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Influence of carbonated recycled concrete aggregate on properties of cement mortar

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HIGHLIGHTS

- Carbonation treatment increased the physical properties of recycled concrete aggregate (RCA).
- Mortar made with carbonated RCA exhibited better workability than the uncarbonated RCA mortar.
- Carbonation of RCA improved both original ITZ and newly formed ITZ in the RCA and RCA mortar.

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ABSTRACT

This work investigated the effect of carbon dioxide treatment of recycled concrete aggregate (RCA) on the performance of RCA and RCA mortar. The results indicated that carbonation increased the apparent density, and reduced both water absorption and the crushing value of the RCA. The flowability and compressive strength of the RCA mortar were lower than those of natural sand mortar. However, the properties of mortar made with carbon dioxide treated RCA were very similar to those of natural sand mortar. Compared with the mortar made of un-carbonated RCA, the mortar made with carbonated RCA showed increased autogenous shrinkage, reduced drying shrinkage, water absorption, and chloride migration coefficient. Scanning electron microscope (SEM) examination on the interfacial transition zone (ITZ) in the RCA and RCA mortar found that carbonation treatment of RCA not only improved the original ITZ in the RCA, but also improved the newly formed ITZ in the RCA mortar.

1. Introduction

With rapid development of economy and construction, many construction and demolition (C & D) wastes are generated and need to be treated. Due to increased landfill cost and demand of aggregates in construction, recycling and reuse of waste concrete are becoming more important for sustainable development [1,2].

Waste concretes can be used to produce recycled concrete aggregate (RCA) after crushing and sieving. However, the mechanical properties and durability of recycled aggregate concrete (RAC) were weaker than those of ordinary concrete, mainly due to the attached cement paste or the cracks formed during crushing [3–5]. Compared with ordinary concrete, the tensile and compressive strength of RAC were reduced by 40% and the drying shrinkage was increased by 60% [6,7]. Cracks were more likely to appear when concrete contained more than 50% RCA, because of the reduced tensile properties of the concrete [8]. Therefore, it is necessary to improve the properties of RCA for getting better quality recycled aggregate concrete.

Several methods for improving the properties of RCA have been proposed in literature and can be classified into two categories: (1) removing the attached mortar by ultrasonic cleaning method [9], ball-milling [10], heating the RCA and then rubbing [11], or pre-soaking the RCAs with HCl, H_2SO_4, H_3PO_4 [12] or with waterglass [13]. (2) Improving the quality of attached paste, such as surface-coating with pozzalanic materials [13,14] or polyvinyl alcohol emulsion [15]. However, each of these methods introduces some negative effects either on the material or the environment.

This work uses CO_2 to pretreat RCA for improving the properties of RCA. The principle of this idea is that CO_2 can react with the adhesived paste on the RCA to form $CaCO_3$ and silica gel. The solid volume of the adhesived paste is increased after carbonation,

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which increased the density and reduced the porosity of RCA. Shi et al. [16] proposed pre-curing technology to enhance and to accelerate CO_2 curing of concrete. After appropriate pre-curing, the strength of concrete cured with CO_2 for 2–4 h was similar to that of the concrete cured under steam for 24 h. Additionally, concrete samples cured with CO_2 demonstrated lower porosity, water absorption, and shrinkage than concrete cured under steam. Shi et al. [17] also found that increasing CO_2 concentration and pressure would accelerate carbonation and increase strength development rate of concrete. However, if the CO_2 pressure was greater than 0.5 MPa, the CO_2 curing degree and compressive strength of the CO_2 cured concrete did not show significant differences.

Carbonation of RCA not only improved the properties of RCAs, but also reduced the greenhouse effect that caused by carbon dioxide emission. Using CO_2 to treat RCA can store CO_2, which reduces the greenhouse effect. The cement industry is one of the major sources of greenhouse gases in particular with carbon dioxide emissions, which contributes about 7% to these emissions [18]. The manufacture of 1 ton cement generates about 0.79 ton carbon dioxide [19]. If those carbon dioxide can be applied for treating the RCA, it can help the cement industry to save the expenses of treating the carbon dioxide emission. This is a laboratory study on the feasibility of using carbonation treatment for improving the properties of RCA.

This work aimed at studying compressive strength, shrinkage, drying shrinkage, water absorption, and chloride ion resistance of the carbonated RCA mortars. Findings from this work provide useful information for improving the properties of recycled concrete.

2. Materials and testing methods

2.1. Raw materials

Recycled gravel concrete aggregate (G-RCA) and recycled crushed stone concrete aggregate (C-RCA) were obtained from concrete beams with the compressive strength of 30 MPa and 50 MPa, respectively. The gravel from a Xiangjiang river was crushed and used as the reference sand (NS). Both G-RCA and C-RCA were sieved to the same gradation as the reference, as shown in Table 1. P.O. 42.5 ordinary Portland cement was used in this work and the chemical composition of the cement is shown in Table 2.

2.2. Carbonation treatment of RCAs

G-RCA and C-RCA were placed in a carbonation chamber at $T = 20 \pm 2$ °C, RH = 60 ± 5%, and CO_2 concentration of 20 ± 2%. After certain period of carbonation, the RCA was ground and spreaded evenly, and then sprayed with 1% alcohol phenolphthalein solution to differentiate the carbonated and un-carbonated portions. G-CI and C-CI stand for the carbonated recycled gravel concrete aggregate and recycled crushed stone concrete aggregate, respectively.

2.3. Mix proportions and sample preparations

The sand to cement ratio of 2.25 and water to cement ratio of 0.50 were used in preparing the mortar samples. Fresh mortar was cast in three different molds. Cube samples with the size of 40 × 40 × 40 mm were prepared for compressive strength and water absorption measurements. Mortar bars with the size of 25 × 25 × 275 mm were prepared for drying shrinkage measurement, while cylinders with the size of Φ100 × 100 mm were prepared for rapid chloride migration measurement. Fresh mortar was injected into corrugated plastic tubes of Φ20 × 345 mm for autogenous shrinkage measurement.

2.4. Testing methods

2.4.1. Physical properties of recycled concrete aggregate

Physical properties of the recycled concrete aggregate were measured in accordance with the Chinese standard JGJ/52-2006, which include density, water absorption, and crushing value.

Table 1
Gradation of the three types of aggregate.

Diameter(mm)	2.5	1.25	0.63	0.315	0.16
Cumulative residue on sieve (%)	0	15	50	85	100

Table 2
Chemical composition of ordinary Portland cement.

CaO	Al_2O_3	MgO	Fe_2O_3	SiO_2	SO_3
65.40	5.40	3.40	2.80	21.00	2.00

Apparent density. Sample was placed in an oven at 105 °C till constant mass, and then placed in laboratory condition (T = 20 °C, RH = 60%) for cooling. Put 50 g sample into a Le pycnometer which contained the volume of water V_1, and record the volume of water V_2 after placed the sample. The solid volume of sample equals to the volume change ($V_2 - V_1$) of the water in the pycnometer when the sample was placed in the pycnometer. The apparent density of the sample equals to the mass of sample divided by the solid volume of the sample ($V_2 - V_1$).

Water absorption. A 500 g oven dried sample was placed in a disk, which contains enough water to ensure the water level was 20 mm above the sample. The sample was taken out after 24 h and then dried under a fan which blows above the sample. A stick was stir on the sample to ensure the sample was uniformly dried until the saturated-surface-dry (SSD) condition was reached. A 500 g SSD sample was placed in an oven at 105 °C till m_o was reached. The water absorption w_{wa} can be determined using equation: $w_{wa} = (500 - m_o)/m_o \times 100\%$.

Crushing value. The oven dried RCA was sieved, and then a 300 g sample, which has a particular particle size, was placed into a steel mold. The mold was placed on a loading machine, loaded at the rate of 500 N/s till 25 kN, and retained for 5 s. The sample was sieved after the loading process, and the material which had the same particle size as the original sample was determined (m_i). The crushing value δ_i can be determined using equation: $\delta_i = (300 - m_i)/300 \times 100\%$.

2.4.2. Properties of fresh recycled aggregate mortar

(1) Flowability
The flowability of fresh mortar was measured using a cone with 60 mm height, 70 mm top diameter and 100 mm bottom diameter. The testing was conducted on a flow table in accordance with the Chinese standard GB/T2419-2005. The maximum diameter and the diameter perpendicular to the maximum diameter of the spread out fresh mortar were measured. The average of the two diameters was used as the flowability of the sample.

(2) Compressive strength
Fresh mortar mixtures were cast in the 40 × 40 × 40 mm cubic molds. The samples were demolded after 24 h, and then cured in lime saturated water at 20 ± 2 °C till 3, 7, 28 and 90 days for compressive strength test.

(3) Autogenous shrinkage
Autogenous shrinkage of mortar was measured using a corrugated plastic mold with the size of Φ20 × 345 mm in accordance with ASTM C1698-09. An eddy current displacement sensor was installed on the steel frame after the fresh mortar sample was filled in the corrugated plastic mold and sealed with a coil. The other end of the sample was fixed by coil springs. Two samples were prepared for each mixture. The eddy current displacement sensor records the longitudinal deformation on the free ends. A multi-channel data acquisition instrument with the measurement range of 0–4 mm, resolution of 0.5 μm, accuracy of 0.05% was used for data collection. The samples were stores in a controlled room with a temperature of 20 °C and relative humidity of 50% during the test.

(4) Drying shrinkage
Three samples with the size of 75 × 75 × 275 mm were prepared for the drying shrinkage measurement. The samples were demolded after 24 h of casting and then placed in a curing room at $T = 20 \pm 1$ °C and RH = 60 ± 2%. The initial length of the sample was recorded after the curing period, and the length of the samples were measured at 1, 7, 14, 21, 28, 35, 42, 49 and 56 days. A vertical length comparator with the accuracy of 0.001 mm was used for calibration.

(5) Water absorption of mortar
The water absorption of mortar was measured in accordance with the Chinese standard JGJ/T70-2009. Samples were removed from the curing room at 28 days, and then dried in an oven at 105 °C for 48 h. The mass of the samples was measured after they reached room temperature, and then they were placed in a water bath which filled with water at 20 ± 2 °C for two days. The top surface of the samples was at least 20 mm below water. Samples were taken out from the water bath and wiped with a filter paper to remove the surface water and then weighed. The water absorption of the samples equals to the mass change of the sample before and after placed in the water bath.

(6) Rapid Chloride Migration (RCM) testing
The central portion of the Φ100 × 100 mm cylinders was cut into slices with the thickness of 50 ± 2 mm, and then cured in curing room at $T = 20 \pm 2$ °C and RH ⩾ 98% for 35 days. The finished surface of the sliced samples was exposed to chloride solution. After that, the specimens were cured in water for another 7 days. The excess water on the sample was wiped off with a brush. The thickness of the sliced samples was measured