

EFFECT OF REPEATED LOAD ON MICRO STRUCTURE AND CARBONATION OF CONCRETE AND MORTAR

Effect of repeated loading

K. TANAKA and J.H. Jeon

Structural Research Center, Tokyo Institute of Technology, Yokohama, Japan

T. NAWA

Faculty of Engineering, Hokkaido University, Sapporo, Japan

H. Hashida

Institute of Technology, Shimizu Corporation, Tokyo, Japan

Durability of Building Materials and Components 8. (1999) *Edited by M.A. Lacasse and D.J. Vanier.* Institute for Research in Construction, Ottawa ON, K1A 0R6, Canada, pp. 256-265.

© National Research Council Canada 1999

Abstract

It is apprehended that durability of concrete and mortar subjected to repeated loads, even though they were in low level, may be lowered durability of them by fatigue failure in their micro structures. The effects of fatigue by flexure on micro structures and carbonation of them were studied in this paper. The three measurements such as dynamic modulus, micro pore volume and carbonation were carried out for the specimens fatigued at several levels of stresses. It was found out that the pore volumes of them increased, though dynamic moduli of them were little affected by the repeated loads. The deeper carbonation was also observed in the severely fatigued specimens and it seems to be closely related to change of their micro structures. To discuss quantitatively the effect of fatigue, a scale to estimate it is needed. Then, we proposed the following fatigue scale (D.F.) which indicates the degree of fatigue; $D.F. = \sigma / f + a (\log N)^b$, where σ ; flexural stress applied, f ; flexural strength, N ; number of repetition, and a, b ; constants. The micro pore volume increased and the depth of carbonation became deep with rise of value of the scale, which means fatigue progressed and thereby carbonation was accelerated. It is concluded that concrete and mortar subjected to repeated loads, even if they are at low levels, are changed in their micro structure by fatigue and thereby durability of them might be lowered.

Keywords: Carbonation, concrete, dynamic modulus, fatigue, flexure test, mortar, micro structure, repeated load

1 Introduction

Concrete used for structures, is subjected to numerous number of repeated loads during their service life. The performance of concrete to repeated load is commonly determined by fatigue tests, and most of them have been carried out mainly for determining the limitation of fatigue rupture of concrete, because structures become seriously dangerous according as mechanical property of concrete closes on its fatigue limitation.

Since members of a structure are designed to keep the stresses occurred in concrete beneath lower level than those of failure limitation, it is therefore quite seldom for concrete in actual structures to be subjected to such a higher level repeated load that may result in fatigue rupture. However, repeated loads give concrete a gradual damage even though the level of stress is low, and it would lead to reduction of durability of concrete. Because, the micro structure of concrete might be changed and thereby permeability of concrete to carbon dioxide gas would be presumed to increase.

Most previous work has focused on fatigue failure of concrete. As for fatigue itself, the effect of fatigue on the relation between pore structure and mechanical properties of concrete was investigated recently. However, there is still few knowledge on effect of fatigue, in particular to durability.

In this paper, the effect of low level fatigue on durability of concrete and mortar, in particular, on change of micro structures and carbonation by repeated load were investigated.

2 Test specimen

Prisms of 10cm×10cm in cross section and 40cm in length were used for all fatigue tests. The mix proportions of concrete and mortar specimens were shown in Table 1. They were kept in water of 20±2°C for three months to expect sufficient cure, and then dried in the room at 20±2°C and 60%R.H. for more than one month.

Table 1: Mix designs of concrete and mortar specimen

Materials	Water/ Cement ratio, %	Sand/ Aggregate ratio, %	Unit weight, kg/m ³				Dosage of AE& WR agent C×%	Slump (Flow), cm	Air content, %
			Water	Cement	Sand	Gravel			
Concrete	60	44	180	300	777	1002	0.10	18.0	5.8
Mortar	60	-	250	417	1554	-	-	(23.0)	4.5

3 Cyclic loading test for determine limitation of fatigue failure

3.1 Measurement of flexural strength

The data of flexural strengths of concrete and mortar are needed to decide the level of load in cyclic loading tests, and therefore flexural tests were carried out in conformity of the JIS Standard A 1106. The mean values of averaged flexural strength of five specimens were 6.67N/mm^2 for concrete and 5.06N/mm^2 for mortar respectively.

3.2 Cyclic loading tests for rupture

Cyclic loading tests were carried out as shown in Photo.1, to obtain a fatigue rupture curve which is used for deciding a level of stress and a number of repetition for further cyclic loading tests for fatigue. The upper ratios in the stress level were 0.8, 0.7, and 0.6 of the flexural strength of each material. The specimens were repeatedly loaded between the upper levels to zero at 5Hz, and the numbers of cycles at rupture were counted.

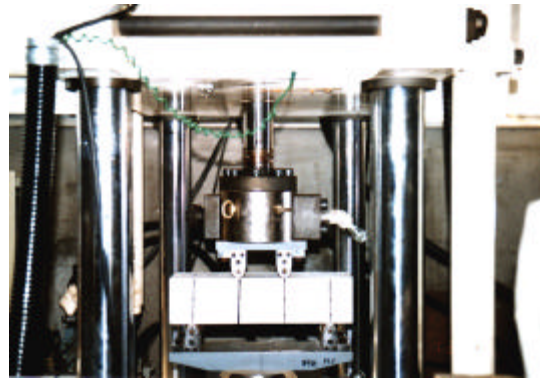


Photo. 1: Cyclic loading test

The relations between the levels of stress and the numbers of cycles to rupture were shown in Fig.1 for the concrete and mortar specimens. The numbers of cycles to rupture reasonably decrease as the levels of stress rise. It can be seen that the results have a smooth relation between the levels of stress and the logarithmic values of number of cycles for the both materials, and then their relations can be expressed by the following empirical equation,

$$\sigma/f = 1 - a (\log N)^b \quad (1)$$

where, σ : applied flexural stress, N/mm^2

f : flexural strength, N/mm^2

N : number of repetition to rupture

a, b : constants.

The two constants were determined from the fatigue test results of concrete and mortar, and the equations expressing the relation between a level of stress and a number of cycles to rupture were obtained as shown respectively in Table 2.

3.3 Cyclic loading tests for fatigue

Considering the former relations, levels of stress and numbers of repetition for cyclic tests for fatigue, in which fatigue rupture is not expected, were decided as shown in Table 3.

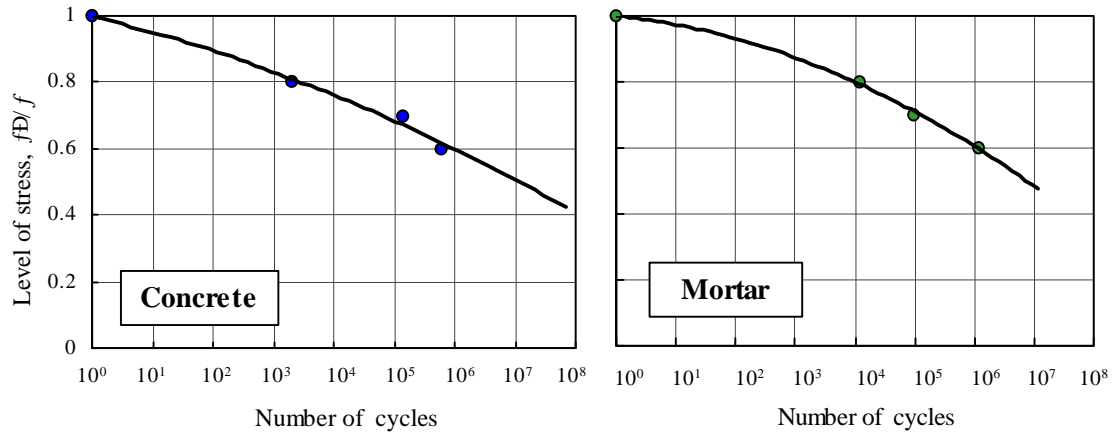


Fig. 1: Relation between level of stress and number of repetition to rupture

Table 2: Equations expressing fatigue rupture

Materials	Equations
Concrete (f : 6.67 N/mm ²)	$\sigma/f = 1 - 0.0431(\log N)^{1.24}$
Mortar (f : 5.06 N/mm ²)	$\sigma/f = 1 - 0.0196(\log N)^{1.68}$

Table 3: Stress level and number of repetition of cyclic test for fatigue

Concrete					Mortar				
Stress level σ/f	Number of repetition ($\times 10^6$)				Stress level σ/f	Number of repetition ($\times 10^6$)			
	0.1	0.4	1	2		1	2	5	10
0.3			✓	✓	0.3	✓			
0.4			✓	✓	0.4	✓			
0.5			✓		0.5	✓	✓	✓	✓
0.6		✓			0.6	✓			
0.7	✓								

✓: A test was carried out.

4 Results of cyclic loading test for fatigue

4.1 Change of dynamic modulus by fatigue

Dynamic moduli of 4 concrete specimens were measured before and after the cyclic loading tests to make clear the effect of fatigue on mechanical property of them. The measurement was carried out by a primary deflection method described in JIS A 1127 and the results thus obtained were shown in Table 4. It can be seen from the table that the dynamic moduli of them decreased by fatigue. However, the difference of them between before and after the fatigue operation was slight.

4.2 Change of micro structure by fatigue

Micro structures of concrete and mortar specimens were also studied before and after the fatigue operation to make clear the effect of fatigue. Pore size and distributions of them were measured in the size from 6nm to 180 μ m in diameter through the Micromeritics Poresizer 9310.

The procedure is as follows. A specimen is first divided into two pieces at the center of it. Five small blocks are then cut out from five positions of the divided piece as shown in Fig.2, (the other half of piece is used for an accelerated carbonation test). The five blocks have been subjected to different kinds and different levels of stress during a fatigue operation, such as maximum compressive stress, maximum tensile stress, composite stress of compressive and shear, composite stress of tensile and shear, and less stress because of out of the loading points. As for concrete specimens, they contain coarse aggregates in them, and therefore, they were crushed and small blocks of only mortar portion of 2.5mm-5mm in size were used to the measurement.

The pore distributions at maximum tensile stressed and less stressed positions were shown in Fig.3. Much pore volumes of the samples from the area of being stressed were observed, compared to that of less stressed area, and the difference between them is more distinguished in smaller pore size regions.

For discussing the difference of pore distributions among the positions in a specimen more clearly, the results were reformed to bar charts as shown in Fig.4, in which pore sizes are divided into the four zones, i.e., a very fine capillary pore zone(6-10nm), a smaller capillary zone(10-100nm), a medium capillary zone(0.1-5.68 μ m) and a larger capillary and entrained air zone(5.68-180 μ m).

Table 4: Dynamic modulus of elasticity of concrete before and after fatigue test

Stress level σ / f	Number of repetition ($\times 10^6$)	Dynamic modulus of elasticity, $\times 10^4 \text{N/mm}^2$		Reduction percentage of dynamic modulus, %
		Before fatigue	After fatigue	
0.3	2	3.74	3.73	0.3
0.4	2	3.70	3.70	0
0.5	0.4	3.71	3.70	0.3
0.6	0.1	3.74	3.71	0.8

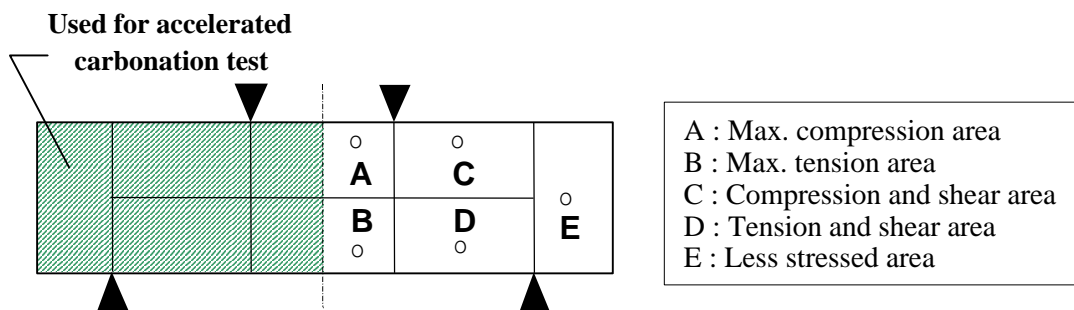


Fig. 2: Sampling position (shown by circles) for pore distribution measurement

Much pore volumes at the positions subjected to higher levels of stress were observed, compared to that of less stressed position for both concrete and mortar specimens. The pore volumes of pore sizes of 10nm-100nm and 0.1 μ m(100nm)-5.68 μ m were particularly increased.

4.3 Change of carbonation rate by fatigue

There is fear that fatigue may lower durability of concrete and mortar, in particular the resistance to carbonation. Then, an accelerated carbonation test was carried out to study the effect of fatigue on carbonation. The remained half of the specimen as mentioned above was used for the test. The four sides of a specimen except the upper and the bottom surfaces where force had been directly applied, were sealed by epoxy resin coatings to prevent from ingress of carbon dioxide gas during the carbonation test.

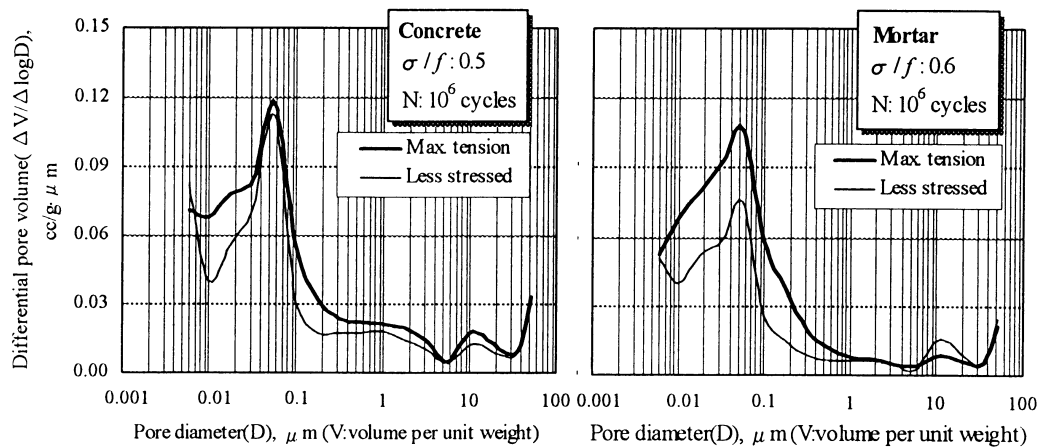


Fig. 3: Pore size distribution of tensile stressed area and less stressed area

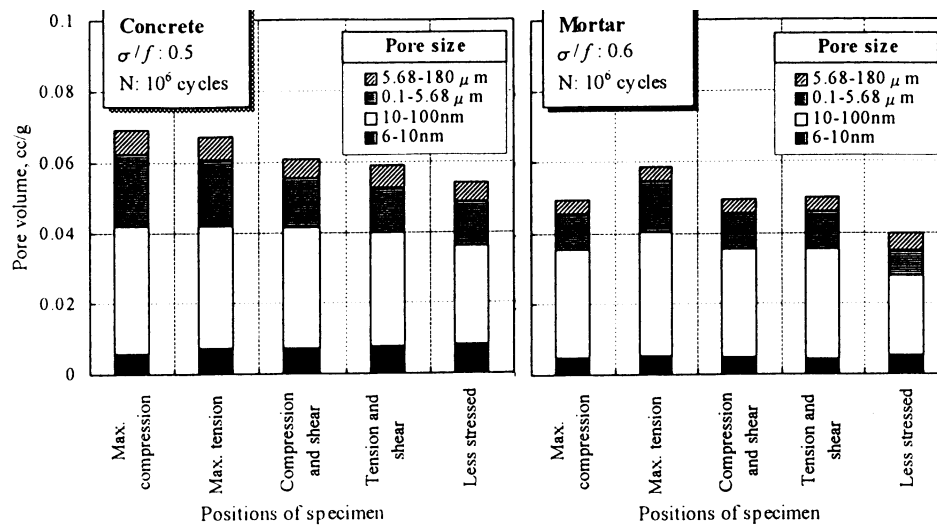


Fig. 4: Volume of four pore size zones at various stressed positions

After being exposed in a chamber filled with carbon dioxide gas of 20% in CO₂ concentration at 20°C and 60%R.H. for 2 months, the specimen was split into two pieces along the longitudinal direction by a compressive test machine. Phenolphthalein liquid reagent was sprayed over the split surface of the specimen, and the carbonated depth was measured at distance of 5mm along the longitudinal direction of the specimen. As for concrete, carbonated depth was measured in the area of mortar avoiding coarse aggregates, because a coarse aggregate does not inherently carbonate. The results were expressed by averaged depth of the measured area as shown in Fig.5. It shows that the carbonation depth of the areas subjected to higher levels of stress become deeper than those of less stressed for both materials.

5 Method for evaluating fatigue

As mentioned in the previous section, fatigue rupture is mainly affected by a level of stress and a number of repetition, and the relation of them was roughly expressed by the equation (1). When the right side of the equation transposes to the left side, it becomes as follows;

$$\sigma/f + a (\log N)^b = 1 \quad (2)$$

This equation means that a specimen does not rupture until the value of the left side of the equation, $\sigma/f + a (\log N)^b$, reaches the value of 1. Therefore, the value of the left side of the equation is considered to use as a scale that indicates progress of fatigue of concrete and mortar specimens. We define it as the degree of fatigue, D.F., it is able to be expressed by the following equation,

$$D.F. = \sigma/f + a (\log N)^b \quad (3)$$

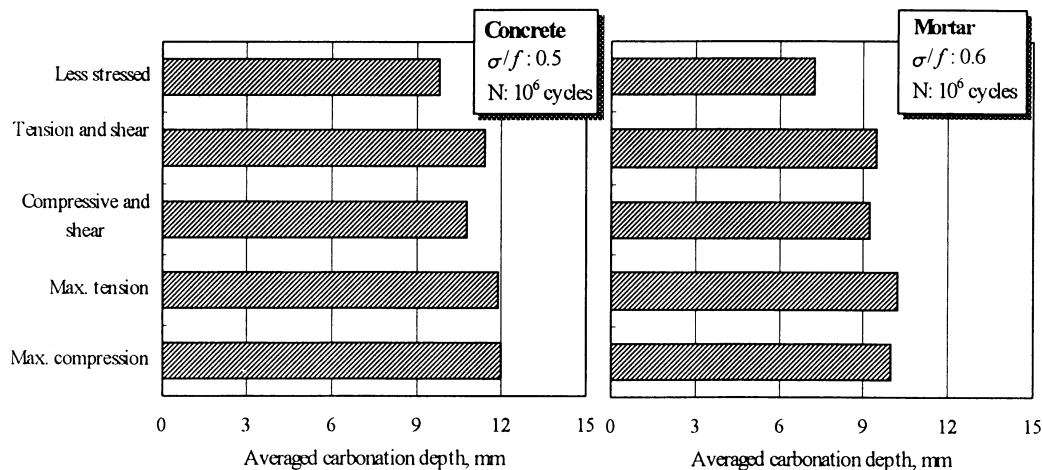


Fig. 5: Averaged carbonated depth of positions subjected to different stress

A level of stress and a number of repetition, both of which are important parameters in a fatigue test, are able to be unified by the equation (3). The degrees of fatigue were calculated by the equation (3) for the fatigued specimens, and they are shown by numeral values in Fig.6.

6 Discussion

6.1 Effect of fatigue on dynamic modulus of concrete

Change of dynamic modulus, which is expressed as the ratio of the value after fatigue test to original one, is shown for concrete specimens in Fig.7. It seems that fatigue little affect dynamic modulus of concrete.

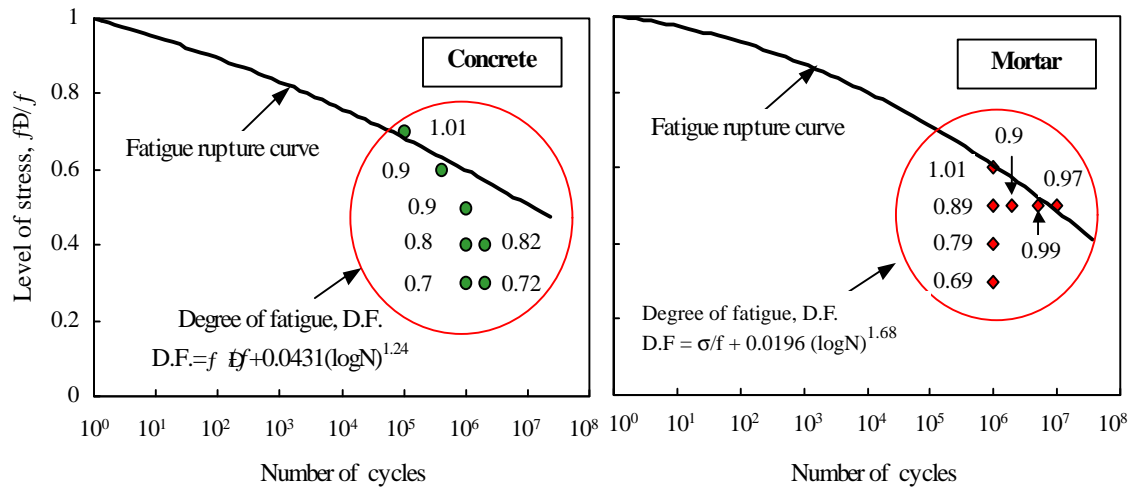


Fig. 6: Degree of fatigue (D.F.) of specimen subjected to various levels of fatigue

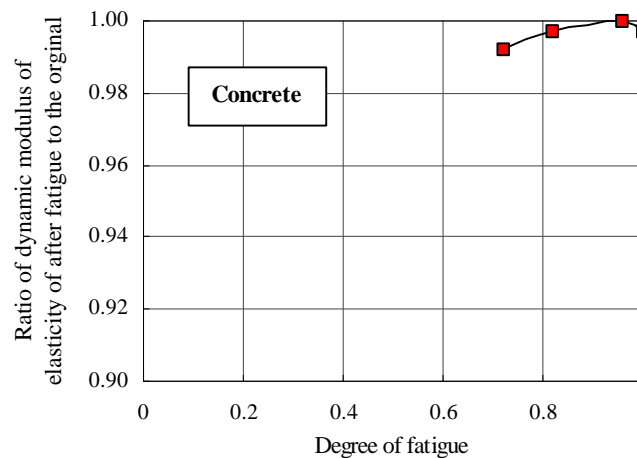


Fig. 7: Relation between dynamic modulus of elasticity and degree of fatigue

6.2 Effect of fatigue on micro structure of concrete and mortar

The relation between pore volumes, which are divided into four zones in pore size, and degree of fatigue was studied. The changes of pore volumes in maximum compressive zone and maximum tensile one were shown in Fig.8 for concrete and Fig.9 for mortar respectively. It can be seen a tendency that total pore volume increases with the degree of fatigue. As for the pore sizes that changed by fatigue, the volumes of capillary pores from 10 to 100nm and 0.1 μ m to 5.68 μ m were increased. The effect of fatigue on micro structures is able to understand as an increase of micro pores.

6.3 Effect of fatigue on carbonation

The relation between carbonation depth of the two materials and degree of fatigue was also investigated. Fig.10 shows their relations in the positions of maximum compressive, maximum tensile and less stressed.

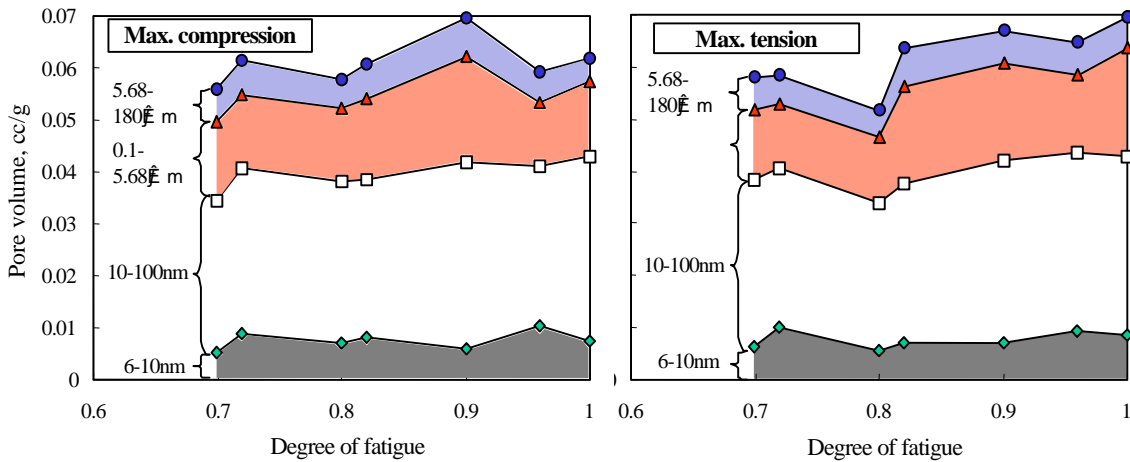


Fig. 8: Relation between pore structure of concrete and degree of fatigue

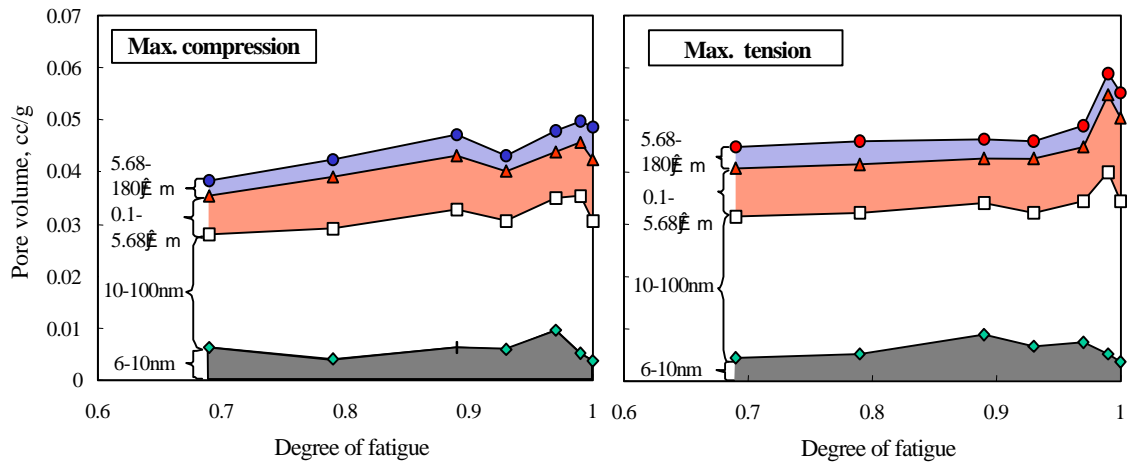


Fig. 9: Relation between pore structure of mortar and degree of fatigue

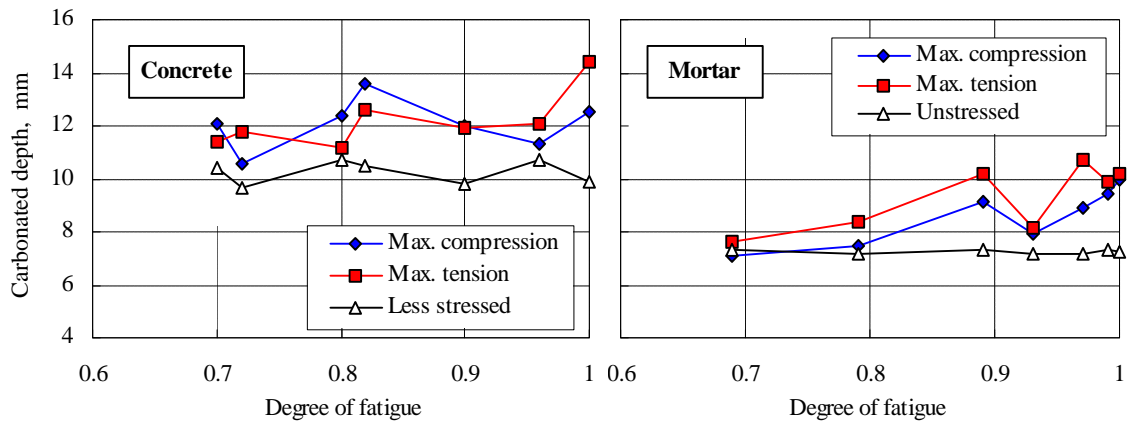


Fig. 10: Relation between carbonation depth and degree of fatigue

The carbonation depth at less stressed hardly changed, however, those at the positions severely stressed such as maximum compression and tension areas, become deep with increase of the degree of fatigue. It is said that carbonation of concrete depends on the pore volume of it, and the deeper carbonation in stressed positions in the tests is considered to be due to an increase of capillary pores of 10-100nm and 0.1-5.68 μ m.

7 Conclusion

The Effect of repeated loads on pore structure and carbonation of concrete and mortar was studied, and the following conclusions were obtained.

- (1) Concrete and mortar subjected to repeat loads, even if they are at low levels, are changed in their micro structures by fatigue and thereby become more sensitive to carbonation.
- (2) A scale of expressing fatigue, which consists of a level of stress and a number of repetition, was proposed. The usefulness of the scale for evaluating degree of fatigue for concrete and mortar was shown through comparing the change of pores and the carbonation depth of them by fatigue.

8 References

- ACI Committee 215. (1974) Considerations for design of concrete structure subjected to fatigue loading , *ACI Materials Journal*, Vol. 71, No. 3. pp. 97-121.
- B. Zhang. (1998) Relationship between pore structure and mechanical properties of ordinary concrete under bending fatigue. *Cement and Concrete Research*, Vol. 28, No. 5. pp. 699-711.
- X.P. Shi. et al. (1993) Flexural fatigue strength of plain concrete, *ACI Materials Journal*, Vol. 90, No. 5. pp. 435-440.