



Sustainable reuse of waste ceramic tiles powder and waste brick powder as a replacement for cement on green high strength concrete properties

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Abstract

Nowadays, reducing construction waste has grabbed the attention. As bricks and ceramic tiles represent more than 50% of the ceramic waste in many European countries. Thus, the recycling of this waste type is one of the most significant challenges within the paradigm of the circular economy. This paper investigated the impact of substitution levels of cement by waste ceramic powder (WCP) and waste brick powder (WBP) at 0%, 5%, 10% and 15%, on the HSC characteristics. The WBP and WCP materials were characterized in detail by laser granulometry, XRF and XRD measurements, followed by standard mixing, production, and curing of concrete samples. The experiments on dry density, modulus of elasticity, flexural strength, splitting tensile strength, compressive strength, resistance to sulfate attack, water absorption and ultrasonic pulse velocity were conducted to evaluate the hardened properties of concrete. It was demonstrated that the durability and strength of concrete containing WBP and WCP as partial replacements for cement are marginally inferior to those of the control sample. On the other hand, samples containing WBP had a lesser negative effect on HSC properties in comparison with samples containing WCP. However, employing a 5% WBP with 10% WCP mixture enhanced the characteristics of the HSC in comparison to samples containing various percentages of WCP individually. In addition, the microstructure analyses revealed that the addition of 10% WCP and 5% WBP to HSC specimens resulted in higher hydration products and a slightly denser concrete matrix compared to samples containing various percentages of WCP individually. Research findings indicate that a 15% substitution of cement with WCP or WBP illustrated an environmental benefit in concrete production due to a 13.1% reduction in specific energy consumption.

Keywords Waste ceramic powder · Waste brick powder · High strength concrete microstructure · Energy consumption

Introduction

Rapid urbanization resulted in the extraction of vast quantities of non-renewable resources (such as river sediment and natural stone) which were employed as construction raw

materials, thereby accelerating their depletion. Simultaneously, enormous amounts of construction and demolition waste (CDW) were produced. Simultaneously, enormous amounts of demolition waste (CDW) and construction were produced. For instance, the landfill was considered as a conventional treatment of CDW that results within the devastation of the ecosystem, the contamination of the natural environment, and the occupation of land resources. The need to preserve nonrenewable resources requires the development and the utilization of renewable resources [1, 2]. For achieving a higher sustainable urban development, scientists have been trying to recycle CDW through a variety of crushing methods [3–5]. The CDW consists of waste from construction and excavation, including roof tiles, rubber, wood, ceramic, glass, brick, and concrete [6, 7]. Recently, researchers have investigated recycled clay bricks [8–12],

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recycled precast concrete [7, 11], recycled asphalt pavement [11], recycled fine aggregates [13], recycled coal bottom ash [14], recycled coarse aggregate [15–17], recycled plastic waste [18], recycled glass [6, 19, 20], recycled aggregate concrete [21], recycled aluminium waste [22] recycling of marine clay [23], and recycled waste marble [24]. Globally, demolition and construction waste generation in 40 countries was over 3 billion tonnes per year by 2012, and this trend is accelerating [25]. This motivates studies in green construction products that utilised lower resources in the nonrenewable and the raw materials building that was compensated through the CDW reuse. The CDW generated by the urbanization in rural regions were composed primarily of mortar waste and clay brick waste acquired during the demolition of brick structures or brick-concrete structures. Accompanied by accelerated urbanisation, the clay bricks accumulation grows in to an urgent issue that must be resolved. Clay brick waste has been studied as a recycled material to supplant natural aggregate [26–28] or as a supplementary cementitious material (SCM) [29, 30].

Recently, scientists have made additional attempts to incorporate recycled brick waste as SCM within products of cement. The procedure for producing waste brick powder (WBP) was crashing brick waste into fine particles (below 150 m); WBP shares certain properties with SCM and can be utilised in preparation of concrete [31–35]. Since the high Al_2O_3 and SiO_2 content of WBP facilitated the creation of C–S–H, integrating WBP increases the strength in the long run for manufactured concrete; for instance, the concrete compressive strength including 10% WBP was greater than 32% compared to plain concrete after a prolonged time of curing [36, 37]. Furthermore, the filler impact and pozzolanic activity increased the concrete's durability. Ortega et al. [38] found that the optimum concrete's absorption coefficient in capillary and porosity containing 20% WBP are, respectively, 40.5% and 19.2% less than those of concrete excluding WBP. The use of WBP reduces the workability of cement-based products because WBP has a high water absorption rate at the same water-to-binder ratio [39–41]. The decrease in water consumption was attributed to the particle size of the CBP, as bigger particles included more pores leading to an increase in the water consumption. Conversely, the reduced size of the WBP particles resulted in improved workability of the fresh mix [39, 40]. To achieve consistent flowability in concrete, it is necessary to increase the concentration of WBP, which in turn requires the use of more water [42]. As the WBP concentration rose, there was a corresponding drop in density [41, 43]. Furthermore, it was noted that there was a little reduction in the dry density of the coarse recycled aggregate concrete as the proportion of WBP increased [34]. At early ages, the WBP mortar compressive strength declined as the WBP content increased. Nevertheless, the mortar including up to 10 wt% CBP could

acquire strength similar to or higher than the control one at later ages [34, 36, 39]. After 90 days, the compressive strength of the cement mortar could reach around 80% when the replacement level was below 30 wt% [44]. The compressive strength of the mortar having WBP particles similar in size to the cement particles was superior to that of the mortar with particles of a different size [40]. After a 90-day curing period, the WBP mortar achieved a flexural strength that was about 90% of the cement mortar's strength [44]. The use of WBP [34, 45] had a minor impact on the elastic modulus and flexural strength. The flexural strength of WBP concrete was determined to be same to that of the control sample.

In addition, Likes et al. [46] found that using WBP and recycled concrete powder (RCP) in concrete as a substitute for 20% of the cement resulted in successful outcomes. The strength activity index values for WBP and RCP were 92% and 86% after seven days, 98% at 28 days, and 105% and 100% at 56 days. The addition of RBP resulted in a 24% increase in surface resistivity, which improved the durability of the material. Nevertheless, a decrease in the static elasticity modulus was noted in WBP concrete [47]. A rise in shrinkage was noted when WBP content and age increased [36]. Decreasing the particle size of WBP can result in a reduction in shrinkage [39]. In addition, Aliabdo et al. [48] determined that irrespective of the substitution level, the strength of concrete decreased. However, Özkılıç et al. [49] found that incorporating waste fire clay into bending reinforced concrete beams (RCBs) enhanced their maximum ability within the range of 20–30%. It may be concluded that the optimal waste fire clay content for shear RCBs was 20%. The brick dust high porosity, which led to its high water absorption, was considered as one of the possible explanations for the reduction in mortar containing brick dust and strength of cement-based concrete.

Nevertheless, waste ceramic is an industrial waste type that possesses the potential to be used as a substitute material in concrete. Numerous varieties of ceramics have been utilised in construction nowadays; however, some are fragile and broken during production, storage, or shipment [50]. After the deconstruction of a building, fractured ceramic tiles with mortar fragments on their surface are considered as another type of waste ceramic where using them in concrete provides an environmentally friendly technique for disposal. Separating them from mortar is expensive, whereas mortar offers no advantage for employing in concrete. Therefore, only pure ceramic tile fragments could be used in concrete [51].

Numerous researchers examined the flexural and compressive strengths of concrete by incorporating waste ceramic (WC) into concrete production [52–56]. Mashitah et al. [52] demonstrated the possibility of using ceramic tile wastes as coarse aggregates with varying volume ratios in the manufacture of concrete blocks with compressive

strengths ranging from (41.4 to 48.8) MPa, however, Abdullah et al. [53] revealed that concrete containing ceramic tile waste as gravel possessed compressive strengths 85–100% greater than concrete obtained with ordinary gravel. Gautam et al. [54] investigated the impact of employing waste ceramic powder (WCP) as a partial replacement for cement on the characteristics of self-compacting concrete (SCC). The scientists noted that adding up to 10% WCP to SCC improved its compressive and flexural strengths. The potency of modified SCC decreased, however, when bone china ceramic waste was added in greater amounts (greater than 10%). Although Huseien et al. [55] determined that the water absorption increased and compressive strength of self-compacting alkali-activated concrete was reduced by raising the WCP percentage as a partial substitution for ground blast furnace slag. In addition, Pacheco-Torgal and Jalali [56] stated that concrete containing WCP loses strength. As a result, the decrease in early compressive strength is primarily attributable to the immature pozzolanic reaction within the concrete and the WCP-affected preventive growth of C–S–H gel. However, the usage of WCP and WBP within mortar and concrete is an environmentally preferable method for reclaiming CDW waste. Gautam et al. [57] reported that the use of waste ceramic powder (WCP) had a beneficial impact on the fresh characteristics of self-compacting concrete (SCC). Specifically, the combination of 10% WCP and 30% granite waste exhibited the highest strength. The enhanced performance may be ascribed to the pozzolanic characteristic of WCP and the improved filling ability of GCW [58]. Nevertheless, detrimental effects were detected over this threshold. However, Aksoylu et al. [59] conducted a study on the flexural behaviour of RCBs that included the use of waste ceramic powder WCP as a substitute for some of the cement. The authors concluded that WCP may be efficiently utilized as a substitute material for up to 10% of cement. The increase of the WCP percentage by over 10% may significantly decrease the stiffness, ductility, and load-carrying capacity of RCBs, particularly when the longitudinal reinforcement's percentage was significant. In addition, Gautam et al. [60, 61] demonstrated that the inclusion of WCP and granite cutting waste in SCC mixes results in reduced embodied carbon dioxide emissions and energy. Additionally, their ecological and economic study showed a decrease in costs. Furthermore, Chang et al. [62] found that the inclusion of 10% WCP in concrete results in a reduction of 7.19%, 7.18%, 8.68%, and 6.78% in the impacts on human health, ecosystem quality, climate change, and natural resources, respectively.

The previous research illustrated the usage of each of WCP and WBP solely as discussed aforementioned. Thus, this research aims to fill the mentioned research gap that was discussed previously through studying the manufacture of eco-friendly high strength concrete (HSC) using a

combination of waste ceramic powder (WCP) and waste brick powder (WBP) as partial replacements for cement (5, 10, and 15% by weight of cement, respectively). For this purpose, concrete mixes incorporate varying proportions of WCP solely (the first group) and WBP (the second group) solely, as well as a control mixture. In addition, a combination of mixes of 5% WBP with 5%, 10%, and 15% WCP (third group) was mixed together in order to distinguish the advantages of using this mixture and to achieve the highest cement replacement while conserving the properties of green HSC. Furthermore, a number of experiments were conducted to examine the hardened state densities, compressive, splitting tensile and flexural strengths, ultrasonic pulse velocity, water absorption, and sulphate attack resistance. Besides, the properties of microstructural for specified mixtures were investigated utilizing X-ray diffraction (XRD) and scanning electron microscopy (SEM) techniques. Environmental benefits were also evaluated.

Experimental program

Materials

Cement

In this investigation, ordinary Portland cement CEM I 52.5 R was used to prepare high strength concrete (HSC). Tests on cement agreed with EN 197-1. The specific gravity and specific area of cement were 3400 cm²/g and 3.14, respectively. The chemical constituents and properties of cement (fineness, specific gravity, and colour) are listed in Table 1. Figure 1 illustrates the particle size distributions.

Waste brick powder (WBP)

On the construction site in Kosice, Slovakia, residual bricks were used to produce waste bricks. Using a jaw crusher, waste bricks cracked pieces were crushed. The brick wastes were crushed into powder at the laboratory scale using a

Table 1 Chemical compositions of cement and of CWP

Chemical compositions (%)	Cement	CWP
CaO (%)	55.0	0.7713
SiO ₂ (%)	25.1	77.44
Fe ₂ O ₃ (%)	5.9	1.013
Al ₂ O ₃ (%)	5.5	16.99
SO ₃ (%)	2.7	<0.00010
MgO (%)	3.4	0.507
LOI (%)	0.9	-
K ₂ O (%)	0.5	2.118

Fig. 1 The cement, WBP and WCP particle size distribution

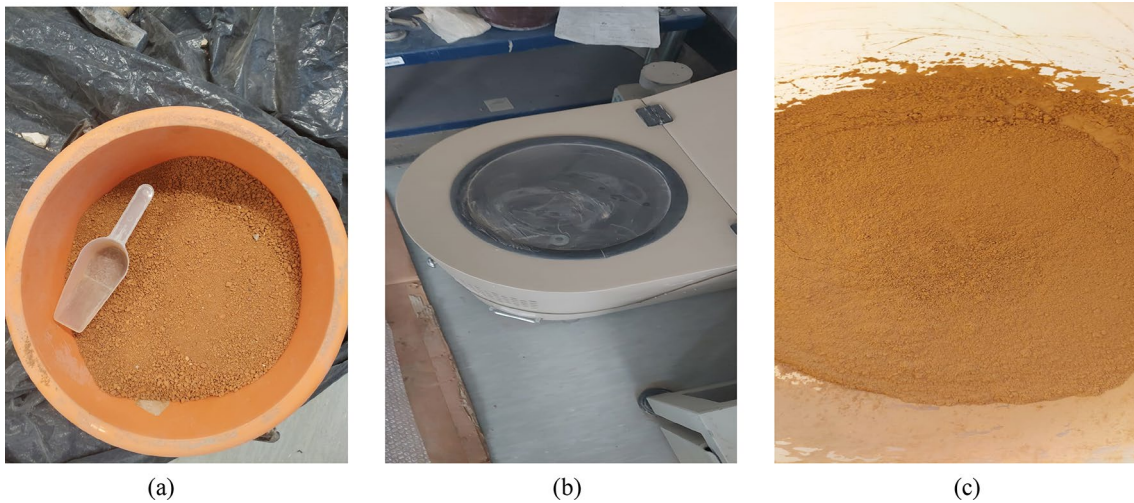
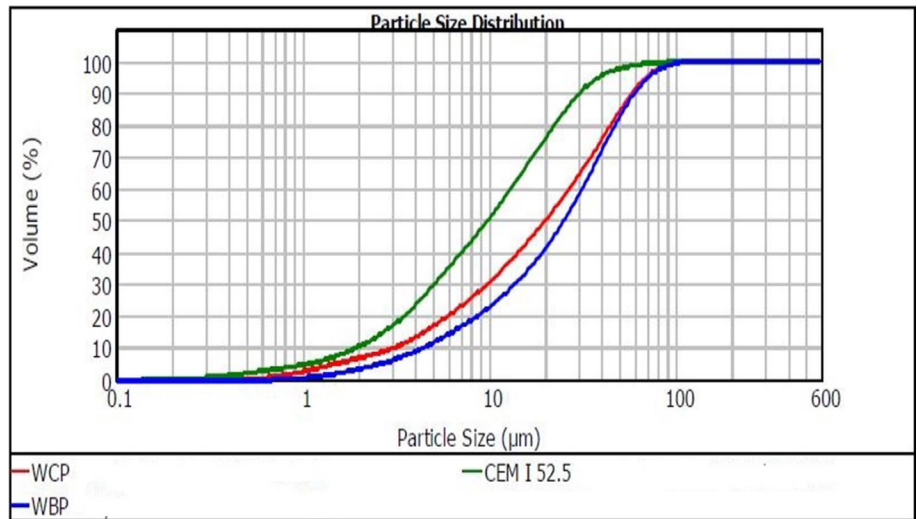


Fig. 2 WBP preparation process: **a** Waste red fire clay **(b)** Planetary ball mill, and **(c)** Recycled brick powder

planter ball mill. The particles that resulted were sieved through a 63-µm sieve. Figure 2 illustrates the preparation procedure for the ground brick. Figure 1 depicts the distribution of particle sizes. WBP contained 68.46% SiO₂, 4.6% CaO, and 2.2% K₂O as its principal constituents. SiO₂, Al₂O₃, and Fe₂O₃ totaled 88.4%. According to ASTM C618, it was marginally greater than 70%, which was needed for natural pozzolan [63], and the specific gravity of WBP was 2.41. Figure 3 depicts the WCBF microscopic morphology as depicted by the SEM image. It can be determined that the microstructure of WBP was amorphous.

Waste ceramic powder (WCP)

Ceramic waste powder (CWP) was obtained from residual white ceramic tiles at the site of construction within

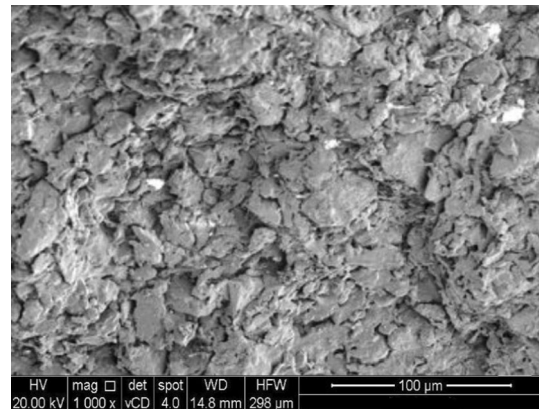


Fig. 3 SEM images of WBP

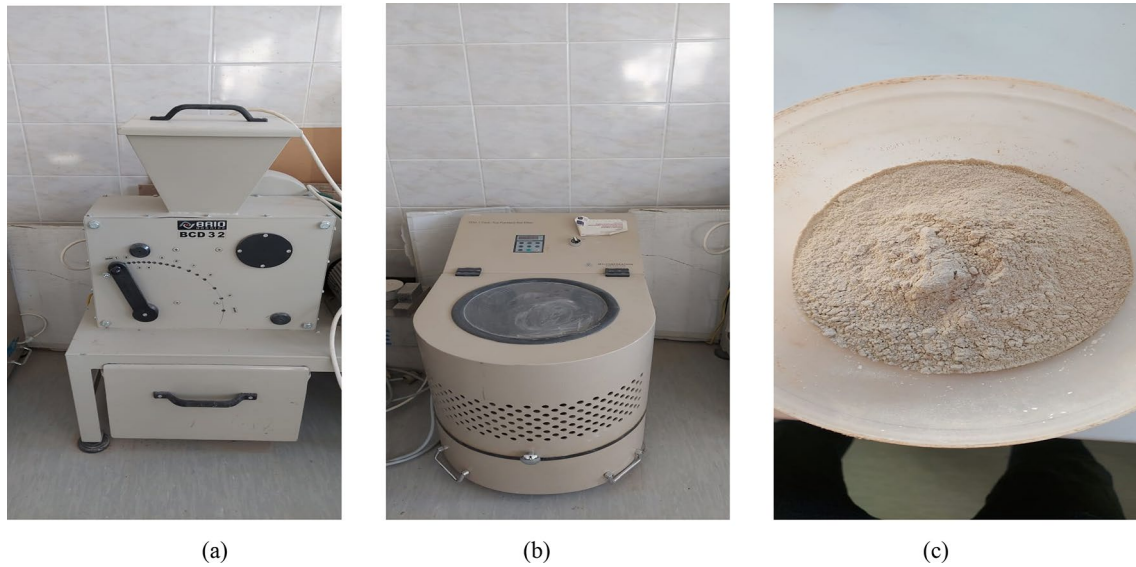


Fig. 4 WCP preparation process: a broken tiles put into a jaw crusher jaw crusher (b) Planetary ball mill, and (c) Recycled ceramic powder

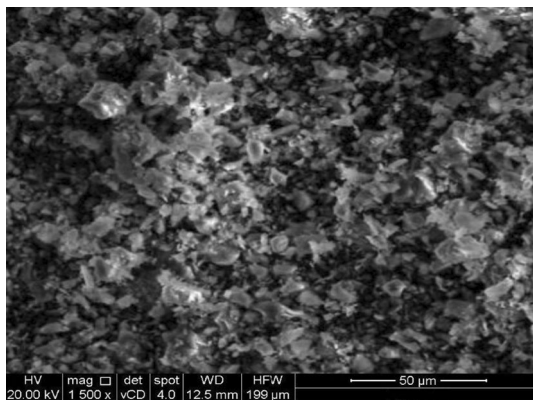


Fig. 5 SEM images of WCP

Kosice, Slovakia, which was conducted by three crushing procedures. The white ceramic tiles were smashed manually by a mallet before being fed into a jaw crusher to produce ceramic particles smaller than 4 mm. The resulting particles were sieved through a 63-µm sieve after being crushed for 1 h in a planter ball mill to produce ceramic powder. Figure 4 depicts the preparatory procedure for ground ceramics. The WCP chemical constituents, as estimated by X-ray fluorescence (XRF), are listed within Table 1. Silicon oxide and alumina were the most predominant oxides in WCP. Figure 1 depicts the WCP particle size distribution as measured by a laser particle analyzer. The specific gravity of WCP is 2.31. The WCP field scanning electron microscope (SEM) image revealed the morphologies of WCP samples. Figure 5 demonstrates that the WCP particles had an irregular shape and an uneven surface texture.

Table 2 Physical and mechanical properties of the aggregates

Property	Fine aggregate	Coarse aggregate
Density (specific weight) ρ_d [kg/m ³]	2570	2510
Bulk density ρ_{bs} [kg/m ³]	1800	1530
Water absorption WA_{24} [%]	0.9	1.3
Void content v_s [%]	30	39

Aggregates

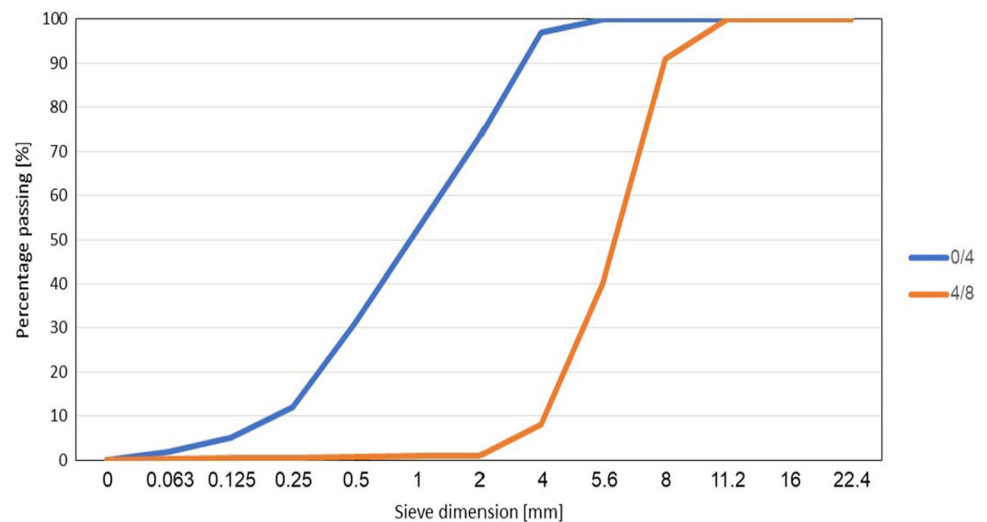
Natural gravel aggregate (4/8 mm) and river sand (0/4 mm) were employed. The aggregates were acquired from a CRH company in Geča, Slovakia. Table 2 lists the physical characteristics of the aggregates according to the European Standards (EN 1097-6). Figure 6 depicts the results of quantifying the particle size distribution of sand and granite.

Superplasticizer

The superplasticizer (SP), MC-Power Flow 3130, manufactured in Germany by MC-Bauchemie, was based on polycarboxylate-ether. The superplasticizer used in the investigation was brown in colour and had a specific gravity of 1.06. SP meets all requirements of the standard EN 934-2/6.

Mixture proportions

The proportions of the mixture are shown in Table 3. Varied ratios (5%, 10%, and 15%) for each waste brick powder

Fig. 6 Grain size distribution of sand and gravel**Table 3** Concrete mixes proportions (kg/m³)

Mixes	Cement	WBP	WCP	NFA	NCA	Water	SP%	W/C
C0	450	–	–	750	1020	170	1.5	0.37
WBP5%	427.5	22.5	–	750	1020	170	1.5	0.37
WBP10%	405	45	–	750	1020	170	1.5	0.37
WBP15%	382.5	67.5	–	750	1020	170	1.5	0.37
WCP5%	427.5	–	22.5	750	1020	170	1.5	0.37
WCP10%	405	–	45	750	1020	170	1.5	0.37
WCP15%	360	–	90	750	1020	170	1.5	0.37
WBP5 + WCP5%	405	22.5	22.5	750	1020	170	1.55	0.37
WBP5 + WCP10%	382.5	22.5	45	750	1020	170	1.6	0.37
WBP5 + WCP15%	337.5	22.5	90	750	1020	170	1.6	0.37

NCA: Natural coarse aggregate, NFA: Natural fine aggregate, WBP: Waste brick powder, WCP: Waste ceramic powder, SP: Super-plasticizer

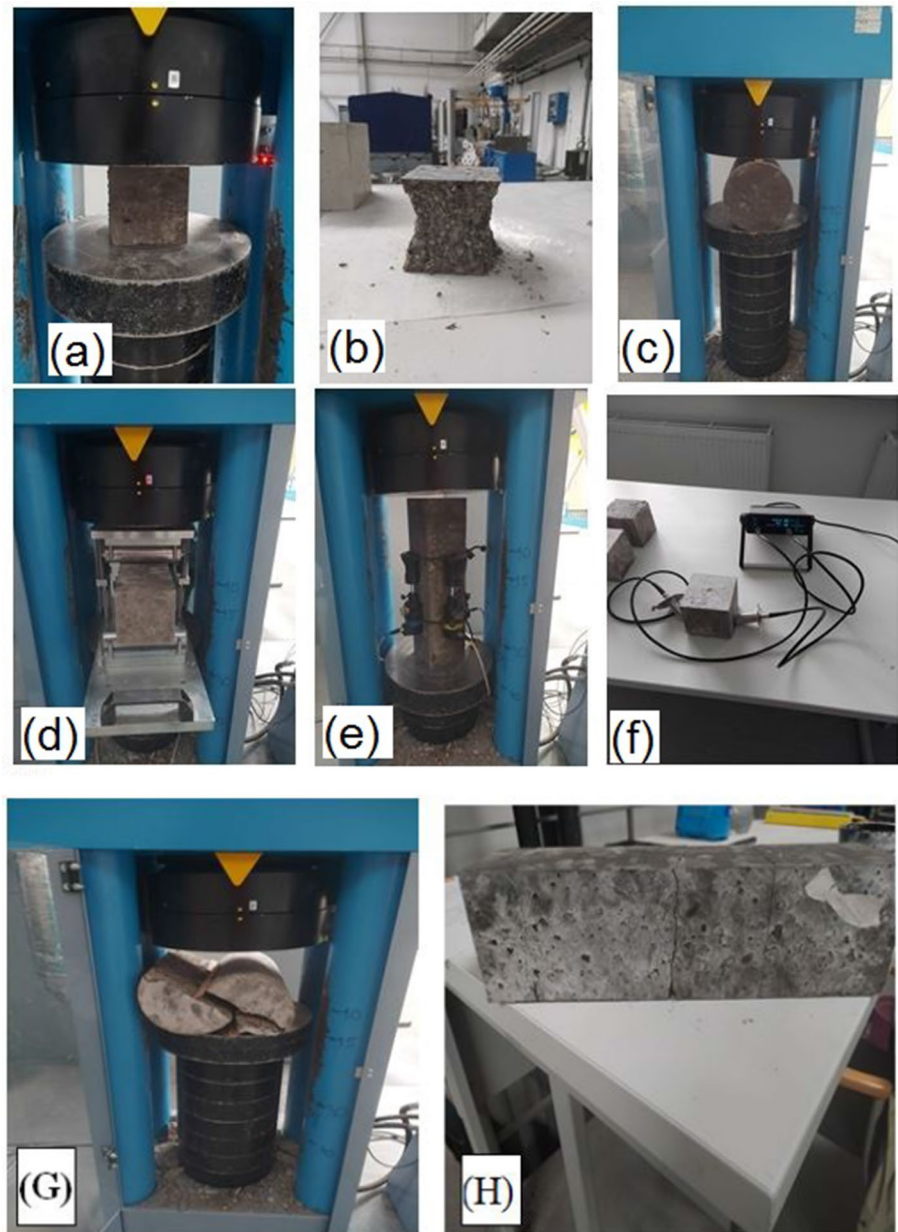
(WBP) and waste ceramic powder (WCP) were incorporated into the HSC mixtures as a partial substitution for cement. In addition, 5% WBP with varied ratios of WCP (5%, 10%, and 15%) was used. Notably, in all mixes, the water-to-cement (w/c) ratio was set in order to agree with the prior research [64, 65]. The mix design was developed to produce high-strength concrete with a desired strength of 100 MPa at 28 days. The samples were poured and stored within the lab for one day before being immersed within water at a temperature of 23 °C until the date of the test.

Test procedure

At the fresh state of high strength concrete (HSC) mixtures, the slump test was carried out in accordance with [66] to determine the concrete consistency. The compressive strength of 100 × 100 × 100 mm cubes was

measured at 7, 28, and 56 days in accordance with [67], while ultrasonic pulse velocity water absorption, and bulk density experiments were conducted at 28 days. For evaluation purposes, the splitting tensile strength at 28 days was measured on a 150 × 300 mm cylinder [68]. The flexural strength after 28 days was evaluated on a 100 × 100 × 500 mm beam in accordance with [69]. On a 100 × 100 × 400 mm beam, the modulus of elasticity at 28 days was measured according to EN 12390-13:2013. Ultrasonic modulus of elasticity, flexural strength, splitting tensile, and compression are illustrated in Fig. 7. In addition, Fig. 7(b, G, H) presents the failure modes of the concrete specimens for splitting tensile, compressive, and flexural strength testing. In addition, water absorption was measured in accordance with ASTM C642. After dehydrating the specimen in an oven at 105 °C for twenty-four hours, its mass was determined. The calculation for absorption was as follows:

Fig. 7 **a** Compression, **b** the standard shape of crushed compressive cubes, **c** splitting tensile, **d** flexural strength, **e** modulus of elasticity, **f** ultrasonic test setup, **G** splitting tensile and **(H)** flexural test failure mode



$$\text{Absorption} = \frac{Mass_{wet} - Mass_{dry}}{Mass_{dry}} \times 100$$

The cubic samples of $100 \times 100 \times 100 \text{ mm}^3$ were first cured in tap water for 28 days and then immersed in the specified solution (5% sodium sulphate and 5% magnesium sulfate solutions by weight %) for three months to determine the concrete sulfate resistance. The degree of sulfate attack was determined by assessing the concrete cubes' compressive strength, the alteration in weight of concrete cubes, and by visually inspecting cracks in concrete samples.

As depicted in Fig. 8, the weight change measurements were carried out three months after exposure to sulfate. The

observed weight changes were considered insignificant and negligible (within $\pm 0.10\%$). The decrease within compressive strength has proven to be the most reliable indicator for the attack of sulfate.

The measurements of compressive strength were carried out when the sulfate exposure duration of 3 months was terminated by employing a compression testing machine. The decrease in (CSR) compressive strength was estimated through the following:

$$\text{CSR}(\%) = \frac{Mass_m - Mass_t}{Mass_t}$$

Fig. 8 a Concrete specimens cured in tap water for 28d (b) concrete specimens exposed to 5% Na₂SO₄ + MgSO₄ solution for 3 months

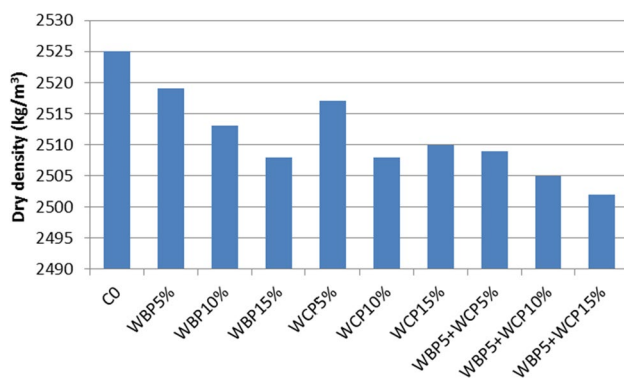
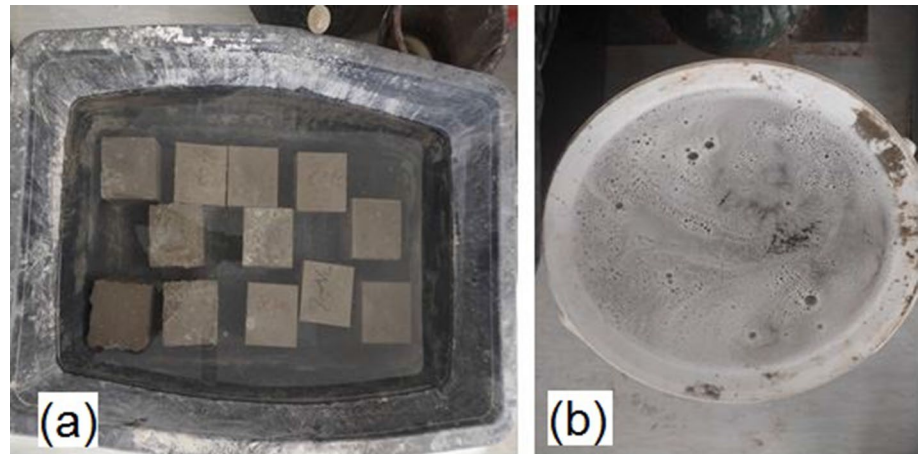


Fig. 9 Dry density of different concrete mixes

where, $Mass_m$: is the average compressive strength (in MPa) of three concrete cubes moist cured for 3 month within 5% sodium sulfate + 5% magnesium sulfate solution.

Masst is the averaging compressive strength (in MPa) for three concrete cubes immersed within tap water for 28 days.

Concrete samples were removed from testing water 4 h prior the testing and dehydrated within air.

In addition, the microstructure of the HSC samples detected via scanning electron microscopy (SEM) was utilized for micrograph production, and XRD analysis was conducted.

Results and discussion

Dry density

Figure 9 provides a summary of the dried densities of the various hardened mixtures. Obviously, the unit weight of concrete incorporating waste ceramic powder (WCP) and waste brick powder (WBP) was observed to be inversely proportional to the degree of substitution. Raising the

proportions of WCP and WBP led to a reduction in the concrete dry density. This decrease within the density of concrete was certainly attributable to the fact that the density of waste ceramic powder and waste brick powder was less than that of cement [(2.66 and 2.45) vs. 3.14], resulting in a lesser density of concrete. In addition, the rise in pore size in the hydration products (gel) might be attributable to an alteration in the clustering of crystals, which in turn influences the other concrete characteristics. The dry density of mixtures containing WBP was greater than that of mixtures containing WCP. The greatest decrease in hardened density was achieved at high levels of substitution with 15% WCP + 5% WBP; the value was 1% less than that of the reference concrete, or 2525 kg/m³. These results were consistent with the conclusions of a number of other authors [70, 71]. In addition, Subas et al. [72] observed a reduction in the density of concrete specimens containing 5%, 10%, 15%, and 20% WCP for both 7 and 28 days, as compared to the reference sample. Nevertheless, Sinkhonde and Mashava [73] found that the addition of a finer 5% WBP to cement paste did not have a significant impact on the density of the mixtures compared to the control. Therefore, it is suggested to utilise up to 15% of WBP and up to 15% of WCP as a substitution in order to achieve a dry density of around 2510–2520 kg/m³ in HSC and reduce the amount of cement used.

Compressive strength

Figure 10 depicts the compressive strength and its variations for mixes of concrete incorporating waste ceramic powder (WCP) and waste brick powder (WBP) particles separately or employing 5% WBP with 5, 10, or 20% WCP as a partial substitution for cement. According to the results, the compressive strength reduced with rising WBP and WCP content, even though the decrease was not significant for specimens. At 7, 28, and 56 days of age, the control mix possessed the largest compressive strength (80.41, 90.6, and

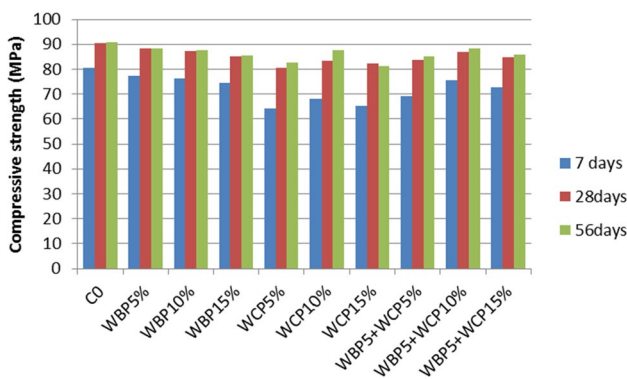


Fig. 10 Compressive strength of different concrete mixes

91 MPa). This relatively high strength is attributable to the mixture's relatively high content of cement. As the quantity of cement progressively decreases, the compressive strength at 28 days decreases by 2.64%, 3.53%, and 6% for 5% WBP, 10% WBP, and 15% WBP, respectively. In comparison to the results at 28 days, the rate of compressive strength development in concrete mixes containing WBP rose marginally after 56 days. At 56 days, all strength measurements were 2.74%, 3.73%, and 6.04% less for 5% WBP, 10% WBP, and 15% WBP, respectively, compared to those of the reference concrete mix. Ge et al. [47] additionally identified a similar finding when the WCP was used as a substitute for cement in concrete.

Nevertheless, Sinkhonde and Mashava [73] observed that the addition of a finer 5% WBP in cement paste exhibited a substantial positive impact on the prismatic compressive strength. As cement was substituted with WBP particles, the CSH gel amount generated by hydration decreased, which could account for the decrease in strength. This decrease in CSH gel could not be compensated by the micro-filling impact caused by these particles [8], and therefore, WBP did not influence the development of strength and weakened the binding between concrete components as its content rose. The high porosity of brick dust, which led to an increase in water absorption, could also be another contributing factor. This increased water demand led to a reduction within the strength of the mortar and concrete [47]. The reduction in strength may also be attributable to the low amorphous brick dust content and the existence of excess unreacted brick dust [8]. However, it is obvious that the 7-day compressive strength of 5% WCP, 10% WCP, and 15% WCP are 20.27%, 15.25%, and 18.91%, respectively, lower than that of C0. Following 28 days of curing, the compressive strength of the specimens, including different WCP percentages, is a little less compared to C0. Subas et al. [72] observed a same pattern by employing CW in concrete. In contrast, specific research documented a 20% improvement in concrete strength when using a substitution level of 20% WCP [74].

At all phases of curing, the compressive strength of materials including 10% WCP was greater than that of those with 5% and 15% WCP. Pozzolan functions only used as a filler and does not endure the pozzolanic reaction, which may account for the reduction in compressive strength of mixtures containing different WCPs. In addition, the decrease in early compressive strength is primarily attributable to the embryonic pozzolanic reaction within the concrete and the inhibited growth of C–S–H gel influenced by components within ground ceramic powder [75]. A slight rise within compressive strength by 10% WCP compared to 5% WCP may be attributable to the fact that the WCP pozzolanic reactions produce more binding phases, thereby enhancing the interactions between cement hydrates and ceramic grains [76]. The sites and additional areas for the hydration products' heterogeneous nucleation, such as calcium hydroxide (CH), calcium-silicate-hydrate (C–S–H), and other hydration products, were provided by the WCP additional surfaces. Additionally, the uniformly dispersed ceramic granules reduce the travel distance of ions from active minerals to nucleating sites. These impacts may encourage cement hydration rates and heterogeneous nucleating densities [77] effectively.

However, employing 5% WBP with various WCP ratios increased the compressive strength compared to samples containing WCP alone. The cause could be attributable to a rise in SP dosage, which endorsed a decrease in the viscosity of mixtures containing 5% WBP and varying WCP ratios. In addition, the minor improvement within strength may be attributable to a more uniform distribution of cement, WCP, and WBP grain within the matrix of mortar when the flow characteristics were enhanced [78]. Thus, the cement mortar packing capability to encapsulate the aggregate could be increased, and voids could exist around or beneath the coarse aggregate, resulting in an improved Interfacial Transition Zone (ITZ). Hence, in terms of compressive strength, replacements containing less than 10% WBP can be suggested as low-risk percentages. Furthermore, for achieving strengths between 83 and 87 MPa, combining various percentages of WCP with 5% WBP is preferable to utilising WCP separately.

Splitting tensile strength

At 28 days, Fig. 11 illustrates the splitting tensile strength of various mixes of concrete. The splitting tensile strength of the control concrete was found to be 5.63 MPa, which was reduced by 2.84%, 4.11%, and 5.32% for composites containing 5% WBP, 10% WBP, and 15% WBP, respectively. However, the decrease rates were 9%, 7%, and 8% for 5% WCP, 10% WCP, and 15% WCP, respectively, when compared to the reference mix. Employing 5% WBP with different ratios of WCP enhanced the splitting tensile strength

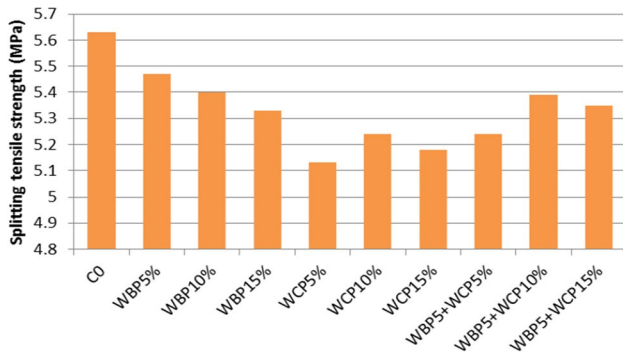


Fig. 11 Splitting tensile strength of different concrete mixes

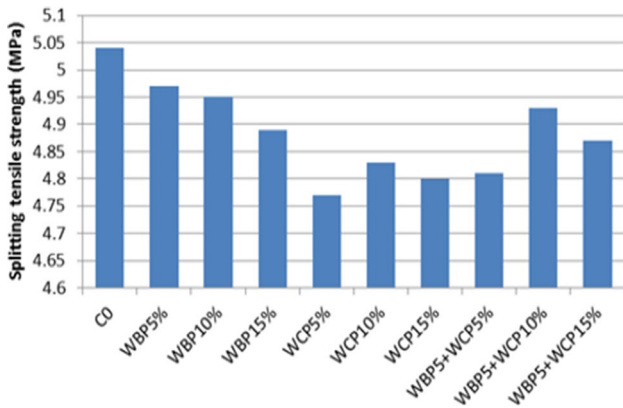
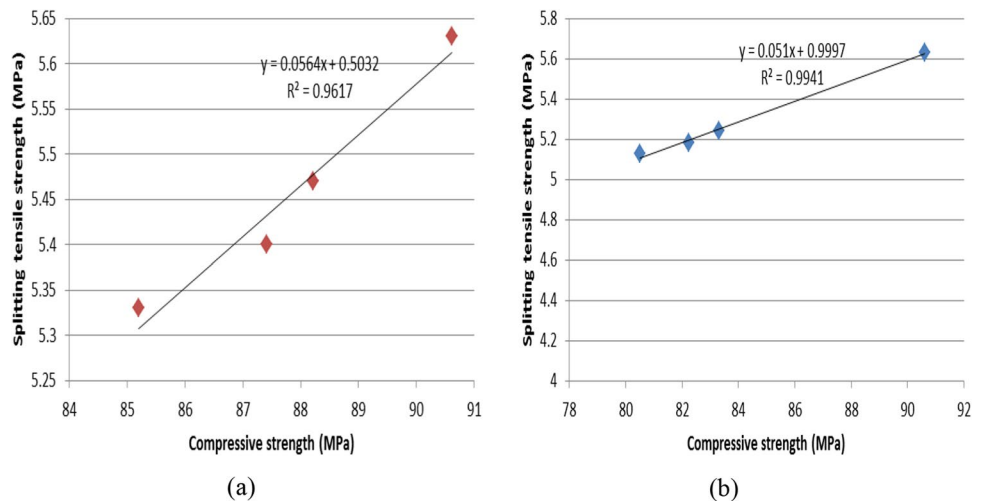


Fig. 12 Splitting tensile strength obtained by ACI 318

results by 2.14%, 2.86%, and 3.28% compared to 5% WCP, 10% WCP, and 15% WCP respectively. Similar to compressive strength, splitting tensile strength follows a similar pattern. The decrease in splitting tensile strength with growing WBP content may be a result of the greater amount of crystalline minerals within WBP [79]. Komnitsas et al. [80]

Fig. 13 Correlation between splitting tensile and compressive strength values of different HSC samples with (a) varied percentage of waste brick powder and (b) varied percentage of waste ceramic powder



proposed that the particle size of WBP is considered one of the variables affecting its pozzolanicity, with smaller particle sizes tending to speed up the pozzolanic reaction because of a rise in specific surface area. A similar phenomenon has also been reported regarding particle size distributions (Sects. “Cement” and “Waste brick powder (WBP)”). Subas et al. [72] discovered that the tensile strength of self-consolidating concrete decreased when WCP was used to replace cement. The results indicated that the compressive strength falls within the range of 6.2–6.3%. Consequently, the splitting tensile strengths met the requirements for structural concrete as specified in the ACI 318 standards, as depicted in Fig. 12. This means that the ACI 318 expression can be used to figure out the splitting tensile strength of HSC that has WBP, WCP, or a mix of 5% WBP and different amounts of WCP. The ACI 318 formula yielded the most accurate prediction of the splitting tensile strength, as demonstrated in the testing data.

As shown in Fig. 13, a significant correlation was also observed between the compressive and splitting tensile strength results of WBP and WCP, whose high coefficients of measurement were $R^2 = 0.9617$ and 0.9941 , respectively.

Flexural strength

Figure 14 depicts the findings of the flexural strength experiment after 28 days of curing. The flexural strength findings exhibited a similar trend to the splitting tensile and compressive strength results. The findings indicated that the flexural strength at 28 days was reduced when WCP and WBP were substituted for cement, primarily because of the dilution impact of WBP, and WCP had a greater dominating impact as the pozzolanic and hydration products decreased proportionally. The flexural strength measurements for specimens having varying ratios of WBP range from 6.8 MPa to 6.97 MPa, whereas the values for specimens having various

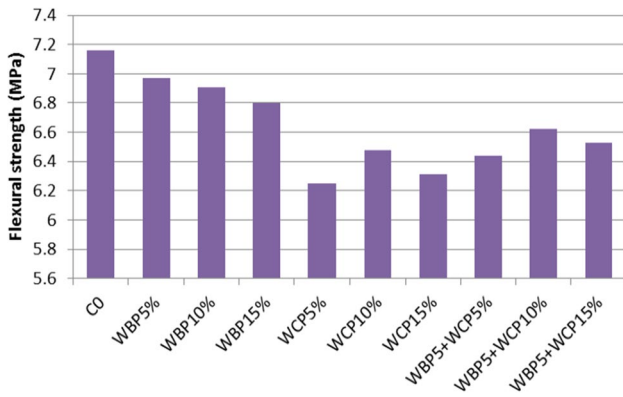
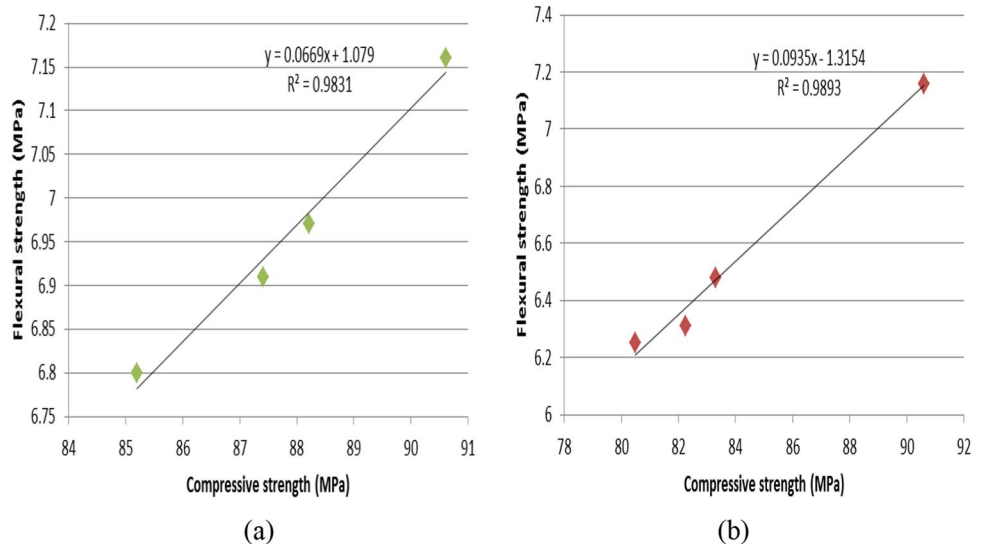


Fig. 14 Flexural strength of different concrete mixes

percentages of WBP range from 6.25 to 6.46 MPa. Comparing with the control mix, the flexural strength results decreased by 2.65%, 3.5%, and 5.02% for 5% WBP, 10% WBP, and 15% WBP, respectively. However, the flexural strength values were decreased by 12.7%, 9.77%, and 11% with 5, 10, and 15% WCP, respectively. The same results were published by ElDieb et al. et al. [81], who used WCP as a partial substitution for cement (0%, 10%, 20%, 30%, and 40%) within concrete.

Nevertheless, the addition of 5% WBP to mixtures of 5, 10, and 15% WCP marginally increased the flexural strength values, which were 3.04%, 2.3%, and 2.5% when compared to mixtures of 5, 10, and 15% WCP. The minor rise in flexural strength could be attributable to the similar chemical composition of ceramic powder and brick powder, which resulted in a homogeneous structure leading to a uniform strain field. Figure 15 displays a significant correlation between the flexural strength and compressive strength values of WBP and WCP. The coefficients of determination

Fig. 15 Correlation among compressive and flexural strength results of various HSC specimens with (a) varied percentage of waste brick powder and (b) varied percentage of waste ceramic powder



(R²) for WBP and WCP were 0.9831 and 0.9893, respectively, which were considered to be high. Furthermore, it was noted in Fig. 16 that the experimental outcomes were most closely aligned with the flexural strength predicted by the ACI 318 expression. This suggests that the aforementioned expressions possess the capability to compute the flexural strength of HSC containing WBP, or WCP, or 5% WBP with different percentages of WCP. To achieve a desired flexural strength of around 5.47 MPa and a range of 5.24–5.39 MPa for HSC while minimizing the usage of cement, it is recommended to either use 5% WBP alone or varying quantities of WCP with a 5% WBP substitution ratio. This approach yields a flexural strength range of 5.24–5.39 MPa.

Ultrasonic Pulse Velocity Test (UPV)

Figure 17 depicts the UPV results of all mixtures containing WBP and WCP separately or 5% WBP and varied ratios of WCP after 28 days. Based on the results of this investigation, the reference mix produced the highest UPV among

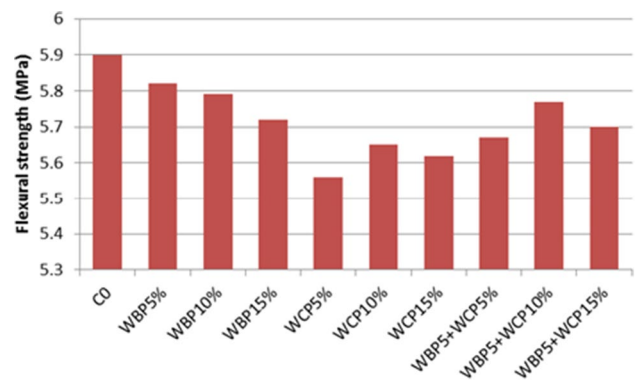


Fig. 16 Flexural strength obtained by ACI 318

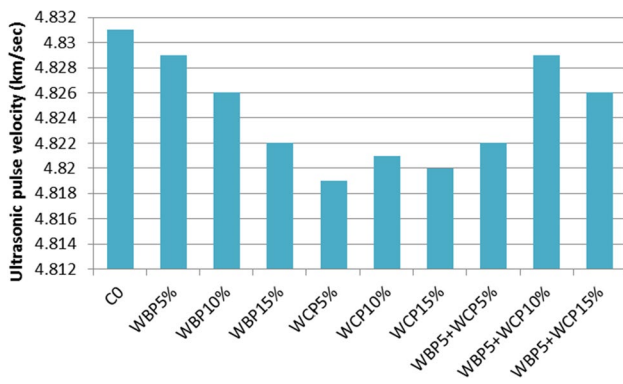


Fig. 17 Ultrasonic Pulse Velocity of different concrete mixes

all mixtures. However, the mixes including WBP had a faster pulse velocity than those containing WCP alone, or 5% WBP. The 5%, 10%, and 15% WBP decreased the UPV by approximately 0.041%, 0.103%, and 0.14%, respectively, relative to the control mix. Nevertheless, the UPV decrement rate with 5%, 10%, and 15% of WCP was 0.24%, 0.21%, and 0.23%, respectively. The results also demonstrated that the use of WBP and WCP has a marginally negative effect on the UPV of HSC. Nevertheless, all UPV measurements for specimens containing varying ratios of WBP and WCP separately, or 5% WBP and various ratios of WCP concrete, as well as reference concrete samples, fall within the range of 4819–4831 km/s. There are two efficient parameter impacts on the UPV, consisting of the density and elastic properties of materials [82, 83]. So, UPV results for mixes showed that all of them met the requirements for high-quality concrete set out in IS:13, 311 [84]. Other researchers have previously reported that raising the WBP and WCP ratios in mixes of concrete decreases UPV values [83, 85].

In addition, as shown in Fig. 18, there is a linear correlation between the compressive strength and the UPV results for the HSC mixes after 28 days of curing. The R2 value, which was based on the experimental results, determined

this relationship. According to Fig. 18, there was a significant relationship between the UPV and the compressive strength results of WBP and WCP, which showed high values of 0.94 and 0.98, respectively. The findings of this study indicated that including WBP at a concentration of up to 5% has a little detrimental impact on the quality of the HSC, with negligible influence on its pore structure.

Modulus of elasticity

After 28 days, the elastic modulus of cube-shaped specimens was measured. The variations in the elasticity modulus of concrete formulations are depicted in Fig. 19. Obviously, elastic modulus decreased with a rising amount of WBP and WCP content. For instance, the elastic modulus was reduced from 38.3 GPa to 33.1 GPa in WBP15% and 32.69 GPa in WCP 15%, which corresponds to a reduction of approximately 11.41 and 15.52%, respectively. However, substituting cement with 5% WBP + 15% WCP increased the modulus of elasticity of HSC compared to employing 15% WCP alone. As an example, substituting 20% of cement with 5% WBP + 15% WCP increased the modulus of elasticity of HSC by 2.11% compared to the 15% WCP alone. In a similar way, Dang and Zhao [86] discovered that the modulus of

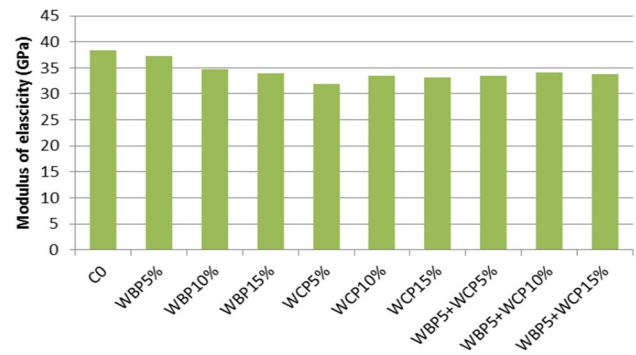


Fig. 19 Modulus of elasticity of different concrete mixes

Fig. 18 Correlation among compressive strength and ultrasonic pulse velocity results of different HSC specimens with (a) varied percentage of waste brick powder and (b) varied percentage of waste ceramic powder

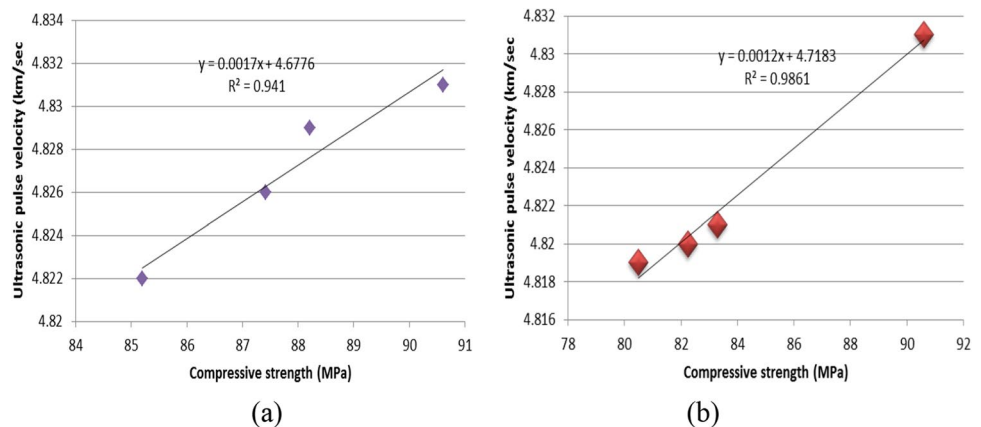
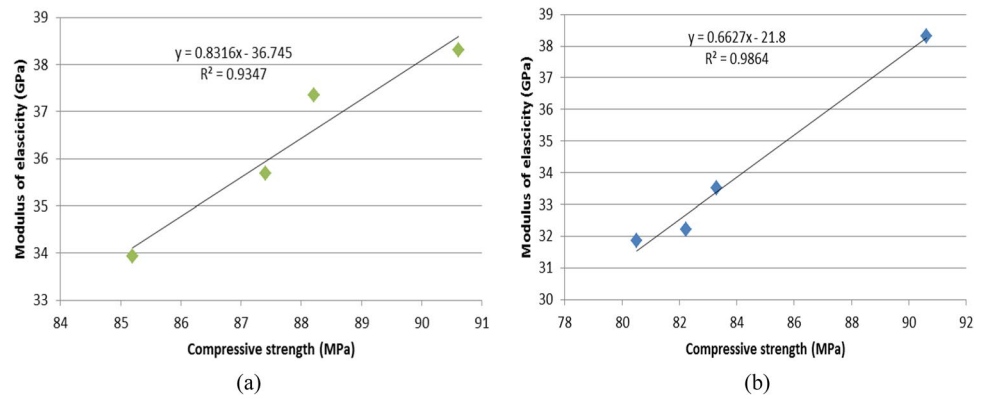


Fig. 20 Correlation among compressive strength and modulus of elasticity result of various HSC samples with (a) varied percentage of waste brick powder and (b) varied percentage of waste ceramic powder



elasticity witnessed a drop when waste bricks were utilised as a substitute for fine aggregate in concrete. Furthermore, these results are consistent with the overall pattern shown in the compressive strength data. Nevertheless, another investigation indicated that the use of waste ceramic as aggregates resulted in an augmentation of the modulus of elasticity of concrete mixtures [87–89].

In addition, a linear regression analysis was conducted to determine the relationship between modulus of elasticity and compressive strength. These characteristics were shown to be directly correlated in Fig. 20, and the following expressions were formulated on the basis of the linear regression analysis:

$$f_c = 0.8316E_c - 36.745 \text{ (WBP)} \tag{1}$$

$$f_c = 0.6627E_c - 21.8 \text{ (WCP)} \tag{2}$$

On the basis of its modulus of elasticity, the expression could be utilized for estimating the compressive strength of HSC with WBP and WCP. Furthermore, the R-factors of 0.9347 and 0.9864 demonstrated the validity of the linear regression analysis and the acceptable accuracy of the suggested expression. Nevertheless, as depicted in Fig. 21, it is obvious that the experimental results for the modulus of elasticity of concrete were slightly lower than the anticipated values derived from the ACI 318 equation. The highest disparity between the experimental and estimated findings was found to be less than 6%.

Water absorption

Figure 22 depicts the results of water absorption (WA) experiments conducted on HSC after 28 days of curing. The results indicated that the water absorption value increased with the rising substitution of cement with WCP, WBP, and 5% WBP at varying ratios of WCP compared to the reference concrete. The WA rose from 2.1% to 2.5%, 2.6%, and 3% as

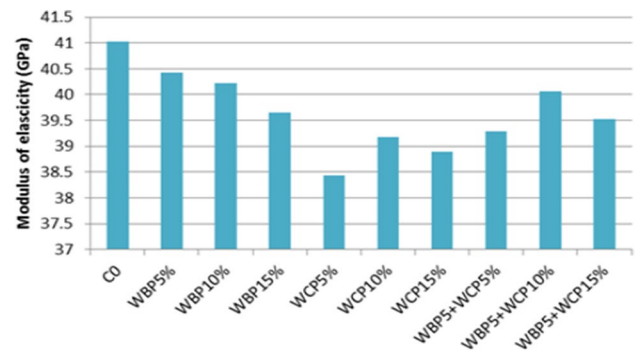


Fig. 21 Modulus of elasticity obtained by ACI 318

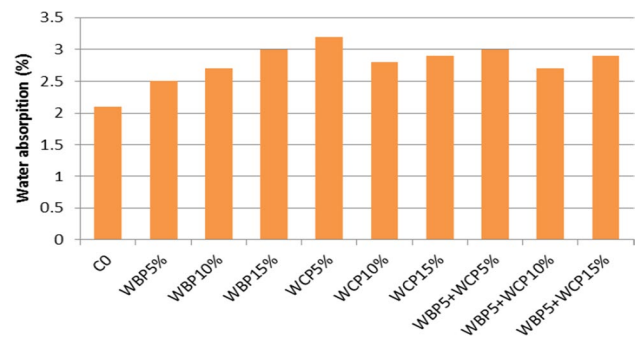


Fig. 22 Water absorption of different concrete mixes

the WBP rose from 0 to 5%, 10%, and 15%, respectively. Employing 5%, 10%, or 15% of WCP, however, raised the WA by 3.7%, 3.2%, and 3.5%, respectively. Nevertheless, 5% of WBP combined with 5% WCP, 10% WCP, and 15% WCP enhanced the WA by 3%, 2.7%, and 2.7%, respectively. In Sects. (4.2–4.4), the explanations for these findings were stated. The results presented in the literature [70] agree with the present study, as the author stated that the use of WCP up to 10% decreased water absorption. The previous study illustrated that usage of 10% WCP was less than control specimen however this condition was not achieved in this

study. Based on the mechanical characteristics, it is advisable to use a substitution ratio of 5% WBP. The findings of this study indicate that including WBP at a concentration of up to 5% resulted in the least water absorption when compared to the other mixtures, including WCP or WBP. As the WBP and WCP concentrations rose, a less dense C–S–H gel developed, resulting in a decrease in strength and an increase in water absorption. It has been noted [56] that an increase in WCP content could have an effect on the partially and non-reacted particles, resulting in a more porous structure and higher water absorption in HSCs [86] samples.

Resistance to sulfate attack

Change in compressive strength

The variance in compressive strength of mixtures exposed to a sulphate solution for 90 days is depicted in Fig. 23. According to the figure, the compressive strength of the WCP and WBP mixtures after 90 days of sulphate exposure was substantially greater than that of the control (C0) mixture. The WCP mixtures exhibited the greatest change in compressive strength (%). After 90 days of being exposed, the compressive strength of 5%, 10%, and 15% of WCP decreased by 12.4%, 9.8%, and 10.2%, respectively, compared to a decrease of 5.3% for the control mixture. Nevertheless, the decrease in 5%, 10%, and 15% of WBP was 6.2%, 7.6%, and 7.6%, respectively.

Alternatively, using 5% WCP in conjunction with 5%, 10%, and 15% WCP reduced the variation in compressive strength when comparing specimens with WCP alone. This finding is consistent with the results reported in the literature [90]. Toledo Filho et al. [90] found that the mortar's tensile strength decreased by 3% and 5% when it contained 10% and 20% WBP, respectively, and was subjected to a magnesium sulphate solution. These values were lower than the control mortar, which had a 12% decrease in tensile strength.

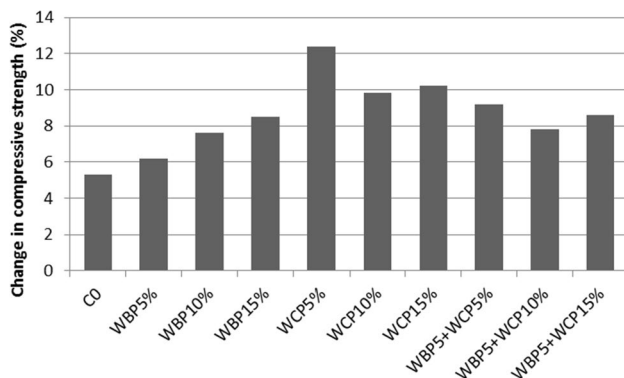


Fig. 23 Change in compressive strength (%) of different concrete mixes after exposure to sulphate attack

Nevertheless, Siddique et al. [91] reported that the reduction in compressive strength was greater in the control concrete compared to the concrete that included waste ceramic as fine aggregate.

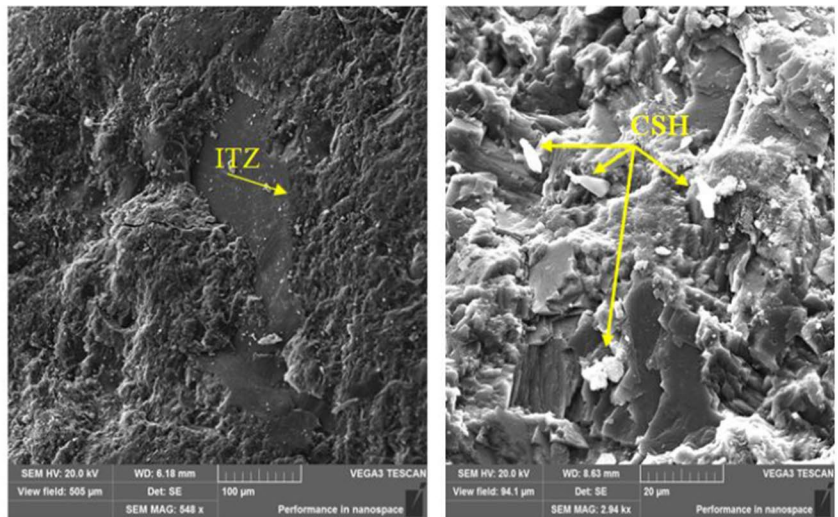
The decrease in sulphate attack resistance of concrete mixtures containing WCP and WBP can be attributed to the impact of Na_2SO_4 and MgSO_4 on the concrete. $\text{Ca}(\text{OH})_2$ is a component of concrete that is readily corroded; however, within concrete blended with waste ceramic powder or waste brick powder, $\text{Ca}(\text{OH})_2$ is reduced since WCP and WBP are replaced with cement. Nevertheless, concrete integrating WCP and WBP contains more voids than control specimens. Nevertheless, concrete integrating WCP and WBP contains more voids than control specimens. Thus, sulfate attacks concrete, and sulfate may interact with the remainder of $\text{Ca}(\text{OH})_2$ to form CaSO_4 ; CaSO_4 then interacts with hydrated calcium aluminate, another hydrate of cement, to form ettringite, resulting in the expansion of volume. When concentration of CaSO_4 is high enough, CaSO_4 might precipitate and directly cause the expansion of volume, resulting in the destruction of concrete. Nevertheless, as shown in SEM Fig. 23, the concrete structure of the control specimen is more compact and uniform than specimens having different ratios of WCP and WBP.

Microstructure

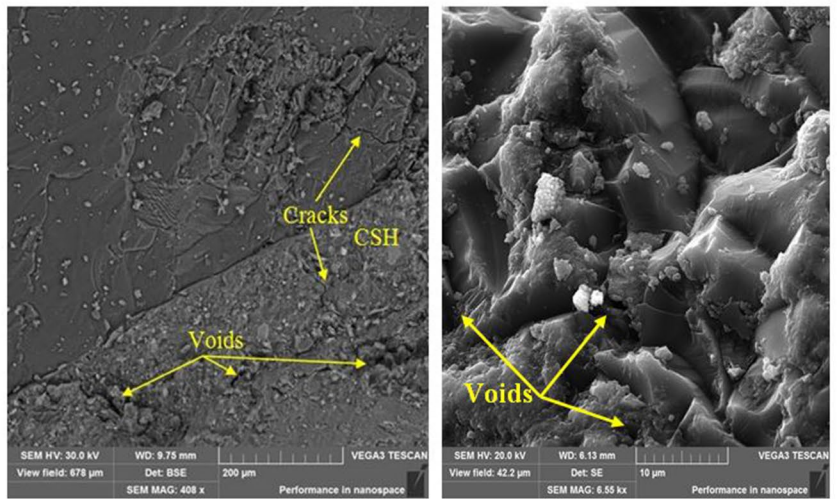
SEM analysis

After 28 days of curing, selected concrete samples (C0, WBP5, WCP10, and WBP5 + WCP10) were subjected to SEM analysis. The determined microstructure characteristics agree with the previously discussed results of mechanical testing. In comparison with blended concrete samples, the microstructure of C0 was more homogenous and compact (Fig. 24a). Besides the highly amorphous character of C–S–H and C–A–S–H phases, can be observed. Partial replacement of cement with waste powders resulted in the increased number of cracks, especially in the case of WCP. This can be explained by roughness of ceramic particles as it is documented by Fig. 5. Stress concentration at sharp corners produces cracks, which in turn leads to decreased strength characteristics [92]. Figure 24d, however, confirms that declinations to crack formation as well as higher porosity of particular sample were significantly improved by implementation of 5% WBP, which can be elucidated as follows. The combination of particles of different sizes and shapes improved the filling of the intergranular voids between cement particles and thus improved the compactness of the concrete. Wei et al. [93] proved that the use of suitable fractions of particles of different morphologies can also enhance concrete fracture behaviour as a result of the dissipation of stress. The observed compactness of a

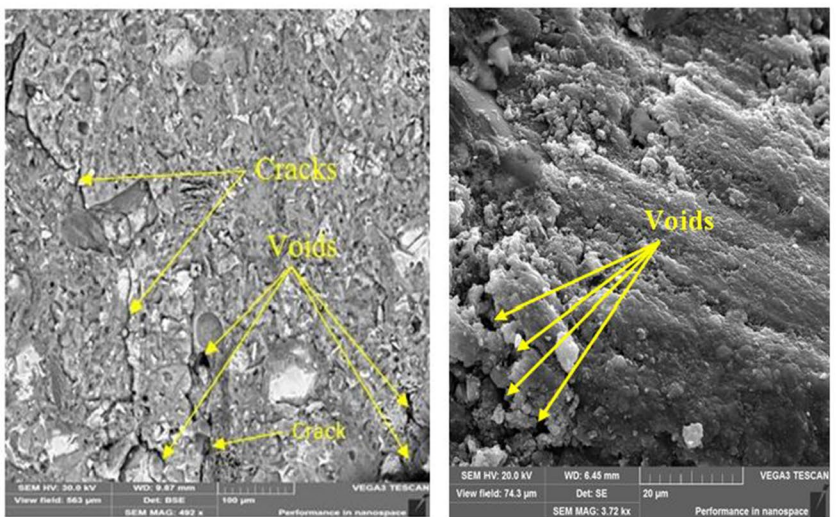
Fig. 24 The SEM images for different HSC mixtures at 28 days



(a) C0

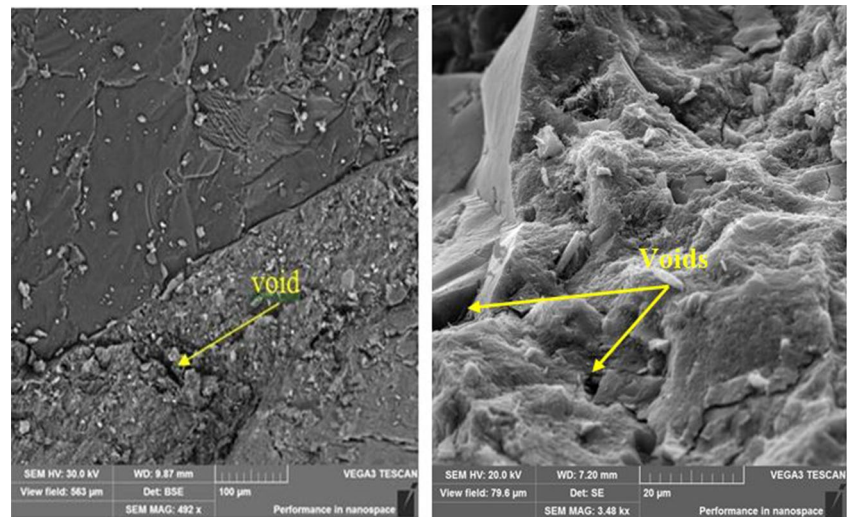


(b) 5%WBP



(c) 10%WCP

Fig. 24 (continued)



(d) 5%WBP+10%WCP

particular 5% WBP + 10% WCP sample resulted also from the additional formation of pozzolanic reaction products.

XRD analysis

Figure 25 depicts the XRD analysis of the chosen concrete specimens (C0, WBP5, and WCP10) after 28 days of curing. The results were obtained in two $10\text{--}70^\circ$ theta step intervals.

Diffraction peaks determined in the XRD pattern of C0 belong mainly to the minerals from the used aggregates, whilst those identified in the patterns of blended concrete samples also belong to the crystalline phases from WBP and CWP. Among them, dolomite ($\text{CaMg}(\text{CO}_3)_2$) and langbeinite ($\text{Mg}_2\text{K}_2(\text{SO}_4)_3$) originate from the coarse aggregate; quartz (SiO_2) is the main crystalline phase of the sand and gravel, but also of the WBP and CWP. Diffraction peaks of unreacted clinker phases are hidden because of the high crystallinity and amount of the quartz, as well as the essentially amorphous nature of the formed C–S–H gel. The presence of free lime coming from the cement was identified only in the XRD patterns of C0 and WBP5. As crystalline hydration products, and portlandite ($\text{Ca}(\text{OH})_2$) were recognized, whilst detected calcite (CaCO_3) was formed mainly by the reaction of hydration products as well as initial clinker phases with CO_2 from the air. Since portlandite is still present in the concrete, due to kinetic reasons, most of the calcite was formed by its carbonation.

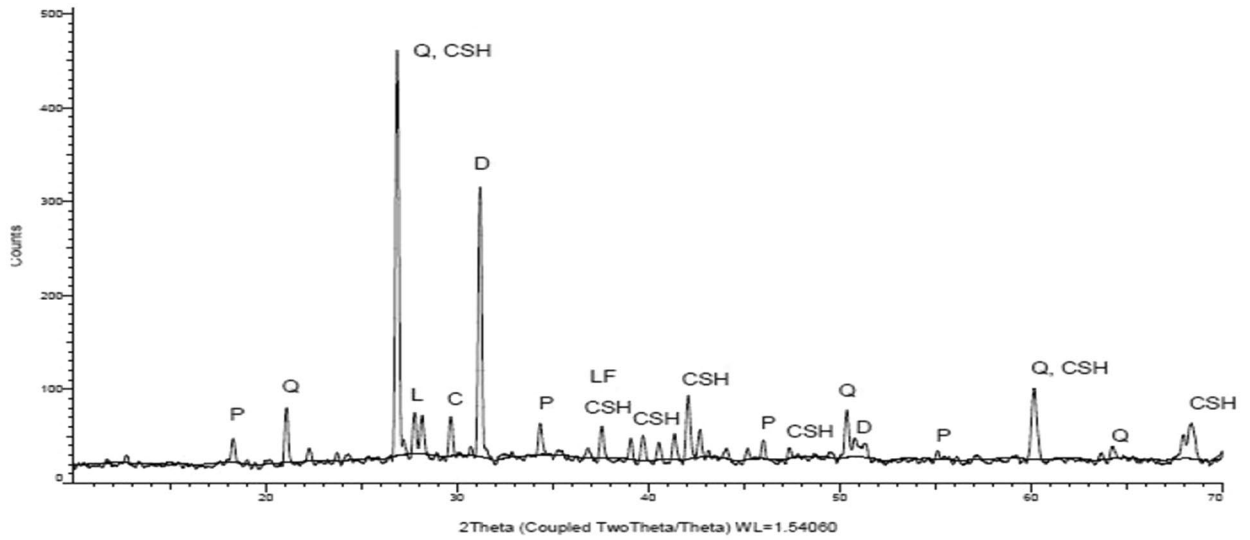
Changes in the course of hydration and pozzolanic reactions due to the substitution of cement by WBP and WCP are reflected in the amount of portlandite. The decreased amount of portlandite results from the lower amount of initial clinker phases in the blended samples as well as its consumption in pozzolanic reactions. In the case of WBP, pozzolanic reactions, leading to the formation of additional strength

possessing phases, together with the filler effect of the waste powder ensured that the determined slight deterioration of mechanical properties in comparison with C0 did not correspond to the particular degree of cement substitution.

Based on the results of mechanical testing, WCP, despite its finer character, demonstrates slower pozzolanic reactions than WBP, which could be caused by recrystallization of some phases at higher temperatures during production process. This led, together with the dilution effect caused by partial replacement of cement, to the formation of less hydration products with strong mechanical properties. However, contrary to the corresponding WBP concrete samples and especially referential C0, more significant improvement in mechanical properties with time is observed. This can be explained both by pozzolanic activity appearing later in time and by the gradual release of water from the structure of CWP. Later, the supply of water from soaked aggregate to the cement matrix through its suction by capillary tension ensured continued hydration and resulted in the increased formation of portlandite detected in the XRD pattern of WCP10 concrete.

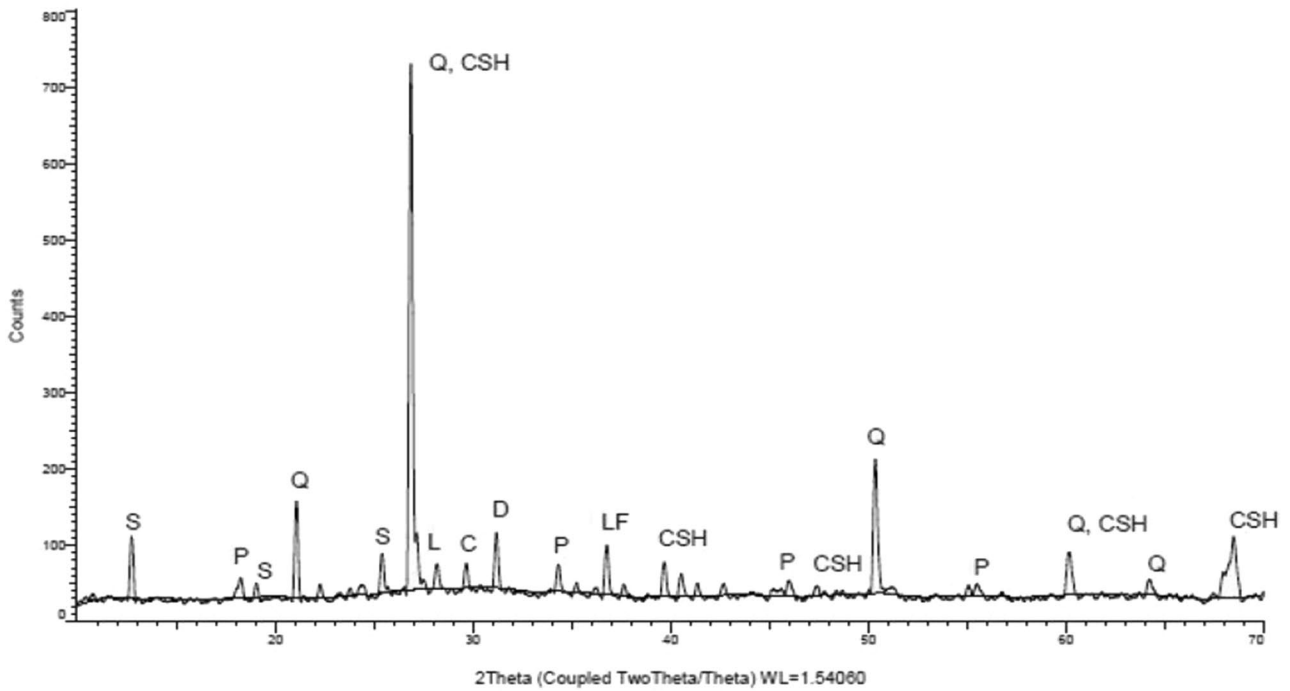
Economic and Environmental benefits

The raw resources' carbon emissions were illustrated in Tables 4 and 5. The values of consumption of electricity and CO_2 emission of electricity in Table 5 were calculated according to Eqs. 1 and 2, respectively. As illustrated in Table 5, the carbon emissions of WCP and WPB were obviously low compared to Portland cement. The implication of substituting cement for WPB and WCP would aid in achieving environmental benefits.



P - Portlandite
 Q - Quartz
 L - Langbeinite
 CSH - CSH phase - hydration minerals
 LF - free lime
 D - Dolomite
 C - Calcite

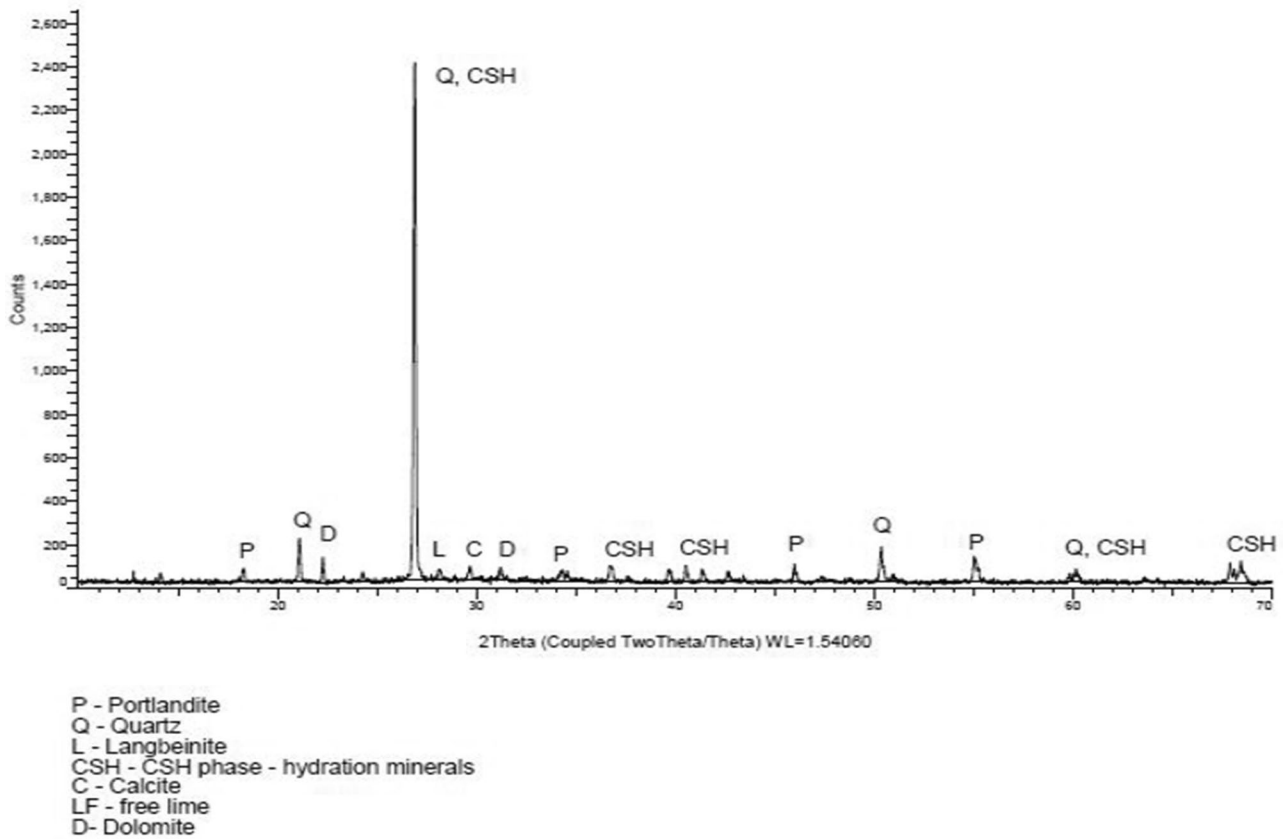
(a) C0



S - Silicate
 Q - Quartz
 P - Portlandite
 CSH - CSH phase - hydration minerals
 L - Langbeinite
 D - Dolomite
 C - calcite
 LF - free lime

(b) WBP5

Fig. 25 XRD patterns of C0, WBP5, and WCP10 concrete samples at 28 days



(c) WCP10

Fig. 25 (continued)

Table 4 Carbon emission of milled waste materials (WBP and WCP)

Waste materials	Milled Mass (t)	Time of Milling (h)	Power (kW)	Consumption of Electricity (kWh/ t)	CO ₂ emission of electricity (kg/t)
WBP	0.1	0.5	3	15	11.77
WCP	0.1	0.5	3	15	11.77

Note: the CO₂ emission of electricity is 0.785 kg/kWh, according to Ref. [92]

$$\text{Consumption of Electricity (kWh/ t)} = \frac{\text{Time of Milling} \times \text{Power}}{\text{Milled Mass}} \quad (3)$$

$$\text{CO}_2\text{emission of electricity (kg/t)} = \text{Consumption of Electricity} \times \text{the CO}_2\text{emission of electricity of material} \quad (4)$$

The energy saving extent, Ψ , can be determined by

$$\psi = \left(1 - \frac{E_{WEP \text{ or } WCP}}{E_c} \right) \times n\%$$

Table 5 carbon emission

	Cement	WBP	WCP
Carbon emission (Kg/t)	930	11.77	11.77

Note: the carbon emission and cost of cement is according to Ref. [92]

where, E_c and $E_{WCP \text{ or } WBP}$ are the specific energy consumption of producing cement and WBP or WCP. By substituting $E_c = 118 \text{ kWh/t}$ [93] and $E_{WCP \text{ or } WBP} = 15 \text{ kWh/t}$ in the previous formula yields to $\Psi = 0.873 \times n\%$. This indicates that every 15% of cement substituted by WCP or WBP could decrease total energy consumption by 13.1%.

Conclusions

This study investigated the impacts of employing waste ceramic powder (WCP) and waste brick powder (WBP) individually. Then, using hybrid waste materials [5% WBP] with varying proportions of WCP (5%, 10%, and

15%) on the mechanical strength, durability behavior, microstructure, and ecological evaluation of high strength concrete (HSC). The optimal WBP and WCP concentrations have been determined to be 5% and 10%, respectively. The primary conclusions are the following:

1. The HSC strength decreased as the WCP and WBP contents increased, as 5% WBP and 10% WCP produced the greatest results compared to other percentages. Nevertheless, the usage of a sufficient quantity of hybrid waste materials and the increase in superplasticizer dosage to 1.6% of cementitious materials can improve the HSC strength relative to using only WCP.
2. The optimal WBP content was determined to be 5%, which decreased the aforementioned properties by 2.84 and 2.65%, respectively, compared to the control mixture, whereas the decreased rates with the optimal WCP content of 10% were 6.92 and 9.4%, respectively. However, the combined use of 5% WCP and 10% WCP raised the compressive strength marginally; although it raised the splitting tensile and flexural strengths by 2.82% and 2.62%, respectively, when compared to the control 10% WCP alone.
3. Because of the existence of various ratios of WCP and WBP in HSC, the density values of HSC mixtures incorporating WCP or WBP were marginally less dense compared to the control concrete.
4. Increasing WBP and WCP replacement levels within HSC mixes caused a decline in UPV outcomes. In contrast, adding up to 15% WBP and 15% WCP to concrete produced exceptional ultrasonic pulse velocity values (i.e., greater than 4.8 km/sec).
5. The water absorption of HSC concrete mixtures increased slightly with the addition of WCP and WBP. The rise within capillary water absorption may be attributable to the higher water absorption capacity of WCP compared to the other specimens. Nevertheless, a combination of 5% WBP with 10% WCP results in a lower water absorption than 10% WCP because of the improved HSC workability that reduces the concrete's porosity.
6. A slight change within the HSC compressive strength of WCP and WBP based cement concrete cubes has been noticed after being subjected to a sulphate environment. This is primarily attributable to the microstructure of HSC with WBP and WCP, where the high porosity of waste materials caused an increase in the water absorption, thereby developing voids in HSC.
7. The SEM micrographs of HSC mixtures with 5% WBP and 10% WCP showed slightly more voids and a slightly poorer distribution of CSH gel in comparison with the control specimens, which led to the lower strength of the 5% WBP and 10% WCP mixtures. Furthermore, in

comparison to the control specimen, the CSH gel in the WCP and WBP modified HSC mixture exhibited a lower pozzolanic performance which was validated by X-ray diffraction analysis.

8. The employment of WCP and WBP was considered an attractive option for producing eco-friendly and clean high strength concrete despite its lower mechanical and durability behaviour.

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Authors' contributions TAT: Conceptualization, Investigation, Formal Analysis, Writing—Review & Editing. AS: Conceptualization, Methodology, Resources, Supervision, Funding Acquisition. EK: Resources, Investigation, Formal Analysis. ŠK: Investigation. AE: Investigation. MB: Investigation. NJ: Investigation.

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Declarations

Conflict of interest The authors declare that they do not have any conflict of interest.

Ethical approval The authors state that the research was conducted according to ethical standards.

Informed consent For the type of this study formal consent not required.

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