in the mixtures' CPR classification from 9.08% for 30%TCWP to 3.3% and 0.57% for 40 and 50%TCWP, respectively. This phenomenon could be attributed to the comparatively lower SEM compaction and refinement of the pore structure facilitated by the fine particles of TCWP, along with its pozzolanic effect, in contrast to SCWP. Finally, as curing time progressed to 28 days, all CWP mixtures exhibited a (Low) CPR according to ASTM C1202 standards [53, 59].

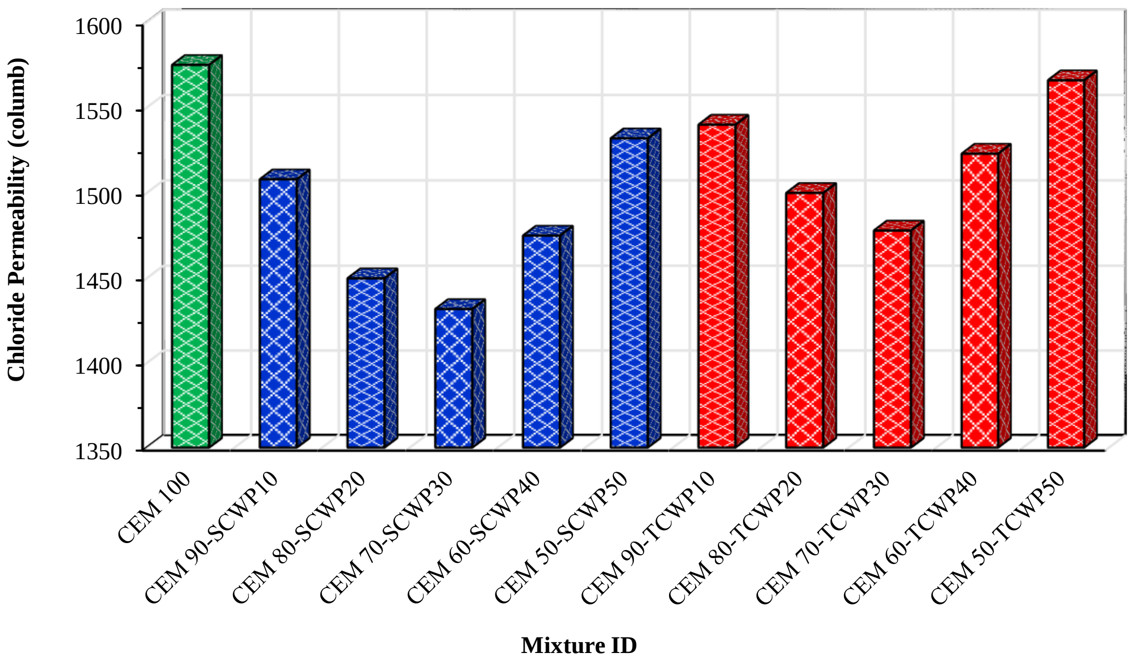

Fig. 10. Chloride Permeability (columb) of HSC samples with and without SCWP and TCWP.

3.3.2 Sorptivity

The sorptivity of various HSC mixes with SWCP and TWCP was investigated to assess water absorption and transmission efficiency during voids, significantly impacting durability. The sorptivity was quantified, allowing for ASTM C1585-13 standards [54]. The sorptivity test was measured during a single stage, encompassing the initial absorption period ranging from 10 minutes to 6 hours. This initial absorption phase is primarily attributed to capillary suction by surface voids [72]. **Table 7** and **Fig.11** illustrate the primary water absorption value of sorptivity through capillary action (unidirectional flow), represented as a performance of the square root of time (√Time, Sec^$^{1/2}$) for each HSC mix investigated. The measures suggest that capillary absorption follows a linear relationship with the square root of time during the initial sorptivity phase. (Sec^1/2) [73]. **Fig. 11** depicts the volume of initial absorption for HSC mixes. Including SWCP improves water infiltration resistance in HSC mixes, with the highest saving of 25.81% and 30.32% observed at 20% and 30% substitute of SWCP for initial and minor absorption, respectively. This advancement can be credited to the more elevated specific surface area of SWCP compared to cement, which reduces the formation of capillary voids in the HSC mix [74]. Substituting cement content with SWCP results in a noteworthy decrease in initial absorption, primarily attributed to the increased production of CSH gel. This phenomenon effectively limits the formation of capillaries within the concrete matrix. **Fig. 11** represents the initial and secondary water absorption rates across different HSC mixes [75]. Similarly, a comparable phenomenon was observed in the HSC mix where OPC content was substituted with TWCP. This replacement led to a noticeable reduction in sorptivity, ascribed to the rough and angular particles of TWCP. The sorptivity coefficient was at its lowest in cases where 20% and 30% TWCP replacement occurred, measuring 19.35% and 23.23%, respectively, compared to 100% cement in the HSC mix. As the TWCP replacement level increased, it showcased enhanced resistance against water ingress in HSC mixes. This observation aligns with similar findings reported by previous research [76]. As the content of TWCP increases, the composites' total water absorption decreases. This decrease is primarily due to SWCP or TWCP permeating voids and weakening the cement mortar's porous range, the composite's first water-absorbing element [74]. The decrease in the gradient of water uptake versus the square root of time tells sorptivity transpiring through more delicate pores. This observation suggests that tiny pores become increasingly significant over time [77]. This is attributed to TWCPs undergoing minor hydration reactions, directing to the founding of C-S-H and the condensation of the microstructure. Notably, even when cement content is replaced with 40% and 50% incorporating SWCP or TWCP, water absorption decreases than in HSC without SWCP or TWCP. The hydration developments performed solely from OPC content in HSC cannot adequately fill the pores in the past. These findings are consistent with the research [75, 76, 78].

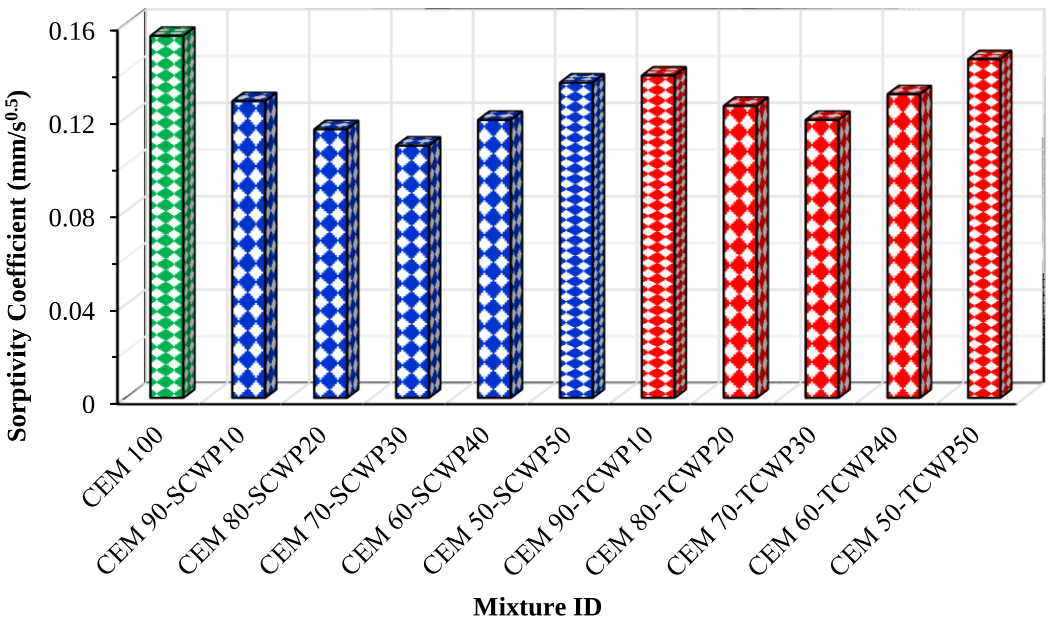

Fig.11. Sorptivity Coefficient ($mm/s^{0.5}$) of HSC samples with and without SCWP and TCWP.

3.4 Microstructure analysis

At the microstructural class, concrete composites can be classified into three main components: aggregates, cement paste, and the interfacial transition zone (ITZ) between cement paste and aggregates. The ITZ, which directs the interfacial shift zone in concrete, significantly influences the properties of concrete due to its abundance of pores and the presence of $CaOH_2$. This study employed scanning electron microscopy (SEM) to investigate the microstructure and morphology of cement paste and the ITZ between aggregate-paste interfaces.

3.4.1 Cement paste microstructure

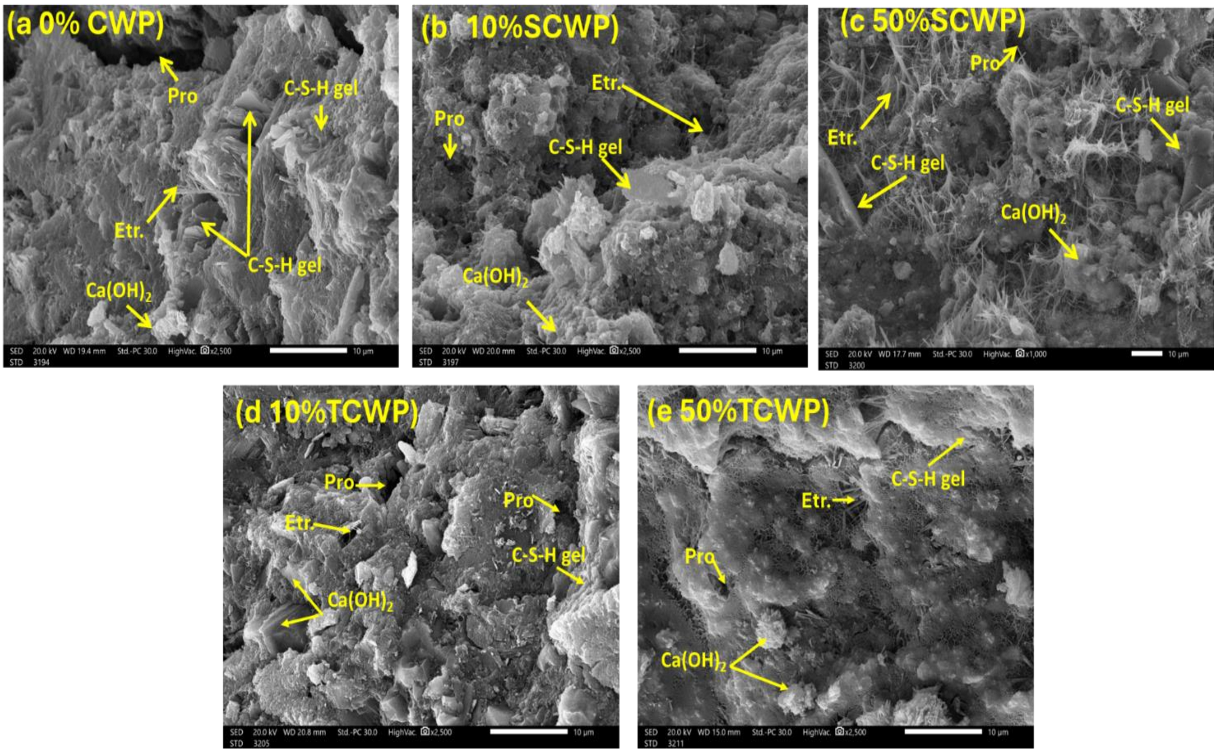

Fig. 12. Cement pastes microstructure (SEM) at 28 days of HSC samples with and without SCWP and TCWP.

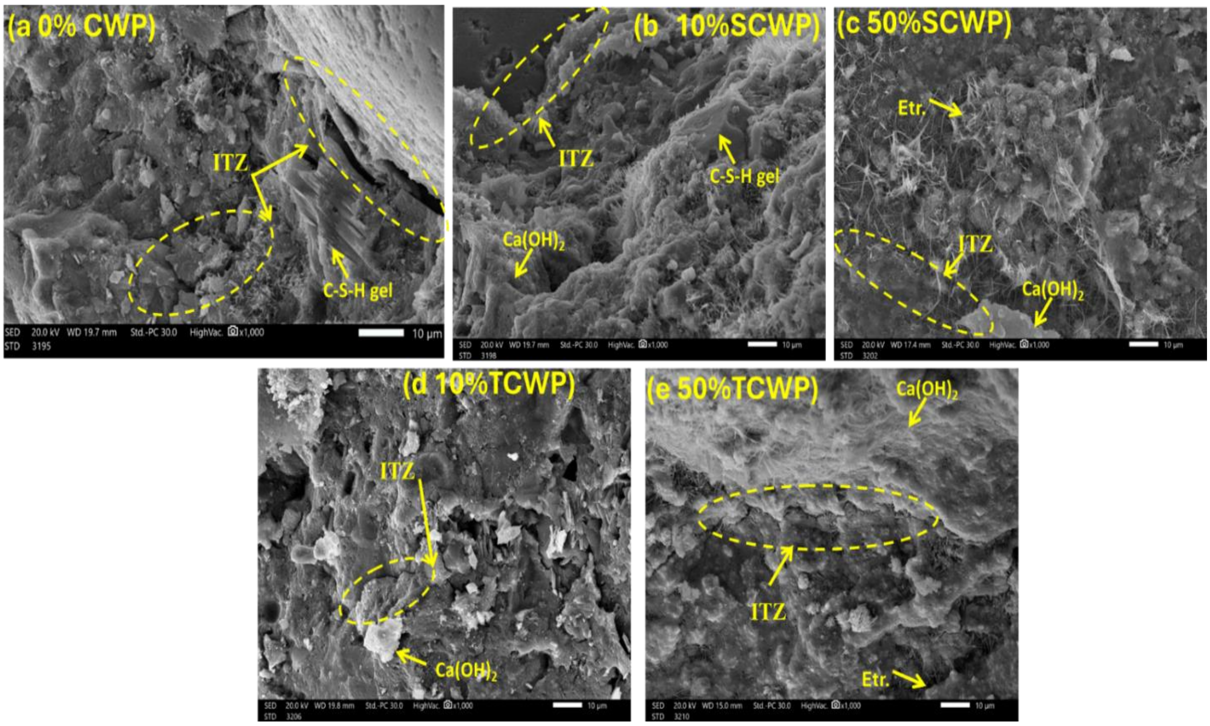

Fig. 13. The interfacial transition zone (ITZ) at 28 days of HSC samples with and without SCWP and TCWP

The SEM images of CEM 100 (100% cement) and 10 and 50% of SCWP and TCWP for HSC cured at 28 days are displayed in **Fig. 12**. As depicted in **Fig. 11a- c**, hydration outcomes like Ca $(OH)_2$ crystals, C–S–H gel, and ettringite are present in the CEM 100 and SCWP and TCWP pastes at 28 days. Additionally, numerous pores are visible in these specimens, with the pores in the 10% and 50% SCWP pastes appearing to be fewer than those in the CEM I 100 pastes, as illustrated in Fig. 11 b, c. After 28 days of curing, needle-like ettringite intertwined with calcium hydroxide and flocculated C–S–H gel became more pronounced. Particularly in specimens containing 10% SCWP, the microstructure appears denser at this stage. This densification is attributed to the pozzolanic reaction initiated by SCWP, which consumes calcium hydroxide and generates more hydration products. **Fig. 12** illustrates that, to a certain extent, similar microstructural outcomes were observed for equivalent replacement levels of 10% and 50% TCWP waste compared to SCWP at 28 days. The observed similarities in the microstructural outcomes between SCWP and TCWP can be attributed to their comparable element size dissemination and similar composition in SiO_2, Al_2O_3, and Fe_2O_3 content. These characteristics suggest that the pozzolanic response of the amorphous periods is generated during the production processes. These ceramic waste materials play a substantial role in influencing the microstructure of the resulting concrete. SEM analysis of the cement mortars containing 50% TCWP revealed that high replacement rates of ceramic waste powder could have a detrimental effect on forming C-S-H gel. This is evidenced by the presence of the above partially responded gel phases such as Mullite, along with non-reacted particles like quartz [15, 79].

Fig. 13 presents the morphology characteristics of ITZ in specimens composed of CEM 100, 10% SCWP, 50% SCWP, 10% TCWP, and 50% TCWP at 28 days. The micrographs reveal that the ITZ in specimens containing SCWP exhibits a denser microstructure than those with CEM 100, where cracks are evident. These findings align with the EDX analysis results [60, 78].

3.4.2 EDX Analysis

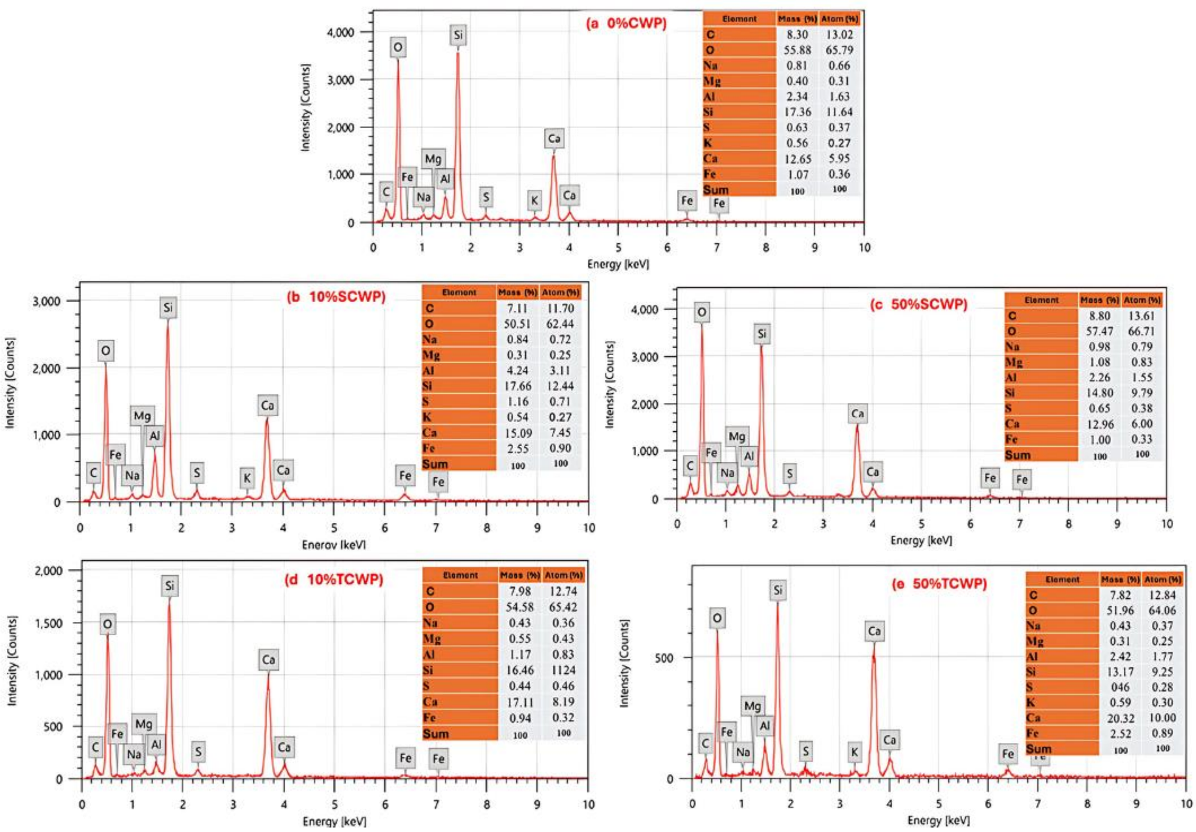

Fig. 14. Energy dispersive spectroscopy (EDX) at 28 days of HSC samples with and without SCWP and TCWP

An energy dispersive spectroscopy (EDX) analysis was prepared to determine the primary oxides present in SCWP and TCWP. **Fig. 14** displays the EDX analysis results of SCWP and TCWP samples, revealing that the CWP is predominantly disposed of SiO_2, Al_2O_3, and calcium (CaO). SCWP and TCWP exhibited compositions with around 75-85% of the sum material mass, although there were slight differences between the two materials' compositions. The higher proportions of aluminate and silicate in both SCWP and TCWP materials suggest the potential for pozzolanic reactivity. The mass elements of (SiO_2 + Fe_2O_3+Al_2O_3) in SCWP and TCWP met the requirement outlined in ASTM C618 for natural pozzolana, which mandates a composition of over 70%. In contrast, SCWP and TCWP exhibited minimal mass ratios of various oxides, including CaO, Fe_2O_3, SO_3, and MgO. Additionally, the levels of SO_3 and the Loss on Ignition (LOI) met the requirements outlined in ASTM C618 [80]. As such, both SCWP and TCWP can be classified as pozzolanic materials based on their mineral compositions [59, 76].

3.5 Economic and Environmental Study Results

Several vital parameters were selected for analysis to assess the sustainability implications of CWP compared to conventional HSC. These parameters include greenhouse gas CO_2 emissions, energy consumption, and production costs associated with HSC manufacturing. While other indicators are significant, these factors are pivotal in utilizing CWP. The determined results are displayed in **Table 8.**

Table 8. The reduction ratio of compressive Strength, Cost of OPC/CWP, Energy consumption, and Greenhouse gases (CO_2) with and without CWP of HSC.

Mixture ID	Compressive Strength		Cost of OPC/CWP		Energy consumption		Greenhouse gases (CO_2)	
	(MPa) 28 days	Reduction (%)	($ /m³)	Reduction (%)	(GJ/m³)	Reduction (%)	(ton/m³)	Reduction (%)
CEM 100	88.5	--	22.0	--	2.57	--	0.45	-
CEM 90-SCWP10	84.3	4.7	20.5	6.99	2.37	7.80	0.41	9.49
CEM 80-SCWP20	78.0	11.9	18.9	13.97	2.17	15.59	0.37	18.98
CEM 70-SCWP30	72.9	17.6	17.4	20.96	1.97	23.39	0.32	28.47
CEM 60-SCWP40	66.5	24.9	15.9	27.95	1.77	31.19	0.28	37.96
CEM 50-SCWP50	62.2	29.7	14.3	34.94	1.57	38.99	0.24	47.46
CEM 90-TCWP10	82.2	7.1	20.5	7.01	2.36	7.82	0.41	9.50
CEM 80-TCWP20	76.1	14.	18.9	14.03	2.16	15.63	0.37	19.00
CEM 70-TCWP30	70.5	20.3	17.4	21.04	1.96	23.45	0.32	28.51
CEM 60-TCWP40	64.9	26.7	15.8	28.06	1.76	31.27	0.28	38.01
CEM 50-TCWP50	61.0	31.1	14.3	35.07	1.56	39.08	0.24	47.51

3.5.1 Greenhouse gases emission (CO_2)

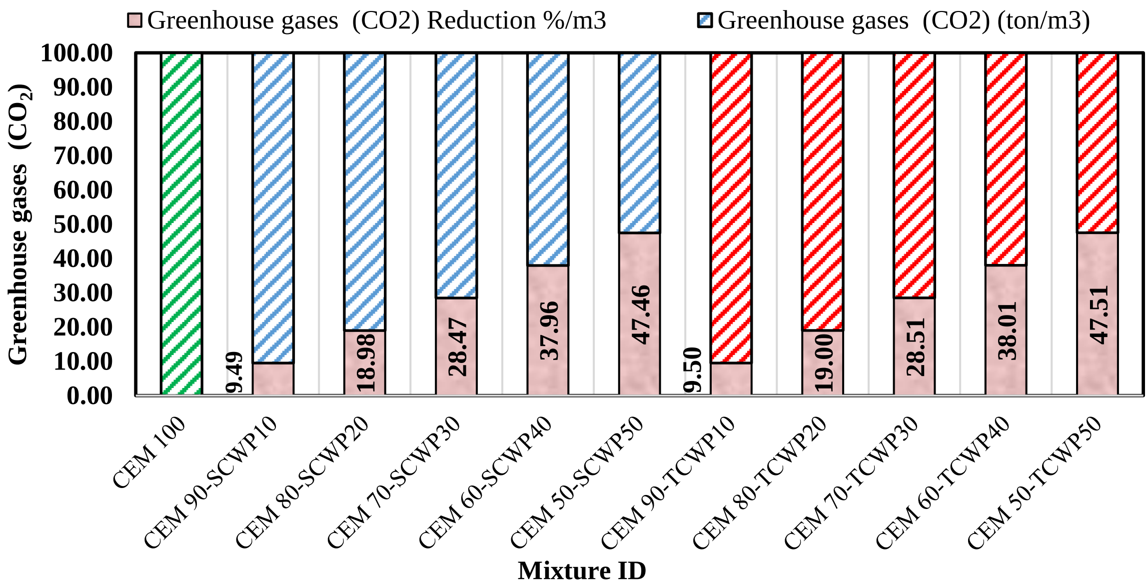

Fig. 15. Greenhouse gas emission (CO_2) analysis of HSC samples with and without SCWP and TCWP.

Table 8 and **Fig. 15** illustrate the impact of CWP substitution for OPC on greenhouse gas emissions in blended cement. It was observed that as the proportion of either SCWP or TCWP increased in the

HSC samples, there was a corresponding reduction in the release of greenhouse gases. The CO_2 released was also reduced by 9.49, 18.98, 28.47, 37.96, and 47.46%, with an increase in SCWP from 10, 20%, 30%, 40%, and 50%, respectively. At the same time, the gases released for TCWP were also reduced in approximately the same proportions for SCWP with slight differences of 9.50, 19.00, 28.51, 38.01, and 47.51%, with an increase in TCWP from 10, 20%, 30%, 40%, and 50%, respectively. Blending CWP with cement results in lower greenhouse gas emissions than standard mixtures containing only OPC, regardless of the replacement percentage. This disparity is attributed to the advanced energy consumption, costs, and CO_2 emissions connected with OPC, which exhibits a considerably higher CO_2 release rate of 0.9040 ton/ton than CWP 0.0450 ton/ton. The consequent reduction in greenhouse gas emissions observed in mortar samples formulated with CWP as a binder suggests the feasibility of producing a green and environmental material that relies minus on OPC [81,82]. Furthermore, the analysis of CO_2 emissions presented in the table and figures indicate that incorporating waste materials as limited replacements for OPC, even at small percentages, can significantly reduce greenhouse gas emissions compared to OPC-based materials [1, 55, 81].

3.5.2 Cost analysis

Fig. 16 illustrates how the replacement of CWP affects the cost efficiency of the suggested HSC samples related to OPC as a cementitious. Substituting a high proportion of CWP (e.g., 50%) for OPC resulted in substantial cost savings. This cost analysis, established on the unit weight of materials and their preparation stages outlined in **Table 8**, presently impacted the last cost of the HSC specimens. Specifically, the cost of the cementitious decreased from $22/m^3 for OPC to $20.5, $18.9, $17.4, $15.9, and $14.3 /m^3 with increasing replacement percentages of SCWP for cement from 0% to 10, 20, 30, 40, and 50%, respectively. The replacement of CWP as a binder in HSC specimens significantly contributed to the production of sustainable products. Furthermore, **Fig. 16** illustrates the impact of replacing TCWP on mortar costs, revealing a relative cost economy through this replacement. As the substitution level of TCWP increased from 0% to 10%, 20%, 30%, 40%, and 50%, the cost of HSC samples decreased by more than 7.01%, 14.03%, 21.04%, 28.06%, and 35.07% per cubic meter, respectively. These findings suggest that utilizing CWP as a complete replacement for OPC could substantially facilitate the development of environmentally friendly products, thereby promoting sustainable progress in construction materials [78].

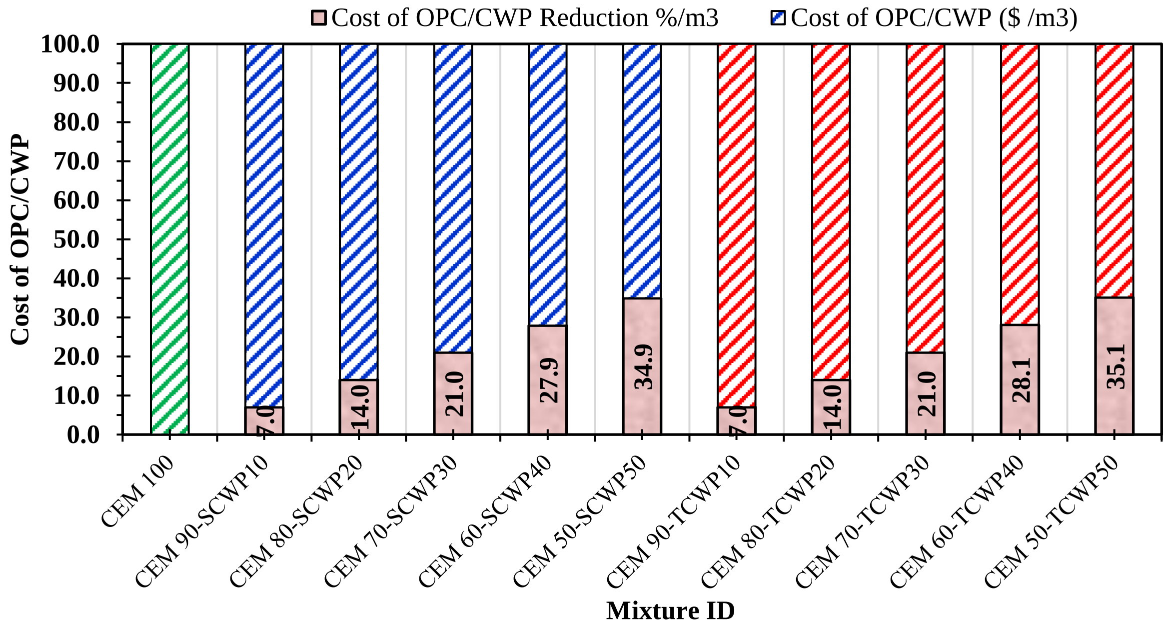

Fig. 16. Cost analysis of HSC samples with and without SCWP and TCWP.

3.5.3 Energy consumption

The energy consumption associated with producing all batches of specimens was determined based on the energy consumption and time life cycle analysis of the materials utilized in their production (**Fig.**

17). It was observed that the energy needed to make the cementitious decreased as the amount of CWP increased as a substitute for OPC. Specifically, energy utilization decreased to 2.37, 2.17, 1.97, 1.77, and 1.57 GJ/m³ with a reduction of 7.80%, 15.59%, 23.39%, 31.19%, and 38.99% as the SCWP level increased to 10%, 20%, 30%, 40%, 50%, and 60%, respectively, compared to the 2.57 GJ/m3 calculated for 100% OPC. The lower electricity cost incurred during the production of CWP directly induced the overall energy costs of the HSC specimens. This minimal expenditure, coupled with lower greenhouse gas emissions and reduced energy consumption of CWP, were critical factors in assessing the feasibility of this sustainable product. Fig. 17 also depicts the energy use of HSC specimens containing various ratios of TCWP as a substitute for OPC. Substituting OPC with TCWP significantly decreased maximum energy consumption, reducing 39.08% to 1.56 GJ/m3 for 50% TCWP. The substantial reduction in energy consumption resulting from TCWP replacement can be attributed to the inherently lower energy consumption associated with TCWP use in HSC mixtures. In conclusion, substituting OPC with SCWP and TCWP significantly reduces energy use due to the substantial energy expenditure in OPC manufacturing. However, challenges such as landfill issues, and the continuation of environmental resources persist. Notably, combining SCWP and TCWP in a similar combination resulted in the lowest calculated energy consumption (1.57 and 1.56 GJ/m³ , respectively) compared to 100% OPC mixes, representing a positive step towards the production of replacement and environmentally responsive HSC structure materials [1, 55, 83].

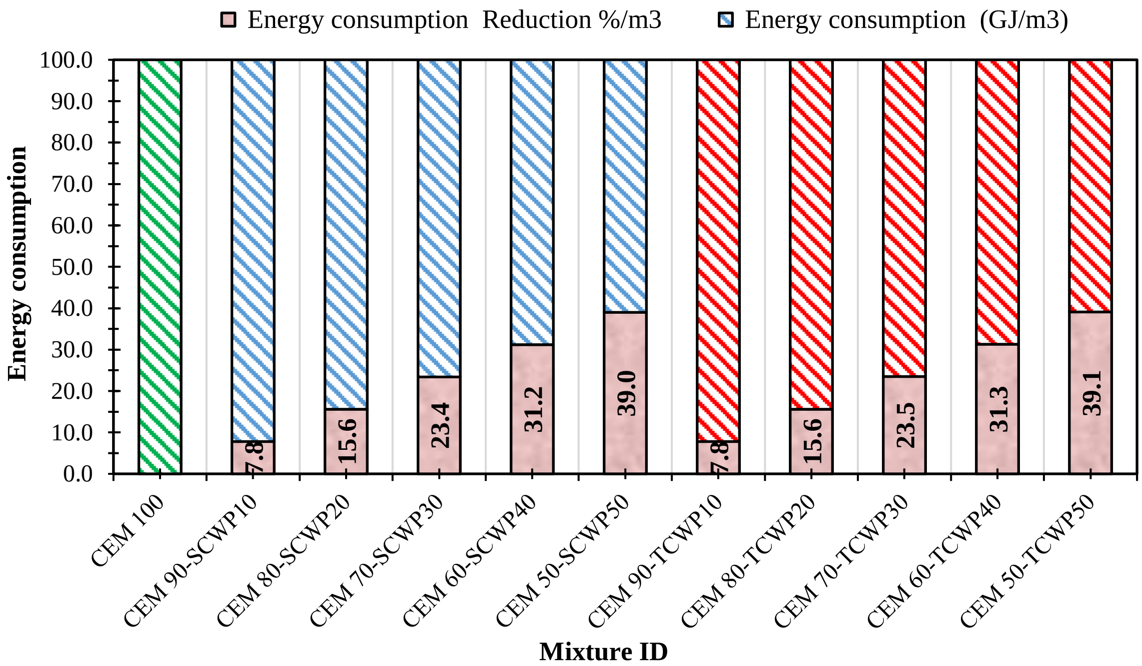

Fig. 17. Energy consumption analysis of HSC samples with and without SCWP and TCWP.

3.5.4 Analysis of Mechanical Performance with economic and environmental study

The economic and environmental analysis presented in this study provides valuable insights that complement the main theme of the study, which is focused on the sustainability of HSC incorporating CWP. The previous comparison of carbon emissions, costs, and energy consumption for each sample group demonstrates the advantages of using CWP as a substitute for OPC, aligning with the paper's objective of enhancing the sustainability of concrete materials.

On the side, a mechanical performance analysis of compressive strength, environmental impact, and economic factors was conducted to assess the optimal substitution rate of SCWP and TCWP in High-Strength Concrete (HSC). The results show that as the percentage of SCWP and TCWP increases, there is a noticeable reduction in compressive strength, but significant improvements in environmental and economic aspects accompany this. Specifically, the substitution of 20% SCWP and 20% TCWP results in up to an 18.98 % and 19% reduction in CO_2 emissions, a 15.59% and 15.63% decrease in energy consumption, and cost savings of up to 13.97% and 14.03% and 14.0 minor decrease in compressive strength, respectively. While it was observed replacement ratios of 50% SCWP and 50%TCWP for OPC resulted in a significant reduction of 47.46% and 47.51% reduction in CO_2 emissions, a 38.99% and 39.08% decrease in energy consumption, and cost savings of up to 34.94% and 35.07%, with a considerable reduction of compressive strength at 29.7% and 31.1 % respectively. Despite this decrease, the material retains acceptable mechanical properties of more than 60 MPa for compressive strength.

Based on the results in **Table 8**, making 30% to 40% substitutions are the most optimal balance between maintaining sufficient mechanical performance achieving substantial environmental cost benefits, and sustainability goals. These findings suggest that utilizing SCWP and TCWP as partial replacements for OPC in HSC offers an effective solution for enhancing sustainability while mitigating environmental impacts and reducing production costs despite its slight implications for compressive strength. Finally, the economic and ecological analysis conclusions do not directly contradict the material performance conclusions but indicate a clear trade-off.

4 Conclusions:

This paper studied the mechanical properties, durability factors, microstructure, and economic and environmental valuation of HSC containing SCW and TCW up to 50%. The main conclusions obtained from the study are as follows:

Slump test values for mixtures containing SCWP and TCWP decreased with increased SCWP percentage. The 21.2% and 16.9% reduction ratios for 50% SCWP and 50% TCWP, respectively, contrasted to the conventional mix, indicate a notable impact on workability. The reduction in slump is attributed to the particular surface area of SCWP or TCWP exceeding that of cement.

The compressive strength observed at brief curing times decreased notably compared to the reference concrete. However, they progressively approached those of the reference concrete with prolonged curing time, particularly in samples containing up to 10 and 20% SCWP waste (reaching approximately 96.3 and 98.1 MPa after 91 days of curing). Results demonstrate that incorporating up to 50% of ceramic waste does not compromise concrete's compressive strength, exceeding 60 MPa targets.

The experimental findings indicate that substituting cement with 10%, 20%, and 30% SCWP or TCWP particles resulted in a marginal decrease in the concrete's tensile strength, with 0.8%, 7.6%, and 12.6% decrease for SCWP and 2.6%, 9.2%, and 14.5% decrease, respectively, relative to the control mix. The relative tensile strength relationship to compressive strength improved somewhat, at 8.58% and 7.6 % for specimens at 40% for SCWP and TCWP, respectively.

The relative flexural strength and modulus of elasticity relationship to compressive strength improved somewhat, at 7. 36 and 17.73% for 40% SCWP and 5.42% and 17.98% specimens with 40% TCWP, respectively.

The Chloride Penetration Resistance outcomes showed that incorporating finely scrunched SCWP and TCWP as cement substitutes positively influenced the chloride ion penetration in concrete mixtures with up to 50% substitute levels. The chloride ion penetration of mixtures incorporating SCWP decreased by 9.08% and 6.16% compared to the conventional mixture for mixing 30% SCWP and TCWP, respectively.

Including SWCP and TCWP improve water infiltration resistance in HSC mixes, with a maximum reduction of 25.81% and 30.32% for SCWP and 19.35% and 23.23% for TWCP, at the same 20% and 30% replacement of initial and secondary absorption, respectively. This advancement can be attributed to the more elevated specific surface area of SWCP compared to cement, which reduces the formation of capillary voids in the HSC mix.

Similar microstructural outcomes were displayed for equivalent replacement levels of 10% and 50% TCWP waste compared to SCWP at 28 days of curing. The observed similarities in the microstructural outcomes between SCWP and TCWP can be attributed to their comparable particle size distribution and similar composition in SiO_2, Al_2O_3, and Fe_2O_3 content. The morphology characteristics of ITZ in specimens with SCWP and TCWP replacements showed hydration products filling the zone, resulting in refinement and densification of the microstructure due to the pozzolanic reaction.

The economic and environmental study demonstrates that incorporating Ceramic Waste Products in High-Strength Concrete production reduces greenhouse gas emissions (CO_2) by 9.49% to 47.46% for SCWP and similar reductions for TCWP. Cost savings range from over 35% at a 50% replacement level, while energy consumption decreases by 7.80% to 38.99% for SCWP, with even more significant reductions for TCWP.

Finally, the mechanical performance analysis, environmental impact, and economic factors showed the optimal substitution rates for SCWP and TCWP between 30% and 40% in HSC. At these levels, energy, cost, and CO_2 emissions have been considerably minimized while achieving higher compressive strength above 60MPa. This aligns with global efforts towards sustainable development and green construction practices.

Nevertheless, additional research in the future is needed to investigate the combined integration of SCWP and TCWP to evaluate their combined effects on the properties of HSC. Moreover, it is necessary also to explore the long-term durability and structural behavior of concrete blends containing SCWP and TCWP and conduct tests to assess cracking behavior under direct loads. This is crucial to evaluate their suitability for particular applications. Additionally, using ceramic waste with cement under varying temperatures before actual application in concrete mixtures must be assessed. Finally, incorporating the recovery costs of SCWP and TCWP into environmental and economic analyses will provide a more comprehensive and accurate sustainability assessment.

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CRediT authorship contribution statement

Mohamed Amin: Supervision and Conceptualization, Investigation, Writing- Review and Editing. **Yara Elsakhawy**: Methodology, Conceptualization, Investigation, Writing- Review and Editing. **Khaled Abu El-Hassan**: Conceptualization, Methodology, Investigation, Writing-Review and Editing. **Nour Bassim Frahat**: Methodology, Resources, Investigation, Data curation, Writing-Original draft preparation, Visualization, Writing – review & editing.

Conflicts of Interest

The authors declare that they have no known competing financial or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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