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Utilization of Brick and Ceramic Tile Powder for Sustainable Mortar Production

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Abstract

Sustainable concrete can be created by replacing cement with ceramic and brick waste in appropriate proportions. Using brick tile powder (BTP) and ceramic tile powder (CTP) as SCMs is cost-efficient because they recycle ceramic industry waste and offer new output disposal methods. In this study, the effect of replacing cement with BTP and CTP in different ratios and finenesses on workability and strength properties of the mixture was investigated. A sustainability analysis was conducted to estimate the environmental impact of using BTP or CTP as a partial substitute for cement. The performance index approach was used to select the suitable replacement level to obtain a multifunctional mortar mix. Findings reveal that partial replacement of cement with BTP or CTP results in more environmentally friendly binders, reducing production costs and carbon emissions without compromising compressive strength. 20% cement replacement demonstrates a balance between cost efficiency, carbon emission reduction, and compressive strength.

Keywords

ceramic tile powder, brick tile powder, cementitious mortar, performance index, life cycle assessment

1 Introduction

It is known that the ceramic industry produces large amounts of waste every year. Even only during the production and transportation of ceramics, 30% of the materials turn into waste [1]. Bricks, roof tiles, wall tiles, sanitary wares and floor tiles are some of the sources of ceramic waste [2]. Evaluation of these wastes in concrete production will contribute to waste minimization, cost reduction and energy saving. In addition, converting waste materials to an alternative source will protect non-renewable material resources and contribute to the solution of environmental pollution [3].

The ceramic waste powder is a fine-grained material with high silica and alumina content [4] and shows pozzolanic properties [5]. Zhu and Zhu [6] indicate that clay brick powder has pozzolanic activity as a result of the exposure of the clay to high temperatures during brick production and the transformation of its crystal structure into amorphous structure. Researchers have used ceramic waste as an alternative binder in concrete due to its pozzolanic properties. Devi and Venkateswarlu [7] used ceramic tile powder as a partial replacement of cement and found that replacing cement with ceramic tile waste by up to 15% increased both compressive and split tensile strength. Similarly, Bhargav and Kansal [8] used waste ceramic tiles as a substitute for cement in concrete manufacturing and found that replacing up to 15% of waste improves mechanical properties. However, using high percentages of ceramic powder can negatively impact mechanical properties, highlighting the importance of utilizing optimal, lower replacement levels [9]. Researchers have also conducted studies examining the potential of ceramics to replace natural aggregates. As a green material, the use of recycled aggregate contributes to solving the shortage of natural aggregates and conserving natural resources [10]. Senthamarai and Devadas Manoharan [11] used ceramic wastes as coarse aggregate in concrete and compared the fresh and hardened properties of concrete produced using waste aggregates and crushed stone aggregates.

Awoyera et al. [12] investigated the usability of ceramic wall and floor tile wastes as alternative fine and coarse aggregates for construction and reported that the use of waste aggregates improved mechanical properties. Batikha et al. [13] carried out studies by replacing cement with ceramic waste powder, fine aggregate with ceramic fine aggregate and coarse aggregate with recycled

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coarse aggregate, reporting that ceramic fine aggregate enhances mechanical properties and reduces shrinkage. Zhu and Zhu [6] researched the use of clay brick waste as binder and aggregate in mortar and concrete. Çavuş et al. [14] replaced air lime with brick dust and investigated the usability of the obtained lime mortar in repair works. Researchers have also examined the usability of ceramic waste in geopolymer-based materials [15, 16]. Pokorný et al. [17] evaluated that the inclusion of ceramic waste powder in concrete reduces heat transfer and can be used for thermal insulation purposes. Reiterman et al. [18] reported that partial replacement of cement by ceramic powder up to 10% by weight had almost no adverse effects on the mechanical properties of concrete. Heidari and Tavakoli [19] and Vejmelková et al. [20] revealed that the addition of ceramic powder reduces the early age compressive strength of concrete, but the 28-day strengths are quite close to conventional concrete. This was attributed to the pozzolanic effect of the ceramic powder and the slow progression of the pozzolanic reactions. On the other hand, Mishra and Vasugi [21] revealed that the early strength increased due to early hardening in mixtures containing ceramic powder and ground granulated blast furnace slag.

The construction industry faces the challenge of reducing carbon emissions and promoting sustainable practices. Recent studies demonstrate that incorporating these waste materials can reduce the embodied CO_2 of concrete by up to 26% while also lowering overall production costs [13]. To comprehensively evaluate this balance of mechanical, economic, and environmental factors, researchers have proposed various comprehensive metrics, such as the Benefit Index [9] and the Performance Index [22]. This study contributes to the development of sustainable and cost-effective mortar products by examining the influence of brick tile powder (BTP) and ceramic tile powder (CTP) on the fresh and hardened properties of mortar, providing insights for the construction industry to manage carbon emissions and promote circular economy practices through waste utilization. Within the scope of the study, powders obtained from brick and ceramic tile wastes were used as alternative binders in mortars. BTP and CTP were cooperated by cement at 10%, 20%, 30%, and 40% of the cement weight. Workability of blended mixes was investigated by the flow table test. Compressive strength tests were performed after 7, 28 and 90 days of curing. BTP and CTP are fine-grained materials rich in silica and alumina and may exhibit pozzolanic activity. Therefore, the pozzolanic activity of BTP and CTP was investigated by the strength activity index test. The performance index (PI) approach was used to determine the mortar mix that gave the best results in terms of fresh and hardened properties. The use of the performance index (PI) approach adds a novel dimension to the evaluation of mortar mixtures, providing practical guidance for engineers and practitioners in selecting the most suitable mortar composition. A sustainability analysis was conducted to estimate the environmental impact associated with the use of BTP and CTP as cement replacements. This analysis provides valuable insights regarding the potential benefits of using these waste materials to reduce the environmental footprint of mortar production, contributing to the growing knowledge on sustainable construction materials and practices. It is expected that the findings from this study will make significant contributions to sustainability in terms of both waste material utilization and the reduction of cement consumption.

1.1 Research significance

The significance of this research lies in addressing the urgent need for sustainable construction by exploring brick and ceramic tile powder (BTP/CTP) as partial cement replacements in mortar. Investigating the impact of BTP/CTP on fresh and hardened mortar properties, including workability and strength, offers crucial insights for their practical application. Furthermore, analyzing their pozzolanic activity and employing a performance index approach will identify optimal, sustainable mortar mixes. The study's sustainability assessment, focusing on carbon emission reduction, provides vital data for promoting eco-friendly practices and circular economy principles within the construction industry by valorizing waste materials.

2 Materials and test procedures

2.1 Materials

Brick tile powder (BTP) and ceramic tile powder (CTP) were used to carry out this study (Fig. 1). These powders were obtained from brick tile and ceramic tile production industries. These waste materials originate from

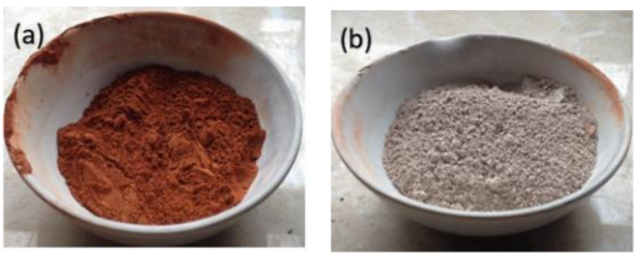


Fig. 1 Waste materials used in the study: (a) Brick tile powder; (b) Ceramic tile powder

materials that have been damaged for various reasons during production or transportation. In the first step, BTP and CTP were ground to a fineness of 13 μ using a cross-beater mill. Then, in the second step, a portion of the ground materials was further pulverized for 90 s using a Ring Mill Pulverizer to examine the effect of different finenesses. In this way, tile and ceramic tile powders with median sizes of 5 μ and 13 μ were obtained. BTP and CTP in two different fineness were named BTP-5, BTP-13, CTP-5 and CTP-13 according to their median diameters. The median diameter parameter was used to quantify the fineness of BTP and CTP in this study, and a low median diameter represents a high degree of fineness.

The CEMI 42.5R Portland cement was used in the experiments. The physical and chemical properties of the cement are given in Table 1 and chemical compositions of BTP and CTP are summarized in Table 2. The particle size distributions of Portland cement, BTP and CTP were measured using a laser diffraction particle size analyzer (Mastersizer 2000, Malvern Inst.). The particle size distribution of Portland cement was determined in isopropyl alcohol and water media. Particle size distributions of cement, brick tile powder, and ceramic tile powder with two different fineness (5 μ and 13 μ) named BTP-5, BTP-13, CTP-5 and CTP-13, respectively, are given in Fig. 2.

Table 1 The physical properties of the cement

Property	Value
Specific gravity (g/cm^3)	3.16
Specific surface (cm^2/g)	3942
Initial setting time (min)	139
Soundness (Le Chatelier) (mm)	1
Insoluble residue (%)	1.02

Table 2 Chemical composition of cement, BTP and CTP

Chemical composition (%)	CEM I 42.5R	BTP	CTP
SiO_2	19.12	50.26	68.15
Al_2O_3	4.94	15.05	18.74
Fe_2O_3	3.34	12.51	2.04
CaO	63.67	9.23	1.23
TiO_2	0.22	2.28	0.60
MgO	1.94	5.67	0.89
Na_2O	0.37	2.00	5.34
K_2O	0.56	0.96	1.85
P_2O_5	0.23	0.29	–
CO_2	2.74	1.70	0.6
ZnO	–	–	0.22
ZrO_2	–	–	0.34
SO_3	2.86	0.07	–

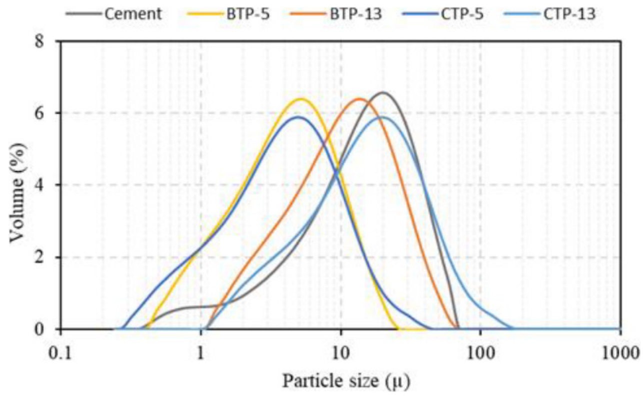


Fig. 2 Particle size distribution

Mineralogical analysis of brick tile powder and ceramic tile powder was studied by X-ray diffraction (XRD) technique (Rigaku Rint 2000) in 2θ range of 10–70° with a scan speed of 0.5°/min (Fig. 3). The major crystalline phases were identified as albite ($NaAlSi_3O_8$), quartz (SiO_2), hematite (Fe_2O_3) and cordierite ($2MgO \cdot 2Al_2O_3 \cdot 5SiO_2$) for BTP and quartz, anorthite ($CaAl_2Si_2O_8$), albite and

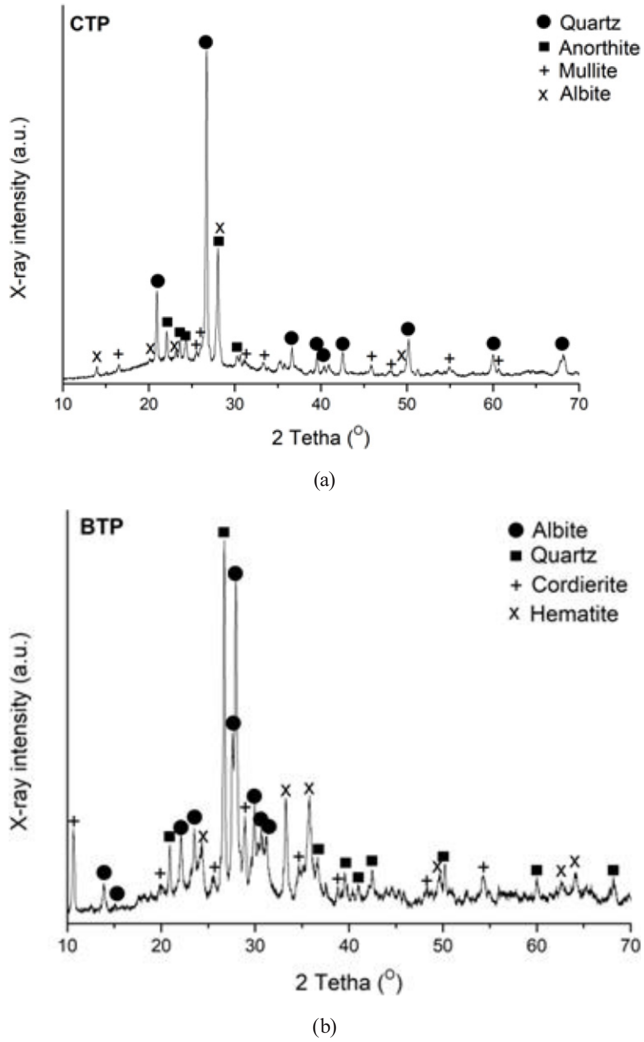


Fig. 3 XRD pattern of: (a) CTP; (b) BTP

mullite ($3Al_2O_3 \cdot 2SiO_2$) for CTP. Albite is a feldspar mineral that nucleates at high temperatures and has an aluminosilicate structure [23]. Mullite is a solid solution phase of alumina and silica and commonly found in ceramics [24]. It has a low coefficient of thermal expansion, low creep rate, high thermal resistance and high flexural strength [25]. Mullite formation is attributed to the high sintering temperature used in ceramic tile production [26]. Cordierite-based ceramics have a low coefficient of thermal expansion, high electrical resistivity and mechanical strength [27].

The hump observed over a wide range indicated that an amorphous phase occurred in both BTP and CTP. Awoyera et al. [28] stated that the presence of a high level of quartz might affect the strength gain in the ceramic replacement. Moreover, studies revealed that the abundance of silicon dioxide (SiO_2) indicates great potential for use as a pozzolanic material [29]. The amorphous phase observed in the XRD results of BTP and CTP also supports the pozzolanic activity. SiO_2 and Al_2O_3 contents in brick and ceramic tile powders react with $Ca(OH)_2$ in cement paste to form C–A–H and C–S–H gels that fill the micropores in the concrete and enhance the bond strength between the aggregate interfaces [19].

Mortar mixes were prepared according to TS EN 196-1 standard [30] with a constant water-to-binder ratio (W/B) of 0.5 and a sand-to-binder ratio (S/B) of 3.0 by weight. CEN standard sand was used in the preparation of the mortars. Cement was partially replaced by BTP and CTP in two different fineness and at 10, 20, 30 and 40% by weight.

2.2 Test procedures

2.2.1 Flow table test

The workability of fresh mortars was examined by a flow table test based on the ASTM C1437-20 standard [31]. Top of the flow table was cleaned and dried. The mold was placed at the center of table and filled with mortar in two layers. Each layer was tamped 20 times with a tamping rod. The mold was lifted away. Then the flow table was dropped 25 times and the spread diameter of the mortar was measured. The specified procedure was repeated for all mortar mixes.

2.2.2 Compressive strength test

A total of 17 batch mortar mixes were prepared. In each batch, three cubic specimens of 50 mm × 50 mm × 50 mm in size were cast for each age to determine the compressive strengths after 7, 28 and 90 days curing and the average of the three values was taken as the result. The specimens were demolded 24 h after casting and then cured in water at 20 ± 2 °C until test age. Compressive strength tests were conducted according to the ASTM C109/C109M-21 standard [32].

2.2.3 Strength activity index (SAI)

Strength activity index (SAI) method was used to observe the effect of cement replacement materials on strength. SAI was based on the compressive strength test performed on mortar cube samples cast by partially replacing cement with substitution materials at 20% by weight. According to ASTM C311-11 standard [33], the strength activity index is reported as follows in Eq. (1):

$$\mathrm{SAI} = A/B \times 100, \tag{1}$$

where A is the average compressive strength of test mixture cubes (MPa), and B is the average compressive strength of control mix cubes (MPa).

Previous studies in the literature have demonstrated that both brick and ceramic waste powders exhibit considerable pozzolanic activity due to their highly amorphous silica and alumina contents. Reported literature values indicate that the SAI of ceramic and brick powders generally ranges between 75% and 95%, successfully meeting standard pozzolanic requirements [2, 34]. In the experiments, test mixture mortar cube specimens were cast by replacing cement with 20% BPT and CPT by weight. As reported by Donatello et al. [35] if the tested material is inert, there should be a 20% reduction in strength due to the dilution effect, but strength development is also affected by many other factors besides cement content. Therefore, samples were also prepared with fine sand as an inert material, and the calculated strength activity index was accepted as a baseline for zero pozzolanic activity. Reported strength results are the averages of three tests performed after 7, 28 and 90 days of curing period and are presented as a percentage of strength relative to the control mortar.

2.2.4 Sustainability assessment

Environmental and economic assessments were conducted to evaluate the sustainability performance of BTP and CTP blended mortar mixes. The "cradle-to-gate" life cycle analysis approach covering raw material extraction, transportation and manufacturing phases was followed according to the TS EN ISO 14040 standard [36]. The steps considered in the cradle-to-gate system boundary condition were:

1. Acquiring/extracting the necessary raw materials for the relevant mortar mix;

2. Transporting the raw materials;
3. Preparing the mortar mix.

Since the primary objective of this study is to compare different sustainable mortar mixes, consumption and demolition stages were not examined and the environmental impact from these stages was assumed to be similar. Embodied CO_2 emission (eCO_2) data were obtained from literature compilation [26, 37–41].

In Çankaya and Pekey's [37] LCA study on cement production in Turkey, it was stated that 850 kg CO_2/ton was emitted during the production of CEM I cement, and this value was taken as a basis for the calculations. The embodied CO_2 emission (eCO_2 (kg CO_2/ton)) of BTP and CTP was obtained from the value determined by Zito et al. [26], by considering the collection, transportation, crushing, screening and grinding stages of ceramic waste. In the literature, eCO_2 values for mixing water and sand were quite similar. These values were taken from the studies of various researchers for water [38, 39] and sand [40, 41].

3 Results and discussion

3.1 Flow table test

The flow diameter changes of the mortars with the addition of BTP and CTP in two different fineness are given in Fig. 4. The control mixture achieved a flow diameter of 210 mm. With the inclusion of BTP or CTP at a constant W/B ratio, the workability was slightly reduced compared to the reference mortar. This situation has been interpreted as more water or plasticizer additives are required to maintain the same workability as the reference mortar. Flow diameter values varied between 185 to 201 mm with the addition of BTP and between 191 to 209 mm with the addition of CTP. Using BTP or CTP with finer particle size in mortars decreased the fluidity due to the increased specific surface area, leading to greater water adsorption and hindering particle movement. For instance, when using finer CTP particles, mortar fluidity decreased by approximately 2% compared to coarser. A more significant reduction in flow diameter occurred in BTP5 and CTP5 mortars compared to the control mortar, regardless of the replacement rate. However, the difference is not that much. The fineness variation of BTP and CTP did not significantly affect workability.

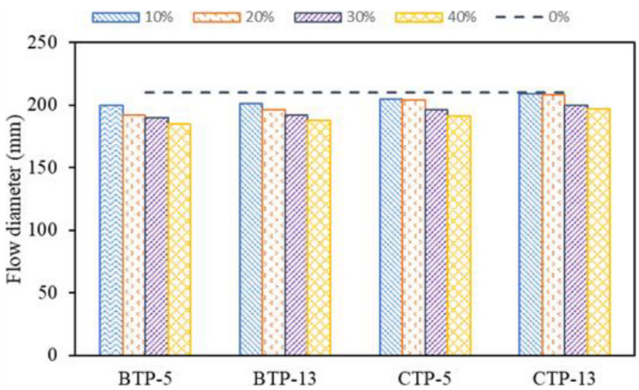


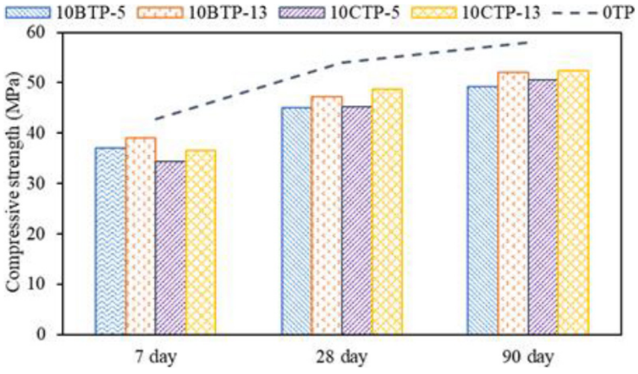
Fig. 4 The flow diameter changes of the mortars

As the substitution level of BTP and CTP increased, the flow diameter value gradually decreased. Replacing cement with BTP reduced workability more than replacing it with CTP. However, neither BTP nor CTP had an adverse effect on workability. This was attributed to the similarity of the fineness of the substitute materials and cement.

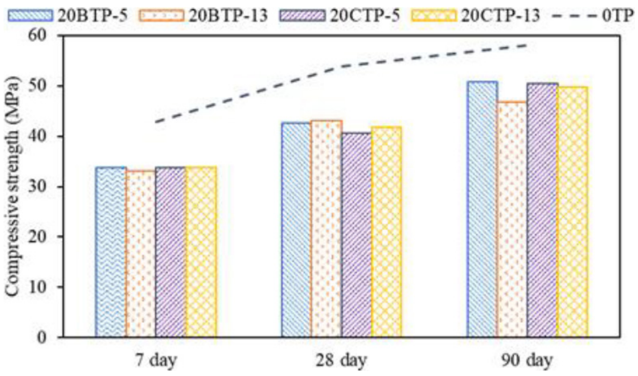
3.2 Compressive strength

Concrete is generally utilized under compressive loads; therefore, its performance under compression is highly significant, especially when considering alternative wastes to produce sustainable concrete. The compressive strength of the mortars containing different percentages and fineness of brick tile powder (BTP) and ceramic tile powder (CTP) as a cement substitute are presented in Fig. 5. The compressive strength decreased with an increasing the substitution rate. However, this impact is most evident at earlier ages. When BTP and CTP replaced 10% and 40% of the cement, the early-age compressive strength of the mortar exhibited a corresponding reduction of 15% and 50%, respectively, compared to the control mixture (0TP). The reduction in the early strength was mainly attributed to the pozzolanic reactions of BTP and CTP and the slow progression of the pozzolanic reactions. As stated by Barreto et al. [42], BTP and CTP can react with calcium hydroxide, which is a cement hydration product, to produce more gel and contribute to an increase in compressive strength. BTP and CTP contribute to strength at an early age primarily due to their micro-filling ability. The substitution of 10% and 40% of cement with BTP and CTP led to a 14% and 40% decrease at the end of 28 days compared to the control sample. By 90 days, the compressive strength reduction becomes smaller, with a 12% and 33% decrease for the 10% and 40% replacement levels, respectively. It was observed that the compressive strength of the mortars containing BTP and CTP at older curing ages was similar to the control mortars up to a certain degree of substitution. These results were consistent with the studies of Hoppe Filho et al. [34] and Chen et al. [43].

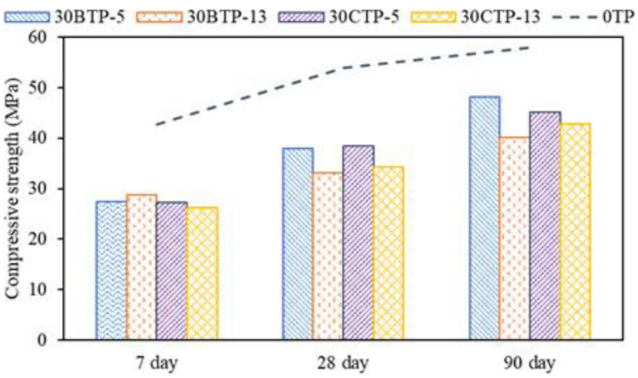
Control mortars gave higher strength at all testing ages than the blended mortars. Nevertheless, when BTP or CPT was added to the mixture up to 20% by weight of cement, the long-term strength of the mixtures approached



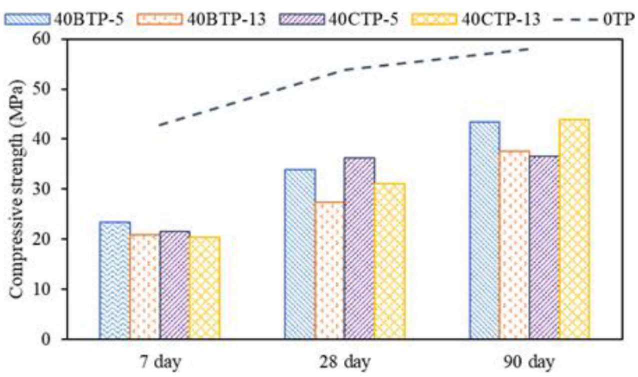
(a)



(b)



(c)



(d)

Fig. 5 Compressive strength of the mortars at replacement rates of: (a) 10%; (b) 20%; (c) 30%; (d) 40%

the control mortar. Thanks to their pozzolanic properties, BTP and CTP showed the potential to enhance compressive strength, especially at longer curing times. From the point of view of strength, using BTP and CTP up to 20% by weight did not cause a significant reduction, especially at older ages. Tang et al. [44] stated that the strength of recycled brick powder decreases with increasing median diameter when the median diameter is over 30 μ and pointed out that the median diameter reducing up to 30 μ has little effect. Similarly, it was observed that the median diameters of tile powders varying between 5 μ and 13 μ slightly affected the strength. When the compressive strength results were examined considering the same particle sizes, it was found that brick and ceramic tile powder exhibited similar behavior. The fact that a similar situation is also valid for fluidity supports the study of Zito et al. [26] which compares the performance of various powdered ceramic wastes and shows that they are classified unnecessarily.

3.3 Strength activity index (SAI)

The pozzolanic reactivity of BTP and CTP was evaluated based on the strength activity index (SAI). The strength activity index of the mixtures at different curing times is illustrated in Fig. 6. As stated by ASTM C618-22 standard [45], SAI results in greater than 75% indicate a positive pozzolanic activity. It should be noted that both BTP and CTP mixes reached the expected target of 75% SAI at the age of 7 days, and SAI exceeded 85% at 90 days. Consequently, the compressive strengths shown in Fig. 5 met and exceeded these initial literature-based design expectations. Therefore, the pozzolanic properties of CTP and BTP were confirmed. As expected, mortar samples containing fine sand showed no pozzolanic activity.

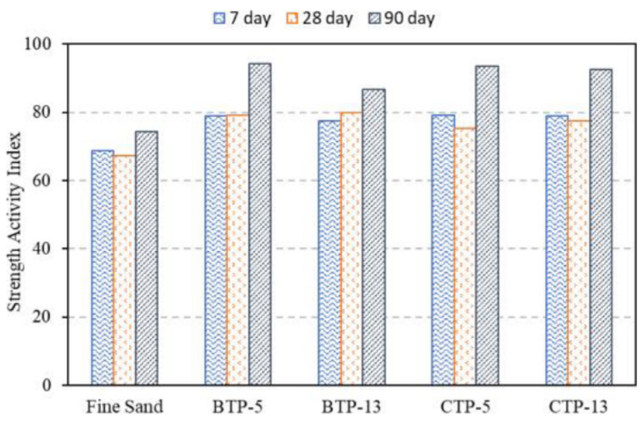


Fig. 6 Strength activity index of BTP and CTP in two different fineness

Compared to the mortars at 7 and 28 days, the inclusion of BTP and CTP significantly increased the SAI values of the mortars at 90 days. The effect of fineness on the strength activity index was more pronounced for BTP samples, while samples containing finer brick tile powder showed higher activity. The effect of fineness was more unclear in CTP samples, and similar SAI values were obtained for both fineness.

4 Performance assessment of mortar mix properties

The performance index (PI) approach can be used to select optimum mixes with different performance criteria, whether fresh or hardened state. The performance index condenses large amounts of data into a single metric to facilitate selection [22]. As a first step, the weight ranking (W_i) of the mixture that reaches the best test value for each criterion is determined as 1.00, and the test values of the other mixtures are calculated by proportioning this best value (Eq. (2)):

$$W_i = \frac{\text{Measured performance of each mixture}}{\text{Best measured performance}}. \tag{2}$$

The numeric index (R_i) is then calculated for each mixture using Eq. (3). In this study, the highest numeric index was set to 5 based on previous studies of El-Dieb et al. [46] and Arum et al. [47]. Table 3 shows the weighted ranks and numeric indexes for all mixtures.

$$R_i = 5 \times W_i \tag{3}$$

Based on the required performance criteria (n criteria), related R_i indices are multiplied to calculate the mixture score (S_n), as defined in Eq. (4). Then, as described in Eq. (5), the performance index (PI) for each mix is calculated as a percentage of the mixture score (S_n) with respect to the highest score $\left(S_{n_{\max}}\right)$ of all mixes [46].

$$S_n = R_{i_1} \times R_{i_2} \times \ldots R_{i_n} \tag{4}$$

$$\mathrm{PI} = \frac{S_n}{S_{n_{\max}}} \times 100 \tag{5}$$

Workability and compressive strength are essential criteria for design performance; therefore, the analysis was carried out based on these criteria. Table 4 determines the selected performance criteria regarding workability and early and final strength, and Table 5 shows performance indexes of mixtures for related criteria.

The mix with the highest score represents the most suitable mix regarding the corresponding multiple criteria. Consistent with the recommendations of previous studies indicating that the optimal cement replacement by ceramic powder generally falls within the range of up to 10% to preserve maximum mechanical integrity [3, 48], the best results in the current study were obtained at the 10% replacement level for both the mixtures containing BTP and the mixtures containing CTP, as shown in Table 5. In addition, it is important to note that the performances

Table 3 The weighted ranks and numeric indexes of the mixtures

Mixture ID	Individual performance criterion							
	Workability		Strength (7 days)		Strength (28 days)		Strength (90 days)	
	W_i	R_i	W_i	R_i	W_i	R_i	W_i	R_i
0TP	1.00	5.00	1.00	5.00	1.00	5.00	1.00	5.00
10BTP-5	0.95	4.76	0.86	4.32	0.83	4.17	0.85	4.24
20BTP-5	0.91	4.57	0.79	3.95	0.79	3.96	0.88	4.39
30BTP-5	0.90	4.52	0.64	3.21	0.70	3.52	0.83	4.15
40BTP-5	0.88	4.40	0.55	2.74	0.63	3.14	0.75	3.75
10BTP-13	0.96	4.79	0.91	4.57	0.87	4.37	0.90	4.50
20BTP-13	0.93	4.67	0.77	3.87	0.80	4.00	0.81	4.03
30BTP-13	0.91	4.57	0.67	3.37	0.61	3.07	0.69	3.46
40BTP-13	0.90	4.48	0.49	2.44	0.51	2.54	0.65	3.24
10CTP-5	0.98	4.88	0.80	4.02	0.84	4.19	0.87	4.36
20CTP-5	0.97	4.86	0.79	3.95	0.75	3.76	0.87	4.35
30CTP-5	0.93	4.67	0.64	3.19	0.71	3.57	0.78	3.89
40CTP-5	0.91	4.55	0.51	2.53	0.67	3.36	0.63	3.16
10CTP-13	1.00	4.98	0.86	4.28	0.91	4.53	0.90	4.52
20CTP-13	0.99	4.95	0.79	3.95	0.78	3.88	0.86	4.30
30CTP-13	0.95	4.76	0.61	3.06	0.64	3.18	0.74	3.69
40CTP-13	0.94	4.69	0.48	2.39	0.58	2.88	0.76	3.79

Table 4 Performance criteria of the mixtures

Performance index (PI)	Performance criteria
PI-1	Workability + 7-day strength
PI-2	Workability + 28-day strength
PI-3	Workability + 90-day strength
PI-4	Workability + 7-day + 28-day strength

Table 5 Performance indexes for related criteria

Mixture ID	Multiple performance criterion			
	PI-1	PI-2	PI-3	PI-4
0TP	100	100	100	100
10BTP-5	82	79	81	69
20BTP-5	72	72	80	57
30BTP-5	58	64	75	41
40BTP-5	48	55	66	30
10BTP-13	87	84	86	76
20BTP-13	72	75	75	58
30BTP-13	62	56	63	38
40BTP-13	44	46	58	22
10CTP-5	79	82	85	66
20CTP-5	77	73	85	58
30CTP-5	59	67	73	42
40CTP-5	46	61	57	31
10CTP-13	85	90	90	77
20CTP-13	78	77	85	61
30CTP-13	58	61	70	37
40CTP-13	45	54	71	26

of the mortars in substitution up to 20% are acceptable, which provides a significant advantage for sustainable material utilization. The mortars containing BTP and CTP with a fineness of 13 μ at replacement rates of 10% and 20% exhibited better performance, while for replacement rates of 30% and above, the mortars containing BTP and CTP with a fineness of 5 μ provided better outcomes. In terms of workability and 90-day strength, no loss in performance was observed in samples containing BTP and CTP with a fineness of 5 μ up to a replacement rate of 20%. As described in Section 3.2 and supported by literature study [26], brick and ceramic tile powder exhibited similar performances for the same particle sizes.

Acceptable results in terms of performance have been achieved for both BTP and CTP at substitution rates of 10% and 20%, and mortars prepared with coarser particles (d_{50} = 13 μ) have yielded better outcomes. Duan et al. [49] prepared mortars with brick powder with median diameters of 9.06 μ and 12.64 μ and obtained slightly higher strengths in mortars prepared with brick powder with a median diameter of 13 μ. Tang et al. [44] reported that a median diameter of less than 10 μ and between 11 μ and 20 μ did not cause a significant decrease in the activity index. Since the environmental impact of the energy consumed to change the particle size is also important, there is no need to use recycled powders with an average particle size of less than 13 μ.

5 Sustainability assessment

Using waste materials in the production of construction materials can lead to the development of more sustainable and environmentally friendly products. However, the cost of these materials should be competitive with existing materials on the market, and they should have ecological benefits. The graphical representation of the system boundary conditions established for this assessment is given in Fig. 7 [50]. Based on the established methodology, total CO_2 emissions were calculated considering the amount of each component in the mixture and their embedded CO_2 emissions (Table 6), which cover the raw material extraction, manufacturing, and transportation phases.

The eCO_2 emission of the reference mortar was 411.1 kg CO_2/m^3. CEMI 42.5 R cement had the highest emission production percentage among all precursors. On the contrary, carbon emissions of BTP and CTP were approximately 5% of cement. Therefore, with the increase of BTP and CTP levels in the mortar mixes, the CO_2 gas emission decreased. The eCO_2 emissions were recorded as 372.9 kg CO_2/m^3 and 334.2 kg CO_2/m^3 for mortars with 10% TP and 20% TP, respectively, representing a reduction in eCO_2 emissions of 9.3% and 18.6% compared to the reference mix. Although BTP and CTP are waste materials, their collection and grinding processes contribute to CO_2 emissions. However, using closer collection points will help make BTP and CTP a greener approach.

The total cost of the mixture is one of the most important aspects to be considered during concrete production. Since the amount of aggregate used in mixtures with and without waste is constant and does not affect the comparison results, the costs of the aforementioned mortar mixtures were calculated instead of concrete costs. Only the raw material costs were considered in this study. The market price per unit of raw materials was obtained from the suppliers. The price of brick and ceramic tile powders was assumed to be zero since these materials are waste and available free of charge. It is important to note that this baseline estimation currently excludes processing expenses such as crushing and grinding. However, it should be con-

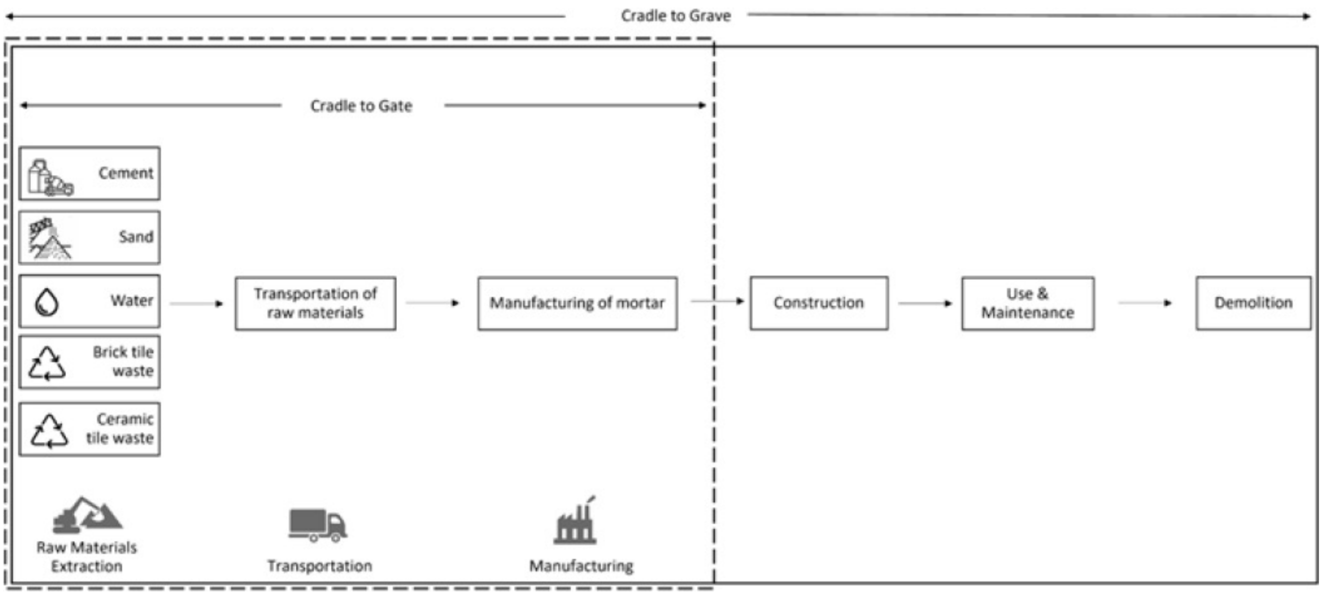


Fig. 7 System boundary of concrete life cycle assessment (adapted from: Kim et al. [50])

Table 6 eCO_2 emissions calculations of mortar mixes

Mortar constituents	eCO_2 (kg CO_2/ton)	eCO_2/m^3 concrete (kg CO_2/m^3)				
		REF	10% TP	20% TP	30% TP	40% TP
CEMI 42.5R	850	403.8	363.4	323.0	282.6	242.3
BTP/CTP	45	0.0	2.1	3.8	5.1	6.0
Water	1	0.2	0.2	0.2	0.2	0.2
Sand	5	7.1	7.1	7.1	7.1	7.1
Total		411.1	372.9	334.2	295.1	255.6

sidered that a specific cost will arise if these wastes are used widely and gain added value. The price of raw materials and cost of mortar mixes are presented in Table 7.

Cement was the primary raw material contributing to the total cost of the mortar mix. Replacement of cement with brick tile powder or ceramic tile powder reduced the cost of mortar. The binder cost decreased from 31.2 USD/m^3 to 28.0 USD/m^3, 24.9 USD/m^3, 21.8 USD/m^3 and 18.7 USD/m^3 with the increase in the replacement percentage of BTP or CTP with cement from 0 to 10%, 20%, 30% and 40%, respectively. The cost of producing conventional REF mortar was calculated as 36.1 USD/m^3. This cost exhibited a decreasing trend with an increasing BTP or CTP ratio. Considering the strength data, it has been determined that using BTP or CTP as an alternate binder is suitable for up to 20% substitution. It was noted that a cost reduction of 8.6% and 17.3%, respectively, was observed in the mortars with 10% TP and 20% TP. Moderate cost savings were achieved through these substitutions.

It is important to mention that the transportation costs of BTP and CTP were not included in this study since no charge was paid for their transportation. Still, usually, transportation and grinding prices should also be considered. Itshould also be highlighted that brick and ceramic factories are locally available in many locations in Türkiye, and therefore, transportation distances are significantly closer.

Table 7 Prices of raw materials and mortar mixes

Prices of raw materials				
Material	CEMI 42.5R	BTP/CTP	Water	Sand
Cost (USD/kg)*	0.066	0.000	0.001	0.003

The cost of mortar mixes (USD/m^3)					
Material	REF	10% TP	20% TP	30% TP	40% TP
Cost (USD/m^3)	36.09	32.98	29.86	26.74	23.62

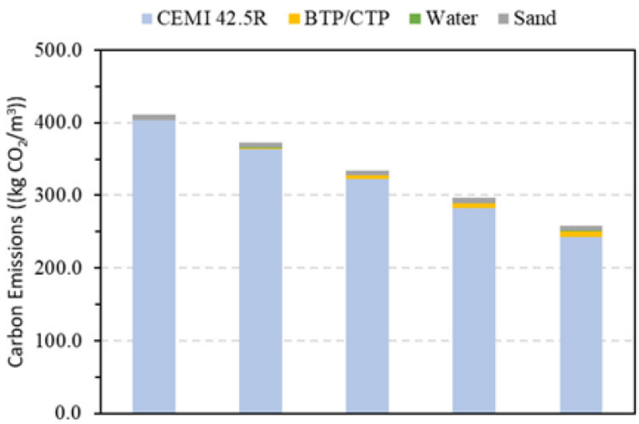
* According to the variance of the dollar price in Türkiye, the raw material costs were estimated with an equivalence factor of 35.03 Turkish Lira/USD (average of the last 90 days).

Consequently, partial replacement of Portland cement with BTP or CTP helps produce more environmentally friendly binders and manage the carbon emissions associated with cement production. Substituting BTP or CTP as a binder in mortar samples makes an important contribution to producing sustainable and cost-efficient products (Fig. 8). 20% cement replacement reduces production costs and carbon emissions without sacrificing compressive strength and contributes to recycling by providing an alternate route to dispose of brick and ceramic tile waste.

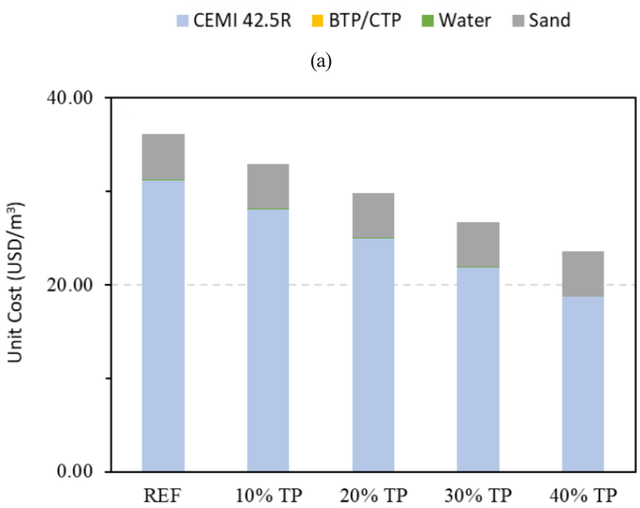
6 Conclusions

The waste brick and ceramic tiles were ground in two different particle sizes and replaced with cement ratios between 10% and 40% to prepare mortars. Workability, compressive strength, and pozzolanic activity of BTP and CTPs with different particle sizes were tested, and the performance of the mortars was analyzed due to various criteria. A new perspective has been provided to the existing literature by examining the use of brick and ceramic tile powder in different finenesses as an alternative binder in concrete. The following are the main conclusions based on the test results obtained in this study:

- Mortar mixtures incorporating brick and ceramic tile powder showed satisfying fresh and hardened properties up to 20% replacement and did not have a negative effect on workability.
- The addition of BTP and CTP slowed the strength gain rate at early ages due to the pozzolanic properties of BTP and CTP and the slow progression of pozzolanic reactions. All mixtures up to 20% substitution showed good strength development at 28 days and beyond.
- Fineness did not make a significant difference in the workability or strength gain rate of mortars. Further investigation is needed to understand the effect of different fineness values on the behavior of fresh and hardened mixes.
- Performance analysis showed that for defined performance criteria, the best results were obtained with the 10% replacement level for both CTP and BTP. Furthermore, the performance of the mortars remained acceptable when substituting up to 20%. Notably, mortars containing BTP and CTP with a fineness of 13 μ, replaced at 10% and 20%, showed improved performance.
- Experimental data confirmed the pozzolanic activity of CTP and BTP, which are currently considered production waste. Also, they revealed that these wastes can be used as an alternate source to cement in mortar and concrete production.
- Using tile and ceramic wastes in concrete can reduce CO_2 emissions depending on the reduction in cement usage, save energy, and significantly reduce the total cost. The use of this material also aids in waste disposal.



(a)



(b)

Fig. 8 Effects of different substitution percentages on: (a) Carbon emissions; (b) Costs

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