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Evaluation Of Carbonation Resistance Of Paint Coated Concrete For Buildings

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Evaluation of carbonation resistance of paint coated concrete for buildings

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HIGHLIGHTS

- Carbonation depth of C35 standard cured concrete is 56% smaller than that of C25.
- Accelerate curing increases carbonation depth of C25 concrete by 61%.
- Paint coating can reduce 28-day carbonation depth of concrete by 46% at least.
- Carbonation suppression ratio varies with exposure time and quality of substrate.
- Exterior paint coating has a longer blockage time and a smaller carbonation rate.

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ABSTRACT

When evaluating the carbonation resistance of paint coated concrete, the effects of both the strength grade and the curing conditions (standard curing and accelerated curing) of concrete substrate on carbonation resistance of paint coated concrete were investigated. The concept of the carbonation suppression ratio of paint was presented for evaluation of the anti-carbonation performance of the two types of paints (exterior and interior paints) when applied to a reference concrete substrate. The test results showed a good linear relationship between the carbonation depths of the paint coated concrete and the square root of exposure times. Concrete with higher strength grade exhibited greater carbonation resistance. The carbonation depth of the C35 standard cured concrete was reduced by 56% in comparison with that of the C25 standard cured concrete. It was found that concrete substrate prepared by accelerated curing method displayed lower carbonation resistance than standard cured concrete. Compared with the standard cured specimen, the carbonation depth of the accelerated cured specimen increased by 61% for the control C25 concrete and by 56% for the control C35 concrete. This phenomenon was attributed to the formation of a higher volume of capillary pores in concrete prepared by accelerated curing. Additionally, the exterior paint had a higher carbonation suppression ratio than the interior paint. The suppression ratios of the exterior and interior paint coatings applied on C25 standard cured concrete were 71% and 56%, respectively. The exterior paint coated concrete had a better carbonation resistance with longer effective blockage time and smaller carbonation rate.

1. Introduction

1.1. Carbonation theory

Natural concrete carbonation is a chemical reaction between the carbon dioxide (CO_2) in the air and cement hydration products of the concrete. Atmospheric carbon dioxide dissolves in the pore water, and it produces a weak carbonic acid (see Eq. (1)) which dissociates and reacts with calcium hydroxide (see Eq. (2)) and then with calcium silicate hydrates (C–S–H) (see Eq. (3)), to form calcium carbonate and water [1,2]. Without doubt, these reactions decrease the alkalinity of concrete.

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

$$Ca(OH)_2 + H_2CO_3 \rightarrow CaCO_3 + 2H_2O \quad (2)$$

$$C{-}S{-}H + H_2CO_3 \rightarrow CaCO_3 + SiO_2 \cdot nH_2O \quad (3)$$

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Carbonation is a diffusion process involving the transportation of CO_2 from one area to another by way of random molecular motion. Under steady state conditions, the diffusion process follows Fick's first law, set out in Eq. (4) [3–5].

$$D = kt^n \tag{4}$$

where D is carbonation depth, k is a constant carbonation coefficient, t is time duration of exposure in years, and n is an exponent smaller than 1.0 (usually taken as 0.5).

Carbonation is a long-term durability problem of reinforced concrete, predominantly because it is the most significant cause of steel bar corrosion which, in turn, leads to concrete structural degradation [1,6]. Under normal conditions, steel reinforcement embedded within ordinary concrete is usually protected from corrosion by the high alkalinity of the surrounding concrete. Hobbs [7] suggested that 9.5 was the pH threshold value for the depassivation of steel. Nevertheless, the carbonation phenomenon leads to a lowering of the alkalinity of the concrete from approximately 12 to less than 9, which depassivates the steel reinforcement and exposes steel reinforcing bars to corrosion [8]. Neves et al. [9] presented a simple indirect assessment model of carbonation resistance which works by way of measuring concrete air permeability. This simple on-site non-destructive test assessment could provide useful and realistic information, upon which estimations of the service life of newly built concrete structure may be calculated.

1.2. Surface protection and carbonation of concrete

According to the research of Bara and Senbu [10], the surface protection of concrete could be classified into three groups: a cementitious finishing layer (such as organic paint coatings), surface improvement (such as barrier penetrants) and a non-cementitious finishing layer (such as mortar screeding); curve illustrations of the carbonation depth of the corresponding surface protected concrete were also proposed (see Fig. 1). This suggested that the carbonation depths of cementitious materials were linear to the square root of the exposure times, while the carbonation rate of concrete with a non-cementitious paint coating increased along with the square root of the exposure time.

Anti-carbonation paints, and some other high quality acrylic and vinyl–acrylic coatings, have proved effective in preventing the carbonation of concrete in tropical environments, with the support of laboratory test results [11]. Park [12] reported that acrylic paint coating had a diffusion coefficient of 6.15×10^{-12} m^2/s and a permeation coefficient of 63.8×10^{-17} kmol/s m kPa for CO_2, and when applying the paint to concrete substrate; the carbonation depth of concrete after ten years was reduced by 40%, from 12.5 mm to 7.5 mm. Franzoni et al. [13] selected inorganic ethyl silicate and sodium silicate paints as the surface coating materials of concrete. The test results of their accelerated carbonation test showed that, after a 60 day exposure in a carbonation chamber (at a concentration of CO_2 = 20 ± 2%, T = 25 ± 5 °C and RH = 70 ± 5%), the carbonation depth of the concrete varied from 11.1 to 3.9 mm in concrete coated with ethyl silicate and from 5.7 to 1.9 mm in concrete coated with sodium silicate. This meant that these two surface treatments both effectively limited the penetration of CO_2.

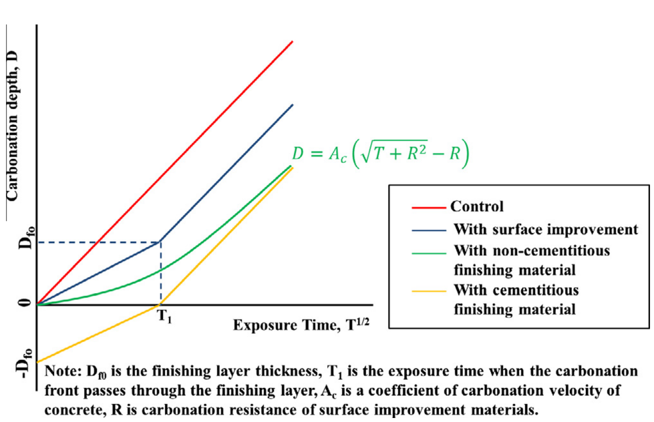

Fig. 1. Carbonation depth development model of concrete with different surface protections[10].

The contribution of concrete strength to carbonation rate has been studied in a number of previous studies [14–16]. Rabehi et al. [17] proved that carbonation depth was a decreasing function of compressive strength and proposed an exponential function ($D = 80e^{(-0.08 \times Cs28days)}$) correlation between the compressive strength Cs_{28days} (MPa) and the carbonation depth D (mm) at 180 days, by way of an accelerated carbonation test conducted at a CO_2 concentration of 50%, T = 20 ± 2 °C and RH = 66%.

Typically, the rate of carbonation depends on how fast CO_2 and/or carbonate ions can move into the concrete and react with the cement paste, a process which is affected by the permeability of the concrete, water/cement (w/c) ratio, curing conditions, cement type, concentration of CO_2 in the atmosphere and other environmental conditions. Additionally, inadequate concrete cover, cracking of the concrete, and low strength grade and poor quality concrete will also result in the high permeability of CO_2 for concrete [BRE 18, 19]. Therefore, the use of surface protection, like paint coating, and a higher strength grade of the concrete substrate should enhance the durability of concrete against carbonation [20,21].

For paint, a current standard (BS EN 1062-6, 2002) used to evaluate the anti-carbonation performance of paint, namely the equivalent air thickness (R-value) method, is based on the diffusion resistance of the paint membrane itself, which is not a direct measurement of the concrete carbonation. The R-value, expressed as an equivalent air layer thickness, is always quoted, which allows the air thickness to be quantified so as to specify both the barrier performance of a coating and how thick a layer of air with the same diffusion resistance would be required to be.

The accelerated carbonation test provides a fast standardized direct measurement method with which to assess the carbonation protection of different paint coatings for concrete substrate.

1.3. Research significance

The service lives of most of paints that are commonly marketed are less than 15 years, while the designed life of residential building is much larger than that. In this case, reapplication of paint is needed in order to maintain the anti-carbonation capacity of buildings when the paint coating is about to be out of function. Meanwhile, the time interval of reapplication of paints should be adjusted with thickness of concrete cover and designed service life of buildings. So, a better understanding of the development of accelerated carbonation depth of paint coated concrete is required when predicting natural carbonation depth of concrete after paint coating.

The durability of a paint coated concrete structure against carbonation is dependent on the cooperative effect of the paint coating and the quality of the concrete substrate, but the effect of quality of concrete substrate was less studied in the existing literatures. A measurement model to evaluate the anti-carbonation performance of paint applied to different qualities of concrete substrates is therefore necessary. Accelerated cured concrete specimens are more sensitive to carbonation because the pores of steam cured concrete are normally larger in size than those found in standard cured concrete. The use of accelerated cured concrete

specimens to evaluate the carbonation rate of paint coated concrete is worth considering.

In this research, the concept of the carbonation suppression ratio of paint is introduced to evaluate the anti-carbonation performance of paints. Two standard grades (C25, C35) of substrate concrete were prepared for the accelerated carbonation test, and the effects of the standard curing method and the accelerated curing method in the preparation of the concrete substrate were also examined. In addition, the relationship between the carbonation resistance and the exposure times of the various paint coated concretes was formulized.

2. Experimental methods

2.1. Materials

In this research, eight paints commonly used as finishing materials for concrete buildings were selected. Their quality and performance requirements [22] are shown in Tables 1 and 2, respectively. The four selected interior paints were all emulsion paints while the four exterior paints were all synthetic paints. Emulsion paints comprising tiny beads of resin binder that, along with pigments, are dispersed in water; Synthetic paint incorporating synthetic resin, such as acrylic, which is a synthetic polymer used in latex-based or water-based paint. The average dry thickness of the paint membranes was 30–40 microns; two coats of the paints were applied, with a two hour interval in between.

Concrete prisms with 28 day compressive strengths, C25 and C35, in accordance with CS1 [23] were used as standard concrete substrates in order to compare the anti-carbonation effect of paint coatings. The size of the concrete prisms was $100 \times 100 \times 300$ mm and the mix proportion was shown in Table 3. The C25 standard cured concrete and C35 standard cured concrete are denoted as C25 SCC and C35 SCC, while the C25 accelerated cured concrete and C35 accelerated cured concrete are denoted as C25 ACC and C35 ACC. The cement used was Portland cement with strength class 52.5, in compliance with BS EN 197-1 [24].

The standard cured concrete (SCC) specimens were placed in a curing room with relative humidity > 95% and temperature 20 ± 2 °C for 28 days. In contrast, the accelerated cured concrete (ACC) specimens were immersed in a hot water tank at 60 ± 3 °C for three days, in consideration of the fact that the strength of the ACC specimens would become stable for testing. The specimens were then air cured at 20 °C for three days to allow the concrete surface to air dry before applying the paint. The paint was applied on one side of the concrete prism while the opposite side of the prism remained uncoated. The other four surfaces of the specimens were sealed with wax.

2.2. Accelerated carbonation test method

The CO_2 concentration in the carbonation acceleration test chamber (following the GB/T 50082 standard (2009)) was maintained at 20 ± 3 °C with RH 70 ± 5%. This concentration of CO_2 simulates the natural carbonation characteristics of concrete under laboratory controlled conditions. If the CO_2 concentration is too high, the early carbonation rate will be high; if the concentration is too low, the carbonation rate will be too slow and the practical testing period will be very long. Standard GB/T50082 [25] projects that coated concrete specimens undergoing accelerated carbonation inside the chamber for 28 days is equivalent to 50 years of concrete carbonation under natural environmental conditions.

Table 3
Mix proportion of the concrete specimens.

Strength Grade	Materials (kg/m^3)				w/c
	Cement	Sand	Aggregate	Water	
C25	350	786	1085	140	0.40
C35	400	787	1086	160	0.40

In this study, the specimens were removed from the accelerated carbonation chamber at 7, 14, 28 and 56 days for carbonation depth measurements. Each sample was sliced into two halves and sprayed with phenolphthalein solution. The color of the specimens changed to purple in areas in which the pH level remained greater than 9. The carbonation depth represented by the frontline of no color change could be distinguished easily from the uncarbonated portion. The final carbonation depth was determined by taking average depth measurements at 10 mm interval points.

There is other method such as the Fourier-transform infrared spectroscopy (FT-IR) method that can assess the carbonation depth of concrete, but, it is limited by the fact that the correlation of FT-IR against pH of concrete has not been well developed and complexity in the analysis method. Using a phenolphthalein indicator solution to monitor carbonation depths has been well documented and is more convenient [26].

2.3. Measurement of the carbonation suppression ratio of paint

The anti-carbonation performance of paint coatings on concrete substrate is measured by way of carbonation suppression ratio, based on the concept of Hara et al. [27]. As shown in Fig. 2, when the carbonation depths of the coated and uncoated sides of the concrete samples were compared, the carbonation suppression ratio ($\mathbf{R}_{cs}$) can be calculated, as follows:

$$\mathbf{R}_{cs} = \frac{(d_p - d_0)}{d_p} \times 100\% \quad (5)$$

where d_p is the carbonation depth measured from the uncoated side of the concrete specimen, and d_0 is the carbonation depth measured from the coated side of the concrete specimen. So, when the paint has a carbonation suppression ratio of x%, it can preserve x% of the un-carbonated section compared to the same concrete substrate without paint coating under the same service period. Compared with the exist evaluation method of equivalent air thickness (R-value) method (BS EN 1062-6, 2002), the carbonation suppression ratio can be used to compare the effect of paint applied on concrete on carbonation reduction directly. Its usage provides a relative accurate comparison parameter to estimation of service life of reinforced concrete structure or for economic evaluation of implementing paint applications to concrete constructions.

3. Results and discussion

3.1. Carbonation depths of paint coated SCC and ACC specimens

There are four interior paints and four exterior paints used in this study. The averages and their deviation ranges of the carbonation depths of the paint coated C25 SCC, C35 SCC, C25 ACC and C35 ACC specimens at 0, 7, 14, 28 and 56 days are presented in

Table 1
Quality and performance requirements for interior paint [22].

Items	Test method	Acceptance criteria
Viscosity	ASTM D562-10	Min. 75 KU, Max 95 KU
Hiding power (contrast ratio %)	BS EN ISO 2814:2006	BS 4800 Min. 60; for colored paints
Drying time – Hard drying	BS EN ISO 9117-1:2009	Max. 1 h
Fineness of grind (μm)	BS EN ISO 1524:2013	Max. 40 μm

Table 2
Quality and performance requirements for exterior paint [22].

Items		Test method	Acceptance criteria
Drying times	Surface drying (hour)	BS EN ISO 9117-3:2010	<=4
	Hard drying (hour)	BS EN ISO 9117-1:2009	<=18
Fineness of grind (μm)		BS EN ISO 1524:2013	<=25
Hiding power (contrast ratio %)		BS EN ISO 2814:2006	Solvent base: >=85 Water base: >=60
Viscosity	Solvent based: by Flow Cup No. 6 (s)	BS EN ISO 2431:2011	45–60
	Water based: by Viscometer (KU)	ASTM D562-10	75–85

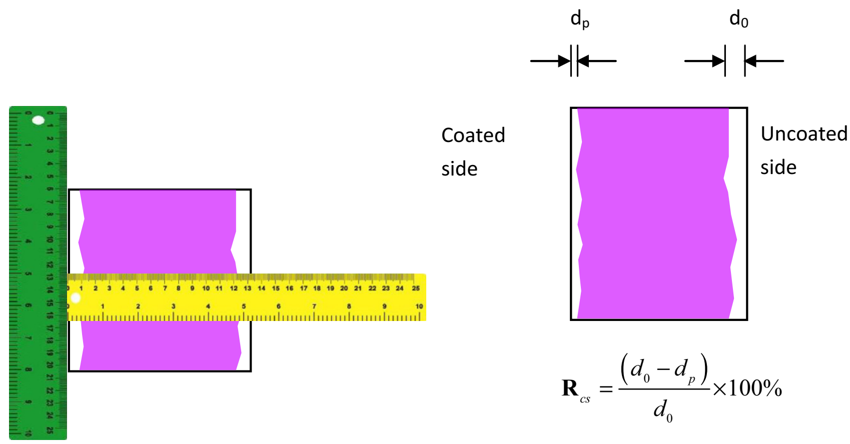

Fig. 2. Schematic diagram of carbonation depth measurement.

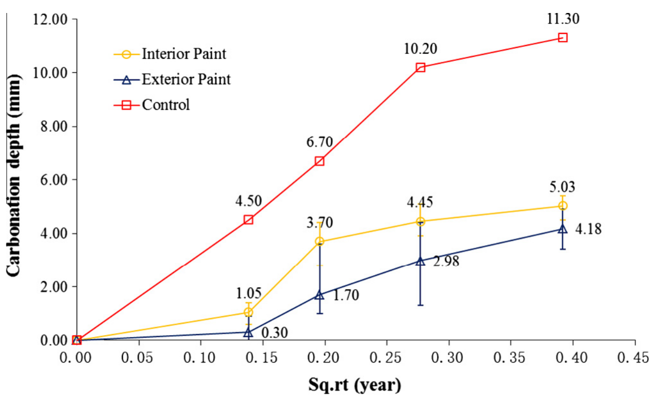

Fig. 3. Average carbonation depth versus exposure time for C25 standard cured concrete (SCC) specimens coated with the interior and exterior paints.

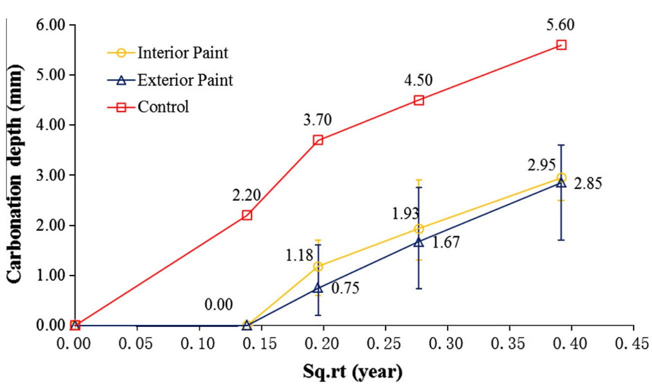

Fig. 4. Average carbonation depth versus exposure time for C35 standard cured concrete (SCC) specimens coated with the interior and exterior paints.

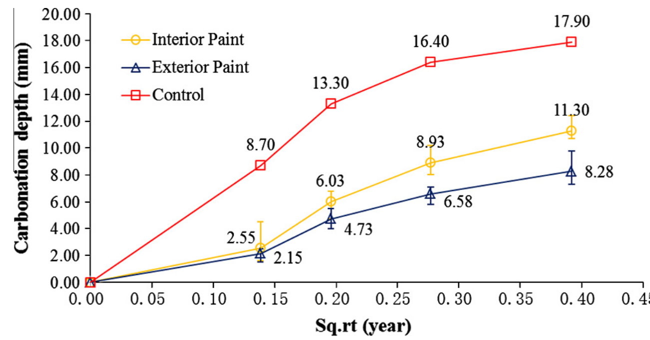

Fig. 5. Average carbonation depth versus exposure time for C25 accelerated cured concrete (ACC) specimens coated with the interior and exterior paints.

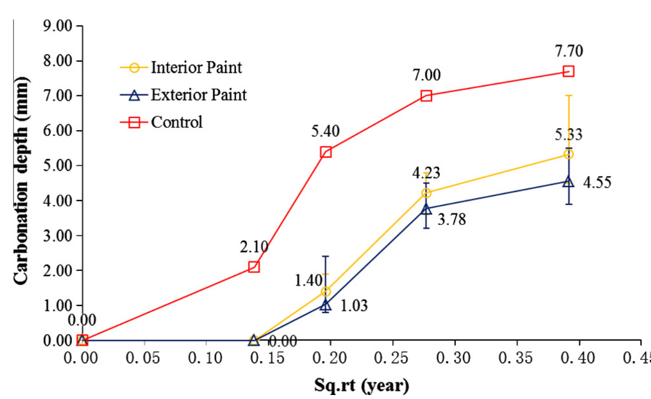

Fig. 6. Average carbonation depth versus exposure time for C35 accelerated cured concrete (ACC) specimens coated with the interior and exterior paints.

Figs. 3–6, respectively. The exposure time in the figures is the square root of the exposure time in years (sq.rt of year). The exposure times of 0, 7, 14, 28 and 56 days are converted to the corresponding square root values of 0, 0.138, 0.196, 0.277 and 0.392, respectively.

In Figs. 3 and 5, the carbonation depths of the control C25 SCC and C25 ACC specimens for the first 28 days generally follows a linear relationship with the square root time, and the carbonation rate slows down obviously after 28 days' accelerated carbonation. The phenomenon of the reduction of carbonation with time can be explained by the closing up of capillary pores in the CSH, making CO_2 diffusion into the hardened concrete difficult [28], and the increase tendency of compressive strength of concrete with uptake of CO_2 [29–31]. For both exterior and interior paint coated C25 SCC and C25 ACC specimens, their carbonation rates during the first seven days are much lower than after the next seven days, due to the enhanced impediment effect of paint coating on concrete carbonation ingress in the early stages.

In contrast, the carbonation depths of the control C35 SCC and C35 ACC specimens throughout the whole accelerated carbonation test remain linear to the square root time with no significant change in carbonation rate, as shown in Figs. 4 and 6. This is contributed to the higher strength grade of the substrate concrete that postpones the occurrence of the changing point.

It is important to note that for the paint coated C35 SCC and C35 ACC specimens, their carbonation depths remained at zero for the first seven days because the cooperative effect of higher strength grade and paint coating can completely prevent CO_2 infiltration in the early stages. After seven days' accelerated carbonation treatment, the carbonation depths of the paint coated concrete began to follow a linear relationship with the square root time. The carbonation rate of the exterior paint coated concrete was more stable than that of the interior paint coated concrete.

In comparison with the 28 day carbonation depth of the control C25 SCC (10.20 mm, Fig. 3) and C35 SCC (4.45 mm, Fig. 4) specimens, the decrease in depth (5.75 mm) of the C35 SCC specimen was 56% smaller than that of the C25 SCC specimen. It can be seen that the higher grade concrete substrate can greatly reduce carbonation depth and increase carbonation resistance. Indeed, reduction of carbonation depth can be achieved by either increasing the concrete grade or by the provision of coatings.

It is well demonstrated that the carbonation depth of the C25 SCC specimen coated with interior paint is closed to that of the control C35 SCC specimen in Figs. 3 and 4; the carbonation depth of the C25 ACC specimen coated with interior paint is slightly greater than that of the control C35 ACC specimen. The improvement in carbonation resistance achieved by increasing the concrete grade from C25 to C35 is the same, or an even greater than that achieved by coating with interior paint.

To compare the effects of the accelerated curing of concrete (for precast components) on carbonation, it can be seen that the carbonation depths of the control C25 ACC and C35 ACC specimens were increased by 61% and 56%, respectively, with respect to the C25 SCC and C35 SCC specimens. This confirms that the ACC specimens have lower carbonation resistance than the SCC specimens. This phenomenon can be explained by the high hydration speed of concrete curing in hot water, which led to a larger volume of capillary pores and increased the permeability of CO_2 [26,32]. With a larger carbonation rate, the ACC specimens are more sensitive for use in the evaluation of the carbonation rate of paint coated concrete.

3.2. Formulation of the carbonation resistance of paint coated concrete

Using the least square method, the linear relationships between carbonation depths and exposure times of the SCC and ACC specimens with interior and exterior paint coatings are developed in Fig. 7. In Fig. 7, the slopes of the equation represent the carbonation rates (mm/year$^{1/2}$), and the intercepts of the x-coordinate indicate the effective blockage times of the paint coating layers to CO_2 (year$^{1/2}$). The effective blockage time and carbonation rate for both SCC and ACC samples are presented summarized in Table 4.

In Fig. 7, there is a minority difference in the carbonation curve to the curve $D = A_c\left(\sqrt{T + R^2} - R\right)$ (see Fig. 1, proposed by Bara et al. [10]) of concrete with a non-cementitious finishing layer. Indeed, they are the same because the dry thicknesses of the paint coatings used in the test are generally less than 100 um. The section of curve before $x < T_1$ looks very short; it becomes a linear line and carbonation start to grow significantly after $x > T_1$.

In the initial stage, as seen in Fig. 7, there is a time delay of the carbonation curves that we call effective blockage time for the paint coated concrete. The time delay of carbonation denoted that the paint coating layer can effectively block the ingress of CO_2 in the initial stage, after its first application. Carbonation within the paint coated concrete only starts to occur at some time after the test begins ($t > 0$).

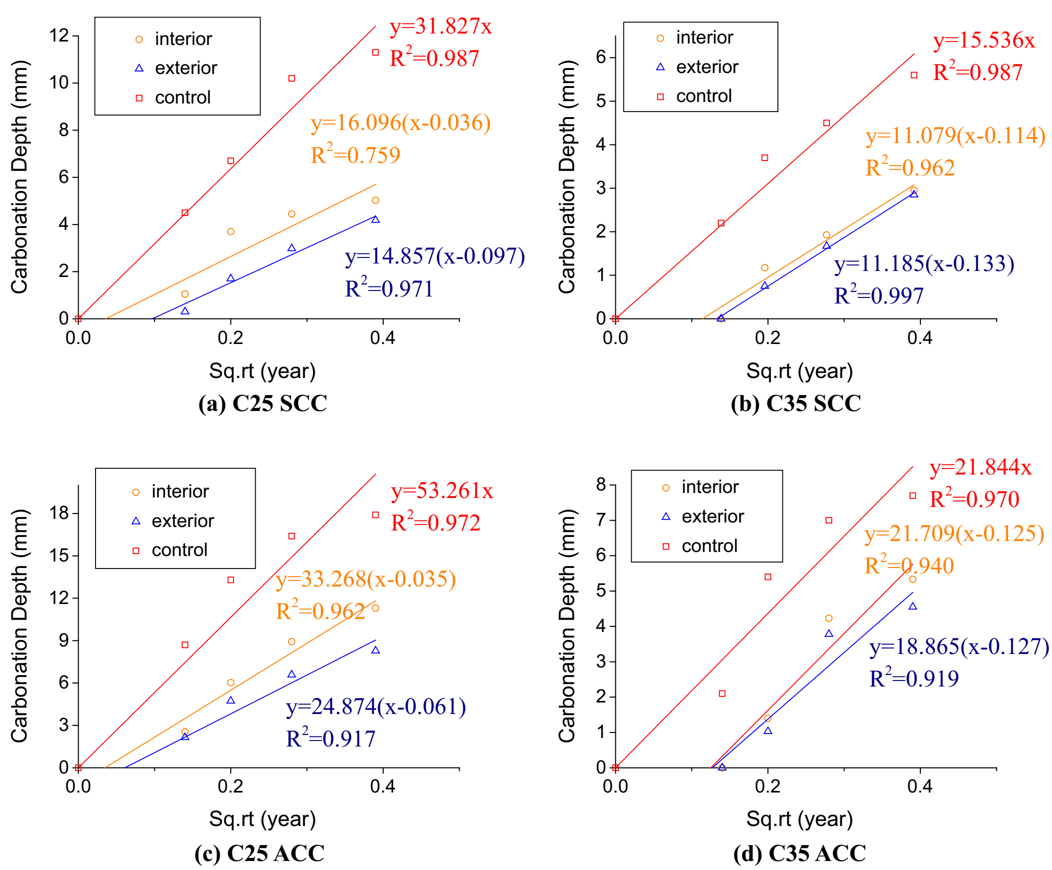

Fig. 7. Linear correlation between carbonation depth and exposure time of paint coated concrete in accelerated carbonation test (based on the average carbonation depths shown in Figs. 3–6).

Table 4
Carbonation resistances of different combinations of paint and concrete substrate.

Paint coated concrete			Carbonation resistance		
Paint	Concrete substrate		Carbonation rate (mm/year$^{1/2}$)	Effective blockage time (year$^{1/2}$)	R^2
	Curing method	Strength grade			
Control	Standard	C25	31.827	0	0.987
		C35	15.536	0	0.987
	Accelerated	C25	53.261	0	0.972
		C35	21.844	0	0.970
Interior	Standard	C25	16.096	0.036	0.759
		C35	11.079	0.114	0.962
	Accelerated	C25	33.268	0.035	0.962
		C35	21.709	0.125	0.940
Exterior	Standard	C25	14.857	0.097	0.971
		C35	11.185	0.133	0.997
	Accelerated	C25	24.874	0.061	0.917
		C35	18.865	0.127	0.919

Table 5
Calculation of carbonation reduction of the C25 and C35 standard cured concrete (SCC) and carbonation suppression ratios of paints.

Concrete substrate	Paint		Average carbonation depth (mm)			
			7-day	14-day	28-day	56-day
C25 SCC	Control (C)		4.50	6.70	10.20	11.30
	Interior (I)		1.05	3.70	4.45	5.03
	Exterior (E)		0.30	1.70	2.98	4.18
	Difference (D) [Suppression Ratio]	C–I [D/C × 100%]	3.45	3.00	5.75	6.28
			[77%]	[45%]	[56%]	[56%]
		I–E [D/I × 100%]	0.75	2.00	1.48	0.85
			[71%]	[54%]	[33%]	[17%]
		C–E [D/C × 100%]	4.20	5.00	7.23	7.13
			[93%]	[75%]	[71%]	[63%]
C35 SCC	Control (C)		2.20	3.70	4.50	5.60
	Interior (I)		0.00	1.18	1.93	2.95
	Exterior (E)		0.00	0.75	1.67	2.85
	Difference (D) [Suppression Ratio]	C–I [D/C × 100%]	2.20	2.52	2.57	2.65
			[100%]	[68%]	[57%]	[47%]
		I–E [D/I × 100%]	0.00	0.43	0.26	0.10
			-	[36%]	[13%]	[3%]
		C–E [D/C × 100%]	2.20	2.95	2.83	2.75
			[100%]	[80%]	[63%]	[49%]

When coating with the interior paint, The time delays for the C25 ACC, C25 SCC, C35 ACC and C35 SCC are 0.036 year$^{1/2}$, 0.035 year$^{1/2}$, 0.114 year$^{1/2}$ and 0.125 year$^{1/2}$, respectively; while coating with exterior paint, the time delays for the C25 ACC, C25 SCC, C35 ACC and C35 SCC are 0.097 year$^{1/2}$, 0.061 year$^{1/2}$, 0.133 year$^{1/2}$ and 0.127 year$^{1/2}$, respectively. Therefore, concrete with the exterior paint coating has a longer effective blockage time than that with the interior paint coating.

After the initial stage, CO_2 begins to infiltrate the paint coated concrete composite when the coating and concrete substrate work together to resist carbonation ingression. The carbonation depths increase linearly to the square root of the exposure times. A high regression coefficients R^2 above 0.9, particularly those for the control concrete whose R^2 is above 0.97, represents a relatively good fitting linear relationship between the carbonation depth of concrete and the square root of exposure time.

The carbonation rates of the four types of control concrete in decreasing order are C25 ACC (53.261 mm/year$^{1/2}$), C25 SCC (31.827 mm/year$^{1/2}$), C35 ACC (21.844 mm/year$^{1/2}$) and C35 SCC (15.536 mm/year$^{1/2}$). After coating with the paints, the carbonation rates of concretes decrease significantly. The carbonation rates of the paint coated concretes in decreasing order are C25 ACC (I: 33.268 mm/year$^{1/2}$, E: 24.874 mm/year$^{1/2}$), C35 ACC (I: 21.709 mm/year$^{1/2}$, E: 18.865 mm/year$^{1/2}$), C25 SCC (I: 16.096 mm/year$^{1/2}$, E: 14.857 mm/year$^{1/2}$) and C35 SCC (I: 11.079 mm/year$^{1/2}$, E: 11.185 mm/year$^{1/2}$). This finding confirms that concrete with the exterior paint coating has a lower carbonation rate than that with the interior paint coating. Carbonation rate is also sensitive to the strength grade and the curing conditions of the concrete substrate.

To conclude, the carbonation resistance of the paint coated concrete is influenced by the type of paint and both the curing conditions and the strength grade of concrete substrate.

3.3. Carbonation reduction and suppression ratio of paint

To evaluate the anti-carbonation performance of paints applied on a reference concrete substrate, the carbonation reduction and suppression ratios of the paints applied to the SCC and ACC substrates are calculated in Tables 5 and 6.

The effect of paint coating in reducing the carbonation depth of concrete specimens is significant. From Table 5, it can be seen that the 28-day carbonation depth of the C25 SCC specimen decreased from 10.2 mm to 4.45 mm (a 56% reduction) for coatings with interior paint and to 2.98 mm (a 71% reduction) for coatings with exterior paint. The 28-day carbonation depth of the C35 SCC concrete decreased from 4.5 mm to 1.93 mm (a 57% reduction) for coatings with interior paint and to 1.67 mm (a 63% reduction) for coatings with exterior paint. For accelerated concrete samples, the 28-day carbonation depth of the C25 ACC specimen, as seen in Table 6, shows a reduction of 46% for coating with interior paint and 60% for coating with exterior paint. As for the C35 ACC, the reduction

Table 6
Calculation of carbonation reduction of the C25 and C35 accelerated cured concrete (ACC) and carbonation suppression ratios of paints.

Concrete substrate	Paint		Average carbonation depth (mm)			
			7-day	14-day	28-day	56-day
C25 ACC	Control (C)		8.70	13.30	16.40	17.90
	Interior (I)		2.55	6.03	8.93	11.30
	Exterior (E)		2.15	4.73	6.58	8.28
	Difference (D) [Suppression Ratio]	C–I [D/C × 100%]	6.15	7.28	7.48	6.60
			[71%]	[55%]	[46%]	[37%]
		I–E [D/I × 100%]	0.40	1.30	2.35	3.03
			(16%)	(22%)	(26%)	(27%)
		C–E [D/C × 100%]	6.55	8.58	9.83	9.63
			[75%]	[64%]	[60%]	[54%]
C35 ACC	Control (C)		2.10	5.40	7.00	7.70
	Interior (I)		0.00	1.40	4.23	5.33
	Exterior (E)		0.00	1.03	3.78	4.55
	Difference (D) [Suppression Ratio]	C–I [D/C × 100%]	2.10	4.00	2.78	2.38
			[100%]	[74%]	[40%]	[31%]
		I–E [D/I × 100%]	0.00	0.38	0.45	0.77
			–	[27%]	[11%]	[15%]
		C–E [D/C × 100%]	2.10	4.38	3.23	3.15
			[100%]	[81%]	[46%]	[41%]

is just 40% for the interior paint coated sample and 46% for the exterior paint coated sample.

Comparing the effect of paint types on carbonation depth, it can be seen that the exterior paint always achieves a better anti-carbonation performance than the interior paint, and the difference between them reduces with the increase of the exposure time and strength grade of the concrete substrate. As seen in Tables 5 and 6, the carbonation depths of the C25 SCC coated with exterior paint are 71%, 54%, 33% and 17% smaller than with the interior paint at the age of 7, 14, 28 and 56 days, respectively. Meanwhile, the differences between the carbonation depths at 14, 28 and 56 days of the C35 SCC coated with interior or exterior paint are smaller than those of the C25 SCC, which are 36%, 13% and 3%.

Suppression ratio can be used to compare the effect of paints on carbonation reduction. According to Tables 5 and 6, the carbonation suppression ratio of the paint decreases with increase of the elapsed time of the accelerated carbonation test. When interior paint is used, the carbonation suppression ratios of the C25 SCC and C35 SCC fall from 77% to 45% and from 100% to 47% during the test period, respectively. Meanwhile, for the exterior paint coating, the carbonation suppression ratios fall from 93% to 63% and from 100% to 49%, respectively. Compared to the ACC specimens, the carbonation suppression ratios of the C25 ACC and C35 ACC with interior paint coating fall from 71% to 37% and from 100% to 31%, respectively, throughout the test period. The carbonation suppression ratios of the C25 ACC and C35 ACC using exterior paint fall from 75% to 54% and from 100% to 41%, respectively.

It is concluded that the exterior paint has a relatively higher carbonation suppression ratio than the interior paint throughout the test period for both SCC and ACC. The carbonation suppression ratio of the paint decreases with an increase in the elapsed time of the accelerated carbonation test.

Although standard GB/T50082 [25] projected that the paint coated concrete specimens undergoing accelerated carbonation inside the chamber for 28 days would be equivalent to concrete carbonation over a 50 year period under natural environmental conditions, a detailed correlation between the exposure time in the accelerated carbonation test and the exposure time in the natural environment is yet to be developed.

4. Conclusions

Based on the above discussion, the following conclusions can be drawn:

(1) The ACC specimens are more sensitive for use in the evaluation of the carbonation rate of paint coated concrete.
(2) The exterior paint has a better anti-carbonation performance than the interior paint, but the difference is not significant when the strength of the concrete substrate is increased.
(3) Concrete with the exterior paint coating has a longer effective blockage time than that with the interior paint coating. After the effective blockage time, the coating and the concrete substrate work together to resist carbonation ingression. There is a linear relationship between the carbonation depths of paint coated concrete to the square root of the exposure times.
(4) Carbonation suppression ratio of the paint decreases with increase of the elapsed time of accelerated carbonation test for both SCC and ACC. The exterior paint has a relatively higher carbonation suppression ratio than the interior paint throughout the test period.

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