Theory and Practice of Science and Technology
2025, VOL. 6, NO. 7, 82-88
DOI: 10.47297/taposatWSP2633-456917.20250607

Effect of Ceramic Particles on the Apparent Density and Mechanical Properties of Cement-Based Mortar

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ABSTRACT

To promote the resource utilization of ceramic waste and reduce the construction industry's reliance on natural resources, this study investigates the effects of various combinations of ceramic powder (10%, 20%, 30%) and ceramic particles (10%, 20%, 30%) on the compressive and flexural strength of cement-based mortar through multifactor comparative experiments. The influence of curing age (7d, 14d, 28d) is also analyzed. The results show that the incorporation of ceramic powder and particles significantly affects the mechanical properties of mortar. In terms of compressive strength, the combination of 10% ceramic powder and 10% ceramic particles (A1B1) performs best, reaching 33.6 MPa at 28 days; however, in high-content combinations (e.g., A3B3, both at 30%), the 28-day compressive strength is only 17.5 MPa. For flexural strength, the A1B2 combination (10% powder, 20% particles) achieves 6.6 MPa at 28 days, while the high-content A3B3 combination drops to 5.1 MPa. This indicates that low to moderate additions (⩽20% with appropriate ratios) favor strength development, whereas high levels (⩾30%) may damage the matrix structure, reducing strength. Most reasonably dosed combinations exhibit a steady strength increase with curing time, while some mismatched ratios show fluctuations or declines. In conclusion, a compatibility range exists for ceramic powder and particles. When dosed appropriately at low to moderate levels, they synergistically enhance mortar performance, offering a reference for the efficient application of ceramic waste in cement-based materials.

KEYWORDS

Ceramic powder; Ceramic particles; Cement-based mortar; Compressive strength; Flexural strength; Waste recycling

1 Introduction

With the rapid development of the global construction industry, the extensive use of cement-based materials not only intensifies the consumption of natural resources but also causes significant environmental pressure due to the large amount of carbon emissions (accounting for 8% of global total emissions) generated during cement production [1]. At the same time, ceramic waste (such as ceramic tiles, insulators, etc.) generated in the process of urbanization is piled up because it is difficult to degrade, which not only occupies land resources but also causes environmental pollution problems [2]. In this context, the resource utilization of ceramic waste in concrete can not only reduce the landfill amount of industrial solid waste but also reduce the dependence on natural aggregates and cement, becoming an important way to promote the sustainable development of the construction industry.

Existing studies have shown that ceramic waste can replace cement, natural sand, or coarse aggregates in concrete in different forms (such as ceramic powder, ceramic aggregates, etc.) and show great potential in optimizing mechanical properties, durability, and environmental benefits. For example, ceramic powder (CWP) as an auxiliary cementitious material can refine the pore structure of concrete through filling effect and pozzolanic reaction, improve compressive strength and reduce chloride ion permeability [3]; while ceramic aggregates (such as waste ceramic tile aggregates, WCTA) can improve the interface transition zone (ITZ) of concrete when replacing natural aggregates, enhancing high-temperature resistance and crack resistance [4]. In addition, the combined use of ceramic waste with other industrial by-products (such as fly ash, slag) or nanomaterials (such as nano-silica) can further improve the comprehensive performance of concrete through synergistic effects. For example, after compounding ceramic powder with blast furnace slag, even if the cement replacement rate reaches 50%, the concrete can still maintain strength and durability comparable to the reference group [5].

However, there are still controversies about the influence of the incorporation proportion and method of ceramic waste on concrete performance. Some studies point out that high proportion replacement (such as more than 30%) may lead to a decrease in workability or early strength [6], which can be alleviated by optimizing particle gradation or composite modification (such as adding nanomaterials) [7]. Therefore, systematically exploring the action mechanism, optimal replacement proportion, and application scenarios of ceramic waste in concrete is of great significance for promoting its engineering application. Based on existing research results, this paper reviews the application progress of ceramic waste in cement-based materials, providing a reference for the research, development, and practice of

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sustainable concrete.

2 Materials and methods

2.1 Materials

This paper selects PO42.5 ordinary Portland cement produced by "Yaobai" Special Cement Group Co., Ltd. as shown in Figure 1. The use of ordinary Portland cement has the following advantages: fast hydration reaction speed; dense cement structure; good early strength and cement frost resistance; high later strength. The 28-day compressive strength of the test cement is 42.5 MPa, and the core physical parameters and element composition of the cement are listed in Table 1 and Table 2.

Table 1

Density/g/cm^3	Standard consis-tency/%	Initial setting time/min	Final setting time/min	Flexural strength/MPa			Compressive strength/MPa
				3d	28d	3d	28d
3.15	25.0	198	254	6.1	7.6	31.4	42.5

Table 2 Chemical composition of cement

Name	CaO	SO_3	MgO	SiO_3	Fe_2O_3	Al_2O_3	Cl^-
Content/%	54.46	2.43	2.01	25.36	2.73	7.82	0.04

Figure 1 Cement

River sand is the main aggregate in mortar, which not only provides strength for the new green mortar but also can reduce the shrinkage deformation during mortar forming. The test sand is natural medium sand from the Weihe River in Shaanxi Province. The basic physical performance indexes of the sand are shown in Table 3. The fineness modulus of the sand is 2.018, and the moisture content is 3.3%. The test sand is sieved, and the sieving results are shown in Table 4. It can be seen that the maximum particle size of the sand is about 4.75mm, and the gradation curve of the sand is shown in Figure 3, which meets the standards of construction sand specified in "Sand for Construction" (GB/T 14684-2022). The tap water used in this test is from Lintong District, Xi'an City, and its usage requirements meet the "Standard for Water Used in Concrete" (JGJ 63-2006).

Fineness modulus calculation formula:

Figure 2 Natural river sand

$$M_x = \frac{A_2 + A_3 + A_4 + A_5 + A_6 - 5A_1}{100 - A_1}$$

In the formula: M_x——fineness modulus; A_1——cumulative screen residue; n=1、2、3、4、5、6 respectively represent the cumulative screen residue percentages of sieve holes of 4.75 mm、2.36 mm、1.18 mm、0.60 mm、0.30 mm、0.15 mm.

Table 3 Basic performance indexes of sand

Apparent density/kg/m^3	Moisture content/%	Bulk density/kg/m^3	Mud content/%	Fineness modulus
2.49	3.3	1418	0.8	2.018

Table 4 Sand sieving results

Sieve aperture/mm	Fractional screen residue mass/kg	Fractional screen residue/%	Cumulative screen residue mass/kg	Cumulative screen residue%
4.75	0.081	8.1	0.	8.1
2.36	0.016	1.6	0.097	9.7
1.18	0.034	3.4	0.131	13.1
0.6	0.175	17.5	0.306	30.6
0.3	0.453	45.3	0.759	75.9
0.15	0.208	20.8	0.967	96.7
Sieve bottom	0.033	3.3	1.000	100
Fineness modulus	2.018			

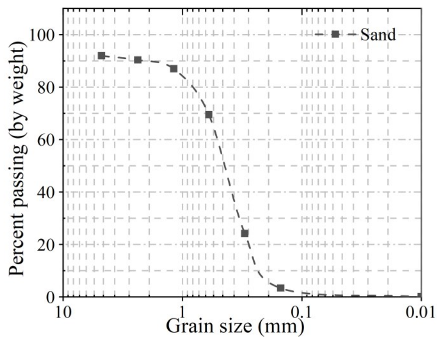

Figure 3 Particle size distribution curve of sand

The waste ceramics used in the test are excess single-sided glazed white and blue ceramic tiles from daily household decoration. The main processing flow of waste ceramic particles (WCP) is shown in Figure 4.

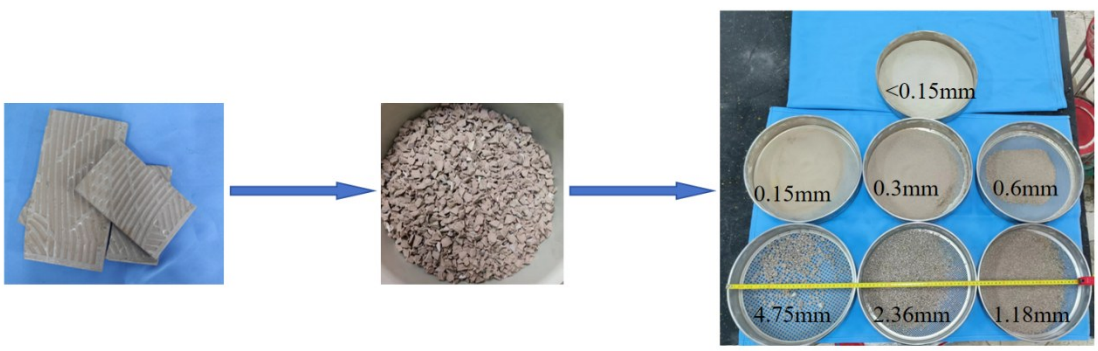

Figure 4 Preparation process of waste ceramic particles

2.2 Mix proportion design

Controlled experiment is a commonly used experimental design method in scientific research. This paper corresponds to a multi-factor controlled experiment containing two independent variables (each with 3 levels). Through mutual comparison between groups, the main effects and interaction effects between variables are explored, which is a commonly used design method for analyzing complex problems in scientific experiments.

In this test, the water-cement ratio (w/c) is fixed at 0.5, and a multi-factor controlled experiment is adopted. The incorporation amount of ceramic powder (A) and the incorporation amount of ceramic particles (B) are taken as two influencing factors, and each influencing factor selects three levels. The control groups are compared with each other to study the main factors affecting the strength of cement-based materials. Macadamia nut shell particles are added by replacing sand with equal mass. The incorporation rate of ceramic particles is 10%, 20%, and 30%, and the incorporation rate of ceramic powder is 10%, 20%, and 30% of the mass of cement, respectively, into the mortar. The factor level table is shown in Table 5, and the mix proportion design table is shown in Table 6.

Table 5 Level table of influencing factors in waste ceramic mortar performance test

Factor level	Ceramic powder incorporation amount (A)/%	Ceramic particle incorporation amount (B)/%
High level	10	10
Intermediate value	20	20
Low level	30	30

Table 6 Mix proportion design table of waste ceramic mortar

Test num - ber	Influencing factors		Material usage/kg/m^3				
	A: Ceramic powder incorporation amount/%	B: Ceramic particle incorporation amount/%	Water	Cement	Ceramic pow-der	Sand	Ceramic sand
A1B1	10	10	225	405	45	1215	135
A1B2	10	20	225	405	45	1080	270
A1B3	10	30	225	405	45	945	405
A2B1	20	10	225	360	90	1215	135
A2B2	20	20	225	360	90	1080	270
A2B3	20	30	225	360	90	945	405
A3B1	30	10	225	315	135	1215	135
A3B2	30	20	225	315	135	1080	270
A3B3	30	30	225	315	135	945	405

2.3 Sample preparation and test methods

2.3.1 Sample preparation

First, the hard waste ceramics are pretreated. The whole piece is first broken, then the dried waste ceramics are crushed with a crusher, and the corresponding particles are separated with a sieving machine, as shown in Figure 2-4.

According to GB/T17671-2021, 9 cubic samples of 70.7mm×70.7mm×70.7mm (for compressive test) and 9 prismatic samples of 40mm×40mm×160mm (for flexural test) are made for each mix proportion. Weigh the materials according to the designed mix proportion. First, mix sand, cement, waste ceramic particles, and waste ceramic powder evenly for 2 minutes, then add water and stir together for 2 minutes. Secondly, after stirring, fill the sample mold in three layers, and place the mold on a vibrating table to vibrate for 90 seconds to remove air. Finally, label the mold, cover the surface with a layer of polyethylene plastic film, and demold with a demolding machine after final setting. The samples are cured in a water tank at 20±1℃. The compressive strength, flexural strength, and density are tested at 7d, 14d, and 28d respectively.

2.3.2 Test methods

The compressive strength and flexural strength are determined according to "Cement Mortar Strength Test Method (ISO Method)" (GB/T17671-2021). The compressive strength test instrument is a microcomputer-controlled electronic universal testing machine, model WDW-300H, with a maximum test force of 3000kN. The loading rate of the pressure testing machine is 1.5kN/s. The flexural strength test instrument is an electric three-point bending testing machine, model AEC501. The loading rate of the flexural testing machine is 50N/s.

Three samples are taken from each group for compressive strength testing to ensure the reliability and accuracy of the test. The Grubbs criterion is used to eliminate data with large deviations in the three groups of data, and the average value of the remaining data is taken as the ultimate compressive strength of the group.

3 Results and discussion

3.1 Compressive strength

It can be seen from Table 7 and Figure 5 that different combinations of ceramic powder (factor A) and ceramic particle (factor B) incorporation amounts significantly affect the compressive strength of the material. When the ceramic powder incorporation amount is 10% (group A1) and the ceramic particle incorporation amount is 10% (B1), the 7d, 14d, and 28d compressive strengths reach 28.4MPa, 31.1MPa, and 33.6MPa in turn, and the strength shows an upward trend with the increase of curing age, reflecting a good strength development law. When the ceramic particle incorporation amount increases to 20% (A1B2), the 14d compressive strength drops to 28.2MPa, and further drops to 25.0MPa at 28d, indicating that an excessively high incorporation amount of ceramic particles (under group A1) may inhibit strength development in the later period due to particle accumulation, interface defects, etc.

When the ceramic powder incorporation amount is increased to 20% (group A2), such as A2B1 (10% ceramic particles), the 7d strength is 20.3MPa, which is lower than the strength of A1B1 at the same curing age, indicating that within a certain range, more ceramic powder is not more beneficial to early strength. In A2B2, both ceramic powder and particles are 20%, and the 14d and 28d strengths are only 19.6MPa and 19.5MPa, with slow strength development and an overall low level, which may be due to the unbalanced incorporation proportion of the two ceramic materials, destroying the continuity of the matrix structure.

When the ceramic powder reaches 30% (group A3), the strength of each combination is generally not high. The 7d, 14d, and 28d strengths of A3B1 are 17.2MPa, 18.2MPa, and 19MPa. Although they increase with age, compared with group A1, the strength increase range is small, reflecting that an excessively high incorporation amount of ceramic powder may reduce the proportion of effective components in the cementitious system, weakening the foundation for strength formation.

Overall, the compressive strengths of different combinations mostly show an increasing trend with the extension of curing age. For example, in A1B1, the strength steadily increases from 28.4MPa at 7d to 33.6MPa at 28d, indicating that under a reasonable material combination, the hydration of cement-based materials continues, and the strength gradually develops and matures. The later strength growth of some combinations slows down or even decreases, such as A1B2, where the 14d strength is 28.2MPa and drops to 25.0MPa at 28d. This may be due to the development of internal microcracks in the material over time, or the deterioration of the bond between ceramic particles and the matrix interface in the later period due to environmental factors (such as changes in humidity and temperature), leading to a decrease in strength. This also reflects that the long-term stability of the material is significantly affected by its composition.

Table 7 Compressive strength test results

Test number	Influencing factors		Compressive strength/MPa		
	A: Ceramic powder incorporation amount/%	B: Ceramic particle incorporation amount/%	7d	14d	28d
A1B1	10	10	28.4	31.1	33.6
A1B2	10	20	29.4	28.2	25.0
A1B3	10	30	22.4	20.8	27.6
A2B1	20	10	20.3	22.9	25.6
A2B2	20	20	14.7	17.6	19.5
A2B3	20	30	17.5	21.5	22.3
A3B1	30	10	17.2	18.2	19
A3B2	30	20	19.8	18.4	17.6
A3B3	30	30	18.2	17.0	17.5

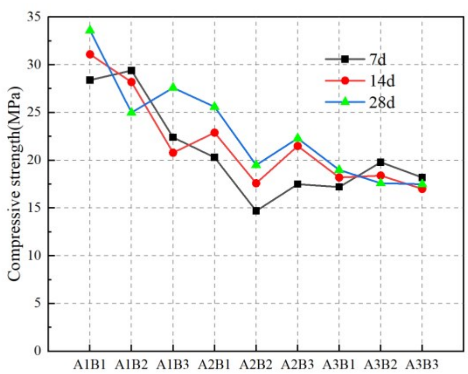

Figure 5 Relationship between compressive strength and curing days

3.2 Flexural strength

As shown in Figure 6, the development trends of flexural strength of different combinations vary. Combinations such as A1B1 and A1B2 show an overall increasing or fluctuating upward trend in strength from 7d to 28d. For example, in A1B1, the 7d strength is 5.8MPa, reaching 6.2MPa at 14d and 6.5MPa at 28d, reflecting that under a reasonable combination, the hydration and interface bonding inside the material continue to develop with curing, enhancing the flexural capacity. The strength development of some combinations (such as A3B1) is unstable, with obvious fluctuations or even decreases from 7d to 14d and 28d. This may be because the hydration reaction is disturbed under high ceramic powder incorporation, and the matrix compactness and interface bonding are affected, leading to hindered development of flexural strength, which is difficult to effectively improve in the later period.

Comprehensive analysis shows that there is an adaptation range for the incorporation amounts of ceramic powder and particles. Low-medium incorporation combinations such as A1B1 and A1B2 have better flexural strength performance, indicating that within this range, ceramic particles can play a "bridging" role to disperse bending stress, and the powder fills pores to optimize the structure; at high incorporation amounts (A⩾30%, B⩾30%), excessive ceramic materials introduce a large number of defects, weakening the continuity of the matrix, and reducing the flexural strength.

Table 8 Flexural strength test results

Test number	Influencing factors		Flexural strength/MPa		
	A: Ceramic powder incorporation amount/%	B: Ceramic particle incorporation amount/%	7d	14d	28d
A1B1	10	10	5.8	6.2	6.5
A1B2	10	20	5.3	5.9	6.6
A1B3	10	30	5.0	5.8	6.1
A2B1	20	10	4.3	5.6	5.6
A2B2	20	20	5.1	4.9	6.0
A2B3	20	30	4.7	4.6	6.1
A3B1	30	10	4.1	4.6	4.8
A3B2	30	20	4.2	4.6	4.7
A3B3	30	30	4.0	4.4	5.1

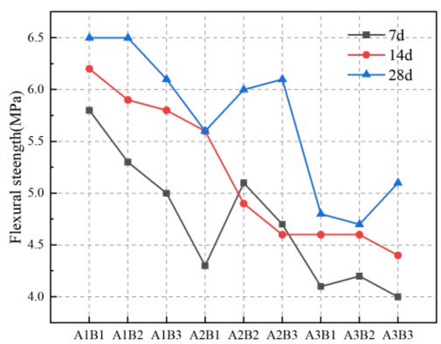

Figure 6 Relationship between flexural strength and curing days

4 Conclusions

Based on the test results of the influence of ceramic powder and particle incorporation amounts on compressive and flexural strengths, the following conclusions can be drawn:

The incorporation amounts of ceramic powder (A) and ceramic particles (B) significantly affect the compressive and flexural strengths of the material. In terms of compressive strength, the A1B1 combination (A=10%, B=10%) performs the best, with a 28d compressive strength of 33.6MPa; the high-incorporation combination (such as A3B3, A=30%, B=30%) has significantly reduced strength, with a 28d compressive strength of only 17.5MPa. In terms of flexural strength, low-medium incorporation combinations such as A1B1 and A1B2 perform better, with the 28d flexural strength of A1B2 (A=10%, B=20%) being 6.6MPa; the 28d flexural strength of the high-incorporation combination (such as A3B3) drops to 5.1MPa. This indicates that low-medium incorporation amounts of ceramic materials (A and B incorporation amounts ⩽ 20% with reasonable matching) are more conducive to strength development; high incorporation amounts (A and B incorporation amounts ⩾30%) will reduce strength due to damaging the matrix structure and increasing weak interfaces.

The compressive and flexural strengths of most reasonably incorporated combinations (such as A1B1) show an increasing or stable development trend with curing days (7d-28d), reflecting that the hydration and interface bonding of the material continue to enhance the structural bearing capacity. The strength development of some combinations (such as A1B2 in compressive strength and A3B1 in flexural strength) fluctuates or even decreases, reflecting that when the ceramic incorporation amount is incompatible, the medium-term strength is easily affected by internal defects (such as stress concentration, hindered hydration), and it is difficult to recover in the later period. This indicates that the compatibility of ceramic incorporation amounts must be strictly controlled to ensure the stable development of strength.

There is a strength adaptation range between ceramic powder and particles. At low-medium incorporation amounts (reasonable proportions of A and B, such as A=10%-20%, B=10%-20%), particles can play a role in skeleton support and stress dispersion, and powder fills pores to optimize the structure, synergistically improving compressive and flexural strengths. In the future, we can focus on this adaptation range, optimize the gradation of ceramic materials (such as particle shape and particle size distribution), and explore surface modification to enhance interface bonding, further improving the application effect of ceramic waste in this system, and achieving the synergistic goal of efficient resource utilization and material performance optimization.

Funding

This work is supported by the Key Research and Development Program of Shaanxi (NO: 2025NC-YBXM-326)

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