Nondestructive quality evaluation of surface concrete with various curing conditions

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ABSTRACT: With a view to a system that inspects the durability of concrete structure based on their practical quality, we conducted experiments on evaluation of the applicability of two types of nondestructive test: rebound hammer and air permeability tests. The strength characteristics and carbonation resistance of concrete specimens with various curing conditions: demold age and subsequent exposure environment were determined to compare to their nondestructive-measured values. The results reveal strong correlation between carbonation resistance and air permeability coefficient. In addition, they indicate that rebound hammer test may be available to inspect the quality of conducted curing for concrete structure.

1 INTRODUCTION

The durability of concrete structures is dependent principally on the thickness and quality of concrete cover protecting reinforcing steel against penetration of corrosion factors such as carbon dioxide, chloride ion, moisture or oxygen. The quality of concrete cover (hereafter called “surface quality”) is sensitive to various factors during the construction phase. In particular, it is widely-recognized that the curing process can greatly affect the surface quality. However, there seems to be no end of deterioration problems due to lack of the surface quality according many reports, researches and technical development related to these problems.

Appropriate control and inspection of the curing process are obviously important in this regard. Recent years in Japan, on the other hand, there is growing discussion about the methodology for direct evaluation of the surface quality of constructed concrete and more accurate verification of its durability. The discussion points out the necessity of a comprehensive system to verify the durability of concrete structures, which is composed of inspection technologies of the surface quality with explicit acceptance/rejection criteria at completion of construction and of evaluation techniques of the durability of concrete structures, based on these inspection results (JSCE 2008a, 2009). Having been studying on the cement-based barrier system for radioactive disposal, we recognize the quality verification of concrete as important accountability for the safety of disposal (Kurashige et al. 2009).

As mentioned in “Materials and Construction Edition of Standard Specifications for Concrete Structures” by JSCE (2008b), the quality of constructed concrete has been conventionally ensured mainly by compressive strength test using concrete specimens or cores, or nondestructive methods for strength evaluation such as rebound hammer test in a conjunction with construction control according to the specifications. One of the aims of this study is to understand how these conventional test methods evaluate the impact of the curing process on surface quality of concrete structures. Although many comprehensive studies of the effects of curing on compressive strength in past years would be helpful, it may be difficult to find study reports on nondestructive evaluation of surface quality affected by curing conditions. Therefore, we examine the effects of curing conditions (demold age and subsequent exposure environment) on strength characteristics or nondestructive-measured results using rebound hammer test, which is the most proven method for actual concrete structures. Assuming that early demolding and exposing to dry air significantly reduce the surface quality level, we analyzed the relationship between strength characteristics and nondestructive-measured results.

In the evaluation of the effect of drying on the quality of concrete, the quality distribution from surface to inside as well as the general quality level should be focused on. Providing the spatial-averaged quality of cylindrical column specimens, the above-mentioned methods such as compressive strength test may underestimate the quality loss of surface quality influencing the durability of concrete. From this point of view, also considering the recent social issue of crack control, we conducted tests of flexural strength correlated to tensile strength. The flexural strength is sensitive to surface quality in principle of the measurement. We determined the relationships between compressive or flexural strength and rebound number of concrete specimens with different curing conditions in order to evaluate the availability of rebound hammer test as an inspection technique of surface quality.

Air permeability tests are also useful as nondestructive evaluating method for mass transfer resistance of surface concrete which correlates more directly with durability of a concrete structure. Various kinds of the method have been proposed up to now; their applicability to inspection for mass transfer resistance has been recently researched by RILEM (2007). Focusing on the Torrent permeability test method which was confirmed to be relatively reliable during the RILEM research, we used it to evaluate the surface quality of concrete specimens with the different curing conditions. The measured values of air permeability of surface concrete were compared with their carbonation resistance affected by the curing conditions.

2 EFFECTS OF DEMOLD AGE OR EXPOSURE CONDITION UPON STRENGTH CHARACTERISTICS (TEST SERIES *I*)

2.1 *Experimental outline*

As shown in Table 1, the mix proportion of concrete using ordinary Portland cement was set up to produce specimens: cylindrical specimens of Φ10 x 20cm for compressive strength test and elastic modulus measurement, prism specimens of 10 x 10 x 40cm for flexural strength test, and prism specimens of 15 x 15 x 53cm for rebound hammer test.

Table 1. Mix proportion of concrete

W/C	s/a	Ac	Unit Content kg/m^3				Slump	Air
%	%	ml/kg-C	W	C	S	G	cm	%
50	48	3.0	165	330	859	956	7.5	5.7

Ac: air-entraining and water-reducing admixture ratio, W: water (including admixture)
C: ordinary Portland cement, S: fine aggregate, G: coarse aggregate

All the specimens were demolded at two kinds of age, and then exposed to three levels of moisture conditions shown in Table 2. The condition of demold age of five day was set with reference to the JSCE Standard Specification that recommends five days as moist curing period for ordinal Portland cement concrete constructed at the daily-averaged temperature higher than 15ºC (2008b). On the other hand, demolding at only one-day age was for evaluating the effect of early-age demolding on the surface quality of concrete. We also arranged the exposure condition of 60%RH based on the average humidity in Japan, the humid air condition for examining the advantage of moisture supply, and water-submerged condition for simulating a typical curing of compressive strength test specimens. In this paper, the code in Table 2 indicates each kind of specimens in following figures and discussion.

Table 2. Curing conditions (demold age and exposure environment) and test items for test series *I*

Code	Demold age and exposure environment (ambient temp. 20ºC)			Test item
1-6		60%RH		Compressive strength, Static and dynamic modulus of elasticity, Flexural strength, Rebound number
1-H		humid air (higher than 98%RH)		
1-W		in water		
5-6	in mold		60%RH	
5-H	in mold		humid air	
Age 0	1day(demold)	5day(demold)	28day(test measurement)	

Measurements at 28-day age of the compressive strength, static and dynamic modulus of elasticity and flexural strength were performed according to the Japanese Industrial Standards. Rebound hammer test were conducted in reference to the Standard of the Japan Society of Civil Engineers: JSCE-G504-2007.

2.2 *Effects of curing conditions on compressive and flexural strengths and elastic modulus*

Figure 1 shows the relationship between compressive strength and static modulus of elasticity for the concrete specimens with different demold age and exposure environment. This figure and the followings for the test series *I* not only plot the average measured values but also include lines representing the maximum and minimum values for checking the variations. The compressive strength and elastic modulus of specimen *5-6*, which was exposed to 60%RH air after demolded at five-day age, were approximately 53N/mm^2 and 32kN/mm^2 respectively, almost conforming to the relational expression presented in the Japanese standard specifications: design edition (2008c). The results of specimen *5-H*, which was exposed to more humid air after demolded at the same age, reached the same or better levels to *5-6*. In contrast, The compressive strength of specimen *1-6*, which was exposed to 60%RH air after demolded at one-day age, show nearly 30% below the values of *5-6* and *5-H*; similarly, the elastic modulus decreased. However, even if demolding at early age like one-day, the compressive strength and elastic modulus of specimens with sufficient moisture supply such as *1-W* or *1-H* developed to near the level on *5-6* or *5-H*. We note here that pre-processing such as saturation or drying was not conducted for these tests. Therefore, it remains possible that the compressive strength of *1-W* was measured apparently at slightly lower value due to the high water content in the specimen. Comparisons of these compressive strength and static modulus values with bulk density of concrete are shown in Figure 2. Both of these values tend to decrease proportionally to the density

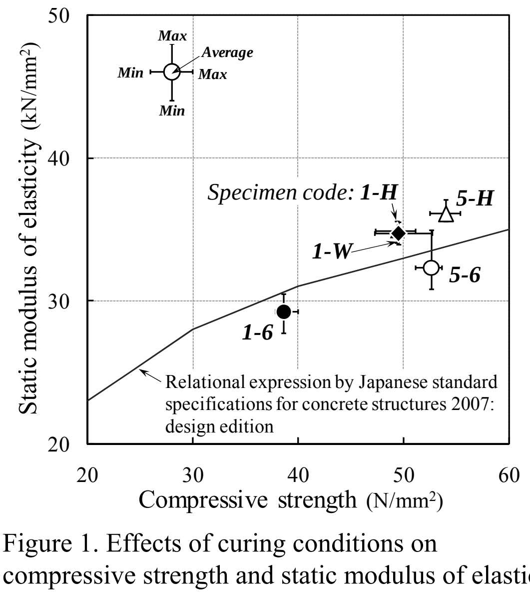

Figure 1. Effects of curing conditions on compressive strength and static modulus of elasticity

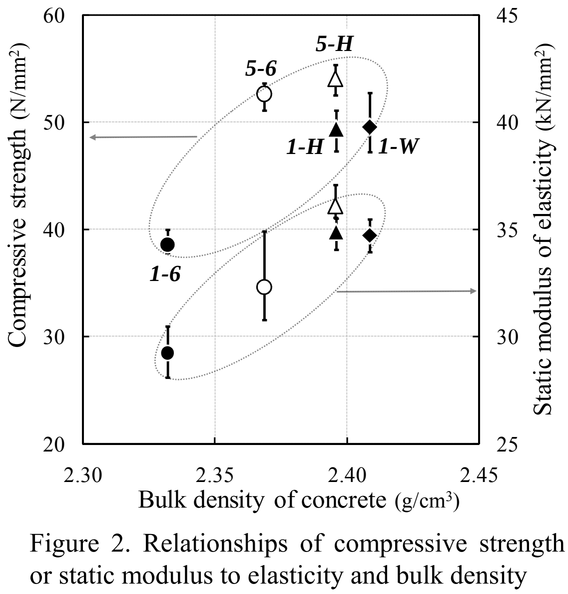

Figure 2. Relationships of compressive strength or static modulus to elasticity and bulk density

reduction due to moisture loss and cement-hydration interference by early demolding and dry air exposure. In addition, the relationship between compressive and flexural strength is shown in Figure 3. It is confirmed that early demolding and dry air exposure also cause the reduction of flexural strength. And, at the same time, it is found that there is no close correlation between their strengths, the details of which is discussed in the next section.

2.3 *Relationship between strength characteristics and rebound number*

The strength characteristics which varied according to the demold age and subsequent exposure environment were compared with rebound number obtained in a nondestructive manner to concrete surface. Figure 4 shows the relationship between the rebound number and compressive strength measured at 28-day age, revealing that the rebound number tends to fall proportionally as the compressive strength increased. It also shows that the rebound number of the specimens (*1-W*, *5-H*), produced under relatively good condition such as water-supplied or kept from drying for days, is larger than that of the other specimens. This trend indicates that the rebound number is more sensitive to surface quality of concrete affected by curing conditions, while the compressive strength can be measured as the volume-average quality of specimen.

Because the rebound hammer test evaluates impact phenomenon which measures the rebound number caused by hitting with a plunger, it is expected to have a stronger relationship with the elastic modulus than with the compressive strength of concrete. Figure 5 shows the relationships of the rebound number with the static and dynamic modulus of elasticity, which reveal a strong positive correlation between them. In addition, the relationship between the rebound number and the flexural strength is shown in Figure 6. In light of the measurement principal on flexural test; the maximum tensile stress at the lower end of a specimen is evaluated, this test method can more sensitively evaluate the surface quality of concrete than the compressive strength test method. This figure shows that as the rebound number decreases, the flexural strength lowers proportionally, confirming that the rebound number has a stronger correlation with the flexural strength than with the compressive strength. From these results, the rebound hammer test may be available as an evaluating method of the resistance to cracking of surface concrete strongly affected by curing condition.

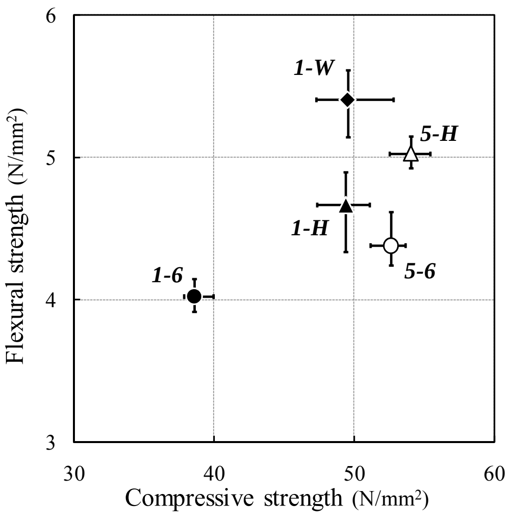

Figure 3. Relationships between compressive and flexural strength

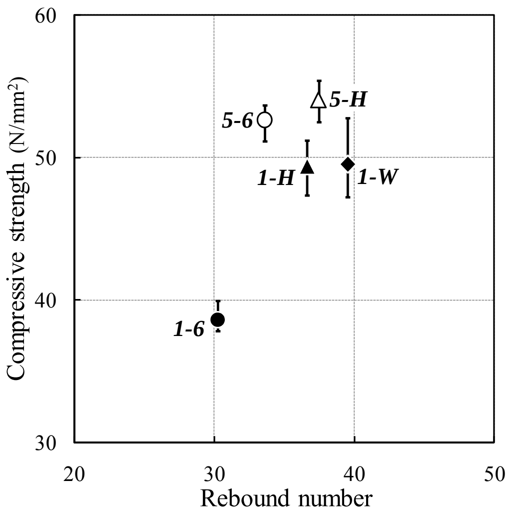

Figure 4. Relationships between rebound number and compressive strength

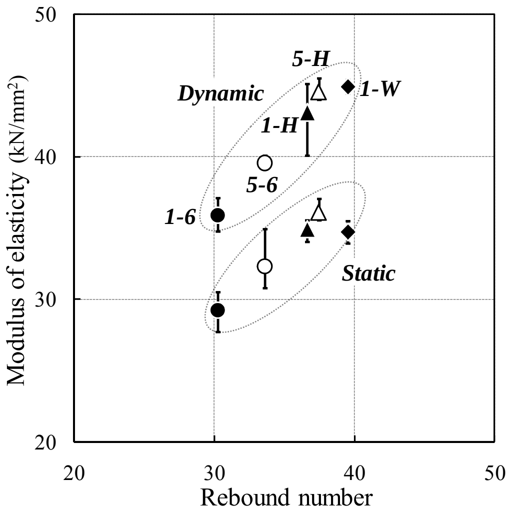

Figure 5. Relationships of rebound number to static or dynamic modulus of elasticity

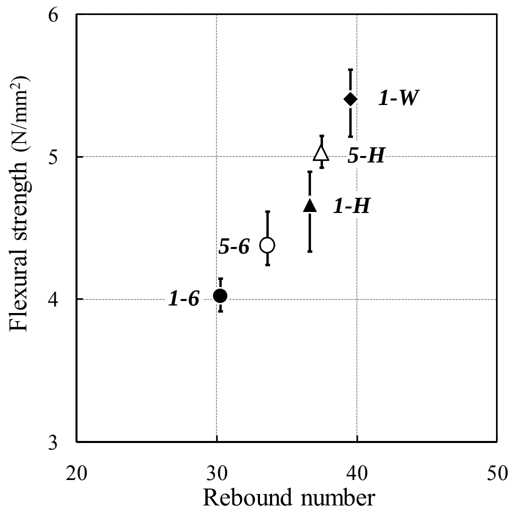

Figure 6. Relationships between rebound number and flexural strength

3 EFFECTS OF DEMOLD AGE OR EXPOSURE CONDITION UPON SURFACE AIR PERMEABILITY (TEST SERIES *II*)

3.1 *Experimental outline*

The mix proportion of concrete specimens for test series *II* was same as that for test series *I* (Table 1). Meanwhile, the conditions of demold age and exposure environment were expanded shown in Table 3. Prism specimens of 15 x 15 x 53cm for nondestructive tests and of 10 x 10 x 40cm for carbonation accelerating test were prepared to be exposed to each condition in Table 3 after demolded. Nondestructive tests (rebound hammer test, surface air permeability test and electric resistivity measurement) were conducted at the age of 56 and 91-day and then the carbonation accelerating test were started at 91-day age. The method used to measure the rebound number was same as that in test series *I*. The Torrent method was adopted to perform the air permeability test (Torrent 1992), and the Wenner method (sensor spacing 50mm) was used to measure the electrical resistivity of surface concrete with a view to evaluating the influence of moisture in concrete. The measurements spots were same as those in the rebound hammer test in test series *I*. The carbonation accelerating test was carried out with the conditions: the temperature of 20°C, relative humidity of 60%, and CO_2 concentration of 5%.

Table 3. Curing conditions (demold age and exposure environment) and test items for test series *II*

Code	Demold age and exposure environment (ambient temp. 20ºC)					Test item
1-4		40%RH			60%RH	Rebound number, Surface air permeability, Electric resistivity, Carbonation depth
1-4H		40%RH			humid air	
1-6		60%RH			60%RH	
1-H		humid air			60%RH	
1-W		in water			60%RH	
5-4		in mold	40%RH		60%RH	
5-6		in mold	60%RH		60%RH	
5-H		in mold	humid air		60%RH	
14-6		in mold		60%RH	60%RH	
Age	0 – 1day	1day – 5day	5day – 14day(demold)	14day – 28day	28day –	56 & 91days (test measurement)

3.2 *Effects of curing condition on air permeability and rebound number of concrete surface*

Figures 7-9 illustrate the measurement results of air permeability coefficient (hereafter abbreviated as kT) and electrical resistivity with respect to comparing specimens. Boundary lines in the graphs represent the grading nomogram proposed by Torrent et al. (1995). Torrent classified surface air permeability measured by the Torrent method to five grades according to electrical resistivity of concrete determined at the same time, while considering the influence of moisture in concrete.

As previously mentioned, the JSCE Standard Specification recommends five days as moist curing period for ordinal Portland cement concrete constructed at the daily-averaged temperature higher than 15ºC. As shown in Figure 7, kT of the specimens demolded at five-day age were measured as around $0.08 \times 10^{-16} m^2$ on 91-day age for all the exposure conditions. A comparison of the effect of demold age revealed that, as shown in Figure 8, kT of the specimen which was demolded at one-day age is ten times higher than that of specimens demolded at five-

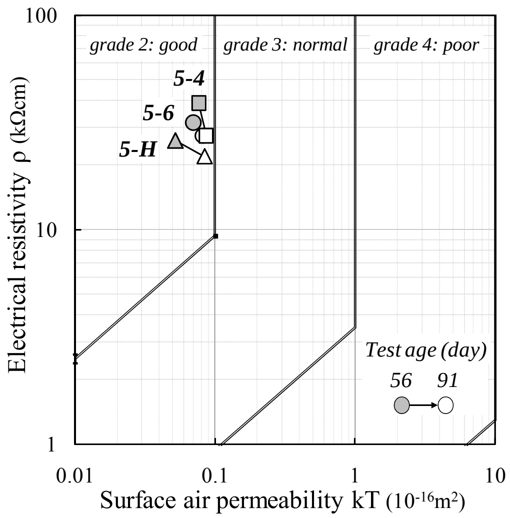

Figure 7. Electrical resistivity and surface air permeability of the specimens demolded at five-day age

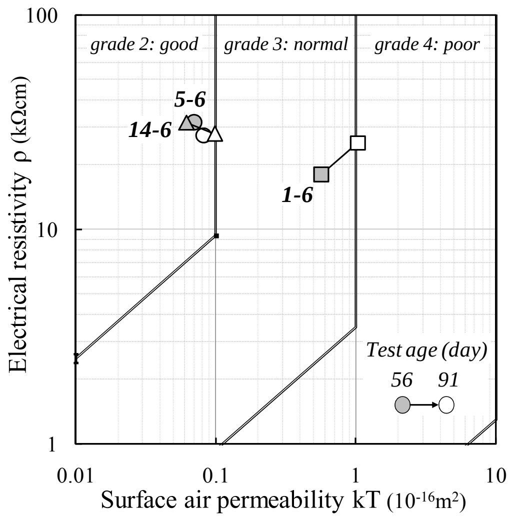

Figure 8. Effects of demold age on electrical resistivity and surface air permeability of the specimens exposed to 60%RH air

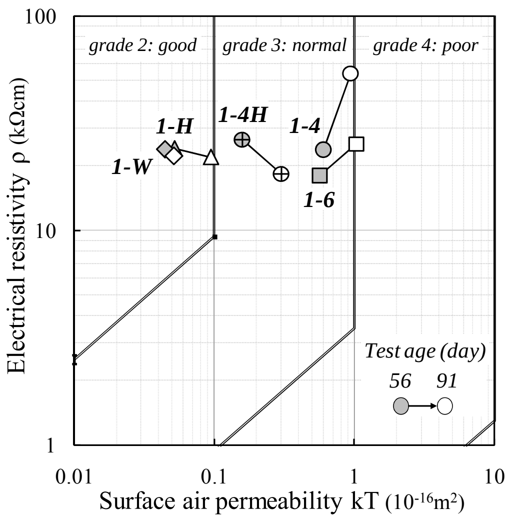

Figure 9. Effects of exposure condition on electrical resistivity and surface air permeability of the specimens demolded at one-day age

or fourteen-day age. As consideration within the limit of these experimental conditions, it can be said that the recommended moisture period shown in the JSCE Standard Specifications has certain significance regarding not only strength characteristics but also air permeability resistance.

In addition, viewing the effect of subsequent exposure condition of specimens demolded at one-day age in Figure 9 has clarified that even the specimens demolded at one-day age can achieve the same level of kT as specimens demolded at five-day age by curing in an adequate moisture supply condition such as humid air or water submergence. And also, though kT of specimen which was exposed to 40%RH air after demolded at only one-day age was very large: approximately $1\text{x}10^{-16}\text{m}^2$, it is found that re-curing in humid air after 28-day age can reduce the kT value.

In conclusion, it is confirmed that demolding at early age is not necessarily harmful, and that adequate surface quality can be ensured by taking an appropriate countermeasure to retain humidity and/or supplying enough water after the demolding. And the measured electrical resistiv-

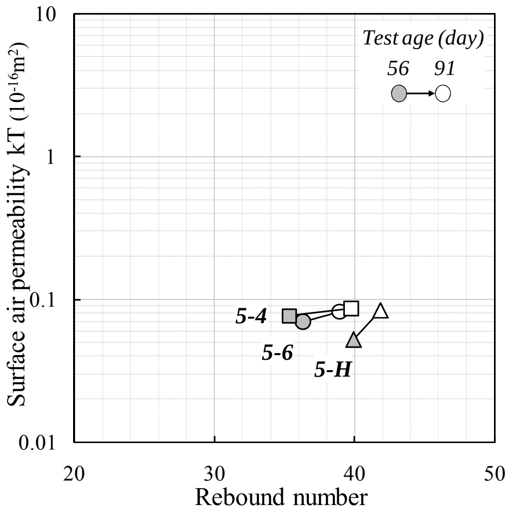

Figure 10. Relationship between surface air permeability and rebound number of the specimens demolded at five-day age

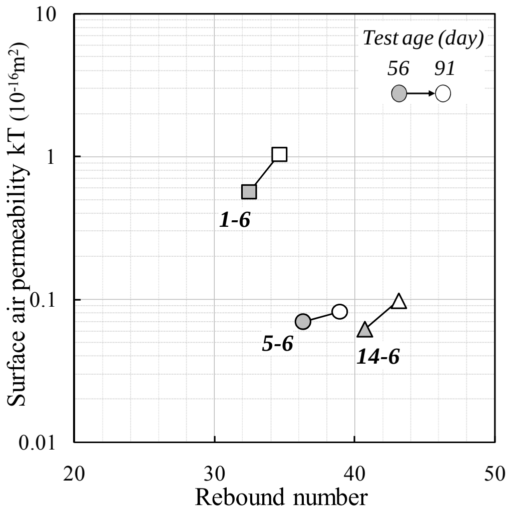

Figure 11. Effects of demold age on surface air permeability or rebound number of the specimens exposed to 60%RH air

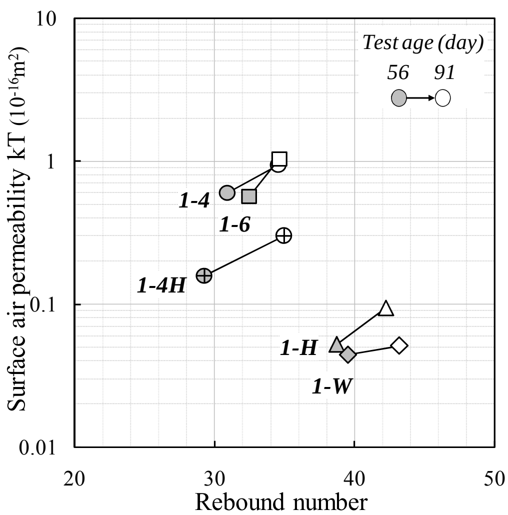

Figure 12. Effects of exposure condition on surface air permeability or rebound number of the specimens demolded at one-day age

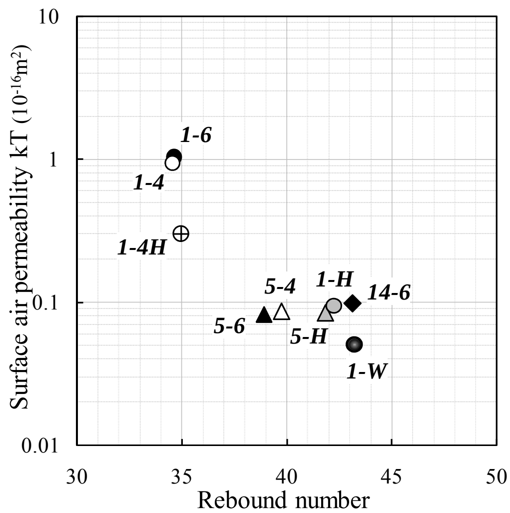

Figure 13. Relationship between surface air permeability and rebound number measured at 91-day age for all the specimens

ity values of all the specimens were more than 10kΩcm, which is within a range where correction based on electrical resistivity for moisture in concrete is not required in the grading nomogram for surface air permeability proposed by Torrent.

Figures 10-12 compare rebound number (hereafter abbreviated as R) and kT. As shown in Figure 10 it is found that the specimens exposed to different environments after demolded at five-day age have similar degrees of R and kT to each other. On the other hand, it is revealed that the specimen exposed to 60%RH air after demolded at one-day age has much lower R and kT than the specimens demolded at five- or fourteen-day age (Figure 11). Regarding the specimens demolded at one-day age, it is confirmed that the sufficient values of R and kT can be obtained by curing in a moist condition after demolded (Figure 12).

Figure 13 shows the relationship between R and kT measured at 91-day age for all the specimens. Though all the specimens were made from the identical fresh concrete, the nondestructive-measured values of surface quality varied a great deal depending upon the curing condition such as demold age or exposure environment; the range of R was approximately from 35 to 45 and the maximum value of kT was more than ten times of minimum one. As an overall trend, negative correlation was revealed between R and kT, at the same time they varied characteristically according to the effect of curing conditions. That is to say, rebound hammer test and surface air permeability test can be available as independent nondestructive-evaluation of the surface quality (strength characteristics and permeability, respectively) according to each measurement principle.

3.3 *Relationships of air permeability or rebound number to carbonation resistance*

The results of carbonation accelerating test for all the specimens were shown in Figure 14. The carbonation resistance of specimen *1-6* is the worst among the tested specimens as can be expected from the measured result of kT, and *1-H* and 1-W show the best carbonation resistance among them. Here, the carbonation of *1-6* had already reached a depth of approximately three mm when the carbonation test started at 91-day age.

The x axis of this graph is a time scale: the square root of acceleration duration (day). Therefore, following the simple law of the square root of time, carbonation depth increases in a linear fashion. The carbonation depth of *1-H* and *1-W* increased approximately linearly with the square root of duration. It was revealed that, however, the carbonation rate of *1-6* decreased with the carbonation reaching deeper zone. It follows from this that the carbonation rate trend corresponds to the degrees of surface quality loss due to early-demolding and dry exposure; it is estimated that the quality loss reaches depth from 15 to 20 mm because the carbonation rate on the depth more than 20 mm of the specimen *1-6* is same as that of the other specimens.

Figure 15 reveals the strong correlation between the carbonation depth measured at any accelerating duration and the surface air permeability of the specimens measured at 91-day age.

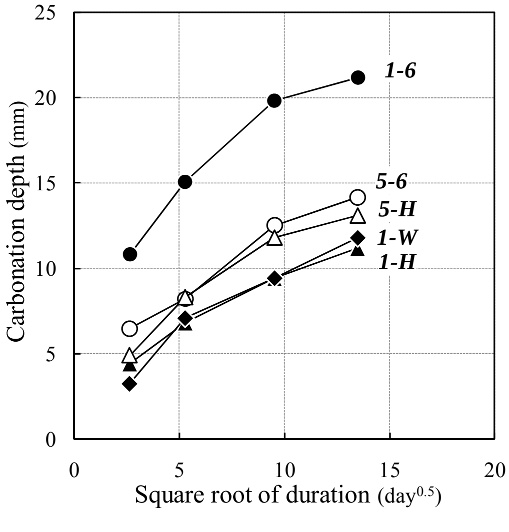

Figure 14. Relationship between duration of acceleration and carbonation depth

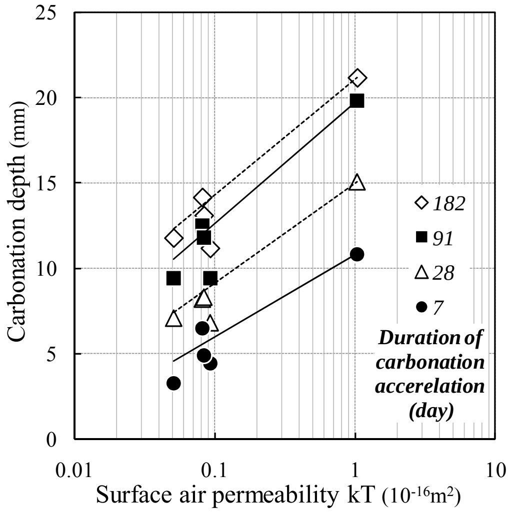

Figure 15. Relationship of carbonation depth to surface air permeability at 91-day age

Consequently, by measuring kT as a surface quality of constructed concrete, it can be possible to inspect the quality of conducted curing for concrete structures in a nondestructive manner. From this point we might go on to a more detailed examination considering also the chemical properties such as types of cement or contents of cement hydrates content.

Additionally, it was clarified that not only the surface air permeability but also the rebound number correlates with the carbonation depths as shown in Figure 16. This fact indicates that the effects of demold age or exposure environment on the rebound number was of similar magnitude to that on the surface air permeability within this experiment. More expanded experimental proof is necessary but rebound hammer test may be also available as an inspection method for the quality of conducted curing.

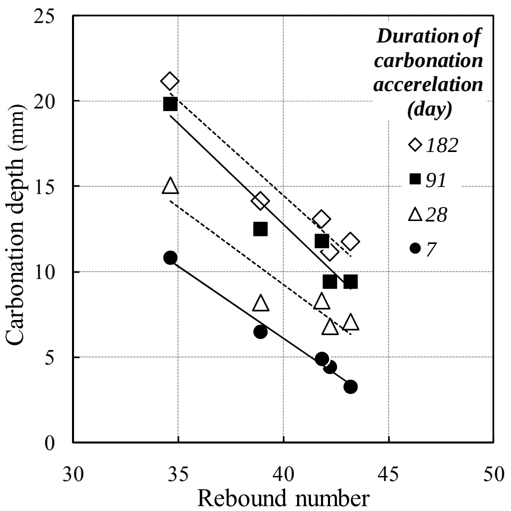

Figure 16. Relationship of carbonation depth to rebound number at 91-day age

4 SUMMARY

(1) Test series *I*: Effects of demold age or exposure condition upon surface air permeability:

It was found that it is possible to detect the loss of flexural strength relating to surface of concrete due to early-demolding and dry air exposure by using the rebound hammer test. On a practical completion inspection of concrete structure, an example of the method includes comparing the rebound number measured at constructed concrete with that measured at a specimen prepared with a standard or contractual curing condition using the same as fresh concrete for construction. The future direction of research on this point will be one that encompasses the evaluation of applicability to a practical concrete structure and the setting of optimal conditions for controlled specimens such as shape and size.

(2) Test series *II*: Effects of demold age or exposure condition upon surface air permeability:

It was clearly shown that by using the surface air permeability measured by Torrent method, it is possible to inspect the surface quality (carbonation resistance) affected by curing conditions. Furthermore, it was also revealed that the rebound number correlates with the carbonation resistance. Future works require the expanded studies with a broader range of materials, mix proportions and curing conditions to clarify the applicability in more detail. Regarding the surface air permeability measurement by Torrent method in particular, it was confirmed that the measured kT increases with age of specimens, even though the measured kT is within the range of electrical resistance which can ignore the influence of moisture in concrete according to the nomogram proposed by Torrent. It remains a matter of research on the influence of the moisture especially in early-age concrete on the nondestructive measurement of surface air permeability.

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