Degradation of submerged/wet concrete under cyclic compression and cyclic shear

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Abstract. The aim of this study is to identify a specific degradation of concrete that has been observed in bridge decks made of reinforced concrete (RC). To control the phenomenon, fundamental studies were conducted. Compressive loads and external water pressure were cyclically applied to submerged concrete cylinder specimens with different pre-loading and restraint conditions. The turbidity of the water in the tank was generally observed during the loading, and the pH of the turbid water steadily increased as the number of cycles increased. Thereafter, fine aggregates without a cement matrix were found on the inner surfaces of split specimens. These phenomena were quantitatively analyzed, and the analyses suggested that cyclic water pressure acted on the inside of pre-cracked specimens and washed out their cement matrix. The degradation of a rough cracked surface was also examined using the cyclic shear test, with/without a water supply to the crack. The shear slip and the orthogonal displacement were clearly amplified with an increase in the number of cycles when the water supply was present. The mechanical properties of cracked concrete with water in shear was discussed in accordance with that of liquefaction. These fundamental studies could help to determine the acceleration factors of the degradation and provide certain thresholds for practical use.

1 Introduction

Bridge decks made of reinforced concrete (RC) have been well known as the typical example of submerged/wet concrete under cyclic compression and cyclic shear. The degradation of upper surface concrete is often associated with the outflow of the broken cement matrix. The concrete that loses its binder is no longer concrete but an aggregate of gravels (see Fig. 1).

This phenomenon has also been observed in wheel running tests for RC slabs where water is supplied to the upper surface [1]. Correspondingly, during the cyclic pull-out test of anchor frames, the pumping out of sludge from anchorage concrete was visible when water was supplied to the specimen [2]. In addition, the degradation of the rough cracked surface under the cyclic shear was clear when water was supplied to concrete specimens [3]. In general, the fact that the water accelerates the degradation of concrete under cyclic loads has been verified by experiments conducted in the past decades.

Researchers have hypothesized that a significant increase of pore water pressure, caused by the impulsive deformation of the concrete skeleton, induces the fracture of the cement matrix [4, 5, 6]. This hypothesis is based on the liquefaction mechanism of soil. However, it is difficult to verify for concrete, because the pore water pressure of concrete cannot be measured directly in experiments. A simplification of the problem is necessary.

Fig. 1 Degradation of bridge deck made of RC

In this study, experiments were therefore conducted that are both fundamental and essential. First, the cyclic water pressure test without external forces that might induce the impulsive deformation of concrete. The method of this experiment was an improvement to that of the previous study [7]. A variety of experimental conditions were prepared, which relate to micro and macro cracks and the confinement of specimens.

Furthermore, the cyclic shear test of cracked concrete with/without a water supply was conducted. The experimental devices that were originally used for the direct shear test for rock were developed for this study.

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Further, the results were carefully compared to that of the process of liquefaction of loose sand.

2 Cyclic water pressure test

2.1 Cyclic water pressure test of submerged concrete cylinder with micro cracks

2.1.1 Test condition and procedures

The experimental conditions and names of the specimens are listed in Table 1. To examine the influence of micro cracks on the degradation due to water pressure, pre-cracked specimens were prepared. The specimens were pre-loaded until the load reached the maximum strength of the specimen, as well as until not-failure. Thereafter, the specimens were unloaded. The presence of micro cracks was expected, even though no visible cracks were found on the outside. The water to cement ratio of the concrete was 65% for all specimens. The average compressive strength of the concrete was 25.8MPa for the prototype, and 18.5MPa for the pre-cracked specimen.

Table 1 Experimental conditions of series 2.1

Case	Cycle of loading	Pre-loading	Number of specimen
AC-0	0	---	3
AC-1000	1,000	---	3
AC-5000	5,000	---	3
AC-10000	10,000	---	3
PL-0	0	done	3
PL-1,000	1,000	done	3
PL10,000	10,000	done	3

The overview of the experimental set up is shown in Fig. 2. Cylindrical specimens of a 100mm diameter and a 100mm height were placed in a water tank. There is a notch simulating a crack at the center of the upper surface. When the load was applied to the upper specimen, the water pressure was generated in the sealed area between the upper and lower specimens. Even though the pore water pressure could not be measured, the applied pressure to the surface of the specimen could be recorded using a hydrometer. After a certain number of cyclic actions, the specimen was picked up and then split. The fine aggregates with diameters between 5 μ m and 2500 μ m on the rough cracked surface were quantified as the results of the degradation. This experimental procedure was based on the study [7].

2.1.2 Results

An example of the measured water pressure is shown in Fig. 3. The maximum water pressure was between 1500kPa and 2000kPa for each case, and the minimum was almost -100kPa for each case. The turbidity of the water in the tank was generally observed during the loading, and the pH of the turbid water tended to increase as the number of cycles increased. The weight of the fine

Fig. 2 Experimental set up

Fig. 3 Fluctuation of water pressure with time

Fig. 4 Relationship between the weight of fine aggregate and the degradation index, focusing on positive water pressure.

Fig. 5 Relation between the weight of fine aggregate and the degradation index, focusing on negative water pressure.

aggregates found on the inner surfaces of the split pre-cracked specimens was larger than that of the specimens without pre-loading.

2.1.3 Discussion

The degradation index proposed in the previous study [7] was adopted for comparison with the previous result obtained for specimens without pre-loading. The index was defined as follows:

Table 2

Case	Crack width (mm)		Confined
	0.2	0.5	
1	✓	---	---
2	---	✓	---
3	✓	---	✓
4	---	✓	✓
5	---	✓	✓
6	---	✓	✓
7	✓	---	✓
8	---	✓	✓
9	---	✓	✓
10	---	---	✓

$$j = \sum_{i=1}^k (n_i p_i) / f_c \tag{1}$$

where j is the degradation index, p is the intensity of water pressure (MPa), n is the number of cycles for p, k is the total number of classified water pressures and f is the compressive strength of concrete specimen. The relationship between the weight of fine aggregates found on the inner surfaces and the degradation index, focusing on positive and negative water pressures, were shown in Figs. 4 and 5, respectively.

According to Figs. 4 and 5, the weight of the fine aggregates of the pre-cracked specimens was generally larger than that of the normal specimens. This suggested that the water pressure created a wedge effect in the micro cracks, and the fracture of the cement matrix was then accelerated for the pre-cracked specimens. This agreed with the hypothesis proposed by researches.

For a further understanding of the phenomena, a multiple regression analysis for both the positive and negative water pressures was performed.

$$F = 0.0023 \times j(p) - 0.0365 \times j(n) + 0.1931 \tag{2}$$

where F is the weight of the fine aggregates, j(p) and j(n) are the degradation indices, focusing on the positive and negative water pressures, respectively. The coefficient of positive pressure (0.0023) was smaller than that of negative pressure (0.0365). This suggests that the negative pressure might play a more important role in the degradation; that is, the suction of the broken matrix out of the micro cracks.

2.2 Cyclic water pressure test with macro cracks

2.2.1 Test condition and procedures

The experimental conditions are shown in Table 2. The dimension of the specimens in this series were the same

Fig. 6 Schematic view of experiment series 2.2.

as those in 2.1. However, the pre-cracks and confinement conditions were different from those in 2.1. Cracks in series 2.2 were visible cracks with widths of 0.1mm and 0.5mm. Eight of the specimens were confined by a hose clamp. Thereafter, high cycle loading, such as that of 50,000; 100,000; and 200,000 cycles could be achieved. In addition, the weight of the load applied to the specimen was set as 10kN, 20kN, and 30 kN. The water to cement ratio was 64.3%, and the average compressive strength at the beginning of loading was 22.7MPa.

The schematic view of experiment series 2.2 is illustrated in Fig. 6. The specimens were placed on a ring-shaped chloroprene rubber, then the rubber was placed on the support plate with the drain. When the specimens were pushed on the upper surface, the water pressure was generated inside the ring-shaped rubber. The sides of the specimens were sealed using butyl tape. These were then set inside a water tank. After a certain number of load cycles, the specimens were picked up and cut to observe their cross sections. The total length of visible macro cracks was then recorded.

2.2.2 Results

The turbidity of the water in the tank was observed during the loading, as shown in Fig. 7. The increase of the pH of the turbid water for specimens No. 5, 8 and 9 are shown in Fig. 8. The pH increased rapidly until the first 20,000

cycles, then steadily after cycle 20,000 for No. 5. It is possible that the changes to the pH were caused by the outflow of fine cement powder from the top surface of the specimen.

A cross section that was 10mm away from the bottom of specimen No. 6 is shown in Fig. 9. The degradation was seen in the lower part of Fig. 9. The development of pre-cracks was also observed. It should be noted that the water pressure measured from the upper surface of specimen No. 6 reached a maximum of 232kPa. The total length of the cracks was calculated using the density of the cracks (mm/mm²) for each section.

2.2.3 Discussion

The influence of confinement and the pre-crack width were examined in Fig. 10. Specimens No. 1, 2, 3 and 5 were compared. There was no significant difference between the densities of cracks No. 1 and 2 without confinement, even though their crack widths were different. In contrast, the difference between Nos. 3 and 5 with confinement was clear. The difference between Nos. 2 and 5 was small. These comparisons suggested that the confinement could effectively restrain the degradation of concrete if the width of the existing crack was small. However, it should be noted that the restraining effect is dependent on the water pressure.

2.3 Summary of cyclic water pressure test

According to the cyclic water pressure tests of series 2.1 and 2.2, the possibility of the degradation of concrete is demonstrated even if the water pressure is lower than the tensile strength of concrete. Suggestions for practical concrete can be listed. First, the concrete structure having a high water to cement ratio of 65% can exhibit degradation. Moreover, concrete that might contain micro cracks due to past excessive loads should be considered. Second, drains should be implemented into structures to prevent the harmful pressure rise and suction. Third, the width of macro cracks should be limited to a maximum of 0.2mm to delay the degradation.

3 Shear test with wet concrete

3.1 Test condition and procedure

3.1.1 Preparation of special device and specimens

The schematic view of experiment series 3 is illustrated in Fig. 11. This system consists of the boxes holding specimens and the apparatus that simultaneously controls the shear and normal loading conditions. This was originally used for the direct shear test for rocks (JGS 2041-5008 [8]). The detail of the boxes is shown in Fig. 12. The cracked surface was set horizontally, and the gap between the boxes and specimens was then filled using gypsum.

The water to cement ratio of specimen was 65%. The square cross section of the specimen was 60mm, and the

Fig. 8 Increase of pH of turbid water in water tank.

Fig. 9 Cross section of No. 6

Fig. 10 The density of cracks with different crack width and confinement conditions

height was 40mm. The method of inducing cracks is shown in Fig. 13. First, the notch was provided to two sides (method 1) or all sides (method 2) using a disk grinder. Next, a steel wedge was placed on the notch. The load was then applied to the wedge, and the specimen was split uniformly.

3.1.2 Conditions

The test conditions and the names of the specimens are shown in Table 4. The only differences are the method used to induce artificial cracks and the water supply condition. The wet specimens were submerged for at least one week prior to loading.

The cyclic shear force was set as a sinusoidal wave, and its amplitudes were 0.2kN, 0.4kN and 0.8kN. The amplitude was increased step by step until the number of cycles reached 50,000. During the shear loading, the normal load was maintained at 0.1kN. The shear and horizontal forces, and the horizontal and vertical displacement of the boxes were continually measured.

3.2 Results

The relationship between the number of cycles and the horizontal and vertical displacements of Case 3 (dry) are shown in Fig. 14. That of Case 4 (wet) are shown in Fig. 15. The maximum and minimum amplitudes can also be seen in the figures. Both the horizontal and vertical displacements of Case 3 exhibited no significant signs; however, those of Case 4 observably shifted upper when the applied load was increased. In particular, the maximum and minimum vertical displacements of Case 4 both decreased. The cracked surfaces of Case 4 are shown in Fig. 16. Considering Figs. 14, 15 and 16, it can be said that the settlement occurred due to the smoothing of the rough cracked surface under the cyclic shear. A settlement of more than 1mm was recorded at the end of the loading.

In Case 4, a white clouded liquid-like sludge was observed on the cracked surface after the loading. The liquid was flowed by pure water and stored in a tank. It was then dried in the oven at 110°, and powders containing fine aggregate were obtained.

3.3 Discussion

The weights of the powders obtained in the experiment were compared, as shown in Fig. 17. The powders of Cases 1 and 2 contained small blocks. Since the artificial crack made by method 1 did not penetrate the entire cross section, the remaining area was broken and made into small blocks during the loading. In general, the weights of the wet specimens were greater than those of the dry specimens. In addition, there was a clear positive correlation between the horizontal and vertical displacements at the end of the loading and the weights of the powders. The powders should come from crushed cement matrix.

The smoothing process of the rough cracked surface was examined from different points of view. The relationship between the horizontal and vertical displacements was drawn, as shown in Fig. 18. To adjust the expression of the graph to our image, the vertical axis was reversed. It was found that the increase of settlement was associated with an increase in the amplitude of horizontal displacement. Interestingly, the trend of the settlement seemed to tend towards dilation at the later stage.

This accumulation of settlement is known as the behavior of loose sand, which tends to liquefy when it is subjected to cyclic shear. It exhibits negative dilation. The reason why the trend of dilation became positive in experiment series 3 can also be explained by the behavior of granular material under cyclic shear. It is probable that after the crushed cement matrix was changed into fine particles, the remaining fine aggregate and small blocks, which are thought to consist of a somewhat granular material, dominated the behavior.

Fig. 11 Schematic view of experiment series 3

Fig. 12 Details of boxes

Fig. 13 Method of inducing cracks

Fig. 14 Method of inducing cracks

Fig. 15 Method of inducing cracks

4 Conclusions

An experimental study was performed to better understand the degradation of concrete subjected to coupling cyclic loads and water. The following can be concluded from the study:

1. In the cyclic water pressure tests of series 2.1 and 2.2, the possibility of the degradation of concrete is demonstrated even if the water pressure is lower than the tensile strength of concrete.
2. According to the multiple regression analysis, the negative pressure might play a more important role in the degradation; that is, the suction of the broken matrix out of the micro cracks.
3. The broken cement particles can be flowed out from the macro cracks using cyclic water pressure; however, the restraint of the crack width was effective in delaying the degradation.
4. The smoothening of the rough cracked surface under the cyclic shear was accelerated when the concrete was wet. The negative and positive dilation of the concrete with the rough cracked surface can be explained by the behavior of sand and granular materials.

This study was financially supported by JSPS KAKENHI, Grant Number 16H04402. The authors would like to express their gratitude to K. Ogawa, S. Okada, T. Yokota and R. Shinohara for the experiments.

Fig. 16 Cross section of No. 6

Fig. 17 Cross section of No. 6

Fig. 18 Cross section of No. 6

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