Materials Research Proceedings 74 (2026) 188-196 https://doi.org/10.21741/9781644904473-24

Compressive and Flexural Strength of Mortar with Ceramic Tile Waste Powder as Partial Cement Replacement

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Keywords: Mechanical Properties, Ceramic Waste Powder, Cement Replacement, Compressive Strength, Flexural Strength

Abstract. This work studies the mechanical performance of mortar using ceramic tile waste powder (CWP) as a partial replacement of cement in the range from 5% to 30% of total cement weight. Although CWP has been studied in concrete systems, its effect on mortar produced with local Algerian siliceous sand has not been sufficiently investigated. Samples of mortar were made as per standard laboratory protocols and were tested for compressive strength and flexural strength after a curing period of 28 days. Flexural strength increased by 5.3% for 10% CWP replacement with respect to control mortar. In addition, the compressive strengths of MCWP20 and MCWP25 samples were 34.8 MPa and 35.2 MPa, respectively, which are similar to the strength of the control mortar (MO) of 36.2 MPa and satisfy the minimum specifications of ASTM C270 for structural mortar applications. These results indicate that CWP can be used as a partial replacement of cement and yet have the mechanical qualities needed for a structural application. In addition, the use of CWP has economic benefits, as it converts ceramic tile waste into a valuable resource and reduces the carbon footprint of the building industry by reducing Portland cement usage. Further durability tests are necessary to confirm the performance of CWP-based mortars under severe environmental conditions.

Introduction

The increased need for sustainable construction materials has prompted researchers and industry professionals to explore a range of alternatives to ordinary Portland cement. Cement production is an energy-intensive process and a major source of CO_2 emissions globally. Therefore, supplemental cementitious materials from industrial by-products and waste have been widely studied as possible substitutes [1]. The construction and demolition industries generate considerable amounts of ceramic tile trash. Such debris is problematic to dispose of and can cause severe environmental damage. Studies conducted recently have revealed that the incorporation of ceramic waste powder (CWP) into cement mortar might lead to a favorable impact on its mechanical characteristics, such as compressive and flexural strength, owing to the pozzolanic reactivity and filler effect of the waste powder in the mortar matrix [2, 3]. Generally, replacement rates up to 10–25% have been shown to improve or maintain these qualities, and greater ratios are found to lower the strength due to poor hydration and increased porosity [1, 4]. Nevertheless, the optimum CWP dosage is a function of several interrelated factors, such as the particle size distribution, chemical composition, and characteristics of the particular mortar matrix employed, with a replacement ratio of about 10% most consistently being associated with significant gains in both compressive and flexural strength, although higher ratios, while less favorable mechanically, still provide considerable economic and environmental benefits [5, 6]. Ceramic tile waste is considered an environmentally friendly material, besides its mechanical performance, because its incorporation reduces the landfill load and supports a circular economy through the recycling of

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industrial waste by means of current or alternative manufacturing methods [7]. Despite this body of evidence confirming the technical viability and environmental benefits of CWP in cementitious systems, a systematic investigation linking CWP's particle size distribution and chemical composition, together with the mortar's water-to-cement ratio, to its resulting mechanical performance has not been sufficiently addressed in the existing literature—particularly for mortars produced with local Algerian siliceous sand under standardized testing conditions. In particular, the combined influence of CWP fineness and pozzolanic reactivity on both compressive and flexural strength remains unclear. Therefore, the present study has been conducted to fill this gap with a systematic experimental investigation following the ASTM C348 (flexural strength) and ASTM C349 (compressive strength on broken prism halves) to find the optimum CWP replacement ratio and to correlate the physical and chemical properties of CWP with the mechanical behavior of the resulting mortar mixes.

Materials and Methods

Materials

The raw materials used in this study are shown in Fig. 1, presenting (a) Portland cement, (b) local siliceous sand, and (c) ceramic tile waste powder (CWP).



(a) (b) (c)

Fig. 1. Raw material (a) Cement (b) Sand (c) Ceramic tile waste powder (CWP).

Table 1. summarizes the physical properties of the natural sand used in this study. The specific gravity of the aggregates was determined in terms of oven-dry (OD) and saturated surface-dry (SSD) conditions in accordance with ASTM C128, and values of 2.65 and 2.70 were obtained accordingly. The sand is of medium-grade fine aggregate with a fineness modulus of 2.5 suitable for the construction of mortar.

Table 1. Physical properties of the sand.

Property	Value
Specific Gravity (oven-dry)	2.65
Bulk Density [kg/m³]	1,600
Specific Gravity (saturated surface-dry, SSD)	2.7
Water Absorption [%]	1.5
Fineness Modulus	2.5
Sand Equivalent [%]	75

The recycling procedure for producing the ceramic tile waste powder is shown in Fig. 2. Waste ceramic tiles were collected from building sites, crushed and ground in a ball mill, sieved through a 0.08 mm sieve, and dried in an oven at 100–110°C for 24 h to obtain the final CWP used in the mortar formulation. Table 2 gives a summary of the physical properties of the CWP. The cement used was ordinary Portland cement type CPA–CEM I 42.5 R, manufactured by the Lafarge cement factory in Biskra, Algeria, conforming to ASTM C150 [9]. The cement has a Blaine-specific surface area of 3700 cm²/g and a specific gravity of 3.14 g/cm³. The specific gravity of CWP is less than that of cement. This finding agrees with the values in previous studies [4, 8].

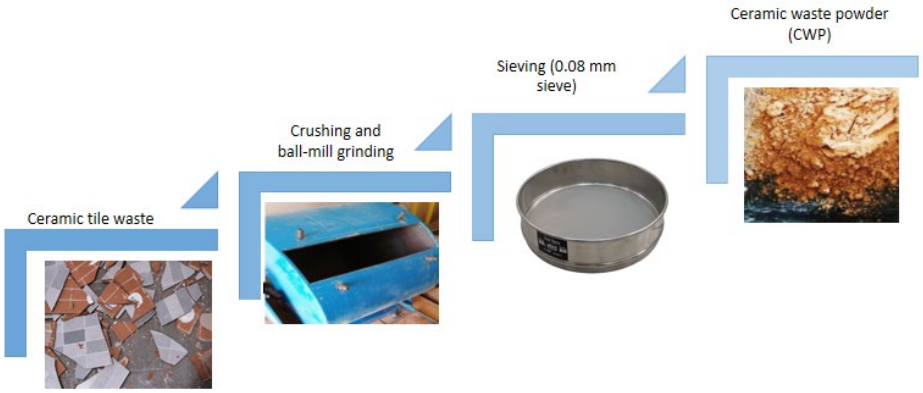


Fig. 2. Flowchart of the recycling process for ceramic tile waste.

Table 2. Physical Properties of Ceramic Tile Powder (CWP).

Property	Value
Bulk density [kg/m³]	1.125
Specific gravity	2.3
Moisture content [%]	0.10
Water absorption [%]	21.5
Fineness [µm]	~75
Color	Light brown

Mix Design

Mortar mixes were prepared in six formulations (Table 3). The reference (control) mix was prepared with only ordinary Portland cement (OPC) without ceramic tile waste powder (CWP). The other five mixes were prepared by replacing cement with CWP gradually at 5%, 10%, 20%, 25%, and 30% by weight of cement, respectively. The selected replacement levels were chosen to achieve a broad range of substitution ratios (0–30%) based on the previous literature indicating optimal mechanical performance in the 10–25% range [2, 3, 4, 5, 6, 8] and also to study the behavior at higher replacement levels. All mixes were prepared with a fixed water-to-cement ratio (w/c) of 0.5, corresponding to 225 ml of water for 450 g of cement, so that the workability and consistency were kept constant during the experimental program.

All mixtures were poured into rectangular molds of size 160 × 40 × 40 mm. The specimens were demolded after 24 h of casting and cured for 28 days under standard laboratory conditions (20 ± 2°C and 95 ± 5% relative humidity). The compressive strength was measured on the halves of the broken prisms according to ASTM C349 [10], and the flexural strength was measured according to ASTM C348 [11].

Table 3. Mixture Proportions of Prepared Mortar Specimens.

Mixture	Cement [g]	CWP [g]	Sand [g]	Water [ml]	W/C
MO-Control	450	0	1350	225	0.5
MCWP5%	427.5	22.5	1350	225	0.5
MCWP10%	405	45	1350	225	0.5
MCWP20%	360	90	1350	225	0.5
MCWP25%	337.5	112.5	1350	225	0.5
MCWP30%	315	135	1350	225	0.5

Testing

Mechanical properties of mortar specimens were determined with compressive and flexural strength tests after 28 days of curing. Flexural strength was determined using a universal testing machine with a capacity of 50 kN in a three-point bending test in accordance with ASTM C348 [11]. The test was performed at room temperature, and each result is an average of three specimens. After the flexural test, the two broken halves of each specimen were tested for compressive strength using a 2000 kN capacity machine in accordance with ASTM C349 [10] at a loading rate of 0.5 MPa/s. Three specimens were tested in each test to ensure the results were reliable and reproducible.

Results and Discussion

Fig. 3 shows the microstructure of the sand particles. The image shows irregular, angular particles with a rough surface texture, characteristic of siliceous sand from southern Algeria. This angular morphology is beneficial for mortar performance, as it promotes mechanical interlocking between particles and positively contributes to strength development. Fig. 4 shows the particle size distribution of the sand, which is continuously graded from 0.08 to 5 mm, indicating that the sand is well graded and suitable for mortar production. This well-graded distribution helps efficient particle packing and a lower void content in the mortar matrix. This explains the relatively high compressive strength reached by the control mix (36.2 MPa) and the favorable mechanical behavior reported for the CWP replaced mixtures.

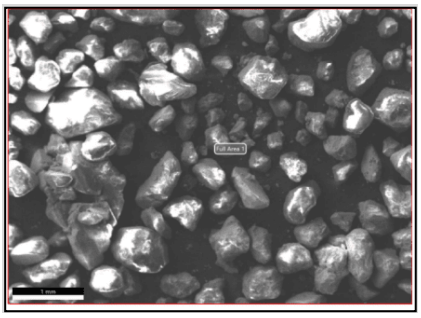


Fig. 3. SEM image of the sand particles used.

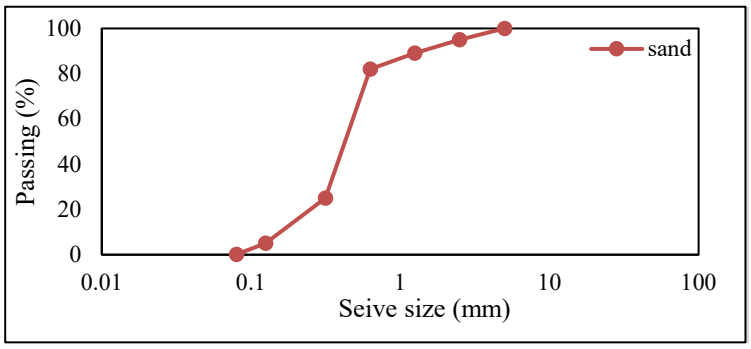


Fig. 4. Particle size analysis of the sand used.

The elemental composition and microstructural features of CWP were determined by energy dispersive X-ray (EDX) spectroscopy and scanning electron microscopy (SEM), respectively. The EDX spectrum (Fig. 5) indicated that CWP is composed of oxygen, silicon, and aluminum as the main elements, with small amounts of calcium, iron, potassium, sodium, magnesium, and carbon. The elemental profile dominated by silica and alumina is consistent with an aluminosilicate-rich composition and supports the potential pozzolanic activity of CWP, as reactive silica and alumina could combine with calcium hydroxide ($Ca(OH)_2$) released during cement hydration to form additional calcium silicate hydrate (C-S-H) gel, contributing to strength development at later ages. The SEM image (Fig. 6) shows that the CWP particles had an irregular angular morphology with a rough surface texture due to the ball mill grinding process. It is expected that this morphology would lead to better particle packing and mechanical interlocking within the mortar matrix, particularly at low replacement levels, which might be a partial reason for the observed improvement in flexural strength at 10% CWP replacement.

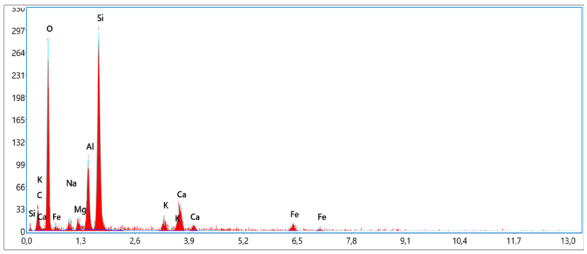


Fig. 5. EDX spectrum of the CWP.

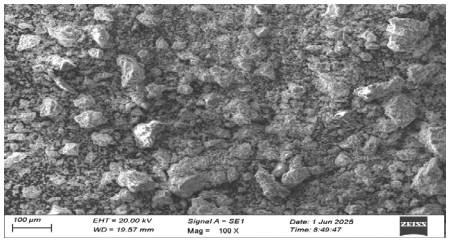


Fig. 6. SEM micrograph of ceramic tile powder (100X).

The chemical composition of the cement, as obtained from Table 4, shows that the cement conforms to the ASTM C150 requirements, with CaO (64.10%) and SiO_2 (20.54%) as the main oxides and MgO (3.01%) and SO_3 (2.22%) within the permissible limits, which confirms the suitability of this cement for use in the production of structural mortar. Table 5 summarizes the compressive and flexural strength results for all mortar mixes. Figs. 7 and 8 also present the data graphically.

Table 4. Chemical composition of the Portland cement used [%].

CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	SrO	TiO_2	P_2O_5	Cl	SO_3
64.10	20.54	4.45	3.41	3.01	0.67	0.18	0.06	0.25	0.15	0.02	2.22

Table 5. Compressive and flexural strength of mortar mixes (mean ± SD, n = 3).

Mixture	Compressive Strength [MPa]	Flexural Strength [MPa]
MO-Control	36.2 ± 0.56	5.61 ± 0.16
MCWP5%	31.6 ± 0.70	5.72 ± 0.11
MCWP10%	33.1 ± 0.70	5.91 ± 0.13
MCWP20%	34.8 ± 0.89	5.60 ± 0.12
MCWP25%	35.2 ± 0.36	5.22 ± 0.12
MCWP30%	32.0 ± 0.87	4.89 ± 0.11

Compressive Strength

Fig. 7 shows the compressive strength results of all the mortar mixtures after curing for 28 days. The control mortar (MO) without CWP gave the highest compressive strength of 36.2 MPa. The compressive strength dropped to 31.6 MPa and 33.1 MPa at 5% and 10% CWP replacement. The decrease is attributed to the lower cement content at these replacement levels, which limits the amount of calcium silicate hydrate (C-S-H) gel formed during hydration, and the relatively low pozzolanic activity of CWP at early ages. These results are consistent with prior studies [2, 3, 12] that showed that moderate CWP replacement levels might not be pozzolanically sufficient to compensate for the decrease in cement content. The compressive strength was gradually restored to 34.8 MPa and 35.2 MPa at 20% and 25% CWP replacement, respectively. This improvement is attributed to the synergistic effect of the pozzolanic activity of CWP and its microfilling effect, which reduces the porosity and densifies the mortar matrix to the level of the control mix. With 30% replacement of CWP, the compressive strength decreased to 32.0 MPa. This finding is in agreement with literature [8, 13] stating that an excessive cement replacement leads to a binder content that is not enough for adequate hydration and strength development in the mortar matrix. The irregular particle morphology of CWP as seen from the SEM images (Fig. 6) influenced the packing density of the mortar matrix, which was a factor for the strength variations observed at different replacement levels.

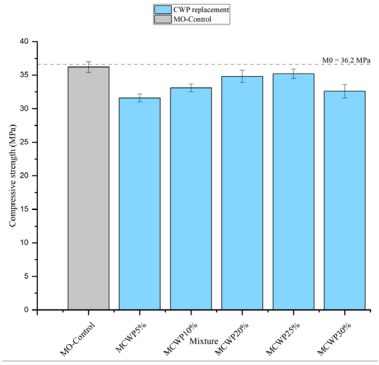


Fig. 7. Influence of CWP content on compressive strength of cementitious mortar (MPa).

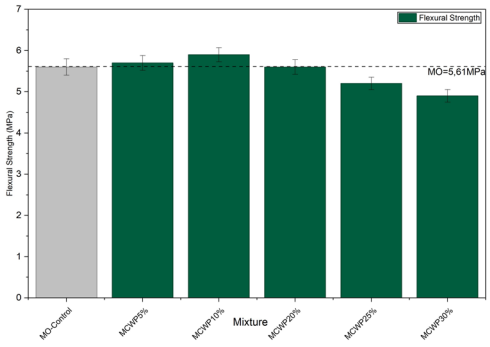


Fig. 8. Influence of CWP content on flexural strength of cementitious mortar (MPa).

Fig. 8 displays the flexural strength results. The flexural strength of control mortar (MO) was 5.61 MPa. The maximum flexural strength was achieved for 10% CWP replacement, which was 5.91 MPa, 5.3% higher than the control mix. This improvement results from the refinement and densification of the microstructure, which occurs due to better particle packing at low levels of replacement, as reported in previous studies [12, 13, 14, 15, 16]. Low-to-moderate CWP contents not only maintain the flexural resistance but can even improve it due to the combined filler effect and pozzolanic reactivity of fine ceramic particles within the mortar matrix. With an increase in replacement beyond 10%, flexural strength started decreasing. Values of flexural strength at 20%, 25%, and 30% replacement were 5.60 MPa, 5.22 MPa, and 4.89 MPa, respectively. The minimum flexural strength of 4.89 MPa was obtained at 30% CWP replacement. This means that the mortar matrix deteriorates with CWP content above this level because the cement paste is not enough to complete the hydration process. This behavior is in agreement with the results found in the literature [17], where an upper limit in strength development was observed, beyond which increasing the amount of CWP negatively affected the mechanical properties [2]. In general, replacing 10% to 25% of CWP gives the best balance between mechanical performance and environmental impact. The pozzolanic and filler effects of CWP are fully exploited in this range, but the strength values in compression and flexion still satisfy the ASTM C349 and ASTM C348 requirements for cementitious mortars. These results confirm that CWP is a feasible and sustainable supplementary cementitious material for construction applications [13].

The results indicated that the compressive and flexural strength showed different trends with increasing CWP replacement ratios. The compressive strength progressively reduced beyond 25% replacement. The flexural strength was observed to be the highest at 10% CWP content (5.91 MPa) and progressively reduced at higher replacement levels. This difference can be explained by the double role of CWP particles in the mortar matrix. At low replacement ratios (5–10%), the fine CWP particles mainly act as a physical filler, improving the packing density of the particles and refining the pore structure of the mortar. This densification effect is especially beneficial for flexural strength since it improves the interfacial transition zone (ITZ) between the cement paste and sand particles, leading to higher resistance to bending stresses. At higher replacement ratios (20–30%), the continuous reduction in cement content results in a reduction in the total amount of calcium silicate hydrate (C-S-H) gel formed during hydration. C-S-H is the main binding phase that contributes to the mechanical strength, so its reduction directly influences the compressive performance. Furthermore, the partial pozzolanic reaction of CWP at higher dosages due to insufficient calcium hydroxide ($Ca(OH)_2$) leads to unreacted CWP particles, which act as weak points in the mortar matrix, accelerating the strength reduction under compressive loading. These results are in agreement with the literature [6, 7], where similar behavior was reported for mortars

containing fine ceramic waste particles, where the filler effect dominates at low replacement rates and the dilution effect dominates at higher contents.

Conclusion

The present study investigates the possibility of using ceramic tile waste powder (CWP) as a sustainable partial replacement for cement in mortar at replacement levels of 0 to 30% by cement weight. The results demonstrate that CWP can be incorporated into mortar mixtures with acceptable mechanical performance and offer technical and environmental benefits. From the mechanical perspective, the results indicated that the compressive strength was better preserved among the treated mixes with replacement levels of 20% and 25% with values of 34.8 MPa and 35.2 MPa for MCWP20 and MCWP25, respectively. These values are close to the strength of the control mortar of 36.2 MPa and meet the minimum requirements of ASTM C270 [18] for structural mortar applications. The maximum flexural strength was achieved at 10% CWP replacement, which was 5.91 MPa (increased by 5.3% compared to the control mortar with a flexural strength of 5.61 MPa). This difference in behavior of the two strength parameters reflects the dual role of CWP in the mortar matrix: at low replacement levels, fine CWP particles improve the particle packing and reduce the interfacial transition zone, which benefits the flexural resistance; at higher levels, the reduction of cement content limits the formation of C-S-H gel, which gradually reduces the compressive performance. The flexural strength gradually decreased beyond 10% replacement, while the compressive strength decreased significantly beyond 25% replacement, which confirmed that the excessive CWP content affects the hydration process and reduces the mortar matrix strength. These results emphasize the importance of finding a replacement ratio that optimally balances mechanical performance with sustainability objectives. From the sustainability perspective, the use of CWP as a partial cement replacement is a feasible approach to address two important issues: the minimization of the ceramic waste disposed of in landfills and the reduction of the carbon footprint due to the Portland cement manufacturing. CWP substitution for up to 25% of cement produces similar mechanical performance and makes a significant contribution to sustainable construction practices. Future studies should focus on optimizing the replacement ratio of CWP in the range of 10-25% using different types of cement, water-to-cement ratios, and curing conditions. The long-term durability of CWP-based mortars should also be investigated under aggressive environments such as sulfate attack, chloride ingress, and freeze-thaw cycles. The elastic modulus should also be assessed to complete the mechanical characterization of optimized mixes. Furthermore, the present findings should be validated through field applications and case studies to promote wider use of CWP in sustainable construction. It is worth mentioning that the elastic modulus testing and X-ray diffraction (XRD)-based mineralogical characterization of CWP were not performed in the present study, which are valuable directions for future works to further understand the pozzolanic mechanisms and stiffness behavior of CWP-based mortars.

Acknowledgments

The author would like to thank the Research Centre in Analytical Chemistry and Physics (CRAPC Ouargla) in Algeria for their support in conducting advanced analyses, such as energy-dispersive X-ray (EDX) spectroscopy and scanning electron microscopy (SEM). The authors also gratefully acknowledge the Laboratory of Public Works of the South (LTPS) in Ouargla for their assistance in providing all relevant standards and overseeing the process of experimental mortar investigations.

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