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Ceramic waste powder as a cement replacement in concrete paving blocks: Mechanical properties and environmental assessment

In the quest for eco-friendly alternatives to ordinary Portland cement, a material extensively used in the manufacture of concrete paving blocks, this study explores the potential of ceramic waste powder. The research is driven by the pressing need to mitigate the significant carbon footprint associated with cement production. Towards this, a parametric investigation is conducted into the effects of substituting cement with ceramic waste powder on the mechanical properties and durability performance of mass-produced pressed concrete blocks. The findings reveal that the incorporation of ceramic waste powder as a partial cement replacement can markedly enhance the strength and durability of the paving blocks. Specifically, mixtures containing 20% and 30% ceramic waste powder demonstrated an increase in compressive and tensile strength by 30% and 19% respectively, compared to their control counterparts. In addition, the modified blocks exhibited a decrease in water absorption and weight loss after undergoing freezing and thawing cycles by 8% and 40%, respectively. The influence of ceramic waste powder on abrasion resistance was found to be negligible. A life cycle assessment corroborates the environmental viability of ceramic waste powder as a cement substitute, indicating reductions across all environmental impact categories, with notable improvements. This research paves the way for more sustainable solutions in pedestrian pavement construction, underscoring the potential of ceramic waste powder as a significant contributor to global sustainability efforts in the construction industry.

Keywords: concrete paving blocks; ceramic waste powder; sustainability; strength; durability; life cycle assessment

Introduction

Ordinary Portland cement (OPC), a significant contributor to global CO_2 emissions, accounting for approximately 8% (Chatterjee 2021), is facing increasing demand due to rapid population growth and urbanization. This demand is particularly high in the production of concrete paving blocks (CPBs), a popular choice for pavement construction in landscaping projects ranging from pedestrian pathways to expansive public spaces (Mampearachchi 2019).

CPBs offer numerous advantages, including simple manufacturing processes, ease of transportation, quick construction, low-cost maintenance and removal, and aesthetic appeal (Mampearachchi 2019). However, the escalating demand for CPBs and the associated environmental impacts underscore the urgent need for more sustainable mixtures based on recycled materials (Chaikaew et al. 2019; da Silva et al. 2015; Shah et al. 2022; Suleman et al. 2021). The reuse or recycling of materials is a viable solution, benefiting not only the environment but also reducing the consumption of raw materials such as cement and aggregates. While recycled materials have been found effective in enhancing the life cycle performance of pavements in terms of strength and durability in certain instances (Chaikaew et al. 2019; Penteado et al. 2016; Shah et al. 2022; Solouki et al. 2022; Suleman et al. 2021), they (e.g. recycled aggregates and crumb rubber) may inversely affect the mechanical and durability performance of concrete products (da Silva et al. 2015; Dimitriou et al. 2018; Fan et al. 2024; Guo et al. 2018).

A significant body of research has been dedicated to the use of recycled materials derived from tyres, such as crumb rubber, steel fibers, and polymer fibers, in the production of CPBs. While rubber can yield softer surfaces due to its high Poisson's ratio, it negatively impacts the compressive and flexural strengths of concrete (da Silva et al. 2015).

The strength deficit in rubberized pedestrian CPBs can be addressed by incorporating short steel fibers. Experiments on blocks with varying crumb rubber content have demonstrated that the addition of steel fibers can notably enhance flexural strength, toughness, and abrasion resistance (Chaikaew et al. 2019). Suleman et al. (2021) explored the potential of waste steel fibers in the production of composite pavements. Their findings highlighted the beneficial effects of these fibers on cement-treated base mixtures, improving tensile strength, dynamic modulus, flexural strength, and fatigue life. In a separate study, Shah et al. (2022) examined the impact of recycled steel fibers on the mechanical strength and impact toughness of CPBs. They found that a small volume of fibers (around 0.25%) marginally improved the compressive strength. However, an increase in steel fiber content can gradually diminish compressive strength, despite their effectiveness in boosting the flexural strength and impact toughness of CPBs.

A key challenge with using steel fibers is their unsuitability for pressed products. The fibers tend to spring back after compression, creating voids near the surface and leading to rust stains on the paving block surface when exposed to the environment.

Other studies explored the use of various waste materials such as furnace slag (Evangelista et al. 2018), waste basalt powder (Tataranni 2019), waste silt (Solouki et al. 2022), and mixed recycled aggregates (Juan-Valdés et al. 2021). These studies are not limited to technical aspects; assessments have been conducted to support the environmental and economic benefits of using recycled material in concrete products such as CPBs. Hossain et al. (2016) compared the environmental impacts of concrete paving blocks manufactured with virgin materials and three variants of eco-blocks manufactured with recycled construction and demolition (C&D) waste and waste glass using lifecycle assessment (LCA) techniques. The comparison demonstrated significant environmental gains in terms of energy consumption, greenhouse gas emissions, global warming potential (GWP), and other impact categories. In similar studies (Ali et al. 2022; Evangelista et al. 2018) the environmental performance of ground-granulated blast furnace slag (GGBS) as a cement replacement and electric arc furnace aggregate as a natural aggregate substitution were evaluated. The LCA analyses indicated that using 25% GGBS as a replacement for cement can result in a 17% lower global warming potential (GWP) compared to conventional CPB manufacturing (Ali et al. 2022). Similar results confirmed the environmental advantages of using electric arc furnace aggregate as a substitution for natural coarse aggregate (Evangelista et al. 2018). Even when transport distances are significant, the use of the alternative aggregate remains advantageous (Evangelista et al. 2018). Goyal et al. (2023) used LCA techniques to evaluate environmental emissions from CPB production using waste plastics. The outcomes indicated that emissions from conventional CPBs are approximately 1.6 times higher than blocks in which plastic is used as a binder. Guo et al. (2018) compared conventional concrete building blocks with those incorporating recycled concrete aggregates across different environmental impact categories. The results showed that blocks made with recycled concrete aggregates have a lower environmental impact compared to normal concrete blocks.

One of the waste materials gaining attention in this topic is ceramic waste. It can be sourced from C&D waste or rejected low-quality ceramic products, though that requires additional processing to be separated from other wastes and crushed and ground into appropriate size for aggregate or cement replacement. In the form of powder, ceramic waste can also be sourced from tile manufacturing units. Due to shrinkage all tiles are ground or cut to size using high-speed mechanically erosive methods, resulting in a very fine ready-to-use ceramic waste powder. Offcuts and defective products can also be crushed and ground into powder or aggregate forms.

Ceramic waste, due to its resistance to chemical and physical degradation, presents a significant environmental disposal challenge (Heidari and Tavakoli, 2013; Senthamarai and Manoharan, 2005). Ceramic waste powder (CWP), which is typically landfilled, contains extremely fine particles that further exacerbate its environmental impact. The primary constituents of CWP are clays, quartz, and feldspar. The production process, which involves firing these raw materials up to 1200 °C, endows them with pozzolanic properties. Consequently, ceramic wastes with appropriate fineness have been identified as promising substitutes for cement (Ay and Ünal, 2000; Lavat et al., 2009; Penteado et al., 2016; Puertas et al., 2008).

Most previous studies (Ay and Ünal 2000; Ferrara et al. 2019; Heidari and Tavakoli 2013; Jackiewicz-Rek et al. 2015; Lavat et al. 2009; Li et al. 2020; Puertas et al. 2008; Senthamarai and Manoharan 2005; Subaşı et al. 2017) have focused on the use of ceramic wastes in cast-in-situ concrete, with limited research available on their application in CPBs. Wattanasiriwech et al. (2009) explored the feasibility of using waste mud from ceramic production as both coarse and fine aggregates in CPBs. Their findings suggested that several parameters, including the water-to-cement ratio, curing, and compaction pressure, influence the compressive strength. However, their CPBs achieved strengths exceeding 35 MPa. Penteado et al. (2016) employed ceramic polishing wastes as a partial substitute for cement and sand in CPBs using the wet-cast technique. They evaluated the compressive strength, water absorption, and porosity of mixtures with various sand and cement replacement ratios. The blocks demonstrated compressive strengths higher than 50 MPa, meeting the standard requirement for heavy vehicle traffic. The water absorption parameter also improved when sand was replaced with ceramic waste. They recommended a 30% fine aggregate or 20% cement replacement in CPBs intended for heavy vehicle traffic (Penteado et al. 2016). In a related study, Sadek and El Nouhy (2014) used crushed ceramic as an aggregate replacement to produce interlocking paving units using the wet-cast technique. They tested mixtures with various sizes of crushed ceramic, ranging from coarse to fine, for compressive strength, abrasion resistance, water absorption, split tensile strength, and skid resistance. Generally, they concluded that finely crushed ceramic was more effective than coarse particles in enhancing block performance (Sadek and El Nouhy 2014). While the wet-cast technique is predominantly used in laboratory investigations, as high-capacity hydraulic machines and molds are required for pressed blocks (Penteado et al., 2016;

Sadek and El Nouhy, 2014), the majority of commercially produced CPBs are pressed blocks. These are made with a substantially different mixture, particularly in terms of particle size distribution and water content, as the hydraulic pressing method enables the production of large quantities of high early-strength CPBs more quickly and with less cement. This technique utilises a semi-dry concrete mixture (low water content) that is pressed with additional vibration. The resulting blocks offer high resistance in terms of strength and durability, with a consistent quality that can be inspected to ensure compliance with standard requirements. Therefore, further investigations into this type of block are necessary to explore the effect of CWP on the performance of compressed CPB under mass production conditions. While most of the environmental and economic assessments in the literature have focused on the use of ceramic waste in cast-in-situ (Chen et al. 2022) and roller-compacted concrete pavement (Aghayan et al. 2021), life cycle assessments are also essential for the application of CWP in pressed CPBs.

This study explores the potential of ceramic waste powder (CWP) as a substitute for ordinary Portland cement (OPC) in enhancing the strength and durability of pressed concrete paving blocks (CPBs). A series of tests are conducted on various mixtures to assess the strength and durability of the pressed CPBs. The experimental parameters under scrutiny include the cement replacement rate and the water-to-cement ratio. Following the identification of an optimal replacement ratio, a cradle-to-gate life cycle assessment is carried out on a case study. This assessment aims to illustrate the efficacy of CWP in mitigating the environmental impact associated with CPB production.

Material properties

The CPBs used in this study were produced by a local manufacturer using a hydraulic press used for mass production. The process starts with weighing ingredients (i.e., aggregates, cement, water, and admixtures) and combining them in a batching unit. A belt conveyor then delivers the mixtures to the hydraulic machine for molding and pressing. The machine feeds twenty molds (200×200×60 mm) and presses them with a load of about 40 tons which imposes 5 kg/cm^2 pressure along with vibration. Fig. 1 shows the block manufacturing machine used in the mass production plant.

Table 1 presents the details of all mixtures considered in this study. The designation of each mixture starts with the letter "W" followed by a number referring to water to cementitious material (w/c) ratio (22 and 19.5 for w/c of 0.22 and 0.195, respectively). The control mixes and implemented water-to-cement (w/c) ratios were established according to the typical practices of the local manufacturer. It is important to note that, unlike cast-in-place concrete, there are more technical and manufacturing limitations when using a wider range of w/c ratios. Mixtures with a higher w/c ratio can decrease pressing efficiency as excess water makes the mixture incompressible and can lead to cement leaching. Conversely, smaller ratios may not provide sufficient water for proper cement hydration.

The number after the letter "T" indicates the replacement rate of cement by CWP. Previous studies (Ebrahimi et al. 2023; Mohit and Sharifi 2019) conducted on using CWP as a cement replacement in concrete and cementitious mortars have confirmed the optimal replacement rate between 10-20%. Consequently, three replacement ratios of 10, 20, and 30% were incorporated into the current experimental program. In addition, the mixtures ending with the letter "R" stand for the control specimens. In all mixtures, tap water was used, conforming to ASTM C1602 (ASTM International 2018) requirements.

All pressed blocks were moved to a curing room for 24 hours in the production plant. In this study, curing by immersion in water saturated with calcium hydroxide (ASTM International 2016; ASTM International 2019) was additionally applied until the testing date.

Table 1. Details of various mixes considered for CPBs in this study (per m^3).

Mix designation	Crushed filtered sand (kg)	Washed natural sand (kg)	Pea Gravel (kg)	Cement (kg)	CWP (kg)	Cement replacement ratio (%)	Water (L)	w/c
W22-R				473.0	0.0	0		
W22-T10				425.7	47.3	10	104.0	0.22
W22-T20				378.4	94.6	20		
W22-T30				331.1	141.9	30		
W19.5-R	710.0	615.0	497.0	473.0	0.0	0		
W19.5-T10				425.7	47.3	10	92.2	0.195
W19.5-T20				378.4	94.6	20		
W19.5-T30				331.1	141.9	30		

Aggregates

All mixtures consisted of natural and crushed new aggregates from sand to pea-sized gravel. Fig. 2 shows the particle size distributions of the aggregates used. It is seen that the fines are much coarser than the requirements of ASTM C33 (ASTM International 2018) for conventional concrete. However, based on production experience, these particle sizes provide good workability and compressibility for molding and pressing.

Cement

In all mixtures, OPC Type II was used with physical properties and chemical composition provided in Table 2. The implemented cement complies with the requirements stipulated by ASTM C150 (ASTM International 2016) for Portland cement Type II. The particle grading of cement is shown in Fig. 3.

Table 2. Properties of the cement used in block production and standard limits.

	Physical properties							Chemical composition						
	Specific surface (m^2/kg)	Max. autoclave expansion (%)	Setting time (min)		Compressive strength (MPa)			SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	Loss on ignition (%)
			initial	final	3 days	7 days	28 days							
Cement used in this study	335	0.03	145	200	27	36	49	21.56	4.48	3.2	63.39	2.09	2.37	1.87
ASTM C150 (ASTM International 2016)	≥ 260	≤ 0.8	≥ 45	≤ 375	≥10	≥ 17	Not given	Not given	≤ 6	≤ 6	Not given	≤ 6	≤ 3	≤ 3

Ceramic waste powder

The CWP used in this study is the byproduct of the rectifying process of tiles, as described above. Therefore, no additional crushing or grinding was necessary. The physical and chemical properties of CWP are reported in Table 3. From a fineness viewpoint, the specific surface area of CWP determined according to ASTM C204 (ASTM International 2018) is 414 m^2/kg. This is about 24% higher than cement (i.e., 335 m^2/kg). Fig. 3 compares the particle size distribution of CWP obtained through sedimentation (hydrometer) analysis (ASTM International 2017) with the used cement. The mean value of CWP particle size was around 8 μm, confirming that this CWP is much finer than cement.

In terms of chemical properties, the results of X-ray Fluorescence (XRF) analysis given in Table 3 verify that CWP successfully passes the minimum criteria stipulated by ASTM C618 (ASTM International 2019) for pozzolans in concrete. Siliceous and aluminous materials (i.e., SiO_2 and Al_2O_3) can chemically react with calcium hydroxide (CaOH) generated by hydrating cement and form additional cementitious materials, hence are known as the main pozzolanic elements (Shi et al. 2003; Taylor 1997). Nonetheless, Fe_2O_3 can also enhance the mechanical, physical, and microstructure of cementitious composites by producing compact integrated morphology in the microstructure of the hardened cement (Kani et al. 2021).

Table 3. Chemical composition and physical properties of CWP and the related standard limits.

	Chemical composition									Physical properties		
	SiO_2 (%)	Al2O_3 (%)	Fe2O_3 (%)	SiO_2+Al2O_3+Fe2O3 (%)	CaO (%)	MgO (%)	SO_3 (%)	K_2O (%)	Na_2O (%)	Moisture content (%)	Density (kg/m^3)	Specific surface area(m^2/kg)
Ceramic powder	59.9	16.7	5.74	82.3	2.7	2.64	0.21	3.67	5.97	0.1	2640	414
ASTM C618 (ASTM International 2019)	-	-	-	≥ 70	-	-	≤ 4	-	-	≤ 3	-	-

Test methods

Compressive and tensile splitting tests were carried out after 14, 28, and 56 days of curing to investigate the strength evolution of the blocks. To optimize the experimental program, durability tests were only performed for mixtures offering the highest strength after 56 days of curing. In this regard, water absorption, abrasion, and freezing-and-thawing tests were conducted. This section describes the standard testing procedures and details of specimens, as well as the acceptance criteria (see Table 4).

Table 4. Summary of the experimental tests.

Test	Standard	Test ages	Specimen size in mm (L×W×T)	Measured parameters	Acceptable limits	
Compressive test	ASTM C936 (ASTM International 2018)	14, 28, 56	200×100×60	Compressive strength	Individual	>50 MPa
					Average	>55 MPa
Tensile splitting test	EN 1338:2003 (European Committee for Standardization (CEN) 2003)	14, 28, 56	200×200×60	Tensile strength	Individual	>2.9 MPa
					Average	>3.6 MPa
				Failure load	Individual	>250 N/mm
Water absorption test	EN 1338:2003 (European Committee for Standardization (CEN) 2003)	56	200×200×60	Water content	Average	<6%
Abrasion test	EN 1338:2003 (European Committee for Standardization (CEN) 2003)	56	200×100×60	Abrasion width	Individual	<20 mm
Freezing-and-thawing test	ASTM C936 (ASTM International 2018) ASTM C1645 (ASTM	56	100×100×60	Mass loss after 28 cycles	Average	<225 g/m^2

Compressive tests

Compressive tests are used to characterize the crushing strength of blocks under compressive loads, as shown in Fig. 4a for a typical specimen. The full-size blocks were cut into 200 ×100 ×60 mm prisms, allowing a thickness-to-width ratio of 0.6, complying with the range of 0.58 to 1.20 stipulated by ASTM C140 (ASTM International 2020). To provide uniform contact between the specimen and the loading plate, all specimens were capped by high-strength cement capping material with an average thickness of less than 1.5 mm (ASTM International 2020).

According to ASTM C936 (ASTM International 2018), the average compressive strength should be at least 55 MPa, obtained from testing three replicate specimens, with no individual value falling below 50 MPa.

Splitting tests

The splitting test, as described by EN 1338:2003 (European Committee for Standardization (CEN) 2003), was adopted to measure the tensile strength of the blocks. The test machine used was the same as the one used for compressive tests, with two half-bearing rods having a radius of 75 mm on top and bottom to apply splitting load on specimens, as shown in Fig. 4b. Based on this standard to even out the line load, two pieces of plywood (15×4 mm) were placed between the bearers and the blocks. The full-size blocks were immersed in water for 24 hours and surface dried before being loaded to failure under the protocol described in EN 1338:2003 (European Committee for Standardization (CEN) 2003). The failure plane area (S) is calculated by:

$$S(mm^2) = l \times t \qquad (1)$$

where l and t are the average failure length of the top and bottom of the block and the average value of the three thickness measurements at the failure section in mm (European Committee for Standardization (CEN) 2003).

The tensile strength (T) is then calculated based on the following empirical relationship (European Committee for Standardization (CEN) 2003):

$$T(MPa) = 0.637 \times \mathrm{k} \times \frac{P}{S} \qquad (2)$$

where P is the total failure load in N and k is a correction factor for the block thickness, which is 0.87 for the studied blocks with 60 mm thickness according to EN 1338:2003 (European Committee for Standardization (CEN) 2003). The failure can also be characterized by the failure load per unit length (F) as:

$$F(N/mm) = \frac{P}{l} \qquad (3)$$

Based on EN 1338:2003 (European Committee for Standardization (CEN) 2003), the average tensile strength (T) must be more than 3.6 MPa with no individual value less than 2.9 MPa, whilst, for all the tested blocks, the failure load per unit length (F) must be at least 225 N/mm.

Water absorption test

The water absorption test was performed following EN 1338:2003 (Annex E) (European Committee for Standardization (CEN) 2003) for three replicate specimens. According to EN 1338:2003 (European Committee for Standardization (CEN) 2003), the average absorption shall not exceed 6%. For this test, the blocks were immersed in (20±5)℃ potable water for at least three days in compliance with the standard to reach a constant mass. The wet weight (M_1) was measured after the surface drying of the blocks. The blocks were then dried in an oven at 105℃ for three days to reach a constant mass (M_2). The water absorption (W_a) was then calculated based on the block weight before and after saturation as follows:

$$W_a = \frac{M_1 - M_2}{M_2} \times 100 \tag{4}$$

Abrasion test

To quantify the abrasion resistance, the wide wheel abrasion test was performed according to EN 1338:2003 (European Committee for Standardization (CEN) 2003) with three replicate specimens for each mixture. The test machine had a standard wheel that was driven to rotate 75 revolutions per minute on the surface of the blocks. The outcome of the test is the width of the abrasion. Based on EN 1338:2003 (European Committee for Standardization (CEN) 2003), no individual abrasion width shall exceed 20 mm.

For this purpose, the blocks were cut into 200×100×60 mm samples confirming the minimum sample surface size (100×70 mm) identified by EN 1338:2003 (European Committee for Standardization (CEN) 2003). These tests were carried out only for the selected mixtures at 56 days.

Freezing-and-thawing test

Freeze-and-thaw is another test extensively used to evaluate the durability resistance of CPBs exposed to weathering during service. Based on ASTM C1645 (ASTM International 2016), one freeze-thaw cycle includes 16±1 hours of freezing (-5±3°C) and 8±1 hours of thawing. After 7 and 28 cycles, all loose particles on the surface of the specimens are removed and collected. These collected particles are dried in an oven for at least 4 hours until they reach a constant weight (weight reduction smaller than 0.2%). The weight of the dried residue (W_r) is divided by the surface of the specimen (A_s) to calculate mass loss per unit surface area.

According to ASTM C936 (ASTM International 2018), the average mass loss of the tested specimens must be smaller than 225 g/m^2 when subjected to 28 freeze-thaw cycles. Otherwise, the test must be continued to 49 cycles with an average mass loss smaller than 500 g/m^2. These tests were carried out on specimens with dimensions of 100×100×60 mm (i.e., one-quarter of a full-size block).

Results and discussion

This section presents the results of the various tests performed on blocks produced based on different mixtures described in Table 1. The effectiveness of CWP as a cement replacement is discussed for each tested parameter.

Compressive strength

Fig. 5 shows the compressive test results of all mixtures at different ages along with the acceptable limits proposed by ASTM C936 (ASTM International 2018). In this figure, the shaded bands indicate the dispersion around the mean value within a standard deviation (μ±σ). None of the reference mixtures, W22-R and W19.5-R, meet the standard limits even at 56 days. Though they achieve individual strength more than the standard limit, their average compressive strength does not satisfy the ASTM C936 (ASTM International 2018) acceptance criteria. More cement would be required to achieve the required compressive strength.

Comparison between the average strength of the mixtures with two different w/c ratios shows that, in general, the higher w/c ratio (i.e., 0.22) leads to higher strength at all ages. This improvement is more pronounced for specimens containing CWP as cement replacement up to 20%. This may be attributed to incomplete hydration of cement in mixtures with a w/c of 0.195.

Considering the compressive strength of mixtures at different replacement rates, it can be seen that replacing cement with CWP up to 20% provides an increase in strength. This may be either attributed to i) better packing of the material, or ii) increased pozzolanic activity. Fig. 6 indicates the scanning electron microscopy (SEM) images of W22-T0, W22-T20, and W22-T30 at the age of 56 days. As observed, the microstructural densification took place for W22-T20 by more evolution of interparticle hydration. On the other hand, the strength enhancement is more pronounced in the mixes with 0.22 w/c ratio. These findings corroborate that the higher strength is most likely due to the pozzolanic activity of CWP.

The highest strength was found in W22-T20, and these blocks meet both the individual and average limits proposed by ASTM C936 (ASTM International 2018) at all ages. This mixture provided an average strength of 30% greater than its reference mixture (W22-R) at 56 days. In contrast, the higher ratio of CWP in W22-T30 shows lower compressive strength. It appears that replacing cement by 30% in W22-T30 decreased the hydroxide generated by the hydrating cement, as many ceramic particles remained unreacted in the paste matrix compared to W22-T20.

Tensile strength

Figs. 7 and 8 summarize the individual and average results of the tested blocks in terms of tensile strength T and failure load F, respectively. The horizontal lines indicate the acceptable limits adopted by EN 1338:2003 (European Committee for Standardization (CEN) 2003). All mixtures meet the minimum standard requirements in terms of both tensile strength and failure load. The average tensile strength is enhanced with increasing CWP replacement at the age of 28 and 56 days. At 14 days, however, the results show no noticeable trend. This can be explained by the fact that at early ages, the pozzolanic reactions are only partially activated. Therefore, there may be particles of CWP that are not fully reacting and instead act as fillers. These fillers cannot contribute to tensile strength. However, even partially activated particles of CWP could contribute to a denser matrix, thereby improving the compressive strength of the block (see Fig. 5a).

In contrast to the compressive strength, mixtures with both w/c ratios (i.e., 0.22 and 0.195) led to similar tensile strength, particularly at higher ages and in mixtures containing CWP. This may indicate that the tensile strength is highly dependent on the frictional forces between particles across cracks. At 56 days, the maximum average tensile strength and failure load of W22-T30 were approximately 19% higher than its reference mixture (W22-R).

Durability performance

The durability tests were performed on the reference mixture (W22-R) and two mixtures, W22-T20 and W22-T30, that offered the highest compressive and tensile strengths, respectively. Fig. 9 shows the results obtained from the water absorption, abrasion, and freeze-thaw tests for these mixtures. Although almost all blocks absorbed more water content than the standard requirement (6%, as shown in Fig. 9a), CWP improved the water absorption of blocks. This may be attributed to the fineness of CWP that leads to denser concrete with fewer voids. All individual blocks meet the respective standard criteria specified by EN 1338:2003 (European Committee for Standardization (CEN) 2003) and ASTM C936 (ASTM International 2018) for abrasion and freeze-thaw. The ceramic content made a negligible difference (about 1%) in abrasion width (see Fig. 9b), while the mass loss due to 28 freeze-thaw cycles was reduced by 40% for W22-30 (see Fig. 9c), which is a substantial improvement in the durability of CPBs, especially in outdoor applications. Since freeze-thaw performance is primarily influenced by the voids present in the concrete matrix, incorporating more CWP, which is finer than cement, could lead to a denser matrix, thereby reducing the number of voids (as supported by water absorption tests). This densification effect may occur even if not all particles undergo activation in pozzolanic reactions. Consequently, W22-30, with 30% replacement, exhibited the best freeze-thaw performance.

Environmental assessment-case study

Despite the positive effect of CWP on the mechanical properties of CPBs, questions may be raised regarding the additional environmental impact of recycling and transporting waste material which may fade their application efficacy. Thus, a systematic sustainability assessment is necessitated to evaluate the environmental impact of the modified CPBs in comparison with the original ones. A sustainability assessment will enable decision-makers to manage complex systems holistically and balance short-term or local concerns with long-term and regional/global concerns (Hou et al. 2014). In this regard, life cycle assessment (LCA) provides a reliable and scientific evaluation of the environmental impacts of a product or service on human health, the ecosystem, and resources (Song et al. 2018). Such an assessment considers material and energy flow in all stages of the life cycle, from the extraction of raw materials to the destination of the final products (Martins et al. 2017).

In this study, an LCA was performed based on ISO 14040 (International Organization for Standardization 2006) and ISO 14044 (International Organization for Standardization 2006). The main goal of this assessment is to compare the potential environmental impacts of CPBs made based on the reference mixture (W22-R) with those containing 20% CWP as a cement replacement (W22-T20). This comparison was made through a case study on a production plant in Yazd, Iran producing 20 ×20×6 cm CPBs for sidewalk construction. In this study, a cradle-to-gate analysis covering A1 (Raw material), A2 (Transport), and A3 (Manufacturing) stages of standard LCA analysis was performed. The use, maintenance, and final disposal stages of CPBs are expected to be similar for both scenarios. Therefore, they were excluded from the assessment to isolate the effect of production.

Fig. 10 illustrates the system boundaries for paving block production with the two mixtures. The functional unit was defined as 1 m^2 of CPB pavement (i.e., 25 blocks). The inputs (mass and energy flows) and outputs (solid wastes and emissions) of the production processes were quantified regarding the functional unit (Evangelista et al. 2018; Vieira et al. 2016). The process for each scenario is shown in Fig. 11.

LCA modeling was performed using SimaPro 9.4.0.2 software for a cradle-to-gate scenario, and generic data were derived from Ecoinvent v.3.01 (Wernet et al. 2016) database and updated with local data in Iran where possible. In this regard, there were no reliable records for capital goods, including facilities infrastructure, buildings, equipment, and their maintenance. Thus, they were also excluded from both scenarios. The distance from the aggregate production unit, cement factory, and CWP production sites to the CPB manufacturing plant in Yazd city was 18.7, 65.4, and 42.3 km, respectively. The landfilling of the ceramic waste for the W22-R scenario consists of two main activities. First, the transportation of ceramic waste powder to the closest disposal location and second the landfilling itself (e.g., disposal of polluted inorganic wastes). The amount of CWP applied for the functional unit is 5.7 kg and the transportation distance is considered 20 km. Also, for the type of landfill, the residual material landfill was selected. It is notable that in the W22-T20 scenario, it is considered as a process in avoided product in the LCA model.

The materials and energy consumption information in paving block production were collected during a site visit in 2022. The environmental burdens of the electricity consumption were also considered based on the Iranian energy mix, from Ecoinvent data, diesel, and other materials in the CPB manufacturing plant. In the manufacturing plant, the raw materials (aggregate, water, and cement) are stored in silos connected to conveyors that weigh and transport the materials to the mixer. The total area occupied by the facility is 4300 m^2, which will increase to 4600 m^2 in the second scenario considering a new silo for CWP. Further, an additional conveyor system was supposed to move CWP to the mixer. For the studied production plant, a lifetime of twenty years was estimated with a total production capacity of 141856 m^2 CPB per year (62 m2/h). It is worth mentioning that the environmental impacts of the CWP in the production of concrete in W22-T20 are considered as a lack of 5.7 kg cement, which is replaced by CWP. It means in W22-R, there is 28.4 kg of cement and in W22-T20 it is 22.7 kg, while the difference is related to CWP. It should be noted that CWP is assumed as a waste product, and is ready to use without further environmental burdens. Thus, its production and other processes related to making powder from that are not considered in this study.

The life cycle impact assessment (LCIA) was performed using EN 15804 + A2 (adapted) (v1.00) as given in SimaPro with the following impact categories: Global warming potential, Ozone depletion, Acidification potential, Eutrophication potential, Photochem ozone formation, Abiotic depletion potential (elements), Abiotic depletion potential (fossil resources), Water deprivation, Freshwater ecotoxicity and Water consumption (net freshwater). The applied method for each impact category and the results of LCIA for both scenarios are presented in Tables 5 and 6. Moreover, the water consumption is calculated based on ReCiPe2016H v1.07 method (Goedkoop et al. 2009).

Table 5. The life cycle impact assessment (LCIA) for producing concrete pavement blocks (scenario 1, W22-R).

Impact category	Method	Unit	Total	Raw material supply	Transport to Factory	Manufacturing	Landfilling of ceramic waste
Climate change	EN15804+A2ad.v1.00	kg CO2 eq	28.2969	26.9881	0.4071	0.8688	0.0329
Ozone layer depletion/ODP		kg CFC-11 eq	1.068E-07	8.658E-08	8.890E-09	9.435E-09	1.124E-09
Acidification/AP		mol H+ eq	0.0821	0.0785	0.0014	0.0021	0.0002
Eutrophication/EP		kg P eq	0.0003	0.0003	0.0000	0.0000	0.0000
Photochem ozoneform		kg NMVOC eq	0.0743	0.0695	0.0021	0.0024	0.0002
ADP elements		kg Sb eq	0.0001	0.0001	0.0000	0.0000	0.0000
ADP fossil		MJ	143.3970	122.9512	5.9463	13.5615	0.9379
Water deprivation		m3 depriv.	1.4709	1.3651	0.0284	0.0335	0.0439
Ecotox, freshwater	EN15804+A2 v1.04	CTUe	54.6293	49.5997	3.1123	1.4607	0.4567
Water, net fresh	ReCiPe2016H v1.08	m^3	0.0409	0.0374	0.0009	0.0015	0.0011

ADP: Abiotic depletion potential

Table 6. The life cycle impact assessment (LCIA) for producing concrete pavement blocks (scenario 2, W22-T20)

Impact category	Method	Unit	Total	Raw material supply	Transport to Factory	Manufacturing	Landfilling of ceramic waste
Climate change	EN15804+A2ad.v1.00	kg CO2 eq	22.8042	21.5715	0.3968	0.8688	-0.0329
Ozone layer depletion/ODP		kg CFC-11 eq	8.618E-08	6.920E-08	8.665E-09	9.435E-09	-1.124E-09
Acidification/AP		mol H+ eq	0.0660	0.0627	0.0013	0.0021	-0.0002
Eutrophication/EP		kg P eq	0.0002	0.0002	3.20E-06	2.52E-06	-3.80E-07
Photochem ozoneform		kg NMVOC eq	0.0598	0.0556	0.0021	0.0024	-0.0002
ADP elements		kg Sb eq	0.0001	0.0001	1.06E-06	4.36E-07	-8.22E-08
ADP fossil		MJ	116.6939	98.2744	5.7960	13.5615	-0.9379
Water deprivation		m3 depriv.	1.1084	1.0911	0.0277	0.0335	-0.0439
Ecotox, freshwater	EN15804+A2 v1.04	CTUe	43.6824	39.6448	3.0336	1.4607	-0.4567
Water, net fresh	ReCiPe2016H v1.08	m^3	0.0313	0.0299	0.0009	0.0015	-0.0011
ADP: Abiotic depletion potential							

According to the results, replacing 20% cement weight in the block mixture with CWP decreased all environmental impact categories. However, the level of reduction varied between these categories. The highest reduction is observed in the water deprivation impact, with 24.65%, followed by the water consumption, and Ecotox freshwater with 23.57% and 20.04%, respectively. The lowest reduction is noted in the impact category of Res, fossils/ADP, with 18.72%.

Regarding the main drive of emissions reduction, the impact of raw material supply is the main contributor. In this stage, the amount of sand, gravel, and water is the same in both scenarios. Therefore, the difference is due to cement weight. For 1 kg of cement and the market process for ‘cement, Portland' in the Global geography (Cement, Portland {RoW}| market for cement, Portland | Cut-off, S), 0.95 kg CO2 eq is produced (i.e. 5.7*0.95=5.415 kg CO2 eq). In addition, 0,01 kg CO2 eq results from the avoiding transport of 5.7 kg of cement in the W22-T20 scenario. In line with these results, using W22-T20 could improve the sustainability of block production in this case study. This improvement provides the local CPB industries with a viable solution to achieve higher block mechanical performance, greener production, and more efficient waste management.

It is worth noting that depending on the scale of the production line, about 5 tons/day of ready-to-use ceramic powder can be produced on average. The average daily weight of defective tiles rejected by QC units can hit 15 tons in large production lines. Considering 62 active intermediate and large tile producers in Yazd province, a major hub of ceramic production in Iran, potentially around 310 tons/day of waste powder and 930 tons/day of defective tiles can be supplied for concrete-related industries. This total waste can be used to produce 26215 m^2/day CPB with a 60 mm average thickness.

It is worth emphasizing that the outcomes of the presented LCA are valid for the case-study CPB plant described in this section. Therefore, LCA must be repeated for any change in the input parameters to address new production conditions.

Conclusions

Ceramic waste powder (CWP), typically destined for landfills, poses a significant environmental challenge due to its fine particle size. However, these fine particles, produced at high temperatures, often exhibit pozzolanic properties, making them suitable candidates for cement replacement in concrete products. This study delves into the potential application of CWP in the manufacture of pressed concrete paving blocks (CPBs), focusing on aspects such as compressive strength, tensile resistance, durability, and environmental impacts. Seven distinct mixtures were prepared to scrutinize the ratios of CWP-to-cement replacement and water-to-cement. The conclusions drawn from the results are as follows:

- The substitution of cement with CWP can lead to an increase in compressive strength by as much as 30%. The highest enhancement was observed in the mixture containing 20% CWP. The blocks were able to meet both the individual and average limits proposed by ASTM C936 (ASTM International 2018) at all ages. However, higher CWP ratios and lower water-to-cement ratios resulted in reduced strengths, which can be attributed to the presence of unreacted ceramic particles within the cement paste matrix.
- An increase in CWP also leads to an enhancement in tensile strength, particularly noticeable at the age of 56 days. The maximum average tensile strength and failure load of specimens with a 30% CWP composition were nearly 19% higher than their reference counterparts. All mixtures were able to meet the minimum requirement as stipulated by EN 1338:2003 (European Committee for Standardization (CEN) 2003) at the age of 28 days.
- Freeze-thaw tests revealed a 40% reduction in mass loss after 28 cycles in mixtures containing 30% CWP. This suggests the formation of a denser material that could potentially exhibit enhanced durability in outdoor environments. However, in terms of water absorption, the blocks failed to meet the standard limit proposed by EN 1338:2003 (European Committee for Standardization (CEN) 2003), despite the positive influence of CWP on the water absorption characteristics of CPBs.
- Substituting cement with CWP has a negligible effect on the abrasion resistance of the tested blocks. All blocks met the standard requirements.
- A case study life cycle assessment shows that the sustainability of CPB production could be improved using a mixture containing 20% CWP as a cement replacement. This mixture decreases water deprivation, water consumption, Ecotox freshwater, and

climate change impacts by 24.65%, 23.57%, 20.04%, and 19.41%, respectively, compared to its control counterpart.

This work confirms that CWP is a feasible OPC replacement in CPB that can lead to higher mechanical and durability performance and more sustainable production.

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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