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PERFORMANCE ENHANCEMENT OF RECYCLED FINE AGGREGATES THROUGH CARBONATION

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To solve the problem of performance degradation of recycled fine aggregate (RFA), this paper adopted accelerated carbonation with saturated lime water solution (CH) pre-soaking, the crushing value, water absorption rate and apparent density were investigated. The carbonation products and microstructure were characterised by thermal analysis (TG), X-ray diffraction, and scanning electron microscopy (SEM). The results indicate that the calcite produced by the accelerated carbonation is closely packed and filled in the microcracks in the RFA, which reduces its water absorption and crushing value, and increases its apparent density; the RFA pre-treated with the CH solution had a higher CO_2 mass absorption rate. Accelerated carbonation can effectively improve the compressive strength of recycled mortar, but it will reduce the flowability of recycled mortar.

INTRODUCTION

In recent years, with the development of urbanisation and industrialisation, more than five billion tonnes of clay, sand, stone, and other materials are used in the production of cement and concrete every year in China [1], resulting in a large amount of environmental and construction waste resources. On the one hand, the increasing shortage of natural aggregate resources makes it difficult to meet the market demand. On the other hand, about two billion tonnes of waste concrete are produced in China every year [2], and the disposal method is still mainly stacking landfills.

Therefore, the resource utilisation of waste concrete needs to be urgently addressed.

Recycled aggregates are aggregates obtained by crushing and processing waste concrete. According to statistics [3], waste concrete used as recycled aggregate can save 61 % of the limestone resources and reduce the CO_2 emissions by 15 – 20 %. Compared with natural aggregate, recycled aggregate is characterised by high water absorption, high porosity, and a high pressure crushing index due to the accumulation of internal damage caused by the crushing stage and the adhesion of a large amount of cement mortar to the aggregate itself [4]. Related studies [5,6] show that the water absorption rate of recycled aggregate can reach 2.3 – 4.6 times that of natural aggregate, and the crushing value can reach 1.33 – 1.45 times that of natural aggregate. As a result, concrete prepared from recycled aggregates also suffers from mechanical and durability deterioration. Li Qiuyi et al. [7,8] found that the recycled fine aggregate (RFA) replacement rate should be 30 % at most, and the RFA replacement rate should not exceed 50 % when preparing low-strength concrete. Silva et al. [9] found that when the recycled coarse aggregate (RCA) replacement rate is less than 30 %, the dry shrinkage performance of recycled concrete is similar to that of natural concrete. The dry shrinkage rate increases sharply when the replacement rate reaches 100 %.

Numerous experts and scholars have carried out research on strengthening recycled aggregates to improve the performance of recycled aggregates and promote their practical application. At present, there are two main strengthening methods – the removal of the surface attachment mortar and the reinforcement of the surface attachment mortar. Therefore, numerous experts and scholars have studied mechanical grinding, acid treatment, polymer emulsion soaking, ash slurry treatment, water glass treatment, and different methods to help with the strengthening. However, these methods are, in general, very limited. Mechanical grinding consumes a great deal of energy and requires costly equipment. The acid therapy requires the strict control of the solution concentration and strict limits on the amount of calcium that can be recycled into the aggregates; polymer emulsions and pozzolanic slurry

immersion methods are costly and prone to environmental contamination. Therefore, the regenerative aggregate strengthening technique needs to be further investigated.

In recent years, some researchers [10, 11] have found that using carbon dioxide (CO_2) to carbonise recycled aggregate rapidly can effectively improve the physical properties of recycled aggregate. The carbonation process is based on the chemical reaction between CO_2 and cement-hydrated products and cement clinker minerals: CO_2 dissolves in the pore solution within the recycled aggregate matrix and reacts with calcium hydroxide ($Ca(OH)_2$, CH) and calcium silicate hydrate (C-S-H) to form calcium carbonate ($CaCO_3$) and silica gel that fill the pores of the recycled aggregate. The reaction equations are as follows:

Relevant studies [12] have shown that the two

$$Ca(OH)_2+CO_2 \rightarrow CaCO_3+H_2O \quad (1)$$

$$C\text{-}S\text{-}H+ CO_2 \rightarrow CaCO_3+SiO_2 \cdot nH_2O \quad (2)$$

can increase the solid phase volume of recycled aggregate by 11.5 and 23.1 %, respectively. Researchers [10,11] found that the carbonation treatment can effectively reduce the water absorption and crushing index of recycled fine aggregate, and increase the apparent density. Xuan [13, 14] found that the use of recycled fine aggregate carbide (carbonised recycled fine aggregate, CRFA) to replace natural fine aggregate (NFA) can increase the substitution rate to 60 %, while the strength of recycled concrete does not significantly decrease. In addition, carbonised recycled fine aggregate improved the durability of the recycled concrete more significantly than the NFA, and its overall conductivity, chloride ion permeability and gas permeability improved by 15.1, 36.4 and 42.4 %, respectively. Shi [15] found that carbonation can also improve the flowability and mechanical properties of recycled.

Zhan [16] et al. pre-soaked and then carbonised RFA with three different calcium source solutions, including calcium chloride, calcium nitrate, and calcium hydroxide. They found that the water absorption rate, powder content and crushing value of RFA were significantly reduced, and the compressive strength of the recycled mortar was increased by 56 %. Pan et al. [17] adopted a CH solution for pre-soaking in the test, and the results showed that after carbonation of the RFA with the CH solution pre-treatment, the physical properties of the aggregate were significantly improved, the compressive strength and flowability of the recycled mortar were improved, and the porosity of mortar was significantly refined. Kou [11] et al., and Zhan [18] et al. carried out pressurised carbonation of RCA when the CO_2 concentration was 100 %, and found that the smaller the particle size of the recycled aggregate, the more obvious the carbonation improvement.

It can be seen that different accelerated carbonation methods are the main factors affecting the performance of recycled aggregates to improve the CO_2 carbonation. RFA has a tiny grain size, a large specific surface area, and an additional adhesion mortar on the surface that can absorb additional Ca^+ after pre-processing. Researchers can fully exploit the carbonation potential of RFA to prepare the carbonised mortar and, therefore, facilitate engineering applications, which not only valorises the recycling of building materials, but also reduces CO_2 emissions and alleviates the greenhouse effect. In addition, about 40 % of recycled fine aggregate and recycled fine powder will be produced in the process of mechanical crushing and grinding of recycled aggregate [19], which have caused great pollution due to the lack of suitable treatment methods in the past. The carbonation treatment of RFA can improve the underutilisation of waste concrete. In addition, future application research on recycled aggregate should focus on fully recycled concrete that uses recycled coarse aggregate, recycled fine aggregate and recycled fine powder at the same time [20], as the carbonation of RFA is conducive to the development of research on carbonised entirely recycled concrete and entirely recycled mortar.

The purpose of this study is to adopt different accelerated carbonation methods (direct carbonation under a 100 % CO_2 concentration and a 0.3 MPa carbonation pressure; after pre-treatment with a CH solution, carbonation at a 100 % CO_2 concentration and a 0.3 MPa carbonation pressure) on the water absorption, crushing value, apparent density of the RFA, and the flow and mechanical properties of the mortar made with RFA.

EXPERIMENTAL

Test material and matching ratio

In this study, recycled fine aggregate with a particle size below 4.75 mm was obtained by artificial crushing and sifting, using discarded beams from Henan Polytechnic University as the original concrete.

Testing method

Two carbonation methods were used in this experiment. Carbonised recycled fine aggregates are recorded as CRFA1 after immersion in clean water. The recycled fine aggregates were first immersed in clean water for 24 hours, and then gently blown by a hair dryer until the saturated surface was dry before the carbonation began. The recycled fine aggregate carbonised after immersion in a saturated calcium hydroxide solution was recorded as CRFA2 and the CH solution was prepa-

red from quicklime. The recycled fine aggregates were first immersed in the CH solution for 24 h, and then gently blown by a hair dryer until the saturated surface was dry before the carbonation began.

Table 1. Details of all the mix proportions ($kg \cdot m^{-3}$).

Group	Cement	NFA	RFA	Water
NM	3.354	24.057	0	3.324
RM30	3.354	16.84	7.217	3.324
RM50	3.354	12.029	12.029	3.324
RM70	3.354	7.217	16.84	3.324
RM100	3.354	0	24.057	3.324
CRM30	3.354	16.84	7.217	3.324
CRM50	3.354	12.029	12.029	3.324
CRM70	3.354	7.217	16.84	3.324
CRM100	3.354	0	24.057	3.324

Note: NM is natural mortar; RM is recycled mortar; CRM is carbonised recycled mortar.

The carbonation device is shown in Figure 1. The reactor is an airtight cylindrical vessel with a volume of about 50 L. The test material was pre-soaked and treated for 24 h until the saturated surface was dry before being placed in the reactor. The temperature in the reactor is 20 ℃ and the humidity is 70 %. The carbonation pressure is controlled by a regulator. During the carbonation process, the gas pressure was maintained at 0.3 MPa, the carbonation time was 24 h, and the carbonation temperature was 20 ± 2 ℃.

Figure 1. The carbonation device.

In addition, according to GB/T14684-2011 and JGJ/T70-2009, the water absorption, crushing value, apparent density, consistency and compressive strength of the recycled fine aggregate were determined. This test was divided into 9 groups according to different treatment methods and different substitution rates. Each group contained 12 compressive strength test blocks (70.7 × 70.7 × 70.7 mm). Recycled mortar test blocks that were cured to the corresponding age were removed from the standard curing chamber and wiped with a wet towel until clean. The test block was placed on the pad of the press, the position was adjusted until the centre was aligned, the loading speed was 1 $kN \cdot s^{-1}$, and the failure load of the test block was recorded. The arithmetic mean of the three test blocks was calculated and used as the compression intensity of the mortar cube.

RESULTS AND DISCUSSION

Physical properties

The physical properties of CRFA1 and CRFA2 were determined after 24 h of CO_2 carbonation and are shown in Table 3. Before carbonation, the water absorption, crushing value and apparent density of recycled fine aggregates were tested according to GB/T14684-2011, as shown in Table 2.

A thermal analysis test was performed on the RFA before carbonation, as shown in Figure 2, where the decomposition temperature of $Ca(OH)_2$ was set at 430 – 550 ℃. Zhang et al. [21] found that even after the recycled aggregate is fully carbonised, there is still about 1.83 % $Ca(OH)_2$ residue in its attached mortar. Pan et al. [17] conducted a Thermogravimetric (TG) analysis on the RFA stored one year after crushing, and measured that the mass content of $Ca(OH)_2$ was 1.57 %. In this test, the mass content of $Ca(OH)_2$ in the RFA adhesion mortar is 2.67 %.

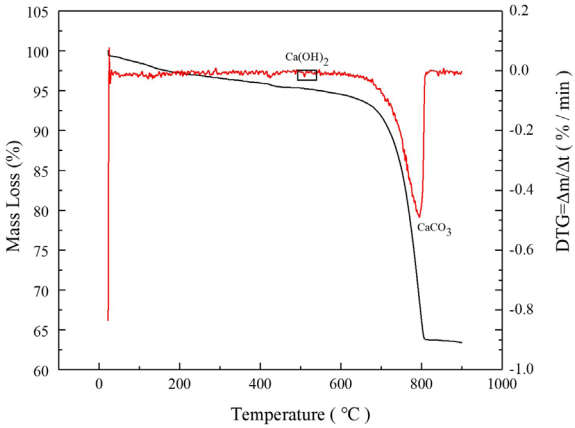


Figure 2. TG-DTG of the RFA.

According to Tables 1 and 2, CRFA1 shows an 8.7 % decrease in the water absorption, a 7.3 % decrease in the crushing value, and a 1.7 % increase in the apparent density compared to the RFA. CRFA2 shows a 17.9 % reduction in the water absorption, a 7.5 % decrease in the fragmentation value, and a 2.1 % increase in the apparent density.

This is mainly due to the carbonation reaction of the CO_2 gas with C-S-H and $Ca(OH)_2$ in the RFA adhesion mortar to produce $CaCO_3$ and silica gel, which

Table 2. Physical properties of the RFA.

water absorption %	crushing value %	apparent density kg·m^{-3}
7. 8	42.8	2584

Table 3. Physical properties of the CRFA.

water absorption %		crushing value %		apparent density kg·m^{-3}	
CRFA1	CRFA2	CRFA1	CRFA2	CRFA1	CRFA2
7.1	6.4	39.7	39.6	2627	2639

can increase the solid phase volume by 11.5 – 23.1 % [12], and the carbonation products can fill the pores and internal micro-cracks of the RFA adhesion mortar. Zhan et al. [18] showed that the water absorption of RCA with different strength grades of the base material significantly decreased after carbonation, while the apparent density slightly increased without any significant change. Zhang [22] et al. determined that the water absorption of recycled gravel aggregate and recycled pebble aggregate after carbonation decreased by 22.6 – 28.3 %, and the crushing value decreased by 7.6 – 9.6 %, which was mainly consistent with the test results. After carbonation, the water absorption rate and crushing value of the RFA significantly decrease, possibly because the RFA has a smaller grain size and larger specific surface area, reacts more fully with CO_2, and the pores of the attached mortar and internal microcracks are more easily blocked by the carbonised product. In addition, the initial water absorption rate and crushing value of the RFA are lower; hence, the CRFA has a significantly lower water absorption rate and crushing value.

Effect of pre-soaking on the carbonation

Since the storage time of the RFA in practical applications is typically extremely long, the amount of material involved in the carbonation reaction in the aggregate is very low, which limits the performance of the conventional carbonation enhancement. Previous studies [16, 17, 24] have proved that pre-soaking the calcium hydroxide (CH) solution before aggregate carbonation can effectively improve the carbonation effect.

As can be seen from Table 3, the performance of CRFA1 directly cured with CO_2 is not as improved as CRFA2 overall, with a 0.3 % reduction in the value of fragmentation and a 9.9 % decrease in the water absorption, and a 0.5 % increase in the apparent density. These results differ from those found by Pan et al. [17] because the storage time of the RFA and the original concrete strength grade are different. The properties of the RFA treated with the CH solution before CO_2 curing were significantly improved, with significantly lower values for the fragmentation and water absorption. This is because the addition of the CH solution increases the Ca^{2+} content involved in the carbonation reaction and promotes the formation of $CaCO_3$ during the carbonation process. The generated $CaCO_3$ refines the pore structure and produces a micro-filling effect on the RFA [17], reduces the crushing value and water absorption.

CO_2 absorption rate

Figure 3 shows the TG images of CRFA1 and CRFA2, which are used to study the effect of the CH pre-soaking on the carbonised RFA. The mass loss caused by the increasing temperature of the attached mortar can be divided into three stages, in which the decomposition temperature of $Ca(OH)_2$, $CaCO_3$ crystals with poor crystallisation and $CaCO_3$ crystals with a superior crystallisation degree is 430 – 550, 550 – 750 and 750 – 950 ℃, respectively [25,26]. Gao Yueqing [27] found, in his study, that when the temperature was higher than 800 ℃, the thermogravimetric properties of CRCA and RCA remained essentially unchanged, and the CO_2 mass absorptivity β of the RCA was calculated based on the mass loss within 550 – 800 ℃. In this study, the CO_2 mass absorption rate β of the RFA was calculated using the mass loss at 550 – 810 ℃, and the calculation formula is shown in Equation 3.

$$\beta = \frac{m_{550} - m_{810}}{m_{150} - (m_{550} - m_{810})} \times 100\% \quad (3)$$

Where: β is the mass absorption rate of CO_2; m_{150} is the mass of the sample at 150 °C; m_{550} is the mass of the sample at 550 °C; m_{810} is the mass of the sample at 810 °C.

The degree of carbonation reaction correlates with the improvement in the physical properties of the RFA. As shown in Tables 1 and 3, the apparent density and fragmentation values do not significantly increase before and after the carbonation due to the large initial values. Therefore, this part will be used to study the relationship between the CO_2 mass absorption rate β and the water absorption rate of CRFA after the carbonation treatment, as shown in Table 4.

Table 4. Water absorption and CO_2 absorption rate (β) of CRFA.

	CRFA1	CRFA2
β (%)	48.9	52.9
water absorption (%)	7.1 (↓10.7 %)	6.4 (↓12.1%)

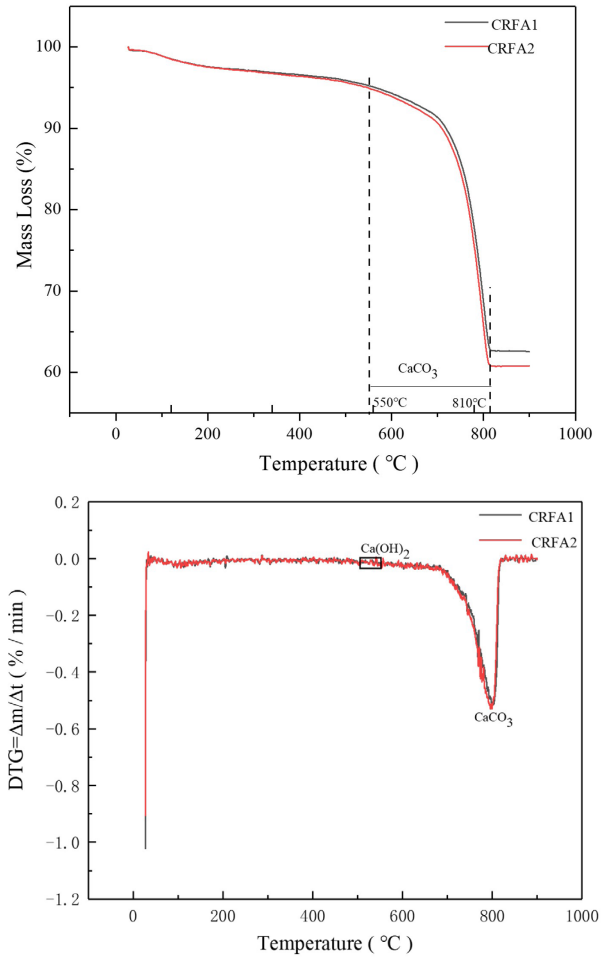


Figure 3. TG-DTG curve of CRFA1 and CRFA2.

As shown in Table 3, the CO_2 absorption rate β of CRFA1 and CRFA2 was 48.9 and 52.9 %, respectively, and the CO_2 absorption rate β of RFA after the CH pre-soaking increased by 8.2 % compared with CRFA1. This trend is consistent with the decrease in the water absorption in the CRFA compared to the RFA, with the water absorption in CRFA1 and CRFA2 decreasing by 10.7 and 12.1 %, respectively. This is because the addition of the CH solution increases the Ca^{2+} content involved in the carbonation reaction and promotes the formation of $CaCO_3$ during the carbonation process.

Effect of carbonation on the microscopic properties of RFA

XRD

Figure 4 shows the XRD pattern before and after the different carbonation treatments. As can be seen from Figure 4, calcite appears in the attached mortar sample before carbonation (23 – 65°). On the one hand, this may be due to the carbonation reaction between some CH in the attached mortar and CO_2 in the air when the recycled fine aggregate is placed and broken. On the other hand, the original concrete used in this test was in a machine-made sand configuration. Its main component is $CaCO_3$, with a large amount of calcite in the XRD mode. It may also be for this reason that the difference between the XRD patterns before and after the different carbonation methods is not apparent.

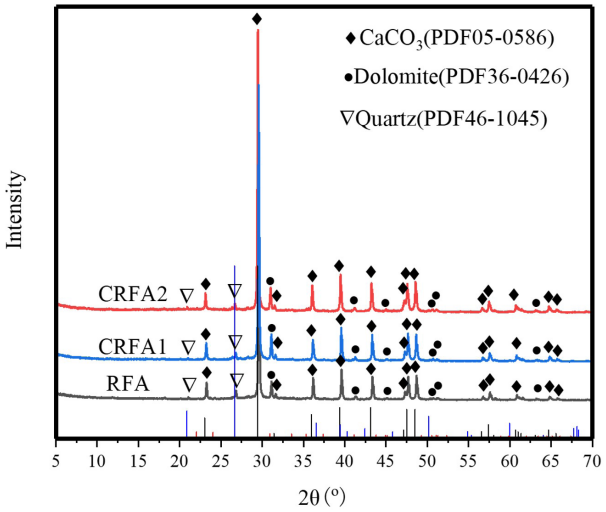


Figure 4. XRD patterns of the RFA.

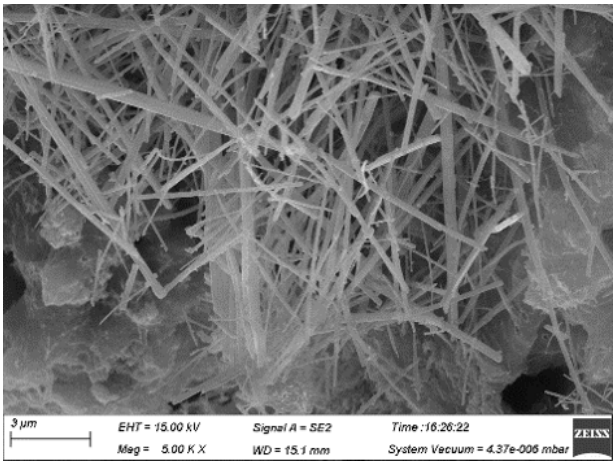
Compared with the samples without the carbonation treatment, the characteristic peaks of calcite at 35.9, 39.4 and 43.1° after carbonation are slightly enhanced, which is due to the $CaCO_3$ produced during the carbonation process. V. Shahah et al. [28] found that at low CO_2 concentrations, $CaCO_3$ formed by carbonation mainly consists of three crystal phases: calcite, aragonite and chondrocranium. However, the XRD pattern currently tested did not detect aragonite and chondrocranium as this test was conducted by a prolonged-term reaction at elevated CO_2 concentration, which is consistent with the study of Guo Hui [29].

The results show that the pre-soaking treatment can promote the carbonation reaction, generate additional $CaCO_3$ to fill the pores and micro-cracks of the RFA, and improve the performance of the RFA. At a concentration of 100 % CO_2 for 24 h, the main crystalline phase of $CaCO_3$ is calcite.

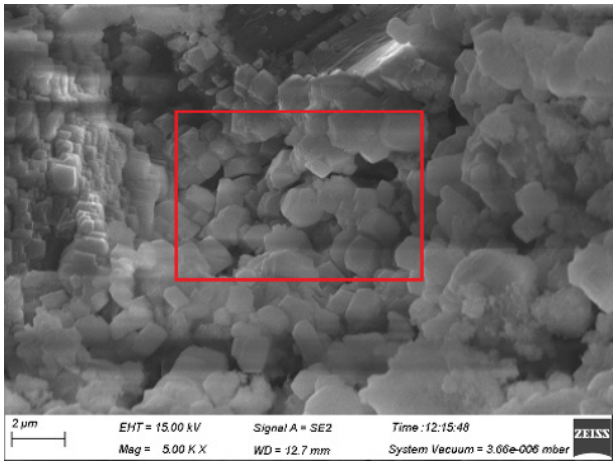
SEM

In order to further understand the effect of the carbonation treatment on the microstructure of the RFA, SEM observations of the microstructure of the RFA before and after carbonation were performed and the results are shown in Figure 5.

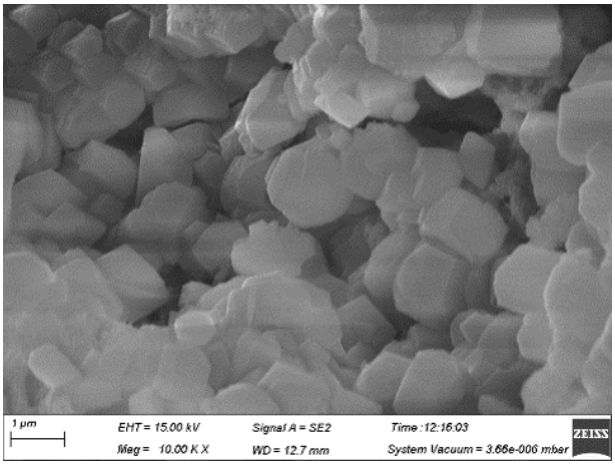
Figure 5a and 5b show the morphological features of the interfacial transition zone of the RFA before and after carbonation, respectively. The typical hydration product ettringite (Aft) can be observed before carbonation, and loose needle-rod structures can be formed on the surface of RFA (Figure 5a). After carbonation, the hydration product reacts as a large



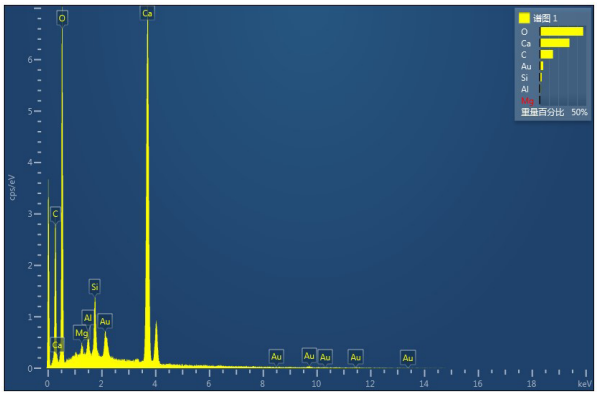
a) Uncarbonised RFA hydration product Aft



b) CRFA carbonation product calcite



c) Carbonated product



d) EDS of the carbonated product

Figure 5. The SEM and EDS images.

amount of carbonate fills the RFA pores and covers the surface. Continuing to zoom in to 10,000 times to obtain Figure 5c, it can be found that the carbonised products mainly appear as cubic crystals. An EDS analysis was performed and the results shown in 6d indicate that the material is a CaCO3 crystal with calcite as its main crystalline phase. In addition, Guo Hui [29] found that the carbonation product CaCO3 is frequently covered or wrapped around silica gel, so a tiny amount of the Si elements in the EDS in this test may come from the silica gel. Therefore, after carbonation, a large amount of calcite is deposited in the microcracks of the RFA, making its microstructure denser and improving its physical properties.

Effect of the CRFA on the physical properties of the recycled mortar

Effect of the CRFA on the consistency of the recycled mortar

According to previous aggregated tests, the performance of CRFA2 is stronger than that of CRFA1, so CRFA2 was used in the mortar test blocks. Figure 6 shows the consistency of the recycled mortar with different replacement levels before and after carbonation, with the natural mortar having a consistency of 62 mm. Figure 6 shows that the consistency of the recycled mortar decreases with a higher replacement level of the recycled aggregate compared to the natural mortar. With a 100 % replacement rate, the RM100 mortar has a consistency of 27 mm, which is 56.5 % lower than the natural mortar. It can be seen that the recycled mortar content decreases the flow properties of the recycled mortar and gradually decreases as its content increases. This is because recycled fine aggregates are mainly composed of an adhesive mortar with strong water absorption and natural aggregates with a large number of micro-cracks inside, and the water absorption of the recycled fine aggregates will be significantly increased due to the high porosity. In addition, the surface of the recycled fine aggregate is rougher and more angular compared to the natural fine aggregate, resulting in greater friction between the aggregate and the cement paste in the newly mixed mortar, which significantly reduces the consistency of the recycled mortar.

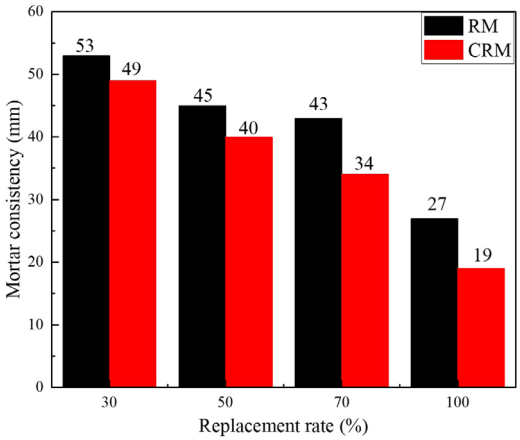


Figure 6. Consistency of the recycled mortar with different replacement rates before and after carbonation.

In addition, Figure 6 shows that the coherence of the recycled fine aggregates decreases significantly after the carbonation treatment, and the decrease is more pronounced for larger replacement levels. The consistency of the carbonised recycled mortar was reduced by 20.9 and 29.6 % when the replacement rate was 70 and 100 %, respectively. However, Pan et al. [10] used carbonised recycled fine aggregate to prepare recycled mortar, and found that the consistency of mortar was significantly reduced and the flow performance was considerably enhanced. This is due to the differences in the composition and strength grade of the original concrete material, the content of the fine powder in the recycled aggregate obtained from crushing is diffe-rent, and the $Ca(OH)_2$ and C-S-H components involved in the carbonation reaction are different. An increase in the C-S-H content will result in the growth of the carbonised silica gel. Xiao [30] et al. used carbonised micro-powder to prepare a cement slurry, and the research results show that the flow performance of the cement slurry prepared by carbonised micro-powder is considerably reduced because it contains a large amount of extremely hydrophilic silica gel. In this experiment, on the one hand, the recycled fine aggregate is graded continuously and includes a large amount of recycled fine powder. On the other hand, the experiment uses pressurised carbonation, which is more complete in the treatment of recycled fine aggregates. As a result, large amounts of $CaCO_3$ and amorphous silica gel are produced during the carbonation process, and the strong hydrophilicity of the silica gel results in a significant decrease in the consistency of the carbonised recycled mortar.

Effect of the CRFA on the compressive strength of the recycled mortar

As can be seen in Table 5, the 3, 7, 14 and 28 d compressive strength of CRM30 increased by 1.3, 3.2, 7.8 and 11.1 %, respectively, when the replacement level was 30 % compared to natural mortar, and its compressive strength was the highest in the whole range of ages. At a replacement rate of 50 %, CRM50's 3 and 7 d compressive intensities decreased by 10.9 and 11.2 %, respectively, while the 14 and 28 d compressive intensities increased by 1.7 and 1.2 %, respectively. At a replacement rate of 70 %, CRM70's 3 and 7 d compressive intensities are reduced by 8.7 and 5.9 %, respectively, and the 14 and 28 d strength increased by 5.4 and 10 %, respectively. The 3, 7, 14 and 28 d strength of the CRM100 was reduced by 30, 20.5, 15.5 and 7.6 %, respectively, when the replacement level was 100 %, giving it the lowest compressive strength in the entire range.

Figure 7 shows a comparison of the carbonised recycled mortar and untreated recycled mortar at an age of 3, 7, 14 and 28 d at the same replacement rate.

It can be seen from Figure 7 that, compared with the recycled mortar, the compressive strength of the carbonised recycled mortar is mostly improved (at 3, 7, 14 and 28 d). When the replacement rate is 70 %, the compressive strength shows the most noticeable improvement, and the increase is 49.7 % at an age of 7 days. This is consistent with the study of Zhan et al. [16], who pre-soaked and carbonised RFA with three different calcium source solutions including calcium chloride, calcium nitrate and calcium hydroxide, and found that the water absorption rate, powder content and crushing value of the RFA were significantly reduced, and the compressive strength

Table 5. Compressive strength of the recycled mortar with the different replacement levels before and after carbonation.

Test number	Replacement rate (%)	Compressive strength (MPa)			
		3d	7d	14d	28d
NM	0	11.03	14	14.8	17.1
RM30	30	10.04	12.9	14.85	17.8
RM50	50	8.65	10.8	12	15.1
RM70	70	8.47	8.8	11.4	15.05
RM100	100	9.57	10.37	12.3	15.3
CRM30	30	11.17	14.45	15.95	19
CRM50	50	9.83	12.43	15.05	17.3
CRM70	70	10.07	13.17	15.6	18.8
CRM100	100	7.73	11.13	12.5	15.8

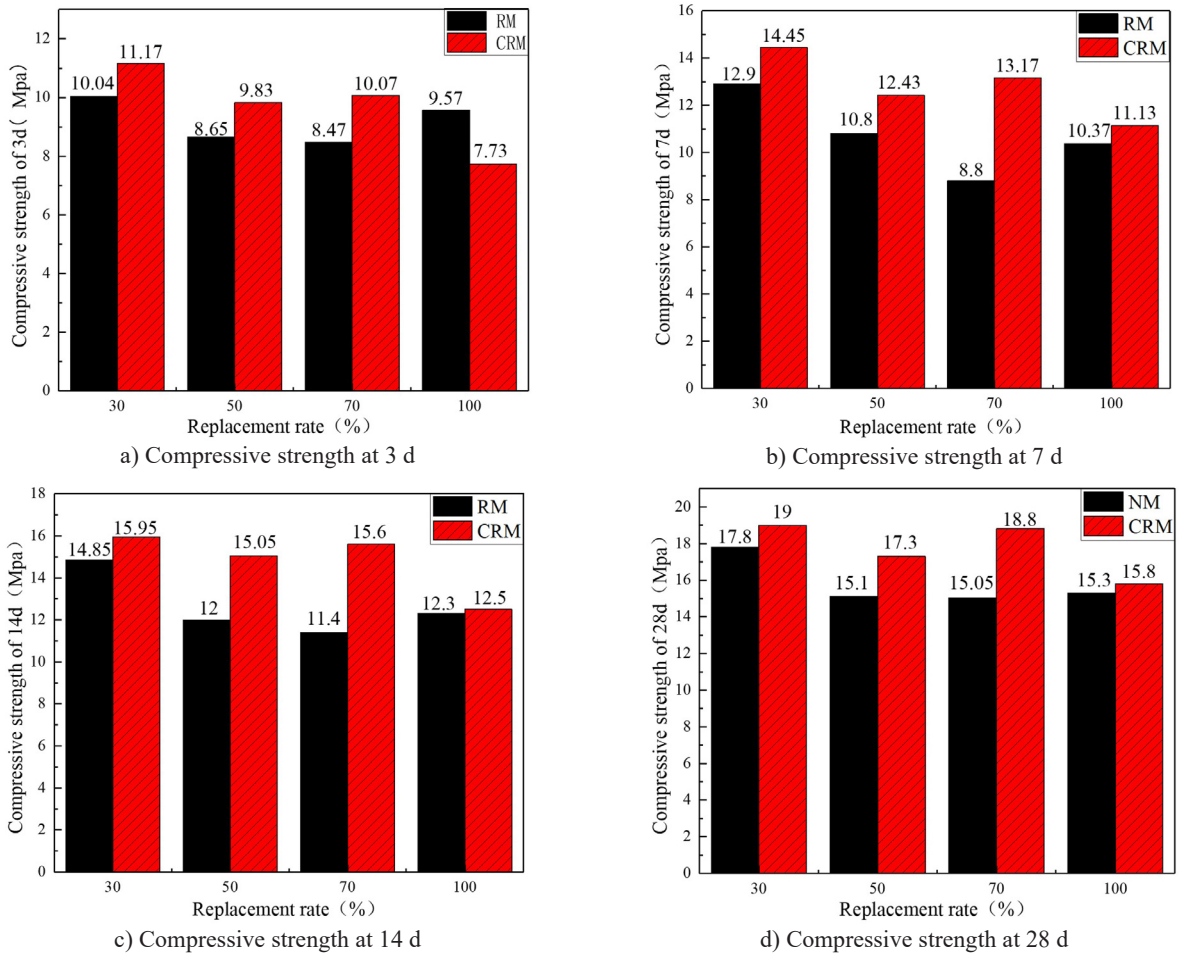


Figure 7. Compressive strength of the recycled mortar with the different replacement rates before and after carbonation.

of the recycled mortar was increased by 56 %. This is because, after carbonation of the recycled fine aggregate, the CO_2 reacts with the $Ca(OH)_2$ and C-S-H in the aggregate, and the $CaCO_3$ and silica gel generated are deposited in the micro-cracks and interfacial transition zone in the aggregate, improving the mechanical strength of the recycled fine aggregate; in addition, in the mortar preparation process, due to the strong hydrophilic water absorption and dissolution of silica gel, the local water-cement ratio is reduced [30], and part of the carbonation product $CaCO_3$ becomes the nucleation site of C-S-H to promote the formation of C-S-H [31]. Under the combined action of the above factors, the compressive strength of the carbonised recycled mortar is enhanced.

CONCLUSIONS

The present paper focused on the influence of the carbonation mode on the microstructure, as well as the physical and mechanical properties of the RFA concrete. The following conclusions were drawn.

(1) The carbonation treatment effectively improves the physical properties of the recycled aggregates, and the RFAs with higher carbonation after pre-treatment with CH solution have CO_2 mass absorption rates of up to 52.9 %. The improvement in the water absorption and crushing values is better than that of direct carbonation.

(2) At a 100 % CO_2 concentration, a 24 h carbonation treatment will convert the crystalline phase of the carbonised product $CaCO_3$ into tightly packed calcite, which is embedded with silica gel to jointly fill the internal microcracks of the RFA.

(3) The addition of RFA decreases the consistency of the RM and the carbonation treatment can further reduce the consistency of the RM.

(4) Compared with the RM, the compressive strength of the CRM is mostly improved (at 3, 7, 14 and 28 d), and when the replacement level is 70 %, the compressive strength shows the most obvious improvement, and the increase is 49.7 % at and age of 7 d.

In addition, as the CO_2 gas strengthens the RFAs, a fraction of the CO_2 gas remains, reducing thus the essentiality of the aggregates. If used in reinforced concrete components, questions about whether the CRFA accelerates the corrosion of steel rods and its long-term effects on the mechanics and durability of concrete materials needs to be further investigated.

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