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Relationship between the Surface Absorption of Concrete Cores and Durability Performance of Existing Structures

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ABSTRACT

The surface absorption property of dried concrete cores was examined as a durability index for the quality of hardened concrete. The apparent diffusion coefficient of chloride ions and the coefficient of the rate of carbonation of concrete were estimated from investigation data obtained from 152 existing structures. The results showed that there is a good relationship between the amount of surface absorption after 6h and the apparent diffusion coefficient of chloride ions, while the apparent coefficient can vary widely even in concrete whose compressive strength is within a certain range. Surface absorption properties, therefore, can be a better durability index for the concrete in structures than the conventional compressive strength of concrete cores. The relationship between the amount of surface absorption after 6h and the coefficient of the rate of carbonation of cores was not significant, while the average coefficient of the rate of carbonation varied widely because of difference in local climates in Japan.

Keywords. Existing structures, Cover concrete, Absorption, Diffusion coefficient of chloride ions, Carbonation

BACKGROUND

It is estimated that in the near future, the public budget for the maintenance of civil infrastructures in Japan will become insufficient. For this reason, effective appraisal methods for existing concrete structures and effective construction techniques that can improve the durability of newly constructed concrete structures are needed.

Although there are various deterioration mechanisms of concrete structures, the corrosion of re-bars in concrete is a high-priority concern because it can significantly affect the safety of structures. The quality of the cover concrete is an important factor in protecting re-bars from corrosion. In this study, corrosion due to chloride attack and carbonation is discussed.

The compressive strength of concrete is conventionally considered to be a general index of the quality of hardened concrete. However, the quality of cover concrete can be significantly affected by the way in which concrete construction is practiced, while compressive strength is more robust. Therefore, test methods that can evaluate the quality of cover concrete are needed.

In this paper, the water absorption properties of concrete cores are discussed as a quality index for cover concrete, since recent research has shown the relationship between the depth of water penetration from the surface and the ingress of chloride ions (Takahashi, 2012). The absorption properties of concrete can also reflect the density of the mortar matrix, which also affects the carbonation of concrete.

RESEARCH METHODS

Collection of data. In this paper, the durability performance of concrete is discussed using the data of 152 existing concrete structures investigated by the Ministry of Construction in 1999 (Kawano, 2001). The investigated concrete structures were selected from bridge substructures, retaining walls, culverts, and river structures. They were considered to be unbiased with regard to age and geographical distribution.

Test methods. Three cores were taken from each investigated structure in principle, and their compressive strength, carbonation depth, total amount of chloride ion, and absorption property were measured (Figure 1). Carbonation depth was measured using phenolphthalein solution on the side surface of the cores. The total amount of chloride ion was measured using the test method for chloride ion content in hardened concrete (JCI-SC4). Measurement of the total amount of chloride ion was carried out using one core per investigated structure. The other tests were carried out using three cores per structure.

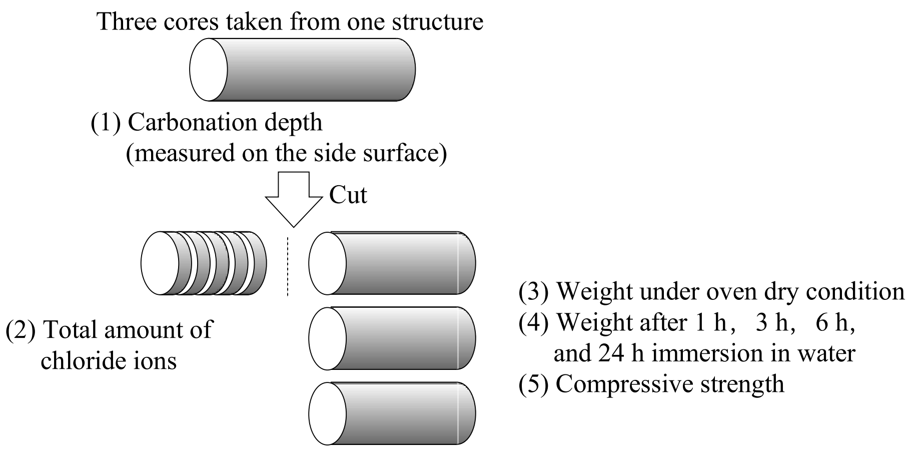


Figure 1. Procedure of tests using core samples

The absorption property of a core was tested using the following method. First, the weight of a core under an oven dry condition (105 °C, 24 h) was measured. Next the core was ponded in water (approx. 20 °C), and the weight was measured after 1, 3, 6, and 24 h. After 24 h, the volume of the core was measured using the Archimedean method.

Coefficient of the rate of carbonation. Durability performance was evaluated using the coefficient of the rate of carbonation as calculated using Equation 1, in order to compare the data from structures that represented a wide range of ages.

$$b = \frac{y}{\sqrt{t}} \tag{1}$$

Where b: the coefficient of the rate of carbonation (mm/√year), y: carbonation depth (mm), and t: time since construction (years)

Diffusion coefficient of chloride ions. It is usually understood that the ingress of chloride ions into hardened concrete is driven by diffusion. Then distribution of the chloride ion concentration in a core can be represented by Equation 2 for the case that chloride ions ingress from one surface of the concrete by diffusion. The apparent diffusion coefficient of chloride ions, the chloride ion concentration on the surface and the initial chloride ion concentration in concrete were estimated using the total amount of chloride ions measured in three to five slices of a core.

$$C_x = C_0\left(1 - erf\left(\frac{0.1 \cdot x}{2\sqrt{D_c \cdot t}}\right)\right) + C_i \tag{2}$$

Where C_x: total amount of chloride ion in x mm from the surface (kg/m^3). C_0: chloride ion concentration on the surface (kg/m^3), D_c: apparent diffusion coefficient of chloride ions (cm^2/year), t: time since construction (years), and C_i: initial chloride ion concentration in concrete (kg/m^3)

Sources of chloride ions, on the other hand, were estimated from the location of the concrete structures. The results are summarized in Table 1. The source of chloride ions was estimated as "airborne salt" where structures were located in the chloride attack circumstances described in the specification for the highway bridge in Japan (Japan Road Association, 2012). The source of chloride ions was estimated as "brackish water" if structures were bridge substructures located in a river that could be intermixed with sea salt. The source of chloride ions was estimated as "deicing salt" if the structures could be affected by deicing salt and whose location did not fit the circumstances for "airborne salt" or "brackish water." There were a small number of structures whose concrete did contain a certain amount of chloride ion, but whose source was uncertain. Such structures were eliminated from the following discussion. In total, there were 45 structures whose cores contained a certain amount of chloride ion, the source of which could be estimated.

Table 1. Estimated sources of chloride ions

Source of chloride ions	Number of samples	Typical conditions of concrete structures
Airborne salt	12	Concrete structures near the sea.
Brackish water	5	Concrete structures in a river at locations several kilometres from the sea.
Deicing salt	28	Concrete structures located where the supply of airborne salt and brackish water can be neglected but deicing salt can be a factor.

Amount of surface absorption. The amount of surface absorption was calculated by Equation 3 in order to compare the data using cores that have a small difference in their sizes.

$$I_t = \frac{W_t - W_d}{A \cdot \rho} \qquad (3)$$

Where It: the amount of surface absorption after t h (mm), Wt: weight of a sample after t hour absorption (g), Wd: weight of a sample just before starting absorption (g), A: surface area of a sample (mm^2), and ρ: specific weight of water (g/mm^3)

RELATIONSHIP BETWEEN AMOUNT OF SURFACE ABSORPTION AND COMPRESSIVE STRENGTH

Relationship between the amount of surface absorption and compressive strength are shown in Figure 2. One conclusion presented by the results is that the greater the compressive strength of a core, the smaller the amount of surface absorption. Since concrete whose compressive strength is relatively high should have a dense mortar matrix, the amount of surface absorption of water should decrease in high strength concrete.

In this report, the amount of surface absorption after 6 h was chosen as an index that represents the absorption property of concrete, while there was no significant difference among the relationship between the amount of surface absorption after 3, 6, and 24 h and the compressive strength of concrete. However, it was considered difficult to use the 1 h of surface absorption as an index for determining concrete quality because the relationship between 1 h of surface absorption and the compressive strength of concrete was not clear enough due to the short testing duration.

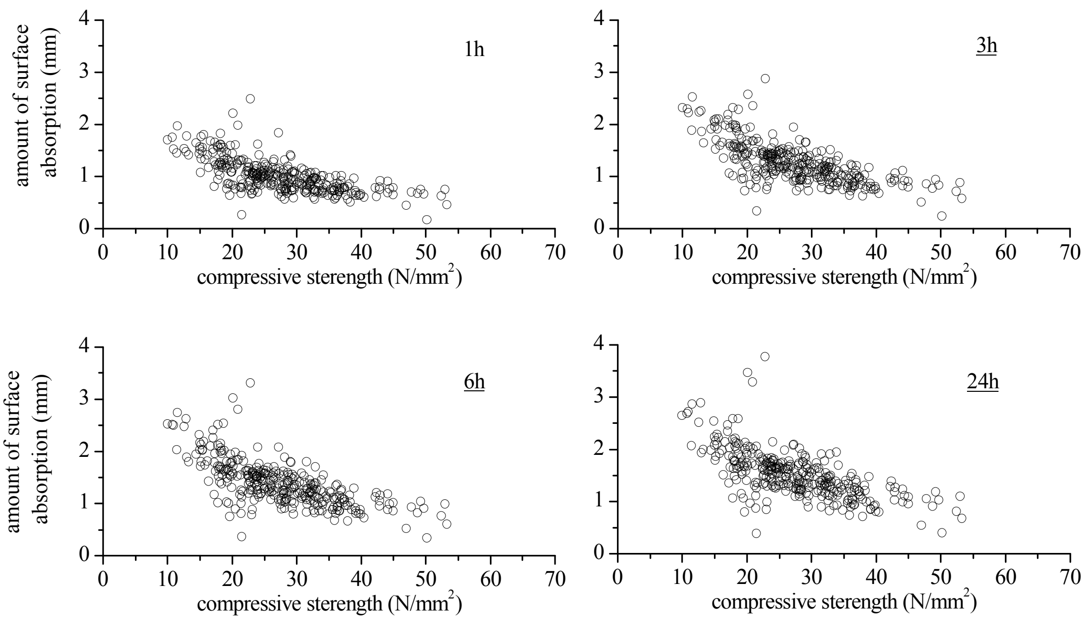
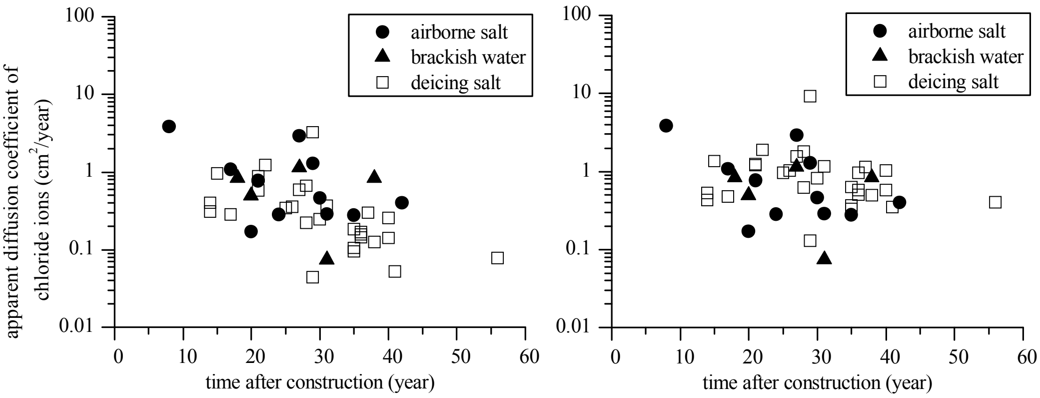


Figure 2. Relationship between compressive strength and amount of surface absorption after 1, 3, 6, and 24 h

RELATIONSHIP BETWEEN AMOUNT OF SURFACE ABSORPTION AND DURABILITY PERFORMANCE AGAINST CHLORIDE ATTACK

Apparent diffusion coefficient of chloride ions in existing structures. The estimated apparent diffusion coefficients of chloride ions in 45 cores are shown in Figure 3. First, the apparent diffusion coefficient was estimated under the assumption that the diffusion period of chloride ions started just after construction, the results are shown in Figure 3(a). With this assumption, the apparent diffusion coefficient shows a tendency to be small in older structures. This tendency is significant in structures affected by deicing salt. This finding is considered to reflect the change in the use of deicing salt. As is well known, the consumption of deicing salt in Japan increased after restriction were imposed on the use of studded tires (JCI, 1999).

For this reason, in the case of deicing salt, the diffusion coefficient was estimated using the assumption that the diffusion period of chloride ions was the 10-years period from 1989 to 1999. The results in this case are shown in Figure 3(b). With this assumption, the estimated diffusion coefficient is almost same whether the structure is old or new.



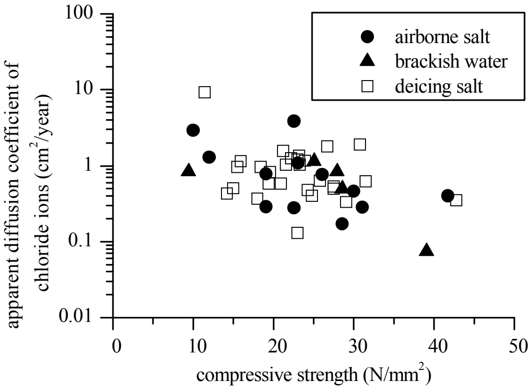
(a) Diffusion period supposed to start just after construction

(b) Diffusion period supposed to start from 1989 in the case of deicing salt

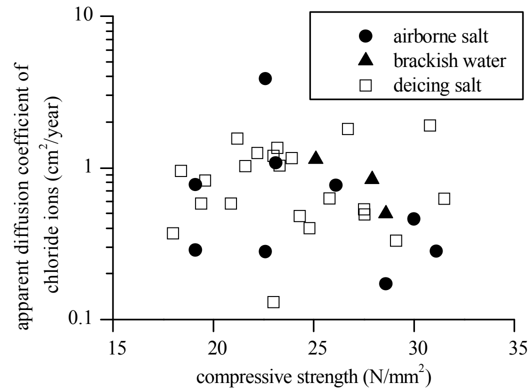
Figure 3. Apparent diffusion coefficient of chloride ions of concrete

Relationship between compressive strength and apparent diffusion coefficient of chloride ion. The quality of hardened concrete is generally evaluated in terms of its compressive strength. The relationship between compressive strength and the apparent diffusion coefficient of chloride ions is shown in Figure 4(a). The results confirm that the apparent diffusion coefficient of chloride ions is relatively small when the compressive strength is high and large when compressive strength is low.

However, there are the cores whose compressive strength is very high or low as is usual for concrete in reinforced concrete structures. For this reason, Figure 4(b) focuses on the 33 cores whose compressive strength is between 18 and 33 N/mm^2. The relationship between compressive strength and the apparent diffusion coefficient is less clear when the range of compressive strength is limited. It is difficult to classify the durability performance against chloride attack in terms of the compressive strength of the concrete cores in much detail.



(a) All data



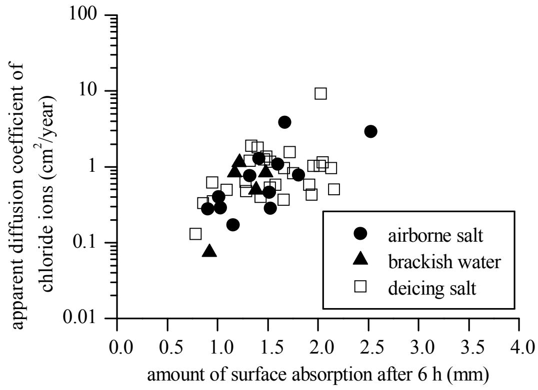
(b) Cores with compressive strengths between 18 and 33N/mm^2

Figure 4. Relationship between compressive strength and apparent diffusion coefficient of chloride ions

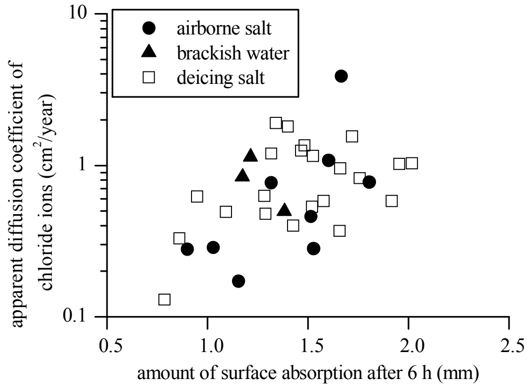
Relationship between amount of surface absorption and apparent diffusion coefficient of chloride ions. The relationship between the amount of surface absorption after 6 h and the apparent diffusion coefficient of chloride ions is shown in Figure 5(a). The apparent diffusion coefficient of chloride ions is relatively small when the amount of surface absorption after 6 h is small and large when the surface absorption is large.

Figure 5(b) shows the relationship between the amount of surface absorption after 6 h and the apparent diffusion coefficient in 33 cores whose compressive strength is between 18 and 33 N/mm^2. As can be seen in the figure, the relationship is also clear when the range of compressive strength is limited.

In Table 2, the data was classified in terms of compressive strength and the amount of surface absorption after 6 h. Although the data vary widely, the durability performance against chloride attack can be classified better by the amount of absorption after 6 h than by the compressive strength of the cores.



(a) All data



(b) Cores with compressive strengths between 18 and 33 N/mm^2

Figure 5. Relationship between the amount of surface absorption after 6 h and apparent diffusion coefficient of chloride ions

Table 2. Apparent diffusion coefficient of chloride ions in different qualities of concrete

Classification of quality of concrete	Apparent diffusion coefficient (cm^2/year)			
	Number of data	Minimum	Average	Maximum
(1) Compressive strength (fc)				
fc < 18	8	0.43	2.2	9.2
18 and 18 < fc <23	12	0.28	1.0	3.9
23 and 23 <fc <28	15	0.13	0.87	1.8
28 and 33 < fc <33	7	0.17	0.61	1.9
33 and 33 < fc	3	0.074	0.27	0.40
(2) The amount of surface absorption after 6 h (I_6)				
I_6 <1.0	6	0.074	0.30	0.62
1.0 and 1.0 < I_6 <1.3	8	0.17	0.55	1.1
1.3 and 1.3 < I_6 < 1.6	15	0.28	0.95	1.9
1.6 and 1.6< I_6 < 1.9	7	0.37	1.35	3.9
1.9< I_6	9	0.43	1.97	9.2

RELATIONSHIP BETWEEN AMOUNT OF SURFACE ABSORPTION AND DURABILITY PERFORMANCE AGAINST CARBONATION

Coefficient of the rate of carbonation in existing structures. At first, the relationship between the rate of carbonation and the local environment of concrete structures are discussed, because it is well known that the carbonation of concrete is affected not only by the quality of concrete, but also by the local environment, e.g., the temperature, humidity, etc., where the concrete structures are located. However, in this study, the information relating to the local environment of investigated structures was limited. In this paper, the local climate of locations and the structures' exposure to the rain were focused on because these properties could be estimated from the obtained documents and pictures.

The local climates where the concrete structures were located were classified into nine climatic divisions based on the classification shown in JIS Z 2381 appendix 1. The exposure conditions of coring spots were classified as "open," "half-sheltered," and "sheltered." For instance, a core sampling spot in a culvert can be sheltered from the rain while a core sampling spot in an abutment could have been half-sheltered by bridge girders. In this study, when cores were taken from the location where they could be submerged regularly, the data was neglected.

The relationship between compressive strength and the coefficient of the rate of carbonation in three representative climatic divisions is shown in Figure 6. It is confirmed that the rate of carbonation is relatively low when the compressive strength is high because of the dense mortar matrix. However, the rate of carbonation varies significantly from one climatic division to another. The average rates of carbonation are listed in Table 3. For instance, in the Seto Inland Sea division, the average carbonation rate is high, which could be due to the dry climate in this division. On the other hand, the average carbonation rates are low in the northern part of Japan, for instance, in the Hokkaido west/east and the Sea of Japan North divisions.

The relationship between exposure conditions and the rate of carbonation is not always significant, while in some climate divisions, the rates of carbonation seem to be lower when core sampling spots were exposed to the rain. The reason for this is not clear, but could be due to the inaccuracy of the classification of exposure conditions due to limited information.

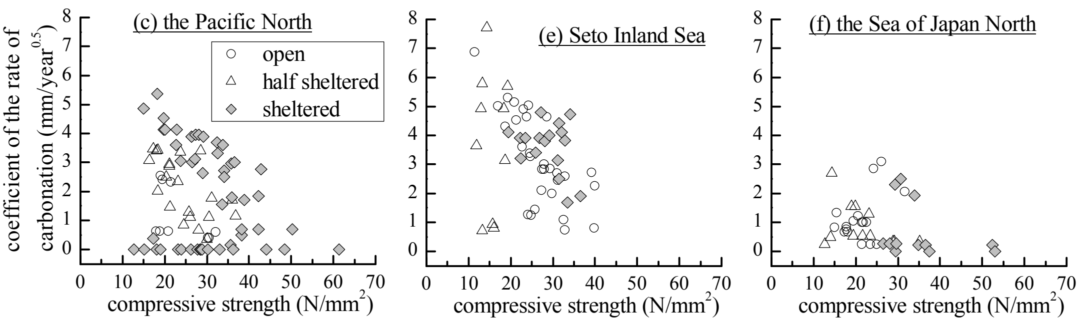


Figure 6. Relationship between compressive strength and the coefficient of the rate of carbonation of cores in representative climatic divisions of Japan

Table 3. Average coefficient of the rate of carbonation

Climatic division	Average coefficient of the rate of carbonation (mm/year$^{0.5}$)	
	18 and 18 < fc <28	28 and 28 < fc <38
(a) Hokkaido West	0.2	0.6
(b) Hokkaido East	1.3	0.3
(c) the Pacific North	2.3	1.6
(d) the Pacific South	2.5	2.4
(e) Seto Inland Sea	3.7	3.0
(f) the Sea of Japan North	1.1	0.8
(g) the Sea of Japan South	2.2	1.1
(h) Kyushu West	1.7	1.3
(i) Nansei Islands	2.0	0.5
total	2.4	1.6

Relationship between the amount of surface absorption and the rate of carbonation. The relationship between the amount of surface absorption after 6 h and the coefficient of the rate of carbonation is shown in Figure 7. As can be seen in the figure, the rate of carbonation is relatively low when the amount of surface absorption after 6 h is small.

However, it is difficult to discuss the rate of carbonation only in terms of the amount of surface absorption after 6 h, because it can be affected significantly by the local climate and the exposure conditions of the concrete structure.

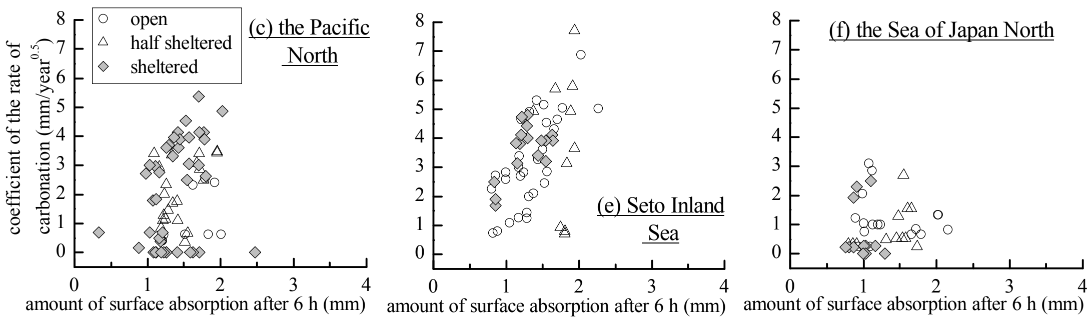


Figure 7. Relationship between the amount of surface absorption after 6 h and coefficient of the rate of carbonation of cores

CONCLUSION

In this paper, the water absorption properties of dried concrete cores were examined as a durability index of cover concrete using data obtained from 152 existing concrete structures, and comparing the compressive strength of cores as the typical quality index for hardened concrete. The following results were obtained.

1) It was confirmed that the apparent diffusion coefficient of chloride ions is relatively small when the compressive strength of concrete is high and large when the compressive strength is low. However, the apparent diffusion coefficient of chloride ions can vary widely, even when the compressive strength of the cores is within a certain range.

2) The diffusion coefficient of chloride ions is relatively small when the amount of surface absorption after 6 h is small and large when the surface absorption is large. The amount of surface absorption after 6 h can explain the diffusion coefficient of chloride ions better than the compressive strength.

3) The rate of carbonation differs significantly in the different climatic divisions of Japan. The average carbonation rate is high in the Seto Inland Sea division.

4) The rate of carbonation is low when the amount of surface absorption after 6 h is small. However, it is difficult to explain the rate of carbonation in existing structures in terms of the quality of concrete, because the rate can be significantly affected by the local climate and exposure conditions.

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