Influence of Using Recycled Ceramic Aggregate and Ultra-fine Sand in Combination on Compressive Strength of Concrete

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ABSTRACT

Recycled ceramic mixed sand (RCMS) was obtained through mixing recycled ceramic coarse sand (RCCS) and ultra-fine sand. Recycled ceramic mixed aggregate concrete (RCMC) was made by using RCMS as fine aggregate, partial substituting recycled ceramic coarse aggregate for crushed stone as coarse aggregate, respectively. Effect of the percentage of RCCS in RCMS was investigated. Experimental results indicate that the optimal percentage of RCCS in RCMS was between 50% and 60%, which could increase the compressive strength of RCMC by 8.19% to 8.44% than that of reference concrete. Moreover, an adjustment coefficient of RCMS which could reflect the effect of the percentage of RCCS on compressive strength of RCMC was proposed. By using regression analysis, the regression equation was obtained between a adjustment coefficient of RCMS and the percentage of RCCS, which could provide reference for choosing reasonable RCCS content and estimating the strength of RCMC. The consumption of recycled ceramic aggregate could reach 30.37% to 33.84% of total weight of aggregate in producing concrete, and this method of recycling waste ceramic is energy-saving and environment friendly.

INTRODUCTION

Waste ceramic is one major component of construction debris, and it’s output reached ten million tons every year in China. Ceramic industry has caused serious destruction to environment. Recycling waste ceramic can bring about great social, economic and environmental benefits. The application of waste ceramic in building materials is of potential research value and has gradually attracted more and more attention. Silva et al.[1] drew the conclusion that a good workability of fresh mortar and high compaction degree of hardened cement pastes could be achieved by partially replacing cement with polished ceramic powder. Cheng et al.[2] hold that it could lower the carbonation resistance and improve the sulphate corrosion...
resistance of concrete when ceramic polishing powder used as a supplementary cementing material in concrete. Studies [3-8] on the basic mechanical properties and microstructure of RCMC concluded that it was feasible to prepare concrete or mortar with recycled ceramic aggregate.

Compared to natural aggregate, recycled ceramic aggregate has obvious different characteristics of low density, high porosity and high abrasion resistance etc. There is a big gap on behavior of concrete that incorporate ultra-fine sand and recycled ceramic aggregate acting as both fine and coarse aggregate. This article analyze the effect of the partial replacement of natural aggregate with recycled ceramic aggregate combining ultra-fine sand on the compressive strength of concrete. And the experiment was carried on to research the effect of the variation of replacement ratio of recycled ceramic aggregate on compressive strength of recycled ceramic mixed aggregate concrete (RCMC).

**EXPERIMENTAL PROGRAM**

**Materials.** Aggregate used in this experiment was composed of two fractions, the coarse fraction (4.75/31.5 mm) and the fines (0/4.75 mm). Waste ceramic was crushed with a jaw crusher and sieved to obtain the 0/9.5mm fraction as recycled ceramic aggregate, in which recycled ceramic coarse sand (RCCS, particles under 4.75 mm) were mixed with ultra-fine sand with different proportion to prepare recycled ceramic mixed sand (RCMS), fractions with the size of between 4.75mm and 9.5mm was used to completely replace the same size particles of crushed stone. Physical properties of fine aggregate are given in Table 1. The sieving results of fine aggregate are shown in Table 2. PO 42.5 cement produced by Mengdian Cement Co. Ltd. in Henan, was used in the fabrication of the test samples. The physical and mechanical properties of cement are listed in Table 3.

**TABLE 1. PHYSICAL PROPERTIES OF FINE AGGREGATE.**

| Sand sample | Apparent density [kg·m⁻³] | Loose piled density [kg·m⁻³] | Compact piled density [kg·m⁻³] | Moisture [%] | Water absorption [%] |
|-------------|---------------------------|-----------------------------|-----------------------------|--------------|----------------------|
| Ultra-fine sand | 2830 | 1450 | 1590 | 0.2 | 0.5 |
| RCCS | 2490 | 1060 | 1100 | 0.1 | 6.3 |

**TABLE 2. SIEVING RESULTS OF FINE AGGREGATE.**

| Sand sample | Add up stay percent [%] | 4.75mm | 2.36mm | 1.18mm | 0.6mm | 0.3mm | 0.15mm | Fineness modulus |
|-------------|-------------------------|--------|--------|--------|-------|-------|--------|------------------|
| Ultra-fine sand | 0.0 | 0.0 | 0.0 | 0.9 | 39.2 | 86.0 | 1.26 |
| RCCS | 0.2 | 57.9 | 78.8 | 92.1 | 98.6 | 99.3 | 4.26 |

**TABLE 3. PHYSICAL AND MECHANICAL PROPERTIES OF CEMENT.**

| Soundness | Specific surface [m²·kg⁻¹] | Setting time [min] | Compressive strength [MPa] | Flexural strength [MPa] |
|-----------|---------------------------|-------------------|---------------------------|------------------------|
|           |                          | Initial time | Final time | 3d | 28d | 3d | 28d |
| Pass      | 380                      | 156 | 209 | 25.9 | 50.7 | 4.7 | 7.8 |
**Experimental method.** The concrete samples are sized at 150mm×150mm×150mm. The compressive strength of concrete was tested according to GB/T 50081-2002 standard for test method of mechanical properties on ordinary concrete.

**EFFECT OF PERCENTAGE OF RCCS IN RCMS ON COMPRESSIVE STRENGTH OF RCMC**

Percentage of RCCS in RCMS has important effect on RCMC, it determents the gradation and the average particle size of aggregate, and it also has an impact on particle shape and surface morphology of RCMS. Therefore, experimental study on compressive strength of concrete with RCMS as fine aggregate and partial substituting recycled ceramic coarse aggregate for crushed stone as coarse aggregate was carried out. In term of experimental results, adjustment coefficient of RCMS which reflects the effect of different composition of fine aggregate on concrete strength was proposed.

Mix proportion the design strength of concrete is C30. Eight concrete mixes were prepared for this study: a reference concrete, NF, and seven recycled concretes, RF-20 to RF-80, having ultra-fine sand replacements by RCCS of 20 to 80 wt. %, with an increment of 10%. In view of RCCS has the feature of high water absorption, outside the free water, the absorbed water which would absorbed completely by recycled ceramic aggregate was added to the mixing water. And similar concrete slump values (55/65mm) were got by adjusting water dosage. Table 4 gives the batching for the concretes used.

**TABLE 4. MIX PROPORTION OF CONCRETE.**

| Sample number | Cement [kg·m⁻³] | Fine aggregate[kg·m⁻³] | Coarse aggregate[kg·m⁻³] | Water[kg·m⁻³] |
|---------------|-----------------|------------------------|--------------------------|--------------|
|               | Natural medium sand | Ultra-fine sand | RCCS | Crushed stone | Crushed stone | RCCA | Free water | Absorbed water |
| NF            | 361             | 636 | - | 1208 | - | 1208 | - | 195 | 0 |
| RF-20         | 361             | - | 509 | 127 | - | 966 | 242 | 195 | 8 |
| RF-30         | 361             | - | 445 | 191 | - | 966 | 242 | 195 | 11 |
| RF-40         | 361             | - | 382 | 254 | - | 966 | 242 | 195 | 15 |
| RF-50         | 361             | - | 318 | 318 | - | 966 | 242 | 195 | 19 |
| RF-60         | 361             | - | 254 | 382 | - | 966 | 242 | 195 | 22 |
| RF-70         | 361             | - | 191 | 445 | - | 966 | 242 | 195 | 26 |
| RF-80         | 361             | - | 127 | 509 | - | 966 | 242 | 195 | 30 |

Note: Natural medium sand has good graduation; RCCS is the abbreviation for recycled ceramic coarse sand; RCCA is the abbreviation for recycled ceramic coarse aggregate.

Experimental results of the 28-day concrete compressive strength are presented in Fig. 1.

**Figure 1.** Effect of RCCS content on compressive strength of concrete.
Results indicate that compressive strength of RCMC did not change significantly with the increasing of the RCCS content, when absorbed water was added in the mixing water. However, it is higher than that of ordinary concrete. The optimal percentage of RCCS in RCMS was between 50% and 60%, which could increase the compressive strength of RCMC by 8.19% to 8.44% than that of reference concrete.

The above mentioned results related to the variation of RCMS properties, such as gradation, average particle size, average water absorption, the shape and surface roughness of aggregate etc., when the percentage of RCCS is different. Especially when the percentage of RCCS was between 50% and 60%, the gradation and average particle size are optimized [9]. The reason why strength of RCMC was higher than that of reference concrete may attribute to the following factors: Firstly, RCCS has irregular shape and rough surface, which could enable good mashing effect between aggregate and hardened cement paste. Secondly, ceramic micro powder generated during the fragmentation processes has pozzolanic activity which could act as supplementary cementing material in RCMC. Thirdly, the effect of internal curing, due to high porosity and high water absorption of RCCS, provided guarantees for the hydration of cement and concrete strength development in the later age. And the major reason for higher strength of RCMC is that the properties of RCCS, such as high water absorption, having ceramic micro powder on surface, improved the performance of interfacial transition zone (ITZ) between aggregate and hardened cement stone. Meanwhile, the high water absorption of RCCS can reduce the effective water-cement ratio of cement paste, thereby giving higher strength of hardened cement stone. Because the performance of ITZ and the strength of hardened cement stone are weak areas in concrete which often cause the damage of concrete.

Adjustment coefficient on compressive strength. Experimental results indicate that the percentage of RCCS in RCMS is an important factor affecting the compressive strength of concrete with RCMS. The relationship between the percentage of RCCS and the compressive strength of concrete was obtained when effective cement-water ratio and all other things were equal. Thus, adjustment coefficient on compressive strength which is a function that depends on the percentage of RCCS could be introduced. Concrete construction batch strength can be expressed as:

$$f_{cu,0} = f_{cu,k} + 1.645\sigma$$

(1)

Where $f_{cu,0}$ is construction batch strength, MPa; $f_{cu,k}$ is design strength, MPa; and $\sigma$ is the standard deviations for the compressive strength of concrete. Substituting $f_{cu,k}=30$MPa, and $\sigma=5$MPa into Eq.(1), we obtain that $f_{cu,0}$ equals 38.2MPa. We define $\gamma$ as adjustment coefficient of RCMS, $\gamma$ is expressed as:

$$\gamma = \frac{f_R}{f_{cu,0}}$$

(2)

Where $f_R$ is the measured average compressive strength of 28d, MPa. Based on experimental results, the value of $\gamma$ can be calculated and listed in table 5.
Table 5. Adjustment coefficient of RCMS.

| Percentage of RCCS (p) [%] | 20  | 30  | 40  | 50  | 60  | 70  | 80  |
|---------------------------|-----|-----|-----|-----|-----|-----|-----|
| $f_{R}$ [MPa]             | 41.7| 42.9| 43.1| 43.6| 43.7| 43.2| 42.4|
| $f_{cu,0}$ [MPa]          | 38.2| 38.2| 38.2| 38.2| 38.2| 38.2| 38.2|
| $\gamma$                  | 1.09| 1.12| 1.13| 1.14| 1.14| 1.13| 1.11|

Note: $p$ represents the percentage of RCCS in RCMS.

Then regression analysis was used, and results are presented in Fig. 2.

![Figure 2](image)

Figure 2. Relationship between percentage of RCCS and adjustment coefficient.

The relationship between adjustment coefficient of RCMS and percentage of RCCS is worked out with the help of regression analysis, and expressed as follows:

$$\gamma = -0.0041p^2 + 0.0367p + 1.0601$$

(3)

Where $\gamma$ is adjustment coefficient of RCMS, and $p$ is the percentage of RCCS in RCMS, %.

CONCLUSION

Satisfied compressive strength (higher than that of reference concrete) was obtained when reusing recycled ceramic aggregate (under 9.5mm) in partial replacement of natural aggregate in the manufacture of concrete. It is feasible for using RCMS composed by RCCS and ultra-fine sand as fine aggregate, and recycled ceramic aggregate (particle size of 4.75/9.5mm) entirely displace the same particle size of crushed stone as coarse aggregate to produce concrete.

The percentage of RCCS in RCMS is an important factor affecting the compressive strength of concrete with RCMS. The optimal percentage of RCCS in RCMS was between 50% and 60%, which could increase the compressive strength of RCMC by 8.19% to 8.44% than that of reference concrete.

The adjustment coefficient of RCMS on compressive strength was introduced. An expression of the adjustment coefficient of RCMS and the percentage of RCCS is regressed and gains a good relativity. It provides reference for choosing reasonable RCCS content and estimating the strength of RCMC.

The consumption of recycled ceramic aggregate could reach 30.37% to 33.84% of total weight of aggregate in producing concrete, and this method of recycling waste ceramic is energy-saving and environment friendly.
REFERENCES

[1] Silva, J., J. de Brito, R. Veiga, Fine ceramics replacing cement in mortars partial replacement of cement with fine ceramics in rendering mortars, Mater Struct. 41 (2008) 1333-1344.

[2] Cheng Yunhong, Huang Fei, Li Guanglu, Test research on effects of ceramic polishing powder on carbonation and sulphate-corrosion resistance of concrete, Constr Build Mater. 55 (2014) 440-446.

[3] Guerra, I., Vivar I., Llamas B., et al. Eco-efficient concretes: the effects of using recycled ceramic material from sanitary installations on the mechanical properties of concrete, Waste Manage. 29 (2009) 643-646.

[4] Medina, C., M.I. Sanchez De Rojas and M. Frias, Freeze-thaw durability of recycled concrete containing ceramic aggregate, J Clean Prod. 40 (2013) 151-160.

[5] Medina, C., Frias M., et al, Gas permeability in concrete containing recycled ceramic sanitary ware aggregate, Constr Build Mater. 37 (2012) 597-605.

[6] Medina, C., M. Frias, M.I. Sanchez De Rojas, Microstructure and properties of recycled concretes using ceramic sanitary ware industry waste as coarse aggregate, Constr Build Mater. 31 (2012) 112-118.

[7] Medina, C., M.I. Sanchez De Rojas, M. Frias, Properties of recycled ceramic aggregate concretes: water resistance, Cem Concr Compos. 40 (2013) 21-29.

[8] Halicka, A., P. Ogrodnik, B. Zegardlo, Using ceramic sanitary ware waste as concrete aggregate, Constr Build Mater. 48 (2013) 295-305.

[9] Liu Fengli, Liu Junhua, Zhang Chengzhi, Modification on properties of ultra-fine sand using recycled ceramic sand, China Concr Cement Prod. 3 (2013) 79-82. (in Chinese)