

# Effect of recycled coarse aggregates enhanced by CO<sub>2</sub> on the mechanical properties of recycled aggregate concrete

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**Abstract.** It is environmentally friendly to crush waste concrete as recycled aggregate for cyclic utilization, and it also can solve the shortage of natural aggregate. However, the performance of the recycled aggregate concrete was poor caused by the surface adhesion of old cement mortar on the aggregate and the micro crack properly generated during the crushing process. The pressure pretreatment on recycled coarse aggregate by CO<sub>2</sub> was used to improve its basic performances. The variables carbonization time (0h, 6h, 12h, 24h, 48h, 72h) and CO<sub>2</sub> carbide gas pressure (0.1MPa, 0.4MPa, 0.8MPa) were studied, and the basic properties of recycled coarse aggregate before and after carbonization were compared and analysed, and the degree of improvement on recycled aggregate concrete were also investigated to determine the optimal scheme for carbonation, which was in the container with 0.4MPa pressure for 24h. Based on the optimum carbonation scheme, the influence of recycled coarse aggregate on mechanical properties of recycled aggregate concrete was studied with the substitution rate of recycled coarse aggregate (30%, 50%, 70% and 100%) before and after carbonization respectively. The results showed that the CO<sub>2</sub> reinforced recycled coarse aggregate water absorption rate and crushing index was decreased, apparent density was increased. At the same substitution rate, the compressive strength and elastic modulus of carbonized recycled aggregate concrete was higher than that of non-carbonized recycled aggregate concrete.

## 1. Introduction

A large proportion in the solid waste is occupied by the large amount of construction waste, and it is important to reuse the building waste to achieve sustainable development. Recent years, the waste concrete has been damaged, cleaned and processed into recycled aggregate (RCA) for reuse. The attention of the environmental protection industry and the construction industry is attracted [1] because the natural aggregate cannot be recycled in a short term, while the volume of recycled aggregate accounts for 60%-75% of the total concrete volume. As a result, the recycling of waste concrete can not only solve the problem of the scarcity of resources, but also can reduce the construction waste landfill site and protect the environment. However, compared with natural aggregate, recycled coarse aggregate has the old mortar adhered to aggregate, and the interface transition zone between the adhered mortar and new mortar matrix, resulting in poor performance of recycled coarse aggregate. The apparent density of recycled aggregate is lower than that of natural aggregate by more than 10% [2], while the water absorption rate is 20 times higher than that of natural aggregate [3], and the crushing index of recycled coarse aggregate is 3.5 times higher than that of natural aggregate [4]. Thus, the mechanical properties of recycled aggregate concrete (RAC) mixed with the former are defective. Xiao [5] concluded that the strength of RAC decreased with the rate of recycled coarse



aggregate, and Chen [6] got the same conclusion. Compared with common concrete, the compressive strength of 28d cube will decrease by 19% when the replacement rate of recycled coarse aggregate is 100%. Etxeberria [7] through that the replacement rate of recycled aggregate increases, and the discreteness of compressive strength of concrete will be increased, which limits the extension and application of recycled concrete in structural engineering.

At present, many scholars at home and abroad on the strengthening of recycled aggregate related research, aggregate pretreatment methods are broadly divided into two categories, respectively, to remove the surface of old mortar and strengthen the surface of old mortar for the purpose, the recycled coarse aggregate is pretreated by using polyvinyl chloride solution [8], silica fume slurry [9], water glass solution [10], waterproof agent [11], acid solution [12]. However, after a short period of immersion or spray treatment, the solution cannot penetrate into the interior of the recycled coarse aggregate, and the treatment effect is poor, while the prolonged immersion will cause problems of mechanical performance reduction and durability.

Pretreatment of recycled coarse aggregate is a new method put forward in recent years, the use of  $\text{CO}_2$ ,  $\text{CO}_2$  and recycled coarse aggregate attached to the surface of the main group of old mortar  $\text{Ca}(\text{OH})_2$  and C-S-H reaction, resulting in more compact  $\text{CaCO}_3$  and silica gel. Research shows that [13-15] can reduce the carbonization of recycled aggregate recycled aggregate water absorption, increase the apparent density and mechanical properties of recycled aggregate concrete carbonation and chloride permeability improvement effect. This paper adopts  $\text{CO}_2$  hardening of recycled coarse aggregate, effect of carbonization time and gas pressure on the regeneration of basic properties of coarse aggregate, a comprehensive analysis of the optimal solution to carbide; before and after the replacement rate of recycled coarse aggregate as the variable, effect of carbonization of recycled coarse aggregate on the properties of recycled concrete.

## 2. Experiment

Carbonization of recycled coarse aggregate and its performance analysis

### 2.1. Materials

**2.1.1. Cement:** Using P.O 42.5 Portland cement (C),  $381\text{m}^2/\text{kg}$  specific surface area; natural river sand as fine aggregate (S), fineness modulus 2.14, apparent density is  $2719\text{kg}/\text{m}^3$ ; the particle size of 5~25mm continuous gradation of natural aggregate (NCA) before and after carbonation of recycled coarse aggregate and processing (RCA) of see Table 1. Water reducing agent; (SP) for polycarboxylate superplasticizer, water reducing rate of 15%~20%;  $\text{CO}_2$  purity higher than 99.9%.

**Table 1.** Chemical composition of cement

Moity	$\text{SiO}_2$	$\text{Al}_2\text{O}_3$	$\text{CaO}$	$\text{Fe}_2\text{O}_3$	$\text{SO}_3$	$\text{MgO}$	f-CaO	Na	K	Alkali Content
Cement	21.69	4.38	62.55	3.34	2.89	2.05	0.57	0.13	0.35	0.36

**2.1.2. Aggregates:** Natural and recycled coarse aggregates were used in the concrete mixtures. In this study, the recycled aggregate sourced from a 11 years old road, which is shown in Figure 1. Through crushing, screening, cleaning and other processes, the production of continuous grading was 5~25mm for recycled coarse aggregate is shown in Figure 2. According to Chinese Code [16], drilling core sample measured strength was 19.95MPa; a large number of old mortar was attached on the surface of recycled coarse aggregate, the content was 39.4% measured by heat treatment method; recycled coarse aggregate surface density was  $2633\text{kg}/\text{m}^3$ , the absorption rate was 3.25%, crushing index was 13.42%, in accordance with the II class in Chinese Code [17].



**Figure 1.** Primary concrete



**Figure 2.** Recycled coarse aggregate

## 2.2. Concrete mixtures

15 groups of mixtures were prepared in the laboratory. The concrete mixtures were prepared with the replacement rate of recycled coarse aggregate of 30%, 50%, 70% and 100% to determine the optimal scheme based on the carbonation of recycled coarse aggregate and recycled aggregate concrete (RAC), compared with ordinary concrete (NC). In the concrete mixtures, the ratio of water-to-cement was 0.4, the sand rate was 38%, and the mix proportion and workability of concrete are shown in Table 2.

**Table 2.** Mix proportion and working performance of concrete

Code	Mix proportion (kg/m <sup>3</sup> )					SP (%)	Slump (mm)
	C	NCA	RCA	S	W		
NC	450	1091	0	669	180	0.7	181
RAC-C0	450	0	1091	669	180	0.8	163
RAC-C6	450	0	1091	669	180	0.8	165
RAC-C12	450	0	1091	669	180	0.7	189
RAC-C24	450	0	1091	669	180	0.7	168
RAC-C48	450	0	1091	669	180	0.7	179
RAC-C72	450	0	1091	669	180	0.7	188
RAC-30	450	764	327	669	180	0.63	173
RAC-50	450	545.5	545.5	669	180	0.7	179
RAC-70	450	327	764	669	180	0.7	183
RAC-100	450	0	1091	669	180	0.8	163
RAC-30-C	450	764	327	669	180	0.65	175
RAC-50-C	450	545.5	545.5	669	180	0.7	189
RAC-70-C	450	327	764	669	180	0.65	158
RAC-100-C	450	0	1091	669	180	0.7	177

Note: NC mean ordinary concrete; RAC means recycled aggregate concrete; RAC-R means the replacement rate is R, the value of R are 30%, 50%, 70%, 100%; RAC-R-C means recycled coarse aggregate of recycled concrete substitution rate of R, R-values are 30%, 50%, 70%, 100% among them, the optimal scheme of carbonation of recycled coarse aggregate processing.

### 2.3. Specimens casting and curing.

A total of 45 cubes (150mm×150mm) and 90 prisms (150mm×150mm×300mm) were cast. They were used to determine the compressive strength, prism compressive strength, elastic modulus of 28 days respectively.

All the specimens were cast in steel molds and compacted using a vibration table. The test of specimens were cured at 20±2°C and relative humidity of 95% until the age of testing.

### 2.4. Tests

**2.4.1. Compressive strengths:** The compressive and prism compressive strength of concrete were determined using a 300t electro-hydraulic servo press machine in accordance with Chinese Code [17].

**2.4.2. Static modulus of elasticity (if the data is available):** The static modulus of elasticity of concrete were determined using a 300t electro-hydraulic servo press machine in accordance with Chinese Code [17].

**2.4.3 Carbonization:** The inner volume is 500L, and a closed reactor is equipped with a hole and a layered material frame, as shown in Figure 3 Carbonization of the recycled coarse aggregate was carried out by it. First to −0.1MPa vacuum, then injected into a concentration higher than 99.9% CO<sub>2</sub>, recycled coarse aggregate carbonization time (0h, 6h, 12h, 24h, 48h, 72h) and CO<sub>2</sub> gas pressure (0.1MPa, 0.4MPa, 0.8MPa) were changed.



**Figure 3.** Recycled coarse aggregate carbonization reaction kettle

## 3. Results and discussion

### 3.1. Optimum carbonation scheme

The recycled coarse aggregate was placed in different CO<sub>2</sub> gas pressure for 24h carbonization, and the basic properties of each group are measured in Table 3.

**Table 3.** Effect of CO<sub>2</sub> gas pressure on basic properties of recycled coarse aggregate

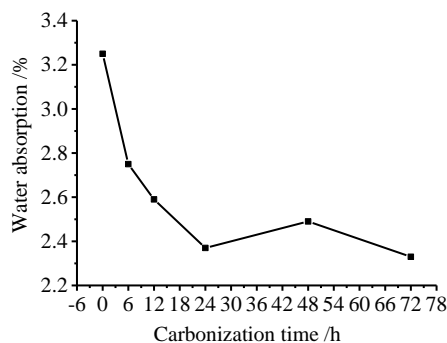
Code	Water absorption (%)	Apparent density (kg/m <sup>3</sup> )	Crushing index (%)
NCA	1.32	2652	4
RCA	3.25	2633	13.42
RCA-0.1MPa	2.4	2660	12.75
RCA-0.4MPa	2.37	2647	12.78
RCA-0.8MPa	2.93	2650	12.76

Note: NCA is natural coarse aggregate; RCA is recycled coarse aggregate; RCA-0.1MPa, RCA-0.4MPa and RCA-0.8MPa respectively indicate recycled coarse aggregate under CO<sub>2</sub> gas pressure of 0.1MPa, 0.4MPa and 0.8MPa; carbonization treatment for 24h.

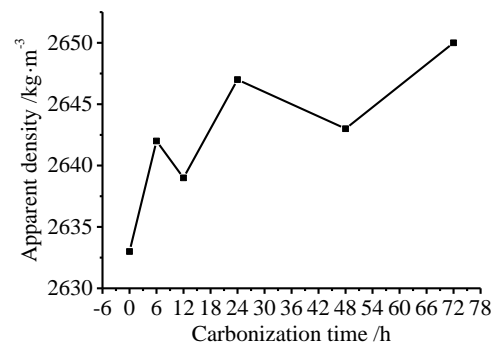
Table 3 shows that when the CO<sub>2</sub> gas pressure was 0.4MPa, compared with non-carbonization recycled coarse aggregate, water absorption and crushing index decreased by 27.1% and 4.8%. By the comparison of the degree of improvement, the economy and convenience of test operation, 0.4MPa was selected as the carbonization gas pressure.

### 3.2. Effect of carbonization time on water absorption of recycled coarse aggregate

The gas pressure in the carbonization reactor was 0.4MPa, and the recycled coarse aggregate was treated by carbonization for 6h, 12h, 24h, 48h and 72h, respectively. The improvement in basic performance was shown in Figure (4-6).



**Figure 4.** Effect of carbonization time on water absorption of recycled coarse aggregate



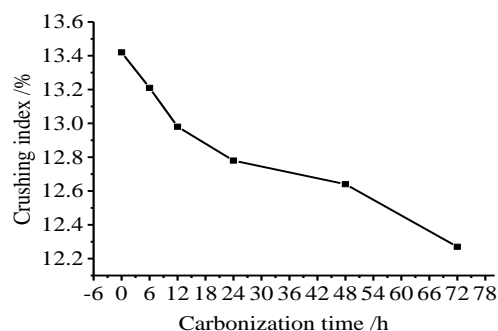
**Figure 5.** Effect of carbonization time on apparent density of recycled coarse aggregate

The water absorption before carbonation of recycled coarse aggregate was 3.25%, the water absorption of 6h, 12h, 24h, 48h, 72h carbonization had reduced by 15.38%, 20.31%, 27.08%, 23.38%, 28.31%, respectively. Water absorption decreased continuously with carbonization time increased. The reduction of water absorption became smaller after 24h while the carbonization time continued to increase.

### 3.3. Effect of carbonization time on apparent density of recycled coarse aggregate

With the increase of carbonization time, the apparent density of recycled coarse aggregate had a certain fluctuation, but the overall trend was increasing, because the carbonation reaction would increase the volume of solid phase. The apparent density of 24h increased little compared with that of 72h treated by carbonization. The absolute value of the apparent density varies little, the results of 12h and 48h might be caused by error in the apparent density test.

### 3.4. Effect of carbonization time on crushing index of recycled coarse aggregate



**Figure 6.** Effect of carbonization time on crushing index of recycled coarse aggregate

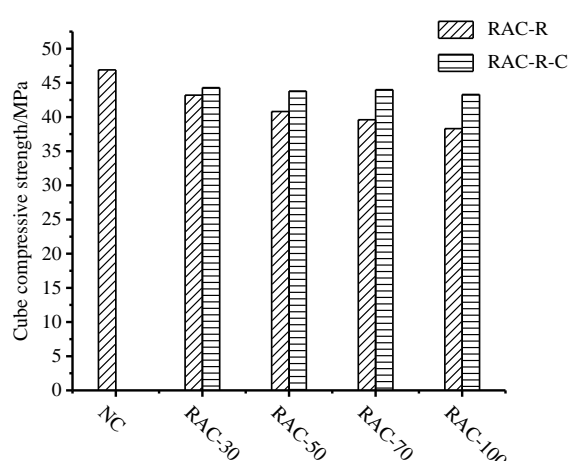
With the carbonization time increased, the crushing index of recycled coarse aggregate continuously decreased, the reason was that the recycled coarse aggregate concrete was broken and the internal defects caused the original crush index high. With the carbonization, the original pore was filled with the formation of  $\text{CaCO}_3$  and silica, which increased the density of the aggregate.

A comprehensive analysis on the basic properties of different time carbonization of recycled coarse aggregate was carried out, it is found that with increasing carbonization time, water absorption index and crushing index decreased, the apparent density had slight fluctuations, but overall increase, the best effect of carbonization of 72h, but compared to the experimental group 24h treatment and carbonization, water absorption decreased only 1.7%, apparent density increased by only 0.1%, the improvement effect of the performance of recycled coarse aggregate had been declined, this was because that with the carbonization reaction, humidity in carbonation reactor increased, the product  $\text{CaCO}_3$  was attached on the surface of aggregate, and blocked to seep into the old mortar, the carbonation reaction rate decreased and improved trend was slowing. Considering the economy of strengthening treatment, 24h was selected as the best carbonization treatment time.

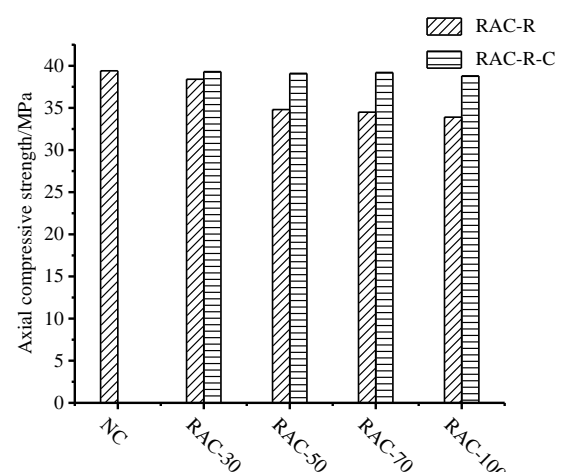
To sum up, the  $\text{CO}_2$  gas pressure in the carbonization reactor was selected as 0.4MPa, and the carbonization of the recycled coarse aggregate was treated for 24h as the optimum carbonization scheme.

### 3.5. Basic mechanical properties of recycled concrete

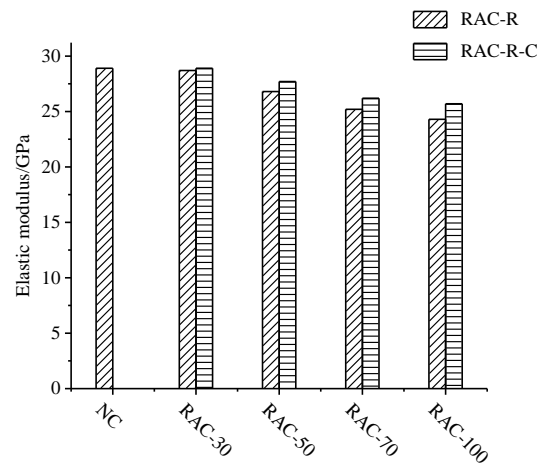
The test results of the cubic compressive strength, the prism compressive strength and the elastic modulus were shown in Figure (7-9), with the increase of replacement ratio. The compressive strength, the prism compressive strength and elastic modulus of the carbonized recycled aggregate concrete and un-carbonized recycled aggregate concrete overall upward trend. In one replacement rate, the mechanical properties of recycled concrete could be improved, when recycled coarse aggregate replacement rate was 100%, compared with un-carbonized recycled aggregate concrete, carbonized recycled aggregate concrete were increased by 13.1%, 14.5% and 5.8% respectively. This was because the carbonization of recycled coarse aggregate improves the basic properties of aggregate, especially the water absorption of aggregates, and then hydration process of cement was more adequate, the interfacial transition zone of recycled aggregate concrete become more compact, therefore, the mechanical properties could be improved.



**Figure 7.** Cubic compressive strength of concrete at 28d age



**Figure 8.** Compressive strength of concrete prism at 28d age



**Figure 9.** Elastic modulus of concrete at 28d age

#### 4. Conclusions

This paper attempts to study the effect of recycle coarse aggregates enhanced by CO<sub>2</sub> on the mechanical properties of recycled aggregate concrete. Based on the results of the research, the following conclusions can be drawn:

- (1) CO<sub>2</sub> gas pressure during carbonization change affects the effect of carbonization, the 0.4MPa carbide gas pressure for 24h, water absorption rate and crushing index of recycled coarse aggregate were decreased by 27.1% and 4.8%, the apparent density increased by 0.5%.
- (2) Carbonization treatment can improve the basic properties of recycled coarse aggregate. Under the pressure of 0.4MPa, the water absorption and crushing index of recycled coarse aggregate decreased continuously as the carbonization time increased, however, the apparent density showed an increasing trend. Carbide 24h, due to increased humidity and resultant attachment, carbonation reaction rate decreased, slowed regeneration to improve the basic performance of coarse aggregate, considering strengthening economic means, 24h is the best time of carbonization.
- (3) The cubic compressive strength, prism compressive strength and elastic modulus of recycled aggregate concrete tended to decrease with the increase of the replacement rate of recycled coarse aggregate.
- (4) Under the same replacement rate, the basic mechanical properties of the recycled aggregate concrete were better than that of the recycled aggregate concrete without carbonation. When the replacement rate of recycled coarse aggregate was 100%, the cubic compressive strength, prism compressive strength and modulus of elasticity of recycled aggregate concrete were increased by 13.1%, 14.5% and 5.8% respectively.

#### 5. References

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