SCIENCE CHINA
Technological Sciences

September 2012 Vol.55 No.9: 2609–2616
doi: 10.1007/s11431-012-4798-5

On carbonation behavior of recycled aggregate concrete

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Received June 30, 2011; accepted October 10, 2011; published online April 12, 2012

This study tries to reveal the carbonation behavior when recycled coarse aggregates (RCAs) are used to mix new concrete. Six series of tests including 22 groups of recycled aggregate concrete (RAC) specimens were carried out, in which the effects of the water/binder (w/b) ratios, the binder content, the types of mineral admixture, the quality of RCAs, the RCAs replacement and the loading levels on the carbonation behavior of RAC were evaluated, respectively. The results showed that the carbonation behavior of RAC was not only influenced by the quality of new mortar but also by the properties of RCAs. The admixture of mineral admixture influenced the carbonation, and the loading stress level might have a significant impact on the evolution of the carbonation.

recycled aggregate concrete (RAC), recycled coarse aggregate (RCA), carbonation, stress levels

Citation: Xiao J Z, Lei B, Zhang C Z. On carbonation behavior of recycled aggregate concrete. Sci China Tech Sci, 2012, 55: 2609–2616, doi: 10.1007/s11431-012-4798-5

1 Introduction

As the result of admixture of recycled aggregates, the microstructure of recycled aggregate concrete (RAC) becomes more complicated and its mechanical properties have been proved to have some difference from those of normal concrete [1]. More types of interfaces exist in concrete with recycled aggregates than in the normal aggregate concrete: the old interfacial transition zone (ITZ) between the original aggregates and the adhesion mortar, and another new ITZ between the adhesion mortar and the new mortar. This complicated microstructure of recycled aggregate concrete makes it very difficult to study the mechanisms of failure and durability. Some primary laboratory investigations on the carbonation behavior of RAC have been undertaken in the past years. The research work by Fung [2] showed that the carbonation depth of recycled aggregate concrete increases with the increase in the replacement percentage of natural aggregates by the recycled aggregates in a mix. Otsuki et al. [3] found that the carbonation depth of recycled aggregate concrete reduces with the decrease in water/cement ratio. Otsuki et al. [3] and Hiroshi et al. [4] reported that the double-mixing method can improve the carbonation resistance of recycled aggregate concrete. Hiroshi et al. [4] further stated that the standard deviation of the carbonation depth of recycled aggregate concrete is larger than that of normal concrete. Ryu [5] primarily concluded that the properties of recycled concrete aggregates (the quality and the content of mortar attached to the recycled concrete aggregates) have no clear effects on the recycled aggregate concrete. Katz [6] found that there is no noticeable difference in the carbonation resistance of recycled aggregate concretes with regard to hydrated level of the source concrete. Shayan and Xu [7] reported that the carbonation depth of recycled aggregate concrete incorporating recycled

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concrete aggregates treated with a sodium silicate is increased, as sodium silicate has a larger tendency for CO_2 absorption. Chen [8] found that the admixture of interface-zone modifying agent does not make a clear contribution to the carbonation resistance. Sun [9] analyzed the effect of mineral admixture on the carbonation of recycled aggregate concrete and stated that the fly ash increases the carbonation depth of recycled aggregate concrete. Limbachiya et al. [10] and Salomon and Paulo [11] found that compared to the same strength grade of normal concrete, the recycled aggregate concrete presents almost the same and sometimes even better behavior than the reference concrete made with natural aggregates in terms of the carbonation resistance.

From the above overview it can be concluded that experiments carried out by different researchers were rather sporadic, and the test results were not well comparable to each other. Furthermore, there exist contradictions among the conclusions drawn by different investigators. At the same time, previous analysis of recycled aggregate concrete carbonation resistance did not consider the impact of the stress level. In many cases, microscopic cracks induced by the tensile stress proliferate channels of CO_2 diffusion in recycled aggregate concrete, and then accelerate the rate of CO_2 diffusion. So, to study the impact of the stress-induced cracks on the carbonation bahavior of recycled aggregate concrete is indispensable. Since the carbonation behavior of recycled aggregate concrete is yet not well understood, a further research is needed to comprehend the resistance of recycled aggregate concrete to carbonation actions accurately and profoundly. In an attempt to contribute to the existing knowledge in this regard, a detailed analysis of the effects of the water/binder (w/b) ratio, the binder content, the kinds of mineral admixture, the quality of recycled coarse aggregates, the recycled coarse aggregate replacement of natural coarse aggregates and the loading levels on the carbonation behavior of recycled aggregate concrete is performed by accelerated carbonation experiments. The essential test results are presented and discussed in this paper.

2 Experimental work

2.1 Source and properties of recycled coarse aggregates

Concrete cubes from construction sites with designed compressive strength grades of C20, C30, and C50, whose mix proportions are not available, and the concrete without any carbonation were used to produce the recycled concrete aggregates. Concrete cubes were crushed with a jaw crusher, then the crushed products from each grade of the original concretes were screened into two size fractions (40 to 20 mm and 20 to 5 mm). Finally, they were recombined proportionately to obtain similar grading of natural coarse aggregates. The properties of recycled concrete aggregates are as listed in Table 1, where the adhered mortar content was tested and calculated by the method of sulphurinc acid with 76% concentration [12].

2.2 Materials

The natural aggregates of the present study were crushed granite coarse aggregate and river sand. An ordinary Portland cement (OPC) with grade of 42.5 was supplied for this experimental investigation. Fly ash, slag and silica fume were used as mineral admixture in the series of D specimens in Table 2, in which f_t is the tensile strength of the recycled aggregate concrete.

2.3 Design and production of the concrete mixtures

Six series of tests including 22 groups of specimens were designed (Table 2) to reveal the effects of the water/binder (w/b) ratio, the binder content, the types of mineral admixture, the quality of recycled coarse aggregates, the recycled coarse aggregate replacement of natural coarse aggregates and the stress level on the carbonation behavior of recycled aggregate concrete, respectively. The recycled coarse aggregate was pre-wetted to fully soak prior to mixing the concrete in order to increase the workability of the fresh concrete. The measured slump of the fresh concrete was about 70 mm.

2.4 Test program and procedure

The measurements of the compressive strength and the splitting tensile strength of 150 mm×150 mm×150 mm recycled aggregate concrete cubes were carried out according to GB/T 50081 [13]. The measurements of the carbonation depth of 100 mm×100 mm×300 mm recycled aggregate concrete prisms were carried out according to JGJ/T 193 [14]. All specimens were cured in a controlled chamber at a

Table 1 Properties of the coarse recycled concrete aggregates

Original concrete[a)]	Adhered mortar content (%)	Compacted bulk density (g/cm^3)	Specific gravity (SSD) (g/cm^3)	Water absorption (%)	Crushing value (%)
C20	44.8	1.37	2.43	4.80	27.26
C30	40.4	1.38	2.45	4.70	23.77
C50	26.4	1.48	2.53	3.25	19.78

a): Recycled coarse aggregates were from C20, C30 and C50 original concretes.

Table 2 List for test groups of carbonation specimens

No.	Stress level	Original concrete grade	Replacement of RCAs by mass (%)	Brick in RCAs (%)	w/b	Type of binder	Binder content (kg/m^3)
A1					0.35		
A2					0.40		
A3	0	C30	100	0	0.50	OPC	400
A4					0.60		
A5					0.70		
B1							200
B2	0	C30	100	0	0.5	OPC	300
B3							500
C1		C20		0			
C2	0	C50	100		0.5	OPC	400
C3		C30		10			
D1						90%OPC+10% fly ash	
D2	0	C30	100	0	0.5	90%OPC+10% slag	400
D3						90%OPC+10% silica fume	
E1			0				
E2	0	C30	30	0	0.5	OPC	400
E3			50				
E4			70				
F1	$0.6f_t$						
F2	$0.8f_t$	C30	100	0	0.5	OPC	400
F3	$1.0f_t$						
F4	$1.2f_t$						

temperature of 20±2°C and relative humidity of 95%. At the age of 26 days prisms for carbonation tests were placed in an oven that was maintained at a temperature of 60°C for 2 days. Thereafter, the surfaces other than the two opposite exposure surfaces of the prisms were coated with the wax, and then the samples were put in an accelerated carbonation test chamber with (20±3)% CO_2 concentration, 20±5°C temperature and (70±5)% relative humidity [15]. After splitting the specimens, the freshly broken surface was sprayed with rainbow indicator. The mean values of carbonation depths for 7 days, 14 days, 28 days and 80 days were measured at the distance from the exposure surface to the place that turned blue as shown in Figure 1. At the age of 28 days, the cubes for the compressive strength and the splitting tensile strength were tested. One test result was evaluated from the mean of the three test determinations of the same material.

Figure 1 Carbonation depth measure.

3 Results and discussions

3.1 Results

The carbonation depths at different ages and the strengths (A to E series were for compressive strength and F series were for tensile strength) at 28 days of recycled aggregate concretes are listed in Table 3.

3.2 Discussions

3.2.1 The effect of the water/binder (w/b) ratio on the carbonation depth

Based on the A series tests, the effect of the water/binder (w/b) ratio on the carbonation depth at 80 days is shown in Figure 2. It is shown that the carbonation depth of recycled aggregate concrete increases with the increasing w/b, and the increase rate of the carbonation depth is accelerated when w/b exceeds 0.5. This result was similar to that reported by Otsuki et al. [3]. The larger the w/b is, the weaker

Table 3 Mean carbonation depths of recycled aggregate concrete and strengths of 28 days

No.	Carbonation depth (mm)				Compressive strength (MPa)	No.	Carbonation depth (mm)				Compressive (Tensile) Strength (MPa)
	7 d	14 d	28 d	80 d			7 d	14 d	28 d	80 d	
A1	10.1	14.5	14.7	24.0	42.9	D1	14.7	18.4	23.1	34.7	27.2
A2	9.5	15.8	16.8	24.8	40.0	D2	7.3	17.2	29.2	45.2	32.0
A3	10.4	13.4	17.1	26.7	31.7	D3	6.3	20.8	25.8	38.5	32.2
A4	13.3	18.2	23.5	36.3	26.8	E1	10.1	12.9	16.5	21.2	34.5
A5	16.6	26.9	28.5	44.8	18.7	E2	9.5	13.1	17.0	22.9	33.6
B1	13.5	18.1	19.6	36.8	27.0	E3	12.2	17.2	22.0	33.8	32.7
B2	11.2	16.7	18.2	29.2	27.4	E4	16.2	23.5	26.0	41.7	31.1
B3	13.9	17.6	20.9	33.4	31.4	F1			21.0		
C1	14.0	17.7	21.2	38.1	22.1	F2			23.6		(3.5)
C2	7.4	10.9	14.3	23.3	24.5	F3			26.3		
C3	10.6	10.9	14.0	28.7	28.0	F4			28.6		

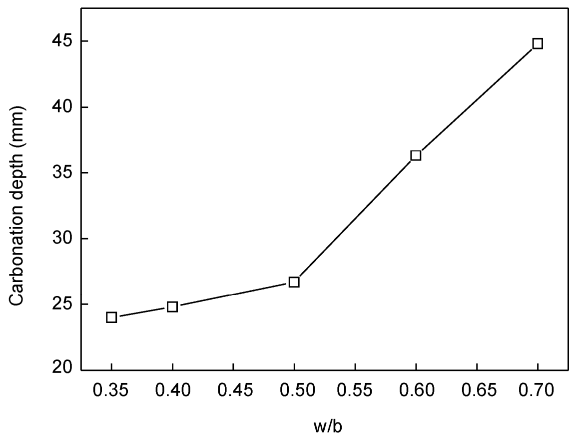

Figure 2 The relationship between RAC carbonation depth and the water/binder (w/b) ratio.

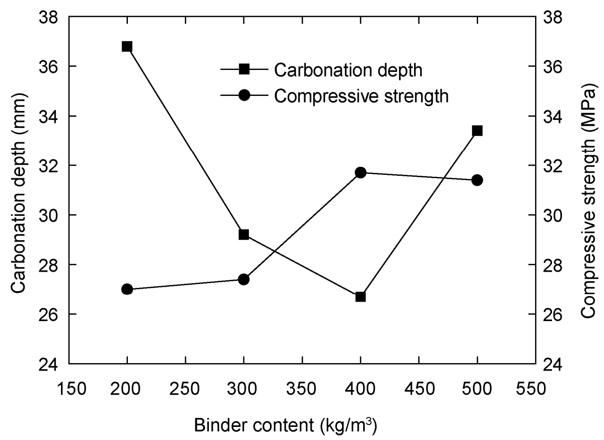

Figure 3 The relationships between RAC carbonation depth and the binder content.

is the matrix permeability of the recycled aggregate concrete, which increases the carbon dioxide permeability of the recycled aggregate concrete and consequently the carbonation depth.

3.2.2 The effect of the binder content on the carbonation depth

Keeping the w/b as a constant and changing the amount of the binder (A3 and B series), the effect of the binder content on the carbonation behavior was analyzed and the results are shown in Figure 3. It is seen that the carbonation depth decreases and the compressive strength increases with the increase in the amount of the binder. For binder content less than 400 kg/m^3, the variation trends of the compressive strength and the carbonation depth with the increase of the amount of the binder are somewhat opposite. For a fixed w/b and increasing amount of the binder, the compactness of the recycled aggregate concrete is improved. Consequently, the compressive strength of the recycled aggregate concrete is higher, and the diffusion velocity of the carbon dioxide is slower, which decreases the carbonation depth. When the amount of the binder exceeds 400 kg/m^3, the carbonation depth increases while the compressive strength decreases with the increasing amount of the binder.

3.2.3 The effect of the RCA replacement on the carbonation depth

Based on the tests of A3 and E series, Figure 4 presents that, when the replacement of the recycled coarse aggregate is less than 70%, the carbonation depth of the recycled aggregate concrete increases with the increase of the recycled coarse aggregate replacement. When the replacement of the recycled coarse aggregate exceeds 70%, the carbonation depth of the recycled aggregate concrete decreases with the increase of the recycled coarse aggregate. When the recycled coarse aggregate replacement equals 70%, the recycled aggregate concrete reaches its maximum carbonation depth.

Porous recycled aggregates result in a much higher porosity of recycled aggregate concrete than that of a similar mix of normal concrete, and leads consequently to a reduction in the carbonation resistance of recycled aggregate concrete (negative effect). On the other hand, recycled aggregate concrete may have a higher total binder content, and then a higher alkaline reserve that can be carbonated due to

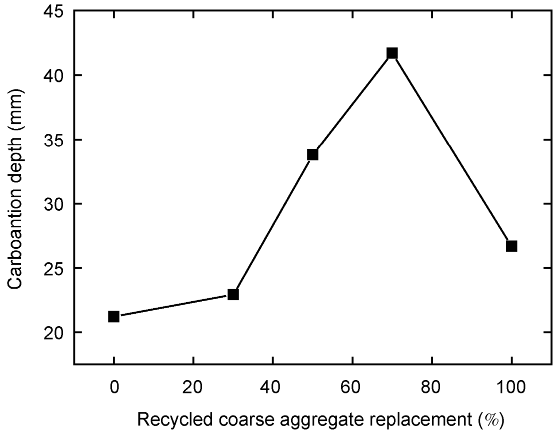

Figure 4 The relationship between RAC carbonation depth and the RCA replacement.

the attached mortar of the recycled coarse aggregates, which is in favor of carbonation resistance (positive effect). So the carbonation behavior of the recycled aggregate concrete is the response to the two competition factors as mentioned above. According to Table 1, the attached mortar content of the original C30 concrete is 40.4%. The mix proportions of the E series and A3 are listed in Table 4. Assuming that the binder content of the old attached mortar is also about 40%, the binder content to the recycled aggregate concrete with different replacement of the recycled coarse aggregate is described in Table 5. The double influences of the recycled coarse aggregate on the carbonation behavior can be illustrated with Figure 5. Sun [16] stated that the permeability of the recycled aggregate concrete increases with the increase in the replacement of the recycled coarse aggregate, and that the increase rate of the permeability exhibits the following trend: firstly slow (when the replacement is less than 20%), then quick (when the replacement is between 20% and 40%), and finally again slow (when the replacement is between 40% and 60%). Otsuki et al. [3] found that when the replacement of the recycled coarse aggregate is 50%, the permeability of the recycled aggregate concrete is larger than that of the recycled aggregate concrete of which the replacement of the recycled coarse aggregate is 100% and reaches its maximum. So the negative influence on the carbonation behavior of the recycled aggregate concrete caused by the recycled coarse aggregate is described by the curves in Figure 5. As explained in section 3.2.2, there is a linear relationship between the carbonation depth of the recycled aggregate concrete and the binder content, so the positive effect on the behavior of the recycled aggregate concrete brought by the recycled coarse aggregate is described by a straight line in Figure 5. When the replacement is low, the rate of the increase in the negative effect caused by the recycled coarse aggregate is over the rate of the increase in the positive effect as the replacement of the recycled coarse aggregate increases. The difference between them reaches the maximum when the replacement of the recycled coarse aggregate equals 70%. The carbonation depth of the corresponding recycled aggregate concrete reaches its maximum when the replacement of the recycled coarse aggregate exceeds 70%. The rate of the increase in the negative effect caused by the recycled coarse aggregate begins to become lower than the rate of the increase in the positive effect as the replacement of the recycled coarse aggregate increases, and then the carbonation depth decreases.

It should be mentioned here that the above discussion is preliminary and exploratory. Due to the limitation of the relatively small number of the experimental tests, the effect of the replacement of the recycled coarse aggregate on the carbonation depth of the recycled aggregate concrete needs further study.

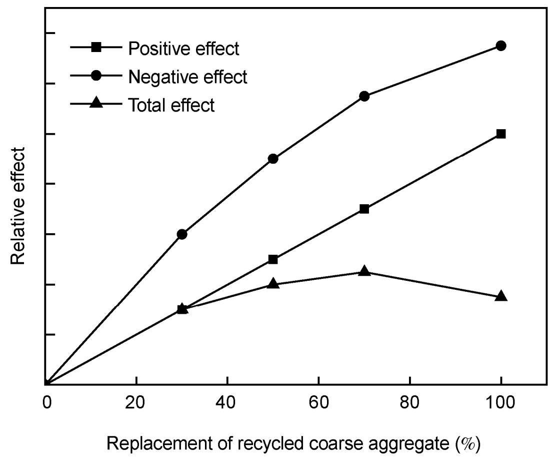

Figure 5 The effects of the RCA replacement on the carbonation performance of RAC.

Table 4 Concrete proportions of the E series and A3 (kg)

No.	Recycled coarse aggregate	Natural coarse aggregate	Natural sand	Binder	Water
E1	0	1090	587	400	200
E2	327	763	587	400	200
E3	545	545	587	400	200
E4	763	327	587	400	200
A3	1090	0	587	400	200

Table 5 Admixtureal cement contents of RAC with different replacements of RCA (kg/m^3)

Replacement of the RCA	0	30%	50%	70%	100%
Admixtureal cement content	0	52.4	87.2	122	174.4

3.2.4 The effect of the original concrete on the carbonation depth

By comparing the carbonation depth of the series C (C1, C2, C3) and A3 at 80 days, as shown in Figure 6, it is seen that with the exception of C3, the carbonation depth of the recycled aggregate concrete decreases with the increase in the strength grade of the original concrete, and the adulterating brick with recycled coarse aggregates can increase the carbonation depth. This test result is similar to that of Ryu [5]. The interface between the adhesion mortar and the new mortar becomes more compact as the strength of the adhesion mortar of the recycled coarse aggregate increases, and the negative effect caused by the recycled coarse aggregate on the carbonation behavior decreases [17].

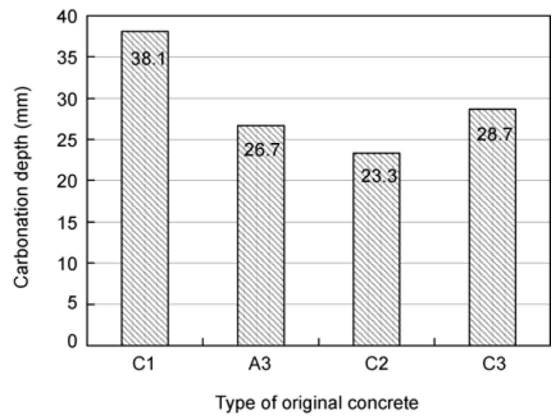

Figure 6 The effect of the original concrete on the carbonation behavior.

3.2.5 The effect of the mineral admixture on the carbonation depth

By comparing the carbonation depths of the D series (D1, D2, and D3) and A3 at 80 days (Figure 7), it can be concluded that the admixture of the mineral admixture replacing cement influences the carbonation. It can be seen that on the one hand the mineral admixture can improve the internal pore structures, decrease the porosity of the recycled aggregate concrete and improve the interface zone between the recycled coarse aggregates and the cement paste in new concrete. Therefore, it is favorable for the properties of the recycled aggregate concrete. On the other hand, it reduces the total alkaline reserve that can be carbonated in the recycled aggregate concrete, and thus has adverse effect on the recycled aggregate concrete. These test results show that the negative effect brought by the dosage of 10% (by the mass of cement) mineral admixture is over the coinstantaneous advantage effect caused by it, and the carbonation resistance performance of the recycled aggregate concrete is therefore reduced. However, further tests will be needed in the future.

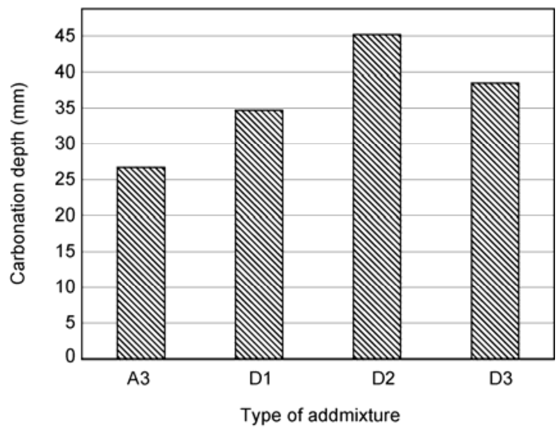

Figure 7 The effect of the mineral addmixture on RAC carbonation depth.

3.2.6 Correlation between compressive strength and carbonation depth

Figure 8 displays the carbonation depth of the recycled aggregate concrete for different compressive strengths. It can be seen from the figure that there is no clear correlation between the compressive strength and the carbonation depth of the recycled aggregate concrete. The carbonation depth of the recycled aggregate concrete with the same compressive strength can be fluctuated in a comparatively wide range.

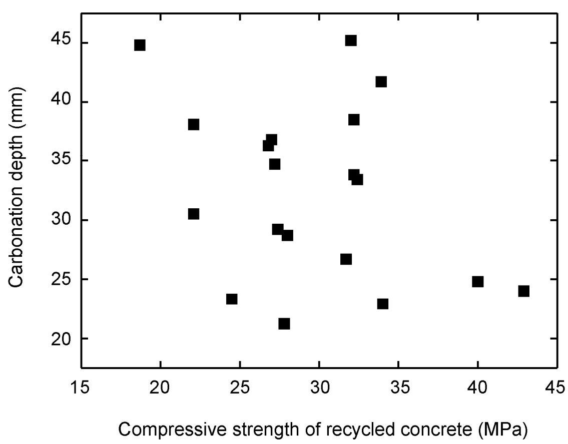

Figure 8 The effect of compressive strength on the carbonation depth of RAC.

3.2.7 The effect of the tensile stress level on the carbonation depth

Since the loading condition of uniaxial tension for structural elements or structures is rarely seen in the practical applications and in most circumstances they are subjected to bending tension, the test set-up was designed as shown in Figure 9.

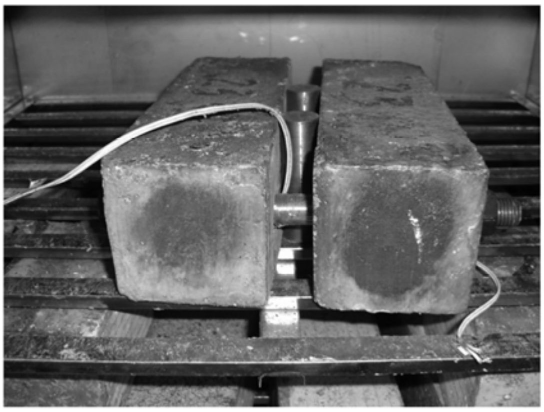

Figure 9 Loading setup photo.

The strain gauges were placed at the middle part of the screws and the part of the recycled aggregate concrete specimens in pure bending tension. Also, fasten the screw nut with wrenches to impose load, and use the tensile stress value of the recycled aggregate concrete to control the external force. According to the design requirements, the imposed stresses were 0.6, 0.8, 1.0 and 1.2 f_t (f_t is the tensile strength of the recycled aggregate concrete). By considering the stress relaxation of the screw and the contract as well as the creep of the recycled aggregate concrete, the actual stress of every specimen was exceeded by 3%; see Table 6.

Figure 10 shows the relative carbonation depths (the ratio of carbonation depth to that of A3) of the recycled aggregate concrete under different tensile stress levels. It can be seen that the relative carbonation depth increases with the increase in the tensile stress. Compared with the recycled aggregate concrete under zero stress (A3), the carbonation depth of the recycled aggregate concrete under the stress level 1.2 is increased by 70%. This phenomenon can be explained by the fact that micro-cracks are initiated and developed in the recycled aggregate concrete under tensile stress, which can accelerate the carbonation of the recycled aggregate concrete.

3.2.8 Comparison between recycled aggregate concrete and normal concrete

The relative speed is defined as the ratio of the carbonation rate to the carbonation rate of E1 at 7 days. Figure 11 shows the comparison between the carbonation relative speed of recycled aggregate concrete (A3) and that of normal concrete (E1). It is seen that for both recycled aggregate concrete and normal concrete the relative speed of carbonation decreases as the carbonation time increases. A reduction of 22% is observed for the relative speed of carbonation of the recycled aggregate concrete at 80 days compared to that at 7 days, and the corresponding reduction for the normal concrete is 38%. The compactness of the concrete increases with the increase in the carbonation, as a result, the relative speed of the carbon dioxide diffusion is slowed down.

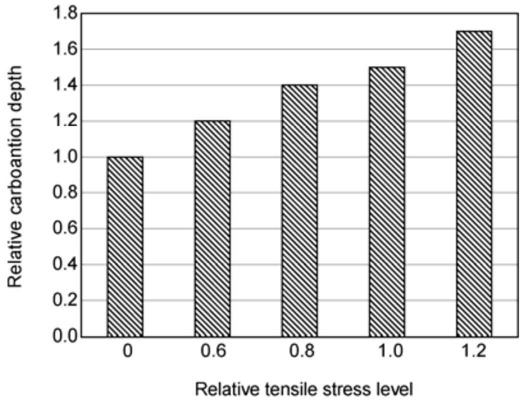

Figure 10 The effect of the relative tensile stress level (σ/f_t) on RAC carbonation depth.

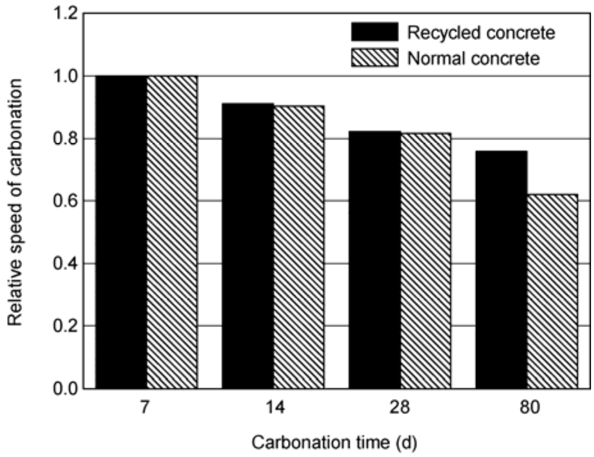

Figure 11 The relationships between carbonation relative speed and the carbonation time.

Table 6 Bending tensile stresses upon recycled aggregate concrete specimens

No.	Tensile strength f_t (MPa)	Stress level (σ_t)	Calculated strain ($\mu\varepsilon$)	Measured strain ($\mu\varepsilon$)	Calculated stress (MPa)	Measured stress (MPa)
F1	3.5	0.6 f_t	95.5	98.4	2.1	2.16
F2	3.5	0.8 f_t	127.3	131.1	2.8	2.88
F3	3.5	1.0 f_t	159.1	163.9	3.5	3.71
F4	3.5	1.2 f_t	190.9	196.6	4.2	4.33

4 Conclusions

Based on the findings of the present study, the following conclusions can be drawn.

1) In general the carbonation depth of the recycled aggregate concrete decreases with the increase in the strength grades of the original concrete. Adulterating brick with recycled coarse aggregate may increase the carbonation depth.

2) When the replacement of the recycled coarse aggregate is less than 70%, the carbonation depth of the recycled aggregate concrete increases with the increase of the recycled coarse aggregate. When the replacement of the recycled coarse aggregate exceeds 70%, the carbonation depth of the recycled aggregate concrete decreases with the increase of the recycled coarse aggregate.

3) The admixture of the mineral admixture replacing cement partially (10% by mass of the cement) seems to accelerate the carbonation. The carbonation resistance performance of the recycled aggregate concrete is reduced. i.e., the negative effect brought by the dosage of 10% (by the mass) mineral admixture is over its positive effect.

4) Compared with the recycled aggregate concrete under zero stress, the carbonation depth of the recycled aggregate concrete under the stress level 1.2 is increased by 70%.

This work was supported by the National Natural Science Foundation of China (Grant No. 51178340), the Shanghai Science and Technology Committee (Grant No. 10231202000), and the New Century Excellent Talents in China Ministry of Education Project (Grant No. NCET-06-0383).

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