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Review on Carbonation Enhancement for Recycled Coarse Aggregate Concrete

Yajing Li[1, a], Wei Ning[1, b]

[1]School of Henan Polytechnic University, Jiaozuo, 454003, China

[a]211908010016@home.hpu.edu.cn, [b]2548972303@qq.com

Abstract

The carbonation technology not only improve the quality of aggregates and enhance the performance of recycled concrete, but also sequester and consume carbon dioxide. This paper firstly reviews the research progress and mechanism of carbonation recycled coarse aggregate, and then analyses the effect of this method on the mechanical properties of recycled coarse aggregate concrete and the microstructure changes of recycled concrete after carbonation.

Keywords

Recycled coarse aggregate; Carbonation enhancement; Recycled concrete; Mechanical properties; Microstructure.

1. INTRODUCTION

Recently, the massive growth of the construction industry has generated an excessive amount of construction and demolition waste. Recycling waste concrete into recycled resources and using them in new construction projects is an effective way to increase the resourceful use of construction solid waste, and this method has been promoted in many countries around the world [1]. However, studies have shown that recycled aggregates currently account for only 3% of the total aggregate demand worldwide. On the one hand, due to the accumulation of internal damage during the crushing of waste concrete, the aggregates accumulate under the action of external forces, producing many micro-cracks and serious losses in grain size and strength; in addition, the loose and porous hardened cement mortar attached to the surface of recycled aggregates leads to the inferior quality of recycled aggregates compared to natural aggregates [2]. On the other hand, the presence of new and old mortar in RAC will form several ITZs [3], one is the old interface transition zone: there is about 30 μm wide old interface transition zone between old mortar and natural aggregate [4], where the porosity is 10% higher than the mortar matrix, and there are a large number of oriented calcium hydroxide crystals in this area [5], resulting in relatively weak local strength in this area; the second is the new interface transition zone zone: during the mixing process of RAC, a new ITZ will be formed after the contact between the aggregate and the freshly mixed cement matrix, due to the high water absorption rate of RCA, it will absorb the water between the surrounding of the matrix, which makes the water-cement ratio in this region rise and the porosity increase, resulting in this region becoming the weakest interface [6]. Based on the above factors, concrete prepared directly from recycled aggregates will show a more significant reduction in concrete workability [7], mechanical properties [8] and durability [9]. Therefore, the study of reinforcement of recycled aggregates is particularly important to improve the performance of RAC.

In recent years, researchers have conducted extensive research on the strengthening of recycled aggregate. The modification methods of recycled aggregates are mainly divided into

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two kinds: (1) strengthening the mortar attached to recycled aggregates, such as pozzolanic solution immersion [10], sodium silicate solution (water glass) immersion [11], adding nano SiO2 material [12], calcium carbonate biological deposition [13], etc; (2) Remove the mortar attached to recycled aggregate, such as heating grinding method [14], ultrasonic cleaning method [15], acid solution immersion [16], etc. Although the above measures can improve the performance of recycled aggregates to a certain extent, they all have certain defects or deficiencies. When using physical methods, complex and expensive mechanical equipment are often required, and the energy consumption is relatively high. Some chemical methods will lead to environmental pollution and have some adverse effects on the aggregate itself and the subsequent performance of RAC. Therefore, adopting an efficient and environmentally friendly method to improve the quality of recycled aggregates is of great significance for the mass preparation of RAC.

As a green modification method, carbonation has attracted extensive attention of experts and scholars. In recent years, scholars have conducted in-depth research on the technology of carbonated recycled aggregates. A large number of data show that strengthening recycled aggregates with carbon dioxide can significantly improve the physical properties of recycled aggregates. At the same time, CO_2 in industrial waste gas can be collected and utilized, consumed and stored, so as to reduce the pollution of greenhouse gases to the atmospheric environment. Carbonation treatment improves the surface hardness and strength of the sample by changing the pore structure of the aggregates. The calcium carbonate generated by carbonation reaction can make the old cement slurry more dense and reduce the porosity and water absorption of recycled aggregates. Carbonation technology is considered to be an efficient and environmental friendly reinforcement method of recycled aggregates [17]. Relevant research data show that after carbonation treatment, the water absorption of recycled aggregates decreases by 16.7% and the crushing index decreases by 25.9% [18]. The research of Ying [19] and others shows that the apparent density, water absorption and crushing index of the aggregates after carbonation are increased by 1.2%, reduced by 27.3% and reduced by 10.5% respectively compared with those before carbonation, and the compressive strength of RAC prepared by carbonated aggregates is significantly improved. Kou et al. [20] studied the effect of carbonation time on recycled aggregates. The results show that with the increase of carbonation time, the carbonation degree of recycled aggregates gradually deepens, and 24 h is the best carbonation time. Lu et al. found that after accelerated carbonation, the water absorption of RCA with particle size of 5 mm ~ 10 mm and 10 mm ~ 20 mm decreased by 30% and 22% respectively, and the apparent density increased by 4.8% and 3.2% respectively [4]. Tam et al. [21] proved the feasibility of pressurized carbonation of RCA by studying the influence of carbonation pressure and time on RCA. Xuan et al. [18] changed the CO_2 gas pressure to 0.1 MPa and 0.5 MPa respectively. After accelerated carbonation treatment, the water absorption decreased by 1.6% ~ 5.5%. Wang et al. [22] through microscopic test found that the improvement effect of new ITZ in RCA after carbonation is the most obvious, and the width is reduced by about 10 nm. The above research show that using accelerated CO_2 to strengthen RCA can not only improve the quality of RCA, but also store carbon dioxide in concrete to reduce the greenhouse effect. High concentration CO_2 reacts with $Ca(OH)_2$ and hydrated calcium silicate (C-S-H) [23], and the solid volume of $CaCO_3$ and silica gel increases by 11.8% and 23% respectively [24, 25]. The reaction products increase the density and strength of RCA by filling the pores, microcracks and ITZ of RCA [26]. Replacing natural aggregate with recycled aggregates can not only save 61% limestone resources, but also reduce 15% ~ 20% CO_2 emissions. Therefore, carbon dioxide reinforced recycled aggregates can not only improve bone quality, but also reduce the production of CO_2. It is of great significance to promote the recycling of waste concrete, develop green concrete and achieve the goal of "carbon peak and carbon neutralization" [27].

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2. CARBONATION ENHANCEMENT MECHANISM

Carbonation reaction refers to the chemical reaction between CO_2 dissolved in water and cement hydration products (such as $Ca(OH)_2$, C-S-H) and cement clinker minerals (such as Dicalcium Silicate (C_2S) and tricalcium silicate (C_3S)). The carbonation reaction includes the following aspects: (1) CO_2 dissolves in water to form carbonic acid (1); (2) H^+, HCO^{3-} and CO_3^{2-} are ionized from carbonic acid; (3) HCO_3^- react with Ca^{2+} and cement mineral C_3S and C_2S in pore solution to form $CaCO_3$ and silicon gel nucleation (2, 3, 4). (4) cement hydration products $Ca(OH)_2$, C-S-H, calcium aluminate hydrate react with CO_2 further, and finally convert into silica gel and $CaCO_3$ (5, 6, 7).

$$CO_2 + H_2O \rightarrow H_2CO_3 \quad (1)$$

$$CO_3^{2-} + Ca^{2+} \rightarrow CaCO_3 \quad (2)$$

$$3CaO{\cdot}SiO_2 + 3CO_2 + yH_2O \rightarrow SiO_2{\cdot}yH_2O + 3CaCO_3 \quad (3)$$

$$2CaO{\cdot}SiO_2 + 2CO_2 + yH_2O \rightarrow SiO_2{\cdot}yH_2O + 2CaCO_3 \quad (4)$$

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 \quad (5)$$

$$xCaO{\cdot}ySiO_2{\cdot}zH_2O + xCO_2 \rightarrow xCaCO_3 + ySiO_2{\cdot}tH_2O + (z-t)H_2O \quad (6)$$

$$4CaO{\cdot}Al2O3{\cdot}13H2O + 4CO2 \rightarrow 4CaCO3 + 2Al(OH)3 + 10H2O \quad (7)$$

3. EFFECT OF CARBONATION ON MECHANICAL PROPERTIES OF RECYCLED CONCRETE

The mechanical property of concrete is the main index to measure whether it can be applied in engineering practice. The safety of building materials can be ensured on the premise of ensuring the feasibility of mechanical properties. At present, the most studied are strength and elastic modulus [26], in which statics includes cube compressive strength, splitting tensile strength and flexural strength, and the elastic modulus can be obtained by uniaxial compression test.

3.1. Compressive Strength

Compressive strength is the most basic and important mechanical property of concrete. Compared with ordinary concrete, the mechanical properties of RAC are significantly reduced, because the multiple ITZ in RAC is the main factor for the deterioration of its mechanical properties. There is only one interface in ordinary concrete: ITZ between aggregate and slurry. There are three interfaces in RAC: the old ITZ between aggregates and old mortar, the new ITZ between aggregates and new mortar, and the new ITZ between old mortar and new mortar. Among them, the interface between new and old mortar is the weakest interface. It is found that when carbonated aggregates are prepared into RAC, the compressive strength is significantly improved. When cured to 90 day, the compressive strength of RAC is equivalent to that of ordinary concrete [20]. Lin [28] shows that when the carbonation time of recycled coarse aggregates is 24 h, the pressure set to 0.4 MPa, and the carbonated recycled coarse aggregates 100% replaces the natural aggregate, the 28 d cube compressive strength increases by 13.1%.

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Lu et al. [4] found that when the replacement rate of recycled coarse aggregates are 50% and 100%, the RAC compressive strength at 28 days increases by 24.1% and 32.9% respectively. In addition, the increase of compressive strength of RAC after carbonation increases with the increase of aggregate replacement rate, which shows that carbonation effectively improves the adverse effect of higher replacement rate on the compressive strength of RAC.

3.2. Splitting Tensile Strength

Splitting tensile strength is the main parameter to measure the cracking resistance of concrete, and to some extent, it is also an important indicator to determine the strength of the bond between concrete and reinforcement. Splitting tensile damage occurs mainly at the interface of the concrete. Therefore, the bond strength between the interfaces of the specimens is the main factor in whether the concrete undergoes splitting tensile damage.Tam et al. [21] showed that the splitting tensile strength of carbonated recycled aggregates concrete at 28 d was increased by 21% compared to untreated RAC when the replacement rate was 30%, which indicates that carbonation plays an enhancing role on the interface. The carbonation products $CaCO_3$ and silica gel filled the pores and cracks of the recycled aggregates, while making the loosely porous adhered mortar more dense, enhancing the bond between the aggregates and the old mortar, the old mortar and the new mortar, thus increasing the splitting tensile strength of RAC. Kou et al. [20] found that the splitting tensile strength of carbonated recycled aggregates concrete was higher than that of normal concrete when the curing age reached 90 d and the replacement rate was 100%. The splitting tensile strength of carbonated recycled aggregates concrete is comparable to that of normal concrete, even 5% ~ 10% higher.

3.3. Flexural Strength

The flexural strength is the ultimate breaking stress per unit area of the material when subjected to bending moment, and is an important parameter to measure the safety of the building structure. The old mortar on the surface of recycled aggregates is the main factor that the flexural strength of RAC is inferior to that of ordinary concrete. The flexural strength is consistent with the splitting tensile strength in that both are related to the bond strength between the mortars, so the strengthening of the mortar to which the recycled aggregates adheres is particularly important. Experimental data from Kazmi et al. [29] showed that the flexural strength of RAC prepared from carbonated recycled aggregates was 22% ~ 27% higher than that of untreated RAC. It was found that when the replacement rate of carbonated recycled coarse aggregates was higher than 50%, the flexural strength of RAC showed a significant decreasing trend, and when the replacement rate of carbonated recycled aggregates reached 100%, the flexural strength of carbonated recycled aggregates concrete was 28.7% higher than that of untreated RAC [18]. The above experimental data indicate that carbonation is conducive to enhancing the bond between mortars and plays a role in promoting the improvement of flexural strength.

3.4. Uniaxial Compressive Stress-strain Full Curve

The uniaxial compressive stress-strain curve of concrete is the main vehicle for analyzing the key indicators such as transverse-longitudinal deformation, ductility and bearing capacity of the specimens, and it is also an important parameter for weighing the safety of engineering structure design. A number of studies [28-30] have shown that the trend and shape of the full stress-strain curves of RAC and normal concrete are basically similar, and Luo et al. [30] found that the peak stress and the slope of the curve rise decreased and the peak strain increased as the replacement rate increased, a phenomenon indicates that the aggregates replacement rate is the main factor affecting the change of the full stress-strain curve of RAC. Compared with the untreated RAC, the rising slope and peak stress of the stress-strain curve were higher and the peak strain was lower for the RAC prepared with carbonated aggregates, indicating that

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carbonation effectively enhanced the load-bearing capacity, deformation performance and ductility of the RAC.

3.5. Modulus of Elasticity

The modulus of elasticity is the main index to characterize the deformation capacity of concrete, and is an important parameter to measure the temperature stress and crack expansion of members, which is the main judgment basis for the feasibility of building material performance in engineering applications. The modulus of elasticity of ordinary concrete is mainly influenced by the porosity and density of the matrix. However, in addition to the above two factors, the recycled aggregates replacement rate, particle shape and particle size play an important role in the modulus of elasticity of RAC. Kazmi et al. [29] found that the elastic modulus values of RAC prepared from carbonated aggregates were 8% ~ 27% higher than those of untreated RAC, indicating that carbonation was not only effective in improving the quality of recycled aggregates, but also the prepared RAC was more dense than untreated ones. It was shown that the 28 d modulus of elasticity of RAC prepared from carbonated recycled aggregates was improved by 5% compared to untreated RAC; the 28 d modulus of elasticity was increased by 0.7%, 3.4%, 4.0%, and 5.8% when the carbonated aggregates replacement was 30%, 50%, 70%, and 100%, respectively [28]. It can also be found that the higher the replacement rate of recycled aggregates, the more significant the effect of carbonation treatment on the improvement of RAC elastic modulus.

4. EFFECT OF CARBONATION ON THE MICROSTRUCTURE OF RECYCLED CONCRETE

Currently, some scholars have used carbonation technique to study the microstructure of recycled concrete, and it was found that the carbonation product $CaCO_3$ has high solid phase volume and microhardness [31].Lu et al. [4] found that the microhardness values of carbonated recycled concrete were 50.1% and 51.7%. Wang et al. [22]comparatively studied the Vickers hardness of recycled concrete at 7 d, 28 d and 140 d curing ages and found that the Vickers hardness of the old mortar was greater than the old ITZ between the aggregate and the old mortar regardless of the age, which was due to the more pores in the ITZ and the directional arrangement of the CH. In addition, the data showed that the width of the old ITZ was about 40 μm ~ 60 μm and the width of the new ITZ formed between the old and new mortar was about 30 μm ~ 50 μm, which was slightly smaller than the width of the old ITZ. The study by Xuan et al. [18] found that an increase in microhardness values near the ITZ between the recycled aggregate and the new cement mortar after carbonation.

The presence of ITZ in the transition zone between the aggregate and cement mortar, which is the weak part of concrete, is a major factor in the deterioration of RAC performance, and carbonation treatment can effectively improve the performance of ITZ [32, 33].Li et al. [34] found that before carbonation, large cracks (6.63 μm), a loose microstructure and a large number of needle-like calcium alumina crystals were observed in the ITZ zone by electron microscopy After accelerated carbonation treatment, it was observed again at 28 d that the calcarenite disappeared and a large amount of $CaCO_3$ was generated, while the ITZ width was significantly reduced (0.94 μm). Guo Hui [35] found that the carbonation treatment effectively reduced the thickness of the interfacial transition zone of the recycled aggregates by about 5 m. Meanwhile, the carbonation treatment changed the main phases of the interfacial transition zone, such as $Ca(OH)_2$ and C-S-H to $CaCO_3$ and silica gel.

Fang [36] found that the carbonation treatment improved the pore structure of the recycled aggregates by mercury-in-pressure (MIP) testing and reduced the number of large pores within the aggregate. In addition, the elimination of pores above 200 nm and the reduction of pores in

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the range of 50 nm ~ 200 nm improved the pore structure distribution within the RAC, thus enhancing the mechanical properties of the RAC. Zhan et al. [37] noted that the increase in the fine pore fraction in the aggregates after carbonation treatment was mainly due to the sharp refinement of the mesopores in the range of 0.1 mm ~ 1 mm after treatment. Among them, the volume of fine pores (d < 0.1 mm) decreased by 0.05 mL/g and the volume of coarse pores decreased by only 0.003 mL/g, which could not provide enough space for the precipitation of calcium carbonate, indicating that the precipitation of calcium carbonate mainly occurred in the pores of the medium during CO_2 carbonation. Guo Hui [35] found through experiments that after carbonation treatment, the porosity of the recycled aggregates decreased by 37.23%, the total pore volume decreased by 46.77%, the average pore size decreased, the proportion of pores >100 nm and 50 nm ~ 100 nm decreased significantly, and the pores <50 nm increased significantly, especially the appearance of micropores (<2 nm). The above experimental results show that the carbonation treatment reduced the pore size of the recycled aggregates, lowered its porosity, and made its structure more dense with uniform pore size distribution.

5. CONCLUSION

1. Carbonation enhancement is a greenhouse gas reduction technology. Carbonation strengthening can not only reduce the water absorption and crushing value of recycled aggregates, increase the apparent density and improve the performance of recycled concrete, but also achieve the consumption and sequestration of CO_2.

2. The reinforcement mechanism of carbonation on recycled aggregates is that calcite generated by carbonation reaction fills the pores of RCA old mortar and interfacial transition zone, which enhances aggregate hardness, reduces the width of interfacial transition zone, decreases aggregate porosity, and makes its structure more dense.

3. The existence of multiple interfaces in recycled concrete is the main cause of its mechanical properties deterioration, and carbonation strengthening can enhance the bond strength between the aggregate and the old and new mortar, improve the bearing capacity of recycled concrete, and enhance its deformation performance and ductility.

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