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ESTIMATION OF CONCRETE STRENGTH BY CONTRAST X-RAY

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Abstract: This study proposes a method of estimating the distributions of voids and strength within concrete by contrast X-ray [1-3] using cores 100 mm in diameter drilled from actual concrete structures. Contrast X-ray is characterized by its capability to detect cracks and voids within concrete by radiographic imaging after impregnating specimens with a contrast medium. The detected values were then quantified and related to the strength. This technique was also applied to small diameter cores to examine if similar measurement is possible by slight destruction. Also, cores were drilled from concrete structures damaged by alkali-silica reaction (ASR). These were subjected to contrast X-rays to investigate the image characteristics of cracking, with which the feasibility of this method for judging ASR was confirmed. The test results demonstrated that the strength of concrete can be accurately estimated from specimens 10 mm in thickness. This method also enables to determine the strength distribution in drilled cores from the surface inward. In regard to tests on cores of different sizes, smaller cores led to greater scatters of void and strength distributions, but these scatters were found to be attributed to scatters of concrete as such. Measurement of void distribution in ASR-affected concrete revealed great changes in void properties when compared with sound concrete. Early ASR may therefore be evaluated by monitoring these void characteristics.

1 INTRODUCTION

In deterioration diagnosis for a concrete structure, it is important to know the void distribution and strength profile from the surface inward, as well as the depth of deterioration, for maintenance purposes. The information of the void distribution and strength profile of a newly built structure enable the assessment of its construction and curing conditions. The data of deterioration depth provide information for deciding the depth of chipping for repair and retrofitting. This study is intended to estimate the strength of concrete and investigate its deterioration depth by drilling cores 100 mm in diameter from concrete structures and examining the state of voids by contrast X-ray imaging. The effect of core diameters (70 mm and 40 mm) on the measurement results is also examined. Contrast X-ray was also applied to cores taken from structures deteriorated by alkali-silica reaction (ASR) to investigate the possibility of detecting ASR from the state of cracking and void distribution.

2 CONTRAST X-RAY IMAGING

Contrast X-ray imaging is a method whereby voids in concrete, such as microcracks and early defects, can be detected by impregnating sliced concrete with a contrast medium for concrete originally developed by the authors' laboratory. Specifically, 10 mm slices of cores are placed in a container filled with the contrast medium to impregnate the slices as shown in Fig. 1. These are removed from the container 60 min later, wiped with a rubber wiper to remove the extra medium on the surfaces, and subjected to radiography (see Fig. 2). Each slice is placed on an image intensifier and exposed to X-ray radiation from above to retrieve the image. An image to an inner diameter of 80 mm is retrieved from a 100 mm diameter slice in consideration of the effects of the core drill bit and infiltration of the contrast medium from the peripheral surface. Note that an X-ray image is also taken under the same conditions before impregnation with the contrast medium.

X-ray images retrieved by the image intensifier before and after impregnation with the contrast medium are used for determining the image density by image analysis / measurement software. The density of an X-ray transfer image is determined by the X-ray transmission dose that reaches the detecting medium through the specimen. In other words, the transmission dose is high through voids, such as air bubbles and cracks, and substances having a low absorption coefficient. A high transmission dose is represented by white when an image intensifier is used as the detection medium. On the contrary, the X-ray transmission dose is low through substances having a high absorption coefficient, such as a contrast medium, and tends to be represented by black. The difference between the densities of X-ray images of concrete taken before and after impregnation with a contrast medium results from the infiltration of the contrast medium into such voids as cracks and early defects of concrete. Therefore, the authors defined this difference as a “transmission dose difference (TDD)” and used this for quantifying such voids to determine its relationship with concrete strength. In this paper, the amount of voids is thus defined as being equal to the TDD.

3 RELATIONSHIP BETWEEN CONCRETE STRENGTH AND TRANSMISSION DOSE DIFFERENCE

The materials for concrete included the following: The cements were normal portland cement, high-early-strength portland cement, and Type-B blast-furnace slag cement. The coarse aggregate was crushed stone with a maximum size of 20 mm, saturated surface-dry (SSD) density of 2.66 g/cm^3, and water absorption of 2.12%. The fine aggregates were land sand A with a SSD density of 2.62 g/cm^3 and water absorption of 1.89% and land sand B with a SSD density of 2.36 g/cm^3 and water absorption of 5.10%. A Type I air-entraining admixture (an alkyl ether-type anionic surfactant) was used as a chemical admixture. To simulate deteriorated conditions, the target water-cement ratio (W/C) and air content ranged between 40-90% and 2-7%, respectively. Concrete specimens 100 mm in diameter and 200 mm in height were

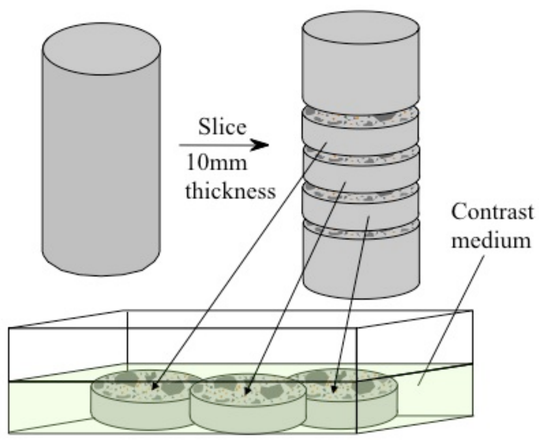


Figure 1: Cutting and impregnate method

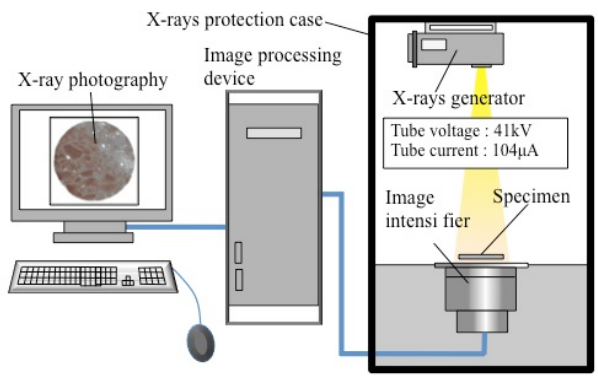


Figure 2: Cutting and impregnate metho2d

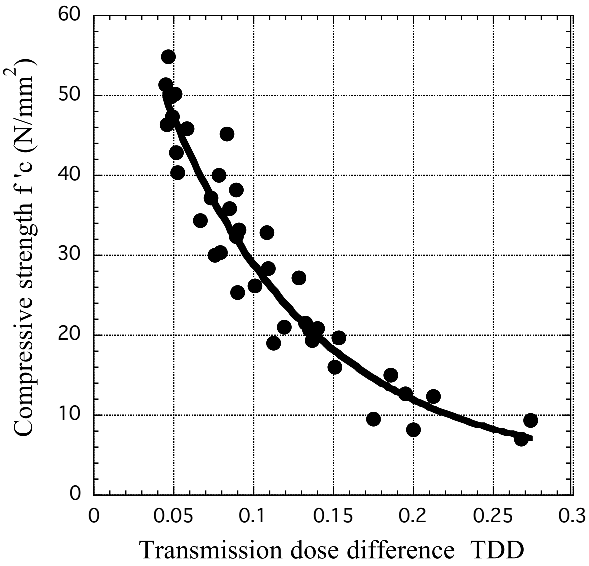


Figure 3: Relationship between f'c and TDD

fabricated by combing these materials and cured either in water or in air. For water curing, specimens were demolded on the day following the placing day and immersed in a curing tank at 20°C for 28 days. For air curing, specimens were demolded on the day following the placing day and left to stand in air in a thermo-hygrostatic room at 20°C and 60% R.H. for 28 days. Three specimens for compressive strength and three for contrast X-ray were fabricated for each of 39 types with strengths eventually ranging from 9.3 to 54.9 N/mm^2. The number of specimens totaled 234. For contrast X-ray imaging, three specimens were cut to discs 10 mm in thickness using a wet diamond cutter and kept in a thermo-hygrostatic room at 20°C and 60% R.H. for 24 h before testing. Only three mid-height discs were used to minimize the effect of bleeding after placing, and the averages of the measurement results of 9 discs were used for analysis.

Figure 3 shows the strength–TDD relationship obtained using 39 types of concrete specimens. This figure reveals that the compressive strength tends to decrease as the TDD increases. Though the results of air-cured specimens tend to be plotted above the regression curve, no appreciable differences are observed among the cement types, water absorptions of fine aggregate, and air contents. The fact that the correlation coefficient was 0.954 suggests that the materials, mixture proportions, and curing conditions have no appreciable effect on this relationship. Note that the amount of voids is defined as being equal to the TDD in this paper. A strong correlation is known to exist between the void amount and strength as expressed by A. N. Talbot in his theory of cement-void ratio. The relationship between the strength and the TDD determined in the present study also showed a strong correlation. The idea that the TDD determined by contrast X-ray imaging is equal to the amount of voids in concrete is therefore considered to be validated

4 EFFECT OF CORE SIZE ON THE STRENGTH ESTIMATION

It is necessary to consider the issue of core size when drilling concrete cores at the jobsite to estimate the strength. While 100 mm cores are generally used for compression tests and carbonation tests in consideration of the scatter of test values, the core size may have to be reduced due to reinforcement intervals. Since the present test intends to estimate the void distribution and strength of concrete in situ, wall-shaped specimens were fabricated, and cores of different sizes (100, 70, and 40 mm) were drilled from the same levels and subjected to contrast X-ray imaging to examine the distribution of voids (= TDD) from the surface inward. The effect of core size on the strength estimation was also examined. As to 40 mm cores, two each were drilled from the same level and their average was taken to minimize the scatter.

Table 1 gives the mixture proportions of concrete used for the tests. Concrete was placed in wall-shaped wooden forms measuring 600 by 300 by 1,400 mm and cured by retaining the forms for 1 week, with water ponding on the top surface. After form removal, the specimens were exposed to outdoor air. The 28-day strength of these cylinders under similar conditions was 28 N/mm^2.

Table 1: Composition of the concrete

G_{max} (mm)	Slump (cm)	W/C (%)	Air (%)	s/a (%)	Concrete composition (Kg/m^3)				
					W	C	S	G	Ad.
20	15	60	5.5	44	180	300	725	975	0.17

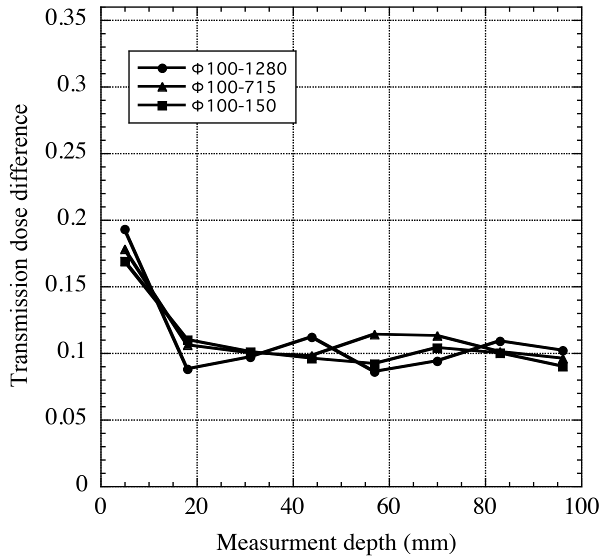


Figure 4: Relationship between TDD and Measurment depth (100 mm core)

Figure 4 shows the distribution of void amount (= TDD) by contrast X-ray imaging from the surface inward in 100 mm cores drilled from the placement depths of 150 mm, 715 mm, and 1,280 mm from the bottom. This figure reveals that the TDD is large to cause low strength only in the surface area (from the surface to around 10 mm), whereas the TDD is nearly constant at 20 mm or deeper. The large TDD near the surface can be attributed to the effect of bleeding along the formwork, which increases the W/C, as the TDD is larger at a higher placement level. It is therefore found that the strength at 20 mm from the surface or deeper inward is constant with little scatter at all levels. Also, the concrete strength estimated from the average TDD was 28.5 Nmm^2, excluding the surficial data at a depth of 10 mm.

Figures 5 and 6 show the distribution of TDD by contrast X-ray imaging from the

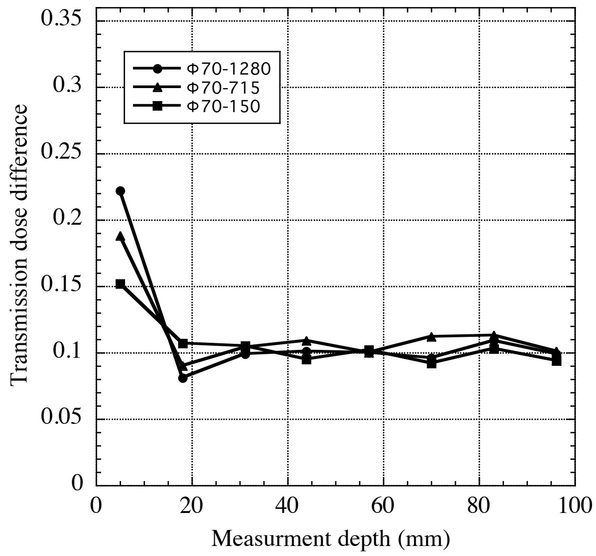


Figure 5: Relationship between TDD and Measurment depth (70 mm core)

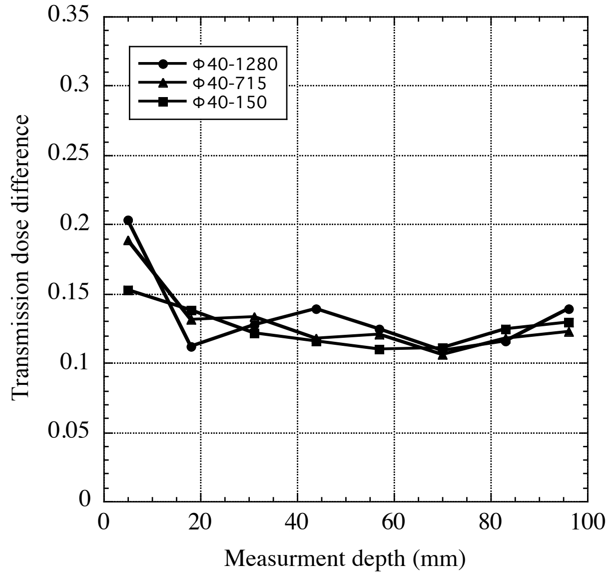


Figure 6: Relationship between TDD and Measurment depth (40 mm core)

surface inward in 70 and 40 mm cores drilled from the placement depths of 150 mm, 715 mm, and 1,280 mm from the bottom. In 70 mm cores, the scatter of TDD of the surface layer is greater than that of 100 mm cores, but the tendencies deeper inward are the same as those of 100 mm cores. In 40 mm cores, however, the TDD deep within concrete tended to be 1.22 times greater than that of 100 and 70 mm cores. While the averages of two cores were taken to represent the results of 40 mm cores, the results of individual cores tended to show greater scatter. This may be because small diameter cores are more sensitive to voids and early defects present or absent in each core, resulting in greater differences from one core to another.

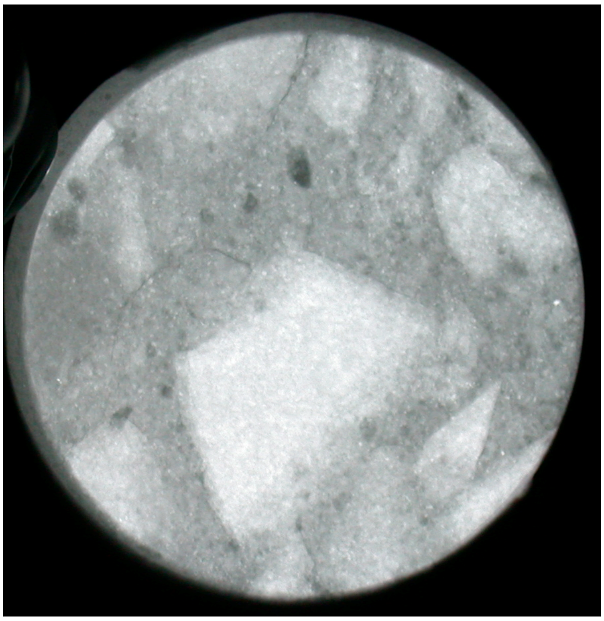
It is known that concrete at a deeper level tends to become denser due to segregation after placing. Such tendencies are clearly observed in the surface layers of concretes shown in Figs. 4, 5, and 6.

Accordingly, when determining the void distribution by contrast X-ray imaging using 40 mm cores, the void amounts tend to be evaluated as being greater than the case of using 70 and 100 mm cores. However, all three sizes of cores accurately represent the state of void distribution within each core. As to strength estimation, the strength of concrete can be determined from the TDD-strength relationship when using 70 and 100 mm cores. When cores 40 mm in diameter are used, the strength can be accurately estimated by multiplying the results by 1.22.

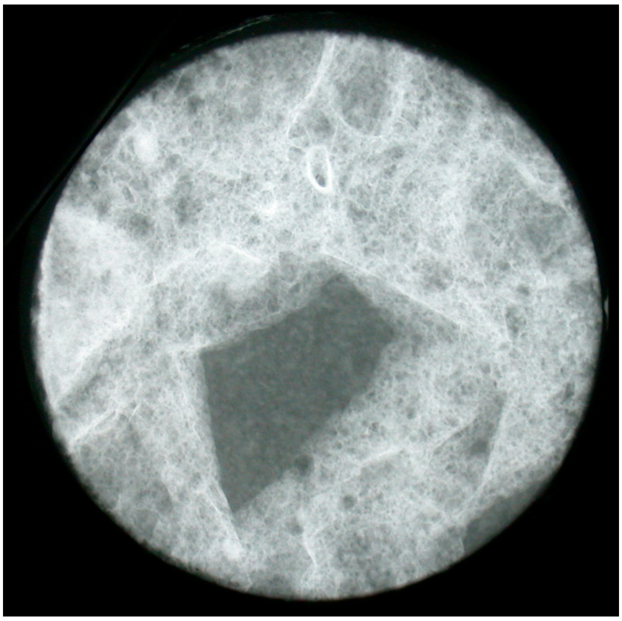
5 VOID PROPERTIES OF ASR-DETERIORATED CONCRETE

Numerous concrete structures are damaged by alkali-silica reaction (ASR) in Japan as well. In most cases, ASR is suspected after map cracks or cracks along the reinforcement become visible on the surfaces of actual structures. It is generally after detailed investigation into such structures and judgment of ASR that countermeasures are finally taken. If cracking characteristic of ASR is recognized at an early stage, then measures to suppress the crack propagation can be initiated before cracking becomes detrimental. In this context, cores were taken from actual ASR-deteriorated concrete structures and subjected to contrast X-ray imaging to examine the TDD within concrete. Cores were drilled from three different piers of a bridge that had been judged as being ASR-deteriorated through detailed investigation.

Photo 1 shows transfer images (X-ray films) of ASR-deteriorated concrete before and after impregnation with a contrast medium. Numerous fine cracks are found to occur near aggregate particles on the image after impregnation, whereas they are not recognized on the image before impregnation.



(a) Before impregnation



(b) After impregnation

Photo 1: Cracks in ASR-deteriorated concrete

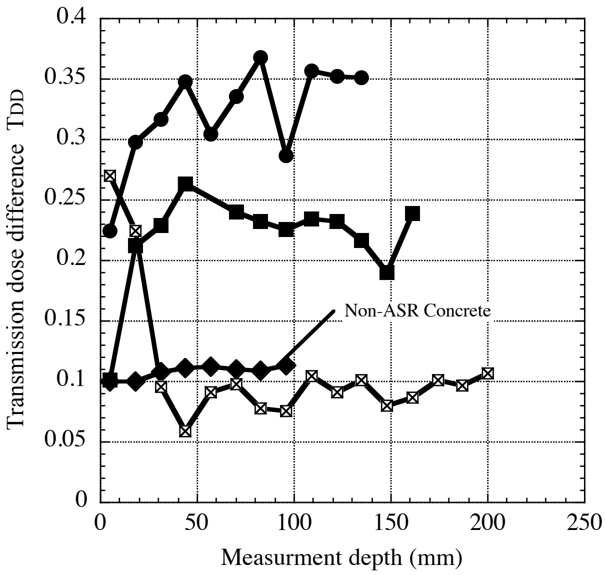


Figure 6: Relationship between TDD and Measurment depth (40 mm core)

Figure 7 shows the relationship between the TDD and the depth from the surface of cores drilled from three bridge piers determined by contrast X-ray imaging. This graph also includes a data example of a structure unaffected by ASR for comparison. This figure reveals that the TDD of ASR-deteriorated concrete tends to be extremely large and changeable when compared with concrete with no ASR. The TDD profiles include two patterns: one in which the TDD at larger depths is much greater than in the surface layer and the other in which the TDD in the surface layer is much greater than at larger depths. The latter pattern was observed in a pier that is exposed to rainwater, where water supply from the surface layers may have caused expansion particularly from the surfaces. The TDD profiles of concrete in which ASR is beginning to occur thus tend to be significantly changeable in a zigzag manner. This characteristic may allow early detection of ASR. Note that strength estimation of ASR-deteriorated concrete by contrast X-ray was impossible due to the extremely large differences. This is presumably because expansive cracks caused by ASR widely differ from those that can be determined by the theory of the cement void ratio. This issue requires further investigation.

6 CONCLUSIONS

Within the range of the present tests, the following were found:

(1) The void distribution and strength of concrete can be estimated by contrast X-ray imaging using 10 mm slices of drilled cores.

(2) For strength estimation by contrast X-ray imaging, the strength can be estimated based on the relationship between the strength and the determined TDD when using 70 mm or 100 mm cores. When the core size is 40 mm, the strength can be estimated by correcting the test values, as 40 mm cores tend to lead to lower strength values.

(3) Investigation into ASR-deteriorated concrete by contrast X-ray revealed that the void properties are widely changeable along the depth from the surface when compared with sound concrete. This characteristic suggests the possibility of detecting ASR at an early stage by contrast X-ray imaging.

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