Cement & Concrete Composites 31 (2009) 139–144

Contents lists available at ScienceDirect

Cement & Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Effect of carbonation on the rebound number and compressive strength of concrete

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ARTICLE INFO

Article history:
Received 29 December 2006
Received in revised form 8 September 2008
Accepted 10 October 2008
Available online 18 October 2008

Keywords:
Carbonation
Compressive strength
Rebound number

ABSTRACT

Experimental research was performed to clarify the influence of carbonation on the rebound number and the strength evolution of concrete for three strength levels. The results reveal that the strength level dependent influence of carbonation is a source of errors in the existing equations for the strength reduction coefficient; these equations are used to compensate for the influence of surface carbonation in the rebound number method. A new equation for the strength reduction coefficient that can consider the influence of strength level was developed based on field test data extracted from technical reports of the Korea Research Institute of Standards and Science and of four universities. Over a wide range of strength levels, the equation shows good agreement with strength reduction coefficients established experimentally.

1. Introduction

The reaction of $Ca(OH)_2$, one of the cement hydration products, with CO_2 in the surrounding atmosphere produces $CaCO_3$. This carbonation process reduces the pH of pore solution in hardened Portland cement paste and may promote corrosion of the reinforcing steel; this issue is mainly considered in durability problems. On the other hand, carbonation reduces the porosity of concrete, because the carbonation product, $CaCO_3$, occupies a greater volume than $Ca(OH)_2$. As a result, strength and hardness of concrete increase.

The Schmidt rebound hammer test, one of the most popular non-destructive testing methods, is an economical and easy method to evaluate the compressive strength of concrete. This method assumes that there is a proportional relation between the rebound number measured by a Schmidt rebound hammer and the compressive strength of concrete. This relation is usually obtained from the 28-day test results. The rebound hammer, however, responds mainly to properties of the near-surface layer of the concrete. Within that region, the hardness of concrete is generally higher than that of the interior region because of carbonation and the difference in hardness increases as the carbonation progresses [1]. This results in a higher rebound number that is not indicative of the interior concrete. Therefore, the strength of concrete is likely to be overestimated after 28 days if the same relation, which is usually based on the 28-day test results, is used to evaluate the compressive strength of concrete from the rebound number without considering the influence of carbonation.

A strength reduction coefficient (α) is generally applied to the evaluated strength to compensate for the effect of surface carbonation [2,3]. The coefficient has a unit value for 28 days and its value decreases with the age of concrete. Consequently, the evaluated strength is reduced if the rebound hammer test is performed after 28 days.

Table 1 shows the strength reduction coefficients proposed by Tanigawa et al. [2] and the Architectural Institute of Japan (AIJ) [3]. Although the two strength reduction coefficients have the same purpose (that is, to compensate the long-term surface carbonation effect), their values are considerably different. In addition, it has been recently observed that neither equation yields accurate results, especially when the strength of the tested concrete is high (that is, when the 28-day strength is greater than 50 MPa). However, the AIJ equation is quite acceptable for low strength concrete (when the 28-day strength is about 25 MPa), and the equation of Tanigawa et al. is suitable for medium strength concrete (when the 28-day strength is about 40 MPa) [4,5]. This implies that the influence of carbonation on the relation between the rebound number and the compressive strength may vary with the strength level of concrete. On the basis of this implication, a series of experiments was conducted on how carbonation affects the rebound and the strength evolution in relation to the strength level of concrete [4]. Thereafter, a new equation for the strength reduction coefficient was developed based on field test data [5–8].

To evaluate the adequacy of the proposed model equation, it was compared with the normalized values of the evaluated strength, the AIJ equation and the equation of Tanigawa et al. It

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doi:10.1016/j.cemconcomp.2008.10.001

Table 1
Strength reduction coefficients (α).

Tanigawa et al.	At the age of less than 4 weeks: At the age between 4 weeks and 26 weeks: At the age of over 26 weeks:	α = 1.0 α = 0.9–1.0 (linearly varying with age) α = 0.9							
Architectural Institute of Japan (AIJ)	Age (days)	28	50	70	100	200	500	1000	3000
	α	1.00	0.87	0.84	0.78	0.72	0.67	0.65	0.63

was determined that the equation suggested in this study better predicts the data than the other model equations.

2. Test specimens and experimental program

2.1. Specimens and test condition

To investigate how the strength level affects the carbonation properties, three kinds of concrete mixture were used: low strength (LS), medium strength (MS), and high strength (HS). Table 2 shows the proportions of each mixture. For each mixture, four cubic specimens (200 × 200 × 200 mm) for the rebound number test, two prism specimens (100 × 100 × 400 mm) for the carbonation depth measurement, and 24 cylindrical specimens (∅ 100 × 200 mm, three specimens for each testing age) for the compressive strength test were fabricated. Twenty-four hours after casting, all the specimens were demolded and placed in lime-saturated water for a month. Half the specimens were subsequently cured in a normal air condition and the other half was cured in an accelerated carbonation chamber, where the concentration of CO_2 was 5% by weight, for 4 months. The relative humidity for each curing condition was kept at the same constant value (70 ± 5%) for each curing condition to prevent possible errors arising from differences in humidity. Fig. 1 briefly describes the curing conditions. At the end of each specimen designation, A or C was added to indicate curing in "normal air" or an "accelerated carbonation chamber", respectively.

2.2. Experimental method

2.2.1. Carbonation depth

As shown in Fig. 2a, two-dimensional penetration of CO_2 was achieved by sealing the two end surfaces of the 100 × 100 × 400 mm prism specimens with an epoxy resin. At each testing age, one end of each specimen was sliced to make a 5 cm thick tile to measure the carbonation depth. The newly made end surface of the prism specimen was sealed again and returned to the curing condition. After spraying phenolphthalein–alcohol solution onto the sliced surface (100 × 100 mm) of the tiles, the carbonation depth, corresponding to the thickness of the unchanged color layer, was measured. To avoid the corner effect resulting from two-dimensional exposure, carbonation depth was measured at the centre of each exposed surface and the average value was taken.

Table 2
Mixture proportions.

Strength level	w/c	Unit weight (kg/m^3)						Ad. (%)[a]
		w	c	s	g	s/(s + g)	Air (%)	
LS	0.68	180	265	887	993	0.47	1.5	0.0
MS	0.46	180	391	785	991	0.44	1.5	0.8
HS	0.28	180	643	567	1000	0.36	1.5	2.0

[a] Superplasticizer.

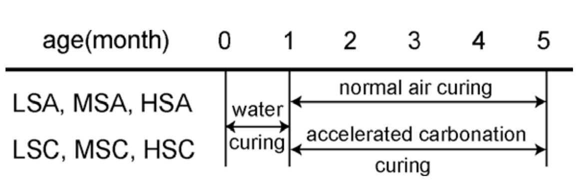

Fig. 1. Curing conditions.

2.2.2. Rebound number

To measure the rebound number, a NR-type Schimidt hammer was used after standard calibration using a test anvil. A uniform compressive stress of 2.5 MPa was provided to the test specimen (200 × 200 × 200 mm) along the vertical direction—the same direction with casting direction, before striking it with the hammer to prevent the dissipation of hammer striking energy due to the lateral movement of the specimen. Striking points were uniformly distributed (64 points, 16 points for each side) to reduce the influence of local aggregates distribution, and the rebound number of the specimen was obtained by averaging the results (see Fig. 2b).

3. Experimental results and evaluation

Fig. 3 shows the sliced surface of the tiles after phenolphthalein–alcohol solution was sprayed. For the high strength concrete, the carbonation depth is almost zero, regardless of the curing condition. However, the accelerated carbonation considerably increases the carbonation depth for the low strength concrete (Fig. 4).

Fig. 5 shows the absolute and normalized values of compressive strength. For normalized values, all the values were divided by the corresponding 28-day values to make the 28-day values equal to unity. Due to carbonation, the compressive strength of concrete cured in the accelerated carbonation chamber was somewhat higher than that of concrete cured in normal air. However, the additional increase of strength is negligible compared to the total evolution of strength, since carbonated area is small compared to the total area of cylinder specimen, except for the low strength concrete. It can therefore be concluded that the compressive strength of the specimen is hardly changed by carbonation because it affects only the near-surface region of concrete. This aspect would be more obvious for larger concrete members, like real structural elements.

Fig. 6 shows that, in contrast to the compressive strength, the rebound number changes drastically in relation to the curing condition. The rebound number of the LSC is about 22% higher than that of the LSA. In addition, the rebound number of the MSC is 10% higher than that of the MSA, whereas the rebound number of the HSC is almost same as that of the HSA (just 2% higher). Thus, the increase in the rebound number due to accelerated carbonation diminishes as the strength of concrete increases. This result confirms that the influence of carbonation on the rebound number differs considerably according to the strength level of concrete.

Fig. 7 shows the ratio of the increase of strength to the increase in the rebound number after 28 days with age for air-cured specimens. These ratios are defined as

$$\Delta f'_c(t)/\Delta R(t) = [f'_c(t) - f'_c(28)]/[R(t) - R(28)] \quad (1)$$

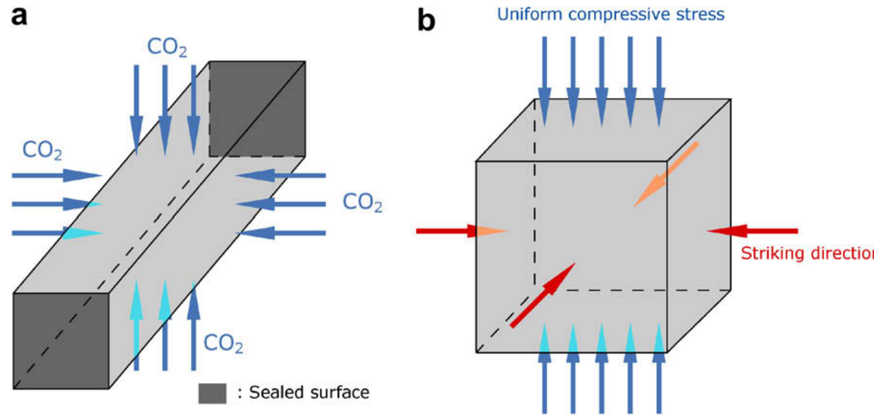

Fig. 2. Schematic view for measurement of: (a) carbonation depth and (b) rebound number.

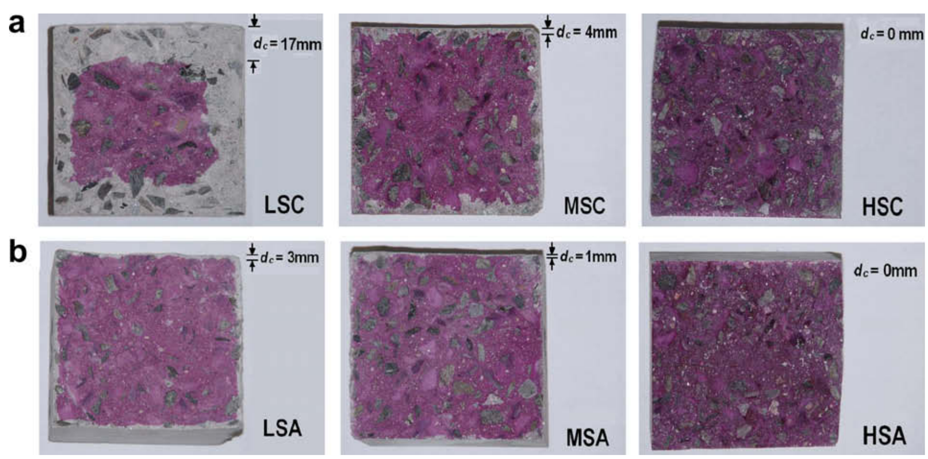

Fig. 3. Carbonation depth measurement: (a) accelerated carbonation curing and (b) normal air curing.

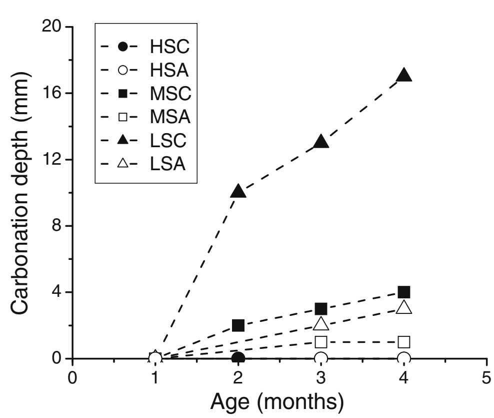

Fig. 4. Measured carbonation depth.

where t is the age of concrete (days); $f'_c(t)$ is the compressive strength of concrete at age t (MPa); and $R(t)$ is the rebound number at age t.

If these ratios are the same for all strength levels, the strength reduction coefficient does not vary with the strength level of concrete, and the same strength reduction coefficient can be used for all strength levels. As shown in Fig. 7, however, these ratios differ considerably according to the strength level. The ratios are lower for the lower strength concrete. The strange decrease in the ratio for the HSA at the age of 2 months may be resulted from experimental error. As noted from Figs. 5 and 6, the reason for this trend is that the influence of carbonation on the rebound number considerably varies according to the strength level, though the influence of carbonation on the whole strength evolution of concrete member is almost negligible regardless of the strength level. Incidentally, the ratios for the medium and high strength concrete are similar before the age of 3 months, at which time the effect of carbonation is negligible. It can be deduced from these facts that the considerable divergence of values in existing equations for the strength reduction coefficient, as well as the limited applicability of these equations to particular strength ranges, is mainly due to the strength level dependent influence of carbonation on the rebound number. Consequently, to accurately evaluate the compressive strength from the rebound number, this dependence should be considered when formulating a new equation for the strength reduction coefficient.

4. Development of a strength reduction coefficient equation

4.1. Strength reduction coefficient

The relations between the rebound number and strength, which are used for the evaluation of compressive strength from the rebound number, are generally obtained on the basis of 28-day test results. Accordingly, the evaluated strength varies considerably from the actual strength if the testing age is not 28 days; the strength is overestimated after 28 days. As previously mentioned in the introduction, the main reason for this age-dependent error

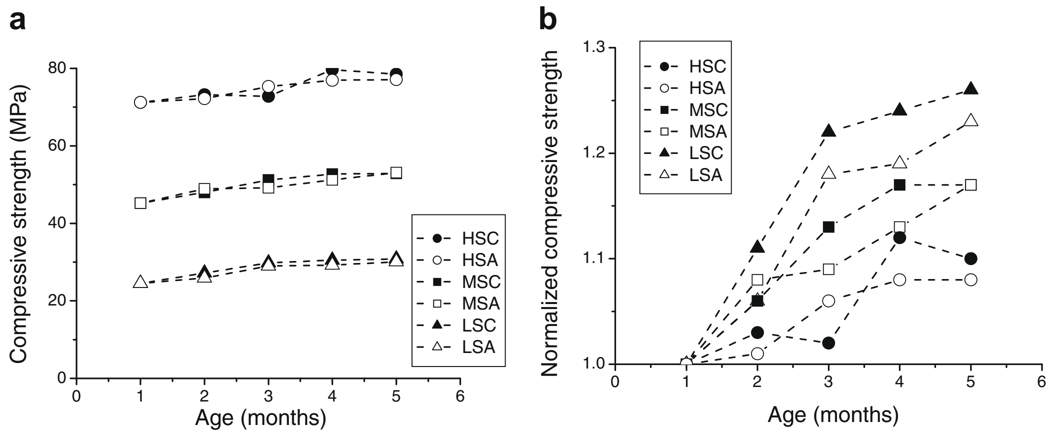

Fig. 5. Measured compressive strength: (a) absolute value and (b) normalized value.

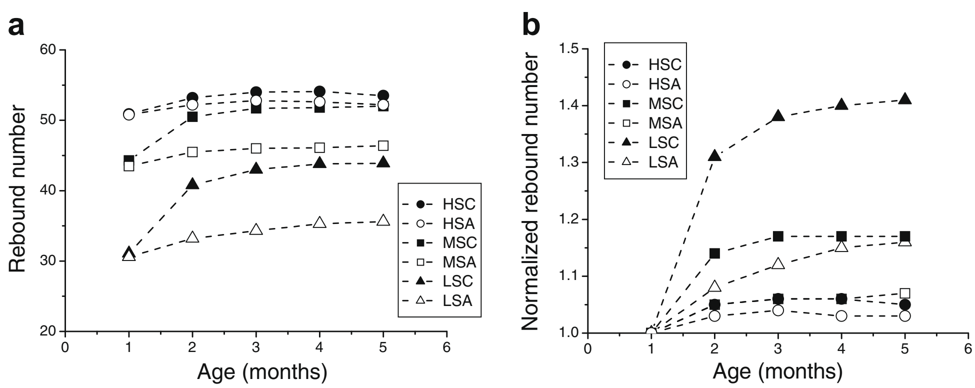

Fig. 6. Measured rebound number: (a) absolute value and (b) normalized value.

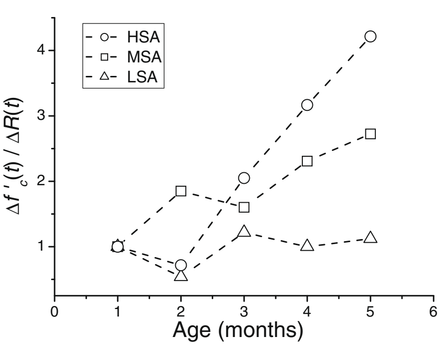

Fig. 7. Ratio of the increase in strength to the increase in the rebound number after 28 days for air-cured specimens.

is the surface carbonation. If the relations between the rebound number and strength for the whole age are obtained, this error can be avoided by using the appropriate relation according to the testing age. However, given the impracticality of this method, the strength reduction coefficient is generally used instead. These methods are briefly described below:

– Method I (ideal case)
  1. Obtain the rebound number at age t, $R(t)$.
  2. Form a direct relation between $R(t)$ and $f'_c(t)$ to evaluate the strength at age t. In this case, there is no need to consider the influence of carbonation.

– Method II (practical case)
  1. Obtain the rebound number at age t, $R(t)$.
  2. Substitute $R(t)$ for $R(28)$ in the relation between $R(28)$ and $f'_c(28)$ to obtain the pre-evaluated strength at age t, $f'_{c28}(t)$. This value is strongly affected by the carbonation.
  3. Multiply $f'_{c28}(t)$ by $\alpha(t)$, the strength reduction coefficient at age t, to obtain the evaluated strength at age t, $f'_c(t) = \alpha(t) \times f'_{c28}(t)$. This value is compensated for the effect of carbonation.

4.2. Suggestion and verification of the new equation for the strength reduction coefficient

By means of linear regression analysis, the relations between the rebound number and strength for each testing age were obtained from field test data extracted from technical reports published by the Korea Research Institute of Standards and Science (KRISS) and by four universities in Korea [5–8], as follows (see Fig. 8):

$$f'_c(28) = 1.24R(28) - 13.0 \tag{2}$$

$$f'_c(90) = 1.37R(90) - 20.8 \tag{3}$$

$$f'_c(180) = 1.76R(180) - 37.0 \tag{4}$$

$$f'_c(360) = 1.72R(360) - 37.0 \tag{5}$$

These equations can be used for the evaluation of strength if the rebound numbers are obtained at 28 days, 90 days, 180 days, or

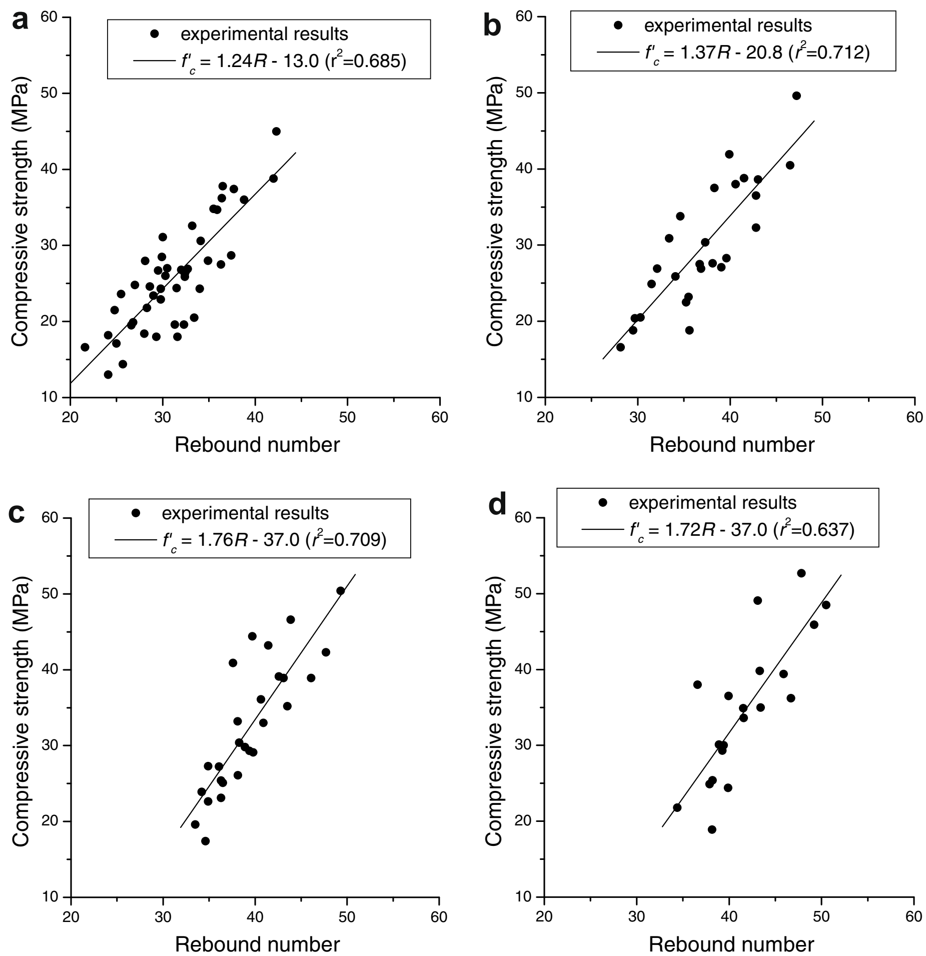

Fig. 8. Relations between the rebound number and strength: (a) 28 days; (b) 90 days; (c) 180 days; and (d) 360 days.

360 days. It should be noted, however, that these equations are based on domestic experimental results in South Korea; hence, the equations have limited applicability and cannot be used generally.

Table 3a shows the evaluated strength values based on Eqs. (2)–(5), for the cases of $R = 30, 35, 40$, and 45. Even if the same rebound number is used for the evaluation, the calculated strength varies considerably according to the testing age; the evaluated strength gradually decreases as the testing age increases. This age-dependent decrease of the evaluated strength (that is, the strength reduction) is much more pronounced for the low strength concrete (that is, for the low rebound number). The relative decrease of the evaluated strength for the period from 28 days to 360 days is 40% for a rebound number of 30 but only 6% for a rebound number of 45. This phenomenon confirms the strength level dependent influence of carbonation on the rebound number and strength, and this behavior has been overlooked in the existing equations for the strength reduction coefficient.

Table 3
Evaluated strength from the rebound number based on Eqs. (2)–(5): (a) absolute value (MPa) and (b) normalized value.

Testing age (days)	Rebound number			
	30	35	40	45
(a)				
28	24.2	30.4	36.6	42.8
90	20.3	27.2	34.0	40.9
180	15.8	24.6	33.4	42.2
360	14.6	23.2	31.8	40.4
(b)				
28	1.000	1.000	1.000	1.000
90	0.839	0.895	0.929	0.956
180	0.653	0.809	0.913	0.986
360	0.603	0.763	0.869	0.944

The values in Table 3a were normalized with the 28 day values, and the results are given in Table 3b. The normalized values are, by definition, the same as the strength reduction coefficient; hence the new equation can be derived from these values by means of regression analysis. To consider the influence of the strength level, the new equation for the strength reduction coefficient should be a function of the rebound number as well as the age of concrete, which is the only parameter of existing equations. The following type of equation was selected:

$$\alpha(R,t) = 1 - \frac{n_1}{(R/R_0)^{n_2}}\left(\frac{t-28}{t+n_3}\right) \quad (6)$$

where n_1, n_2 and n_3 are constants that can be determined by a nonlinear regression analysis; and R_0 is the reference rebound number, which was defined as the rebound number for a strength of 30 MPa at 28 days. For the nonlinear regression analysis, a Levenberg–Marquardt optimization algorithm was used, which yields $n_1 = 0.3064$, $n_2 = 4.20$, and $n_3 = 94.0$ for $R_0 = 34.7$ (obtained from Eq. (2)). Thus, the new equation for the strength reduction coefficient is

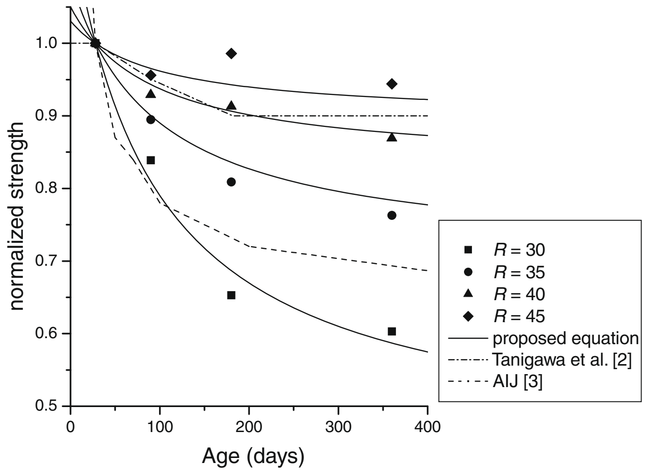

Fig. 9. Strength reduction coefficients versus normalized strengths.

$$\alpha(R,t) = 1 - \frac{0.3064}{(R/34.7)^{4.2}}\left(\frac{t-28}{t+94}\right) \quad (7)$$

Fig. 9 shows Eq. (7) with the normalized values of the evaluated strength (data in Table 3b); it also shows the AIJ equation and the equation of Tanigawa et al. (see Table 1). As noted, the normalized strength reductions show a strong strength level dependence and the new equation reproduces that trend well. In contrast, the AIJ equation only corresponds with the data for a rebound number of about 30–35, and the equation of Tanigawa et al. only corresponds with the data for a rebound number of about 40.

Although more experimental data and careful investigations are needed to obtain a more accurate and practical equation for the strength reduction coefficient, it can be concluded that the existing equations fail to consider the influence of the strength level, and a new equation, as proposed in this study, is therefore required for the accurate strength evaluation from the rebound number.

5. Conclusions

1. The influence of carbonation on the rebound number varies considerably according to the strength level, while the influence of carbonation on the whole strength evolution of concrete member is negligible regardless of the strength level. In addition, the ratios of the increase in strength to the increase in the rebound number after 28 days for medium and high strength concrete are similar before the age of 3 months, at which time the effect of carbonation is negligible. It can be deduced from these facts that the considerable divergence among the values of existing equations for the strength reduction coefficient and their limited applicability to particular strength ranges are mainly due to the strength level dependent influence of carbonation.
2. The normalized strength reductions show a strong strength level dependence, and that trend is well reproduced by the newly proposed equation. In contrast, the AIJ equation and the equation of Tanigawa et al., which overlook the influence of the strength level, only correspond with the data for a low-medium rebound number.

Acknowledgment

The authors would like to thank the Infra-Structures Assessment Research Center (ISARC) funded by Korea Ministry of Construction and Transportation (MOCT) for financial support.

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