Compressive Strength Study of the Recycled Mortar From Waste Tiles

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Abstract. To achieve the resourceful utilization of waste ceramic tiles and reduce the usage of sand in construction, this paper employs waste ceramic tiles to produce recycled fine aggregates. Simultaneously, the recycled fine aggregates undergo surface modification treatment using a silane coupling agent KH550 solution. Utilizing an orthogonal experimental design, four factors including water-binder ratio, replacement ratio, fineness modulus, and solution concentration are set to produce recycled waste tile mortar (RAM), aiming to explore the compressive strength of RAM. Experimental results reveal that the compressive strength of RAM made from waste ceramic tiles has been maximally increased by 47%, and its flowability performance also meets relevant standards.

Keywords: mortar; waste ceramic tiles; orthogonal test; compressive strength

1 INTRODUCTION

As the world's largest producer and consumer of ceramic tiles, China generates significant waste annually due to production, transportation, decoration, renovation, and demolition of buildings, leading to environmental pollution [1]. Combined with the high water absorption and low porosity of ceramic tiles, as well as their volcanic ash activity, and their main chemical composition similar to natural sand and gravel [2,3], if they can be processed into recycled fine aggregates and applied to mortar materials, not only would it demonstrate the secondary utilization value of ceramic tiles, but it would also effectively address the scarcity of natural sand and gravel resources. Compared to traditional mortar under equivalent conditions, RAM exhibits greater mechanical performance advantages, meets relevant technical indicators, incurs lower production costs, and brings economic and social benefits [4].

Currently, the utilization of waste ceramic tiles mainly includes the following four aspects: Firstly, utilizing waste ceramic tiles to produce recycled coarse aggregates. Xu et al. [5] used waste ceramic tiles to prepare recycled coarse aggregates to replace natural coarse aggregates in producing recycled concrete, and conducted experimental

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analysis on its compressive strength. It was proven that with the increase in the replacement ratio of ceramic tile coarse aggregates, the compressive strength of recycled concrete significantly improved. Secondly, using waste ceramic tiles to produce recycled fine aggregates, partially substituting them for sand in traditional mortar and concrete. Mohammadhosseini et al. [6] conducted relevant experiments by making ordinary mortar and mortar with ceramic waste partially replacing cement and natural river sand fine aggregates. They found that the mechanical performance of ceramic mortar was superior to ordinary mortar, and the incorporation of ceramics improved the mortar's pore system, enhancing its durability. Thirdly, utilizing ceramic tile production waste and mechanically crushed ceramic tile powder, combined with the volcanic ash activity of ceramic tile powder, to partially substitute cementitious materials in a certain proportion, reducing the usage of cementitious materials in mortar and concrete, thus increasing the utilization rate of waste ceramic tiles. Samadi et al. [7] found that the combination of ceramic powder and ceramic particles reduced the flowability of mortar, improving its compressive strength. If ceramic polishing powder is used in mortar production, it can not only address the environmental pollution caused by the extensive treatment of ceramic waste but also to some extent solve the carbon emissions caused by the production of cement raw materials. Fourthly, through corresponding surface modification agents, modifying the surface roughness of crushed waste ceramic tile aggregates to enhance their bonding strength with cementitious materials [8], thereby improving the mechanical performance of mortar and concrete. In conclusion, the environmental pollution caused by waste ceramic tiles cannot be ignored. Therefore, studying the incorporation of waste ceramic tiles is of paramount importance for the mechanical performance of mortar.

2 EXPERIMENT

2.1 Raw Materials

The experiment selected Hai Luo brand P.O32.5 ordinary Portland cement, with a cement density of 3.5 g/cm3. Natural fine aggregate was river sand purchased from the local market in Huai'an. Waste ceramic tiles were discarded ceramic polished tiles obtained from the building materials market in Huai'an. They were crushed and sieved using a YAD-2000 pressure testing machine to produce recycled ceramic tile aggregates. Different diameter standard sieves were used to sieve the crushed waste ceramic tile particles. As shown in Figure 1(a)-(g), these included ceramic tiles with diameters larger than 4.75mm, 2.36-4.75mm, 1.18-2.36mm, 0.6-1.18mm, 0.3-0.6mm, 0.15-0.3mm, and less than 0.15mm. Similarly, natural fine aggregates, river sand, were sieved using different diameter standard sieves, as shown in Figure 2(a)-(g), including river sand with diameters larger than 4.75mm, 2.36-4.75mm, 1.18-2.36mm, 0.6-1.18mm, 0.3-0.6mm, 0.15-0.3mm, and less than 0.15mm. The solution used was KH550 solution produced by Nanjing Chuangshi Chemical Additives Co., Ltd. Immersing the recycled ceramic fine aggregates in the KH550 solution can enhance the bonding strength between the waste ceramic tile particles and cementitious materials, thereby improving the compressive strength of the mortar [9]. Gypsum was obtained from Jiangsu Suzhou Kaiong Chemical Co., Ltd., and water was sourced from the local tap water in Huai'an.

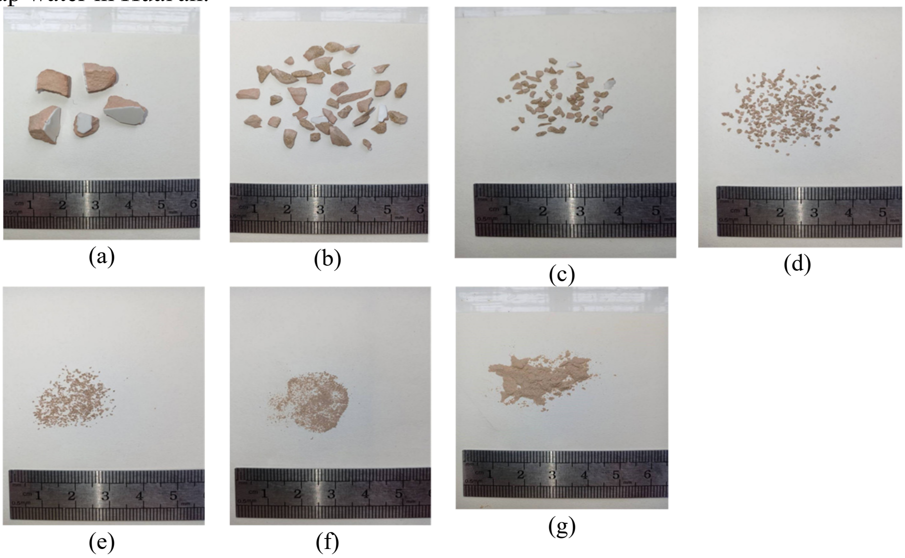

Fig. 1. Recycled fine aggregate particles of waste tiles with different particle sizes.

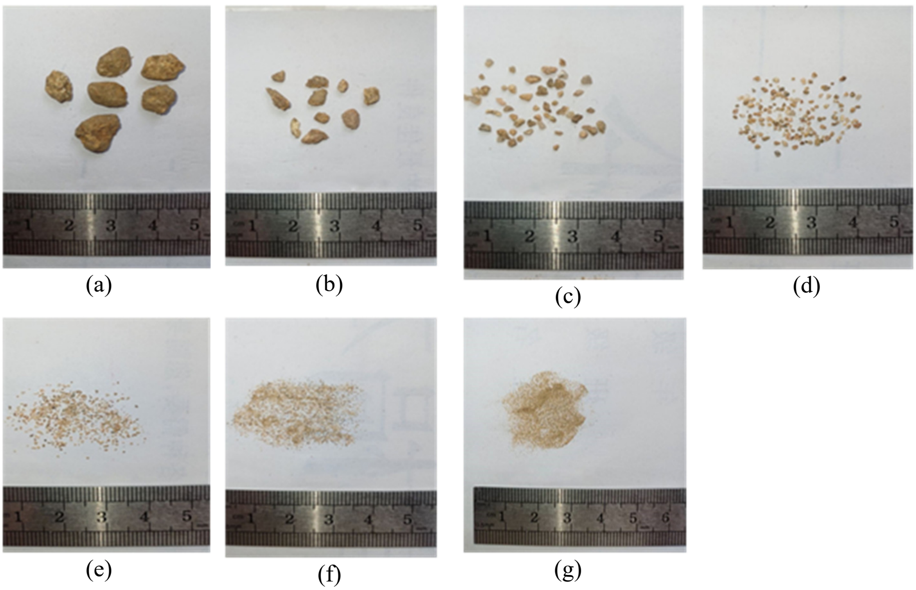

Fig. 2. Fine aggregate particles of river sand with different particle sizes.

In order to minimize the impact of the particle size of natural fine aggregates and recycled ceramic fine aggregates on the experimental results, the sieved waste ceramic tile particles and river sand particles were combined according to the ‘GB/T14684-2011

Standard for Construction Sand' [10] to obtain five sets of fine aggregates with different fineness moduli, namely 2.1, 2.3, 2.5, 2.7, and 2.9. The relevant performance indicators such as bulk density (kg/m^3), apparent density (kg/m^3), void ratio (%), and compactness (%) of the waste ceramic tile fine aggregates and river sand are shown in Table 1(a)-(d).

Table 1. Performance indicators related to waste tile fine aggregate and river sand.

(a)

Fineness modulus / Fine aggregate type	2.1	2.3	2.5	2.7	2.9
Sand	1256	1275	1277	1301	1284
Recycled fine aggregate	1428	1424	1448	1461	1450

(b)

Fineness modulus / Fine aggregate type	2.1	2.3	2.5	2.7	2.9
Sand	2608	2603	2591	2597	2606
Recycled fine aggregate	2431	2419	1448	2409	2402

(c)

Fineness modulus / Fine aggregate type	2.1	2.3	2.5	2.7	2.9
Sand	51.8	51.0	50.7	49.9	50.7
Recycled fine aggregate	41.3	41.1	40.3	39.4	39.6

(d)

Fine aggregate type	mud content	clod content	organic matter content	ruggedness
Sand	2.5	1.4	fulfill requirement	7.2
Recycled fine aggregate	0	0	fulfill requirement	3.6

2.2 Experimental Methods

(1) The mix design was carried out in accordance with JGJT98-2011 'Code for Design of Masonry Mortar Mix Proportions' [11]. The design strength grade was set to 10MPa. Compressive strength tests of the mortar were conducted using a YAD-2000 pressure testing machine. The consistency of RAM was determined using a mortar consistency meter according to the 'JGJ/T70-2009 Standard for Basic Performance Test Methods of Mortar' [12]. This was done to ensure that the mortar meets certain strength requirements while still being suitable for construction and meeting specific flowability requirements.

(2) An orthogonal experiment was conducted, involving four factors: water-to-binder ratio, replacement ratio, fineness modulus [13], and solution concentration [14]. The water-to-binder ratio was set at three levels, while the other three factors were each set at four levels. The arrangement of factor levels is shown in Table 2.

Table 2. Different levels of each factor.

Factor	Level 1	Level 2	Level 3	Level 4	Level 5
Water-binder ratio	1.17	1.23	1.29	—	—
substitution ratio	0%	20%	40%	60%	80%
fineness modulus	2.1	2.3	2.5	2.7	2.9
Solution concentration	0%	2%	4%	6%	8%

3 RESULTS AND DISCUSSION

3.1 Orthogonal Experimental Results for the Compressive Strength of RAM

As shown in Table 3, the orthogonal experimental results for the compressive strength of RAM are presented. Here, A represents the water-binder ratio, B represents the replacement ratio, C represents the fineness modulus, and D represents the solution concentration.

Table 3. Compressive strength and consistency test results of RAM.

Group	Orthogonal design	A	B (%)	C	D (%)	Compressive strength (MPa)	Consistency (mm)
1	$A_1B_1C_3D_3$	1.17	0	2.5	4	7.3	106
2	$A_1B_2C_5D_3$	1.17	20	2.9	4	7.1	108
3	$A_1B_2C_2D_5$	1.17	20	2.3	8	9.5	99
4	$A_1B_4C_5D_4$	1.17	60	2.9	6	9.0	90
5	$A_1B_3C_1D_2$	1.17	40	2.1	2	11.0	64
6	$A_1B_3C_4D_5$	1.17	40	2.7	8	11.1	111
7	$A_1B_1C_1D_1$	1.17	0	2.1	0	9.7	75
8	$A_1B_4C_3D_2$	1.17	60	2.5	2	10.0	72
9	$A_1B_5C_4D_1$	1.17	80	2.7	0	11.7	65
10	$A_1B_5C_2D_4$	1.17	80	2.3	6	10.5	58
11	$A_2B_2C_4D_2$	1.23	20	2.7	2	8.9	105
12	$A_2B_1C_2D_2$	1.23	0	2.3	2	8.5	101
13	$A_2B_3C_3D_4$	1.23	40	2.5	6	9.0	96
14	$A_2B_2C_1D_4$	1.23	20	2.1	6	8.9	94
15	$A_2B_4C_4D_3$	1.23	60	2.7	4	8.4	85
16	$A_2B_4C_2D_1$	1.23	60	2.3	0	7.7	65
17	$A_2B_1C_5D_5$	1.23	0	2.9	8	8.4	117
18	$A_2B_5C_3D_5$	1.23	80	2.5	8	14.7	66
19	$A_2B_5C_1D_3$	1.23	80	2.1	4	12.6	55
20	$A_2B_3C_5D_1$	1.23	40	2.9	0	8.7	88
21	$A_3B_1C_4D_4$	1.29	0	2.7	6	7.3	116

22	$A_3B_4C_1D_5$	1.29	60	2.1	8	9.3	73
23	$A_3B_2C_3D_1$	1.29	20	2.5	0	9.2	101
24	$A_3B_5C_5D_2$	1.29	80	2.9	2	6.9	81
25	$A_3B_3C_3D_3$	1.29	40	2.3	4	7.9	87

3.2 Orthogonal Experimental Analysis of the Compressive Strength of RAM

3.2.1 Range Analysis.

The range analysis of the compressive strength of RAM, based on the orthogonal experimental results presented in Table 3, is shown in Table 4. K1, K2, K3, K4, and K5 respectively represent the sum of mortar compressive strength at the same level of each factor. $\overline{K}1$, $\overline{K}2$, $\overline{K}3$, $\overline{K}4$ and $\overline{K}5$ represent the average values of K1, K2, K3, K4, and K5 at different levels. R represents the range within the same factors of $\overline{K}1$, $\overline{K}2$, $\overline{K}3$, $\overline{K}4$ and $\overline{K}5$. From the range analysis results of the compressive strength of RAM in Table 4, it can be inferred that the influencing factors on the compressive strength of RAM, in descending order of significance, are B, C, D, and A.

Table 4. Analysis of RAM compressive strength extreme deviations.

Number	A	B (%)	C	D (%)
K_1	96.925	41.225	51.525	47.02
K_2	95.8	43.6	44.1	45.3
K_3	40.6	47.7	50.2	43.3
K_4		44.4	47.4	44.7
K_5		56.4	40.1	53
$\overline{K}_1$	9.692	8.245	10.305	9.405
$\overline{K}_2$	9.58	8.72	8.82	9.06
$\overline{K}_3$	8.12	9.54	10.04	8.66
$\overline{K}_4$		8.88	9.48	8.94
$\overline{K}_5$		11.28	8.02	10.6
R	1.572	3.035	2.285	1.94

3.2.2 Influence of Each Factor on the Compressive Strength of RAM.

The range results of RAM compressive strength for each factor at different levels from Table 4 are analyzed individually. Figure 3(a)-(d) respectively represent the influence of replacement ratio, fineness modulus, solution concentration, and water-binder ratio on RAM compressive strength.

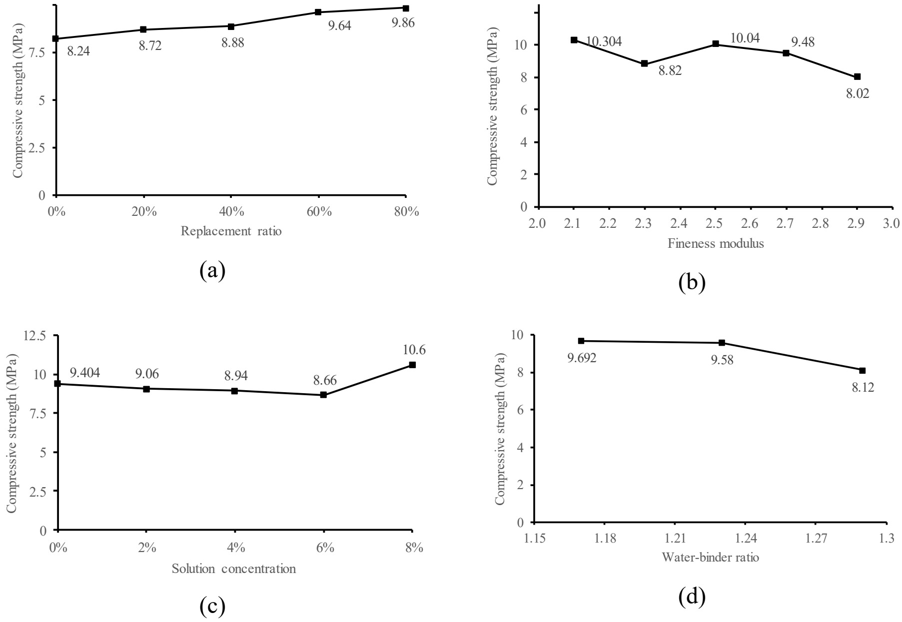

Fig. 3. Influence of each factor of RAM.

From Figure 3(a), it can be observed that as the replacement ratio of recycled ceramic fine aggregates increases, the compressive strength of RAM also increases accordingly. When the mortar's replacement ratio is 0%, the average compressive strength of the mortar is 8.244 MPa. When the substitution rate increases to 80%, the average compressive strength of RAM shows an improvement of 36.83% compared to the control group with a 0% substitution rate. Additionally, according to the compressive strength data of Group 18 in Table 3, where the replacement ratio is 80%, the compressive strength of RAM reaches 14.7 MPa, which is approximately 47% higher than the original design strength of 10 MPa. It is concluded that utilizing recycled ceramic fine aggregates to replace traditional fine aggregates such as river sand in mortar significantly enhances its compressive strength. Furthermore, the ceramic tiles used in this experiment are commonly used in decorative renovation projects, and their strength is significantly higher than that of river sand. This contributes to the noticeable increase in compressive strength of the recycled mortar when crushed waste ceramic tiles are used as fine aggregates; From Figure 3(b), it can be observed that with the increase in the fineness modulus of fine aggregates, the compressive strength of RAM generally exhibits a certain degree of decline. When the fineness modulus of the fine aggregates is 2.1, the average compressive strength of recycled ceramic tile mortar is 10.304 MPa. As the fineness modulus increases, there is a certain degree of decline in the compressive strength of RAM. When the fineness modulus is 2.9, the compressive strength of RAM decreases by 22.17% compared to when the fineness modulus is 2.1. As the fineness modulus increases, the content of coarse particles increases while the content of fine particles decreases. This results in the ineffective filling of voids between the skeleton, poor water retention of the mortar, rapid loss of water dispersion, and impacts the development of later-stage strength. Consequently, the compressive strength of the mortar significantly decreases [15]. This indicates that an appropriate fineness modulus should be adopted for the fine aggregates in RAM to ensure optimal compressive strength; From Figure 3(c), it can be observed that with the increase in the concentration of KH550 solution, the compressive strength of RAM initially shows a slight decrease, and the effect is not significant. However, when the solution concentration reaches 8%, there is a significant increase in the compressive strength of RAM. Compared to when the KH550 solution concentration is 6%, the compressive strength increases by 1.94 MPa. This indicates that when using KH550 solution for surface modification of recycled ceramic tile fine aggregates, at relatively low concentrations, the surface modification treatment has an insignificant effect on the compressive strength of RAM. However, when the solution concentration is further increased, the KH550 solution significantly affects the compressive strength of RAM; From Figure 3(d), it can be observed that with the increase in the water-binder ratio, the compressive strength of RAM exhibits a certain degree of decline. This is because with the increase in the water-binder ratio, there is a relatively reduced amount of cementitious material in RAM, and the moisture content increases relatively. Consequently, during the hydration process of RAM, there is a relatively higher amount of moisture evaporation, leading to the generation of more voids in the cementitious matrix, and thereby reducing the compressive strength of RAM.

Therefore, RAM with different levels of water-binder ratio, replacement ratio, fineness modulus, and solution concentration exhibits certain differences in compressive strength. Through correlation analysis in this experiment, the optimal combination for compressive strength of recycled ceramic tile mortar is determined to be A1B5C1D5, with water-binder ratio of 1.17, replacement ratio of 80%, fineness modulus of 2.1, and solution concentration of 8%.

4 CONCLUSIONS

(1) Due to the limited recycling of waste ceramic tiles, this study proposes a new approach by crushing and sieving waste ceramic tiles, utilizing orthogonal experimental design to formulate RAM. This provides a novel solution for the reuse of waste ceramic tiles, contributing to the sustainable development of society and the economy.

(2) Analysis of the compressive strength of RAM through orthogonal experiments reveals the varying impact of different factors. The order of influence on the compressive strength of RAM is as follows: B > C > D > A.

(3) This experiment demonstrates excellent performance in the compressive strength of mortar with a certain proportion of waste ceramic tile replacing river sand. Particularly, the combination $A_2B_5C_3D_5$ shows a significant increase in compressive strength by approximately 47% compared to the original design strength, indicating the favorable strength properties of using waste ceramic tiles as a substitute for fine aggregate in mortar, while meeting the required consistency properties.

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