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DETERIORATION PROPERTIES OF DAMAGED CONCRETE DUE TO FREEZING AND THAWING

M. Saichi[1] and H. Mihashi[2]

[1]Department of Architecture, Tohoku Institute of Technology,
Sendai, 982-8577, Japan
[2]Department of Architecture and Building Science,
Graduate School of Engineering, Tohoku University,
Sendai, 980-8579, Japan

ABSTRACT

This paper presents a study on statistical feature of internal cracks developed in frost-damaged concrete. Concrete specimens were observed for internal cracking by means of digital microscope after they were subjected to a series of rapid freezing-and-thawing cycles. The intensity of cracking was estimated by means of the intersections of traverse line and cracks. The agreement of shapes between normal distribution and observed histogram of intersects was verified. Furthermore, the expedience of using intersections for quantification as well as applying a probability distribution to the estimation of cracks was substantiated. Although, in this paper, observed cracks were restricted to those observed on the cut surface perpendicular to the direction of length, consequent findings might provide useful information for assessing the feature of damaged concrete due to freezing and thawing.

KEYWORDS

Concrete, frost damage, freezing-and-thawing test, normal distribution, statistical analysis

INTRODUCTION

In our study, the focus of interest is originally put on the field of damage assessment of concrete in existing reinforced concrete (RC) structures. This paper presents a study conducted as a part of series of investigation that was made to reveal the feature of internal cracking caused by frost damage.

Relation between damages and internal cracks

RC structures constructed in a cold district are possible to subject many freezing-and-thawing cycles during their design lives, and concrete is known to be deteriorated after a certain cycles. It has long been recognized that concrete is damaged by the internal pressure caused by freezing of the contained water [1,2]. Many investigators have implied that the intensity of damage is related to irreversible cracking within concrete. These and similar studies underscore the important role of internal cracking for the disruptive behavior and/or life of the concrete structures. On the other hand, in case of the frost-damaged concrete, research interests have been mainly focused on the nature of freezing effects, and little research has been done on the internal cracking.

Microscopic observation of internal cracks

While progressive cracking has mainly been observed by means of indirect examinations such as dynamic elastic modulus, direct observation is preferable because this would provide the precise information pertinent to the mechanism of cracking: for example, the location, the exact size of internal cracks, and so on. The use of powerful microscopes has been able to study the formation of internal cracks [3], and some insight features have been obtained on the change in concrete. A direct observing method by means of microscope for studying microstructure and crack growth within concrete was introduced by Hsu [4] and Shah and Sanker [5]. As demonstrated by them, a meso-level microscopic observation could be a useful tool for detecting distributed internal cracks. The most apparent properties of internal cracks are the number and the size including length, width and depth. In practice, however, the most widely used characteristic is the length of cracks developed on the surface during and/or after the freezing-and-thawing cycles.

The purpose of this paper is to estimate the deteriorated properties of frost-damaged concrete by means of microscopic observation of internal cracks. Statistical features of the cracks are also analyzed.

EXPERIMENTAL WORK

Specimen preparation

The specimens used were concrete prisms whose dimensions were $100 \times 100 \times 400 mm^3$. The nominal value of compressive strength was 30MPa. Ordinary Portland cement was used. The coarse aggregate was crushed gravel with the maximum size of 20 mm and the fine aggregate was crushed sand. No chemical or mineral admixtures were applied to the concrete mix. Approximately 48 hours after casting, specimens were removed from the steel molds and transferred to a standard water curing room where curing was continued at approximately 20℃ until the day freezing and thawing tests started.

Frost damage simulation

A series of rapid freezing-and-thawing test was carried out in this study for frost-damage simulation. The freezing-and-thawing cycles were applied according to the ASTM specification, “C 666, Procedure A”. The cycle consists of alternately lowering the temperature of the specimens from 5 to -18 degree Celsius and raising it from –18 to 5 degree Celsius in 4 hours.

The tests were started when specimens were reached at an age of 14 days. Immediately after the curing period, specimens were weighed, and measured for fundamental transverse frequency, in accordance with the method of ASTM C 215, on the basis of which the frost damage levels were identified. After these measurements, the freezing and thawing cycles were started. The specimens were removed from the apparatus at intervals of 30 cycles. After rinsing out the container as well as adding clean water, they were returned to random positions in the apparatus with upside-down basis. In each interval, one specimen having a role in fixing the data of particular cycle was selected and kept out. The specimen was tested again for fundamental transverse frequency, weighed, and took procedures of preparation for microscopy. The freezing-and-thawing cycles were applied until the number of cycles was reached more than 300.

Preparation for microscopy

Since microscopy requires the specimen of a suitable size, a piece of cube (100mm in length) was taken from the frost-damaged prism. A transverse section, perpendicular to the longitudinal direction, was cut out directly through near the center of the prisms: thus the block of specimen has the size of 100 mm square in the section.

In total 7 concrete prisms were used to observe the cross section under a microscope. Each section was observed for internal cracking by means of optical microscope, which equipped with a high-resolution CCD digital camera and storage devices. Since this microscope did not require thin sections, time-consuming preparations of those samples could mostly be omitted. Cross sectional area was ground carefully by precision grind machine until no trace of saw could be seen. A red liquid for penetration was sprayed over the area for the staining. This was done to distinguish more clearly between cracks at the interface and those through the matrix. After several times, mortar surface became a color of light pink, and deep red lines representing internal cracks could be clearly distinct in the view. The stained surface was then ground again on a grinding wheel. The sections were then slowly dried in room where the atmosphere was kept at 20℃ and approximately 65 percent relative humidity. Neither the sawing process nor the drying process on specimens was considered to significantly affect the measured characteristics of cracking because their effects were verified to be negligible through the preparatory tests.

Observed areas

The observed area used for the microscope observation was $6350mm^2$ in total per section so that a sufficiently wide range of size could be covered. The observed data presented herein were obtained from the sample areas determined by dividing the observe area into 10×12 segments. Each segment has the dimension of $6.4\times8.4mm^2$, and is designated as “sample area” in this paper (see, Figure 1). At first, the feature of each sample area was recorded on a MO-media as a digital image. Subsequently, all images (in total 840) were processed.

EXPERIMENTAL RESULTS AND DISCUSSION

General feature of the internal cracks observed in the sample areas

At the beginning of the observation, relevant sample area was served onto the PC monitor from the MO media. The sample area was composed of matrix and inclusions, as shown in Figure 2. When observed at the previously mentioned magnification, those compositions are regarded to be in the scale of meso-level. The observation indicated that many internal cracks were identified in the sample area, regardless the intensity of the frost damage. Cracks through the mortar area, so called mortar cracks, began to increase noticeably and form continuous crack patterns from initial cycles whereas they would be developed at about 70～90 percent of the ultimate load in case of mechanically damaged concrete [4, 6]. Since internal cracks were shaped like a network pattern similar to cracks of parched earth, and their lengths were spread over a considerable extent, those cracks were not allowed to identify individually. Therefore, neither counting nor tracing of cracks was practicable. Hence, newly devised procedure for quantification would be required. As described later, intersections of traverse line and cracks were used in this paper as a parameter for estimating the intensity of internal cracking.

Relation between internal cracking and intensity of frost damage

Equivalent freezing-and-thawing cycle

Since specimens did not necessarily show the correspondence of damaged feature with nominal number of freezing-and-thawing cycle, the term "equivalent freezing-and-thawing cycle" was introduced to indicate the real stage of intensity of the frost damage. The equivalent freezing-and-thawing cycle was defined as the estimated value led from the correlation between nominal freezing–and-thawing cycle and dynamic Young's modulus of elasticity. The former was indicated by the apparatus, and the latter was calculated from the fundamental transverse frequency measured by the reference specimens. Frost damaged specimens were calibrated according to the established correlation, and the respective equivalent freezing-and-thawing cycle was determined. Hereafter, in this paper, the equivalent number of freezing-and-thawing cycle will be used for representing the number of freezing-and-thawing cycle.

Intersections as a parameter for quantification

Three linear-traverse-lines, which were referred to as test lines in this paper, were first drawn and were superimposed on each sample area as shown in Figure 3. Subsequently, intersections of test lines and cracks were counted. Since this process was repeated for every sample area, in total 360 test lines per observed area were drawn. These procedures were processed by using software, which enables to generate graphics as well as to perform some calculations.

Relation between damage intensity and extent of internal cracking

Figure 4 shows the comparison of extent of cracks within each sample area for sound and damaged specimens. For clarifying, results relating to three specimens are presented. Each bar represents total number of intersections included in respective sample area. Compared damaged specimens (Figure 4-b and c) with sound one (Figure 4-a), it is obvious that damaged specimens produce a higher extent of internal cracking. Figure 4-a also showed that cracks densely distributed are contained widely even in the sound (0cycle) concrete. This is a manifestation of the well-known phenomenon of existing cracks observed experimentally and/or microscopically by many investigators.

Statistical distribution of intersects

Figure 5 illustrates typical relation between damage intensity and increasing feature of intersects for three different freezing-and-thawing cycles. Although other diagrams were omitted to save the space, they showed essentially a similar trend. Each bar represents the number of test lines counted for the certain rank of intersections, and the line superimposed is drawn according to the normal distribution law. As shown in each diagram, there is an interesting agreement between bars and the line, and the Chi-square test carried out on each group of data did not reject the agreement at the usual significance level. These results suggest that the distribution of intersects could be approximated by a normal distribution.

Practical quantification of internal cracks

As intersections are essentially dimensionless data without perceptible area or length, the term "density of cracks" that is estimated by the Eqn. 1 is introduced for the practical quantification:

$$L_A = P_{Lx} = \int_0^{Ly} p_{Lx}(y) \cdot f(y)\, dy \qquad (1)$$

where, L_A is the estimated density of cracks (mm/mm^2); P_{Lx} is the expected density of intersects (points/mm), which is practically estimated by the average value; Ly is the longitudinal length of the sample area; $p_{Lx}(y)$ is the total number per test line at the position on the sample area; and $f(y)$ is the probability of appearance of the test line at the increment of dy.

Figure 7 represents the estimated density of cracks as a function of the freezing-and-thawing cycle increases. As shown in Figure 7-a, internal cracks increased with two stages that are a steeply increasing stage in lower cycles less than 30, and a gradually increasing stage in more than 30 cycles. The relation might be approximated by a bi-linear function when cycles were converted into logarithmic numbers as shown in Figure 7-b. The cyclic number of the break point was in the vicinity of 150 cycles.

CONCLUSIONS

Based on the results of this study, the following conclusion can be made.

1. Mortar cracks began to increase and form continuous patterns even in the initial cycles.
2. Cracks were not allowed to be identified individually since internal cracks were shaped like a network pattern similar to cracks of parched earth, and their lengths were spread over a considerable extent.
3. Damaged specimens produce a higher extent of internal cracking, and those cracks increase as the freezing-and-thawing cycles increase.
4. Intersects of a test line and cracks were utilized for crack quantification, and their distribution could be approximated by a normal distribution.
5. Internal cracks were increased with two stages that are a steeply increasing stage in lower cycles less than 30, and a gradually increasing stage in more than 30 cycles. The relation might be approximated by a bi-linear function, when cycles were converted into logarithmic numbers.

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