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EVALUATION OF CRACKING OF CONCRETE DUE TO ALKALI-AGGREGATE REACTION

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Abstract

This study was planned to clarify the properties of cracking, such as the width, the number and the density of cracks, occurred in the concrete specimen under several testing condition, and to determine the relation between the crack and the expansion.

1. Introduction

When evaluating the degree of damage to a concrete structure caused by alkali-aggregate reaction, a problem arises whether to take characteristic values in terms of expansion or of cracking. For example, while there is an opinion on the one hand that expansion is more harmful from the standpoint of a dam as a whole since surface cracks of widths 2 to 3 mm disappear at depths of 30 to 50 cm in most cases, there is on the other report[1] of an investigation made in the United Kingdom that occurrence of cracking increases uplift pressure on a dam. In evaluating the degree of damage to a structure, it is necessary to make the evaluation based on either expansion or cracking, or both, upon an overall judgment of the degree of importance, scale, and safety of the structure, and further, the environmental conditions under which the structure happens to be placed.

Many investigations and studies have been made up to the present concerning alkali-aggregate reaction, but a precise method of evaluating cracks has not been proposed, and the amount of literature on the subject is extremely small. The research reported here was planned for making a detailed study of the relation between random cracks and expansion produced by alkali-aggregate reaction, and at the same time obtaining data required for quantitatively evaluating cracks.

2. Outline of Tests

(1) Materials

The aggregates were three kinds of reactive coarse aggregates (O, T1, T2) used in actual concrete structures with occurrence of actual damage reported and judged further as deleterious or potentially deleterious by the chemical method (O:Sc=732, Rc=177, T1:Sc=558, Rc=101, T2:Sc=301, Rc=68(m mol/1)), a non-reactive coarse aggregate (NT), and a non-reactive blended fine aggregate (NS) with gradation adjusted by blending sand from a river mouth and standard sand.

The cement was ordinary portland cement containing Na_2O equivalent 0.5 percent, while for adjustment of total alkali content of concrete, first grade reagent NaOH was selected and this was used dissolved in mixing water (tap water).

of applying repetitions of wetting and drying action varying the various factors concerning concretes using one kind of reactive aggregate and one kind of non-reactive aggregate as coarse aggregates. The principal factors in these tests were the proportion of reactive aggregate blended (0, 50 and 100 percent), total alkali content (0.5, 1.5 and 2.0 percent (Na_2O equivalent)), drying temperature (oven drying (60°C) and air drying (20°C)), and immersion water. Regarding concrete mix proportions, using a unit cement content of 450 kg/m^3 and non-reactive aggregate (NT), they were decided by trial mixed for slump of 12 to 15 cm in a condition of no addition of alkali. Stiffening was produced by addition of NaOH, but water content was not cor-rected for the resulting variation in slump. The mix design of the concrete is given in Table 1.

Table 1 Mix proportion of concrete

Max. size (mm)	Slump (mm)	Air (%)	W/C (%)	s/a (%)	Unit weight (kg/m^3)			
					W	C	S	G
20	12~15	2	45	40	203	450	660	969

2.3 Method of Testing

With regard to the method of testing, as shown in the flow chart of Fig. 1, curing was performed in a constant-temperature room for 24 hours after casting concrete and then demolding was done, followed curing in water for 3 days, and testing was started after making initial measurements on the fourth days. Firstly concrete specimens were put in an oven (60 °C) or air (20 °C) for 24 hours to obtain dried conditions, and next, the specimens were immersed for 24 hours in the respective immersion solutions (20 °C) to obtain wet conditions. This operation was considered as one cycle of wetting and drying.

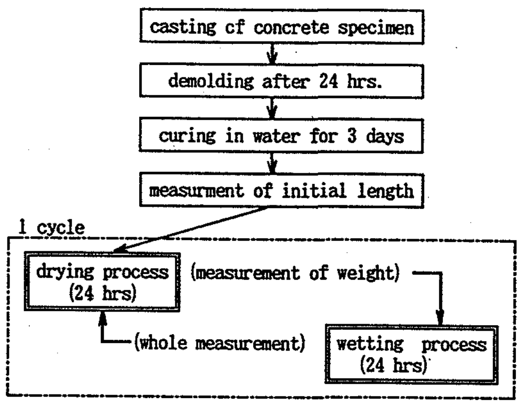

Fig. 1 Condition of wetting and drying test

Weight measurements were made after drying and immediately before starting wetting, while whole measurements were made after wetting and immediately before starting drying at 2, 4, 6, 8, 10, 15, 20, 25, 30, 35, 40, 45, and 50 cycles. "Whole measurements" here means measurements of length change, weight, and dynamic modulus of elasticity, sketching of cracks after crack formation, taking photographs, and evaluations of cracking characteristics by the traverse method.

Regarding specimen numbers, they are made up to indicate in order (Reactive aggregate)-(Blending ratio of reactive aggregate)-(Alkali content)-(Drying method). For example, "T1-100-1.5-D" indicates the aggregate T1, blending ratio of 100 percent, alkali content (Na_2O equivalent) of 1.5 percent, and oven drying ("A" in case of drying done in air). Further, fresh-water immersion in the wetting process is expressed by "D-W" and sea-water immersion by "D-S".

3. Results of Tests and Considerations

3.1 Percentage Expansion (ε) and Daynamic Modulus of Elasticity (E_D) of Concrete

The specimen T1-100-0.5-D had low alkali content of 0.5 percent so that in both fresh-water immersion (D-W) and sea-water immersion (D-S) expansion did not occur, and E_D were constant at 3.7 x 10 kgf/cm^2. Neither could formation of cracks be recognized in visual inspection. Hence, it may be comprehended that this specimen was not subjected at all to alkali-aggregate reaction.

Next, the time-dependent changes in the various physical properties of the specimen T1-100-2.5-D are shown in Fig. 2. With this specimen, expansion began from 4 cycles of wetting and drying testing, and ε converged at 0.35 percent after approximately 20 cycles. The overall trends of D-W and D-S of different immersion waters were similar to each other. With regard to outward appearances, cracks due to alkali-aggregate reactions occurred. It can be assumed from these facts that a fair amount of damage had been sustained due to alkali-aggregate reaction. It may be comprehended that the degree of alkali-aggregate reaction, and further, the various physical properties of concrete differ considerably according to differences in alkali content and immersion water.

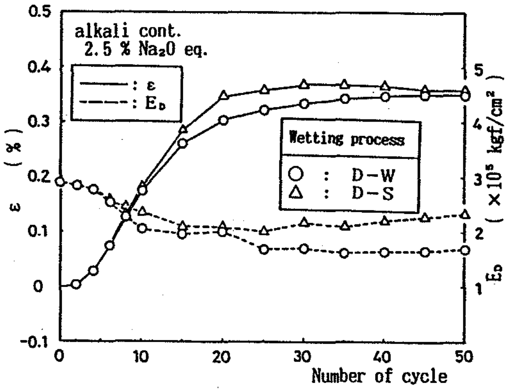

Fig.2 Time-dependent change in ε and E_D.

3.2 Influences of Wetting and Drying Methods

The reasons for selecting the drying temperature at 60°C was that temperature of concrete surface in midsummer reaches roughly this degree at times and that when the temperature becomes higher than this, loss of free water and pore water from the concrete will become severe with even bonding water being affected and there is a risk that the constitution of the concrete itself will be considerably affected.

The time-dependent changes in the various physical properties with the two method of oven drying (T1-100-1.5-D) and air drying (T1-100-1.5-A) are shown in Fig. 3. The wetting processes were both immersion in water. It can be seen from this that the behavior of a specimen in air was that expansion did not occur and E_D was around 3.4 x 10 kgf/cm^2 and more or less constant. On the other hand, with an oven-dried specimen, ε increased gradually, and at 50 cycles, was approximately 0.05 percent higher than for the specimen in air, while E_D gradually decreased and became approximately 0.7 x 10 kgf/cm^2 lower at 50 cycles. Therefore, it may be comprehended that with an oven-dried specimen, the degree of damage due to alkali-aggregate reaction was slightly greater than for a specimen in air. This is thought to have been because with drying in an oven a considerable portion of the moisture contained in the concrete evaporated so that alkali became concentrated to accelerate alkali-aggregate reaction, and along with ε being increased E_D was decreased by deterioration of the constitution inside the concrete due to alkali-aggregate reaction.

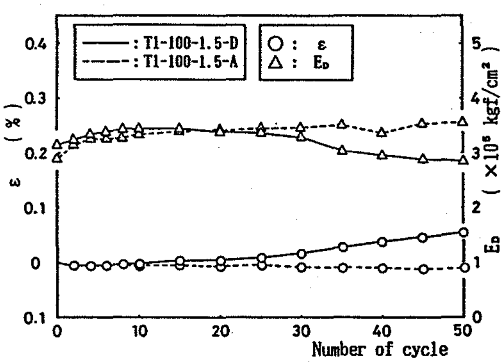

Fig.3 Influence of drying method

Next, the ratio of the time-dependent changes in the difference between ε of the two, (D-W) - (D-S), and the time-dependent changes in the ratio of E_D, (D-W)/(D-S), were examined to consider the influence of immersion water. Fig. 4 shows that ε for D-W were higher than for D-5 with all specimens except the specimen T1-100-2.5-D, while with T1-100-2.5-D, ε was higher for D-S also up to about 20 cycles, but at 50 cycles the percentages became approximately

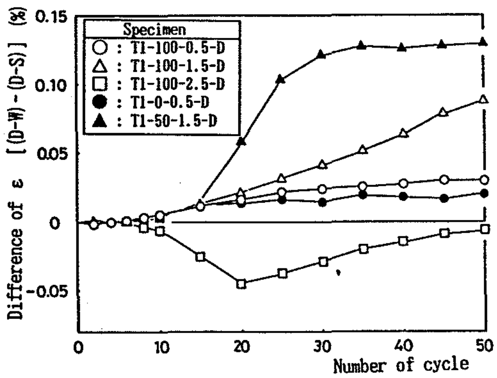

Fig.4 Influence of immersed water

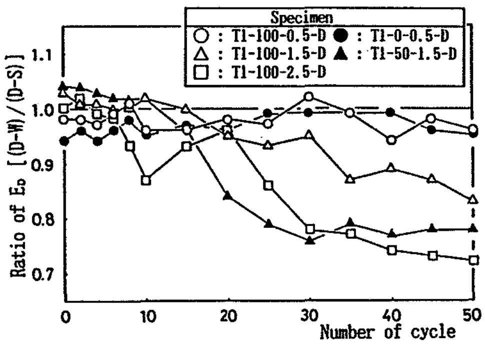

Fig.5 Influence of immersed water (E_D)

the same. As for Fig. 5, it shown that regarding E_D, the values of (D-W)/(D-S) for all specimens were not more than 1, and lower for D-W than for D-S.

The relation between ε and number of cracks is shown in Fig. 6, and the relation between ε and average crack width in Fig. 7. It can be seen that when ε becomes higher the number of cracks and average crack width become larger and there are positive correlations. Although of the same ε, both number of cracks and average crack width were larger for D-W than for D-S. It may be said from the foregoing that in wetting and drying treatments of about 50 cycles, damage from alkali-aggregate reaction is greater for fresh-water immersion than for sea-water immersion.

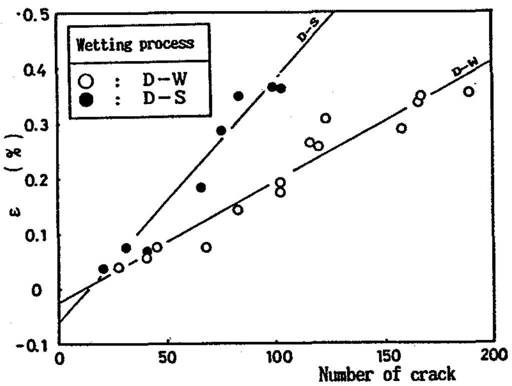

Fig.6 Influence of immersed water (number of cracks)

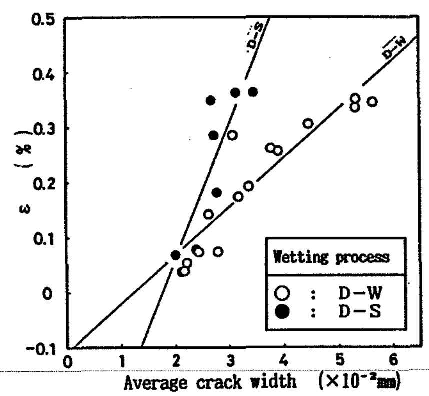

Fig.7 Influence of immersed water (average crack width)

3.3 Evaluation of Degree Deterioration

The degree of deterioration of concrete subjected to cyclic wetting and drying was evaluated referring to the method of evaluating durability of concrete in applying cyclics of freezing and thawing. Firstly, the relation between ε and E_D was examined. Regarding E_D in this case, the relative dynamic modulus of elasticity ($R.E_D$) for E_D in a condition when the hydration reaction and strength of concrete had become more or less constant was considered, and in the cyclic wetting and drying tests E_D at 4 cycles was adopted as the standard. The relation between ε and $R.E_D$ is shown by the white circles in Fig. 8. On the other hand, the black dots in Fig. 8 indicate the results of long-term tests on specimens with the same mix proportions and stored at 40 C, RH 100 percent. From this figure, it can be comprehended that $R.E_D$ declines when ε increases, and there is a negative correlation between the two. On sectioning off these plotted points at ε of 0.1 percent and $R.E_D$ of 0.80, the relation between ε and

$R.E_D$ is broadly separated into the zone of ε under 0.1 percent and $R.E_D$ higher than 0.80, and the zone of ε above 0.1 percent and $R.E_D$ lower than 0.80. That is, if $R.E_D$ was lower than 0.80 almost all were of ε above 0.1 percent, and cracks were formed in this zone. From this, it can be considered that deterioration of concrete by alkali-aggregate reaction has progressed considerably when ε has risen above 0.1 percent and $R.E_D$ has dropped below 0.80.

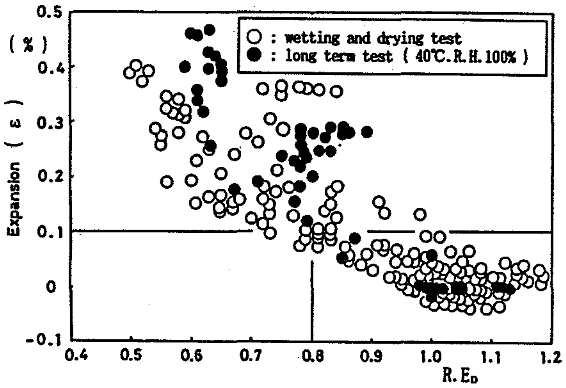

Fig.8 Relation between ε and $R.E_D$

Thereupon, the cyclic wetting and drying deterioration index (DW-DF) was contemplated referring to the durability factor (DF). DW-DF is expressed by the following equation:

$$DW\text{-}DF = Pn \cdot N / M \times 100$$

where, Pn : $R.E_D$ at N cycles
N : number of cycles when $R.E_D$ declined to 0.80. However, final number of cycles when 0.80 not reached
M : number of cycles of test ($M = 50$ cycles)

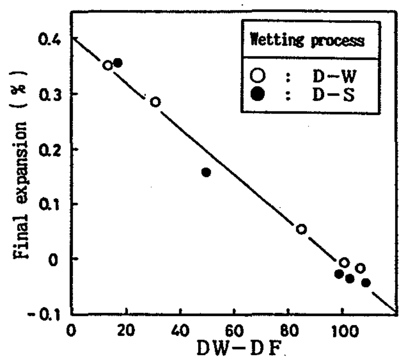

Fig.9 Relation between final expansion and DW-DF

The relation between the final ε of the individual specimens and DW-DF were obtained to contemplate what kind of indicator this index (DW-DF) was, and as shown in Fig. 9. It may be seen that there is strong negative correlation between final ε and DW-DF. It was ascertained that the number of cracks and cracks widths become larger and deterioration due to alkali-aggregate reaction progresses when ε increases. Consequently, it may be considered that deterioration due to alkali-aggregate reaction of concrete progresses more the smaller the value of DW-DF.

3.4 Relation between Long-term Tests and Cyclic Wetting and Drying Tests

The method of evaluating reactivity using concrete specimens at present is to investigate and study the behaviors of the specimens which are 10 x 10 x 40 cm and stored 40°C, RH 100 percent. If the results of the present cyclic wetting and drying tests were to correspond with long-term tests and there were to be a distinct relationship, it would be possible for evaluations of reactivity of concrete to be made in shorter periods of time. Therefore, in this section, the results of long-term tests and the results of cyclic wetting and drying tests were compared and the relationships were examined.

Comparsions were made of the long-term results and cyclic wetting and drying test results regarding the 5 items below for the T1-100-2.5 specimens which showed the most expansion in the cyclic wetting and drying tests.

1. Time until ε showed a trend of increase
2. Time until E_D showed a trend of decrease
3. Time until ε reached 0.1 percent
4. Time until $R.E_D$ reached 0.80
5. Time until cracking occurred

Table 2 Results of long-term test and wetting and drying test

Items	Long-term test (month)	Wetting and drying test (cycle)	
		D-W	D-S
1	0.5	2 (0.25)	2 (0.25)
2	0.5	2 (0.25)	4 (0.13)
3	2	8 (0.25)	8 (0.25)
4	2	8 (0.25)	10 (0.20)
5	2	6 (0.33)	6 (0.33)

( ) days corresponding to 1 cycle

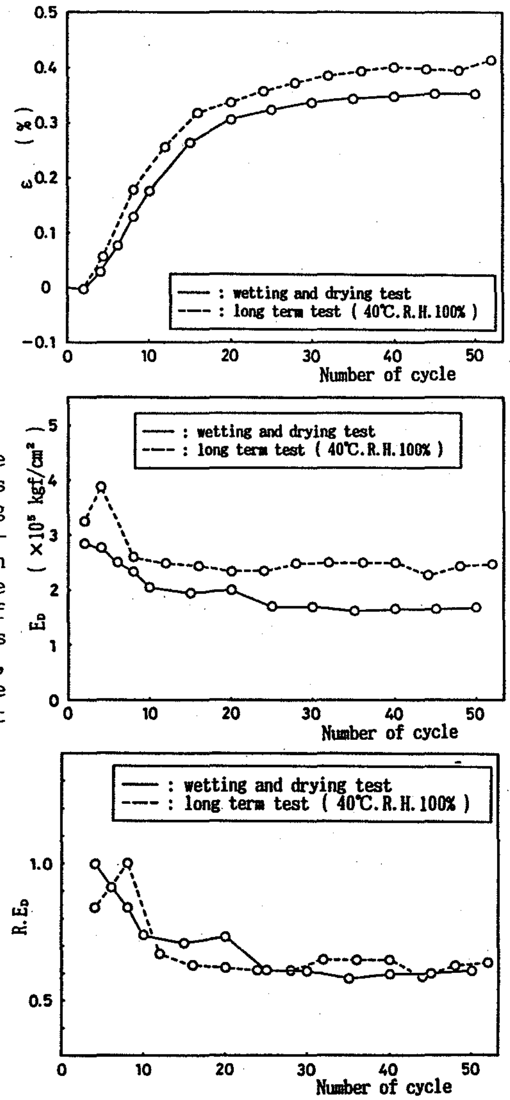

Fig.10 Relation between results of long-term test and wetting and drying test

The results of the comparisons are shown in Table 2. According to this table the number of days corresponding to 1 cycle of wetting and drying treatment will be 0.25(Mo.)= 7 days on average. Therefore, the two tests were compared assuming a cycle to consist of 7 days. From the time-dependent changes in ε, E_D, and R.E_D shown in Fig. 10, it can be seen that although there were slight differences, the two had almost the same trends on the whole.

4. Conclusion

The research reported was a study of the behaviors of various physical properties when concrete specimens using reactive aggregates were put in environments of cyclic wetting and drying. The conclusions of the research are as follows:

(1) The behaviors of the various physical properties of concrete specimens in environments of cyclic wetting and drying differ greatly depend-ing on blending ratio of reactive aggregate and alkali content.

(2) Temperature has a considerable influence in the drying process, and deterioration due to alkali-aggregate reaction is more prominent for a specimen dried in an oven (60°C) than one dried in air (20°C).

(3) The degree of deterioration of concrete in an environment of cyclic wetting and drying can be evaluated to a certain degree by using a deterioration index, (DW-DF).

(4) The number of days corresponding to 1 cycle of wetting and drying treatment is 7 days.

It is intended for further testing to be done changing the number of cycles, drying temperature, and wetting method in various ways to grasp the general picture of alkali-aggregate reaction in environments of cyclic wetting and drying, and to extend it to the development of an accelerated testing method applying this knowledge.