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CHLORIDE PERMEABILITY OF CONCRETE UNDER STATIC AND REPEATED COMPRESSIVE LOADING

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ABSTRACT

The chloride permeability of normal weight concrete subjected to static and repeated compressive loading was evaluated by using the AASHTO T277 test method. The results of concrete under static loading showed that the application of loads up to 90 % of the ultimate strength had little effect on the chloride permeability. It was found from the results of concrete under repeated loading that load repetitions at the maximum stress levels of 60 % or more caused the chloride permeability to increase significantly. The test results also indicated that the chloride permeability of concrete subjected to static and repeated loading increased at an increasing rate with its residual strain. The relation between the chloride permeability obtained and the cracking behavior of concrete previously reported was discussed.

Introduction

The amount of microcracking in concrete structures begins to increase undoubtedly, when the structures are subjected to increasing or repeated loading. With respect to concrete structures exposed to marine environment, the development of microcracks due to loading appears to facilitate the transport of chloride ions from the surrounding media to the surface of reinforcing steel and resultingly promote the corrosion of the steel. Importance of microcracks in the chloride permeability of concrete has been pointed out by Mehta (1). From the viewpoint of inhibiting corrosion of reinforcing steel in concrete structures in survice, the chloride permeability of concrete subjected to loading should be evaluated.

Characteristics of microcracking in normal weight concrete under the various types of loading have been provided by many researchers (2, 3, 4, 5, 6, 7, 8, 9). Hence, it may be possible to estimate the type and amount of microcracking in concrete from the loading conditions such as the types of loading and the levels of load. In this study, the chloride permeability of normal weight concrete subjected to static and repeated compressive loads was evaluated by using the AASHTO T277 test method. The chloride permeability obtained was related to the cracking behavior of concrete estimated from the fruits of the previous investigations.

Experimental Details

Materials and preparation of specimens

The cement used was an ordinary portland cement. Its specific gravity and specific surface determined by the Blaine method were 3.13 and 3,210 cm^2/g, respectively. A river sand was used as fine aggregate; a crushed stone with a maximum size of 25 mm as coarse aggregate. Specific gravity, absorption capacity, and fineness modulus of the fine and coarse aggregates are tabulated in Table 1. The air-entraining admixture used was a neutralized Vinsol resin.

The concrete was prepared with a water:cement ratio of 0.60, a sand ratio of 0.423, and a cement content of 278 kg/m^3. The air content and the slump of the concrete was 4.2 % and 6.0 cm, respectively. Three 10 × 20 cm cylindrical specimens were prepared from each batch of concrete. The concrete mixtures were cast in steel molds and compacted by a mechanical vibrator. The cylindrical specimens were stored in a room maintained at 20 °C and about 85 % relative humidity for 48 hours after casting, and then cured in water at 20 °C for 4 to 5 weeks. 66 cylindrical specimens were altogether produced; 53 were used for evaluating the chloride permeability and 13 for determining the ultimate compressive strength. The ultimate compressive strengths obtained are given in Table 2.

TABLE 1
Properties of Aggregates Used

	Fine aggregate	Coarse aggregate
Specific gravity	2.58	2.61
Absorption capacity (%)	1.92	1.61
Fineness modulus	3.06	6.80

TABLE 2
Compressive Strength of Concrete

Age (weeks)	Average strength (MPa)	Coefficient of variation (%)	Number of specimens
4	25.28	4.9	7
5	26.51	4.2	6

Procedure of static and repeated compressive tests

Static compressive tests were made in a 1,960 kN universal testing machine. 30 cylindrical specimens cured for 4 weeks were monotonically loaded to a preselected fraction of the ultimate strength and then unloaded. The preselected stress levels were 0, 30, 50, 70, 90, and 100 % of the ultimate strength measured at the age of 4 weeks. The rates of loading and unloading were kept at 2 and about 50 kN/s, respectively.

A Shimadzu 196 kN servohydraulic testing machine was used to apply sinusoidal pulsating loads to the specimen at a constant speed of 300 cycles per minute. All repeated tests were allowed to perform at the age of 4 to 5 weeks, since there was little difference in the static compressive strength between the two ages (Table 2). The stress levels were based on the ultimate compressive strength at the age of 4 weeks. 23 cylindrical specimens were tested at the maximum stress levels of 50, 60, 70, and 80 % of the ultimate strength. A minimum stress level was maintained at 6 % in all repeated tests. The repeated tests were discontinued after a given period of repeated loading to avoid the failure of the specimens during test.

Longitudinal axial deformations were measured with a compressometer equipped two electric gages having 0.5 μm sensitivity and a data logger. The residual strain of the specimens immediately after the static and repeated tests was obtained from the results of the deformation measurements. The residual strain is defined as shown in Fig. 1.

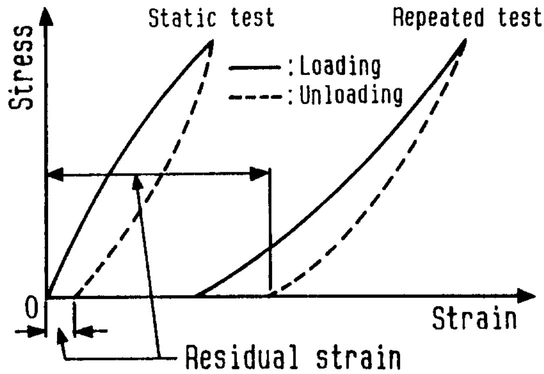

FIG. 1
Definition of Residual Strain

Chloride permeability test

After loading to required stages, concrete disks of 5 cm in thickness were cut off from the central portions of the cylindrical specimens with a diamond blade saw for chloride permeability tests. The chloride permeability was evaluated by the amount of charge passing through the disk according to AASHTO T277. The charge passed was determined from the electric current intensity registered every 30 s by a data logger. Experiments were carried out in a room kept at 20 °C.

Results and Discussion

Chloride permeability of concrete under static compressive loading

The values of charge passed through concrete subjected to static compressive loading are plotted against stress level, as shown in Fig. 2. Fig. 2 shows that the chloride permeability of concrete loaded monotonically to the stress levels ranging from 30 to 90 % is nearly equal to that of concrete before loading, although these plots are somewhat scattered. It is also apparent from Fig. 2 that the application of loads to the stress level of 100 % gives rise to an increase of about 1,400 coulombs in charge passed.

It has been revealed that bond cracks begin to increase in length, width, and number at about 30-50 % of the ultimate strength and that mortar cracks begin to increase noticeably and to form continuous crack patterns at about 70-90 % of the ultimate strength, when concrete is subjected to increasing compressive load (2, 3, 4, 5). Hsu et al. (2) also obtained experimental results showing that the extensive interconnecting of mortar and bond cracks occured in concrete after reaching the ultimate strength. Taking account of these findings, the results given in Fig. 2 show that a considerable amount of bond and mortar cracks developed in concrete prior to reaching the ultimate strength has little effect on its chloride permeability. It can also be inferred from the comparison between the plots at the stress levels of 90 and 100 % in Fig. 2 that an extensively interconnected crack system formed in concrete after reaching the ultimate strength only leads to a comparatively small increase in the chloride permeability. Less effect of microcracking on the chloride permeability of concrete subjected to static compressive loading is interesting from the viewpoint of durability of concrete structures.

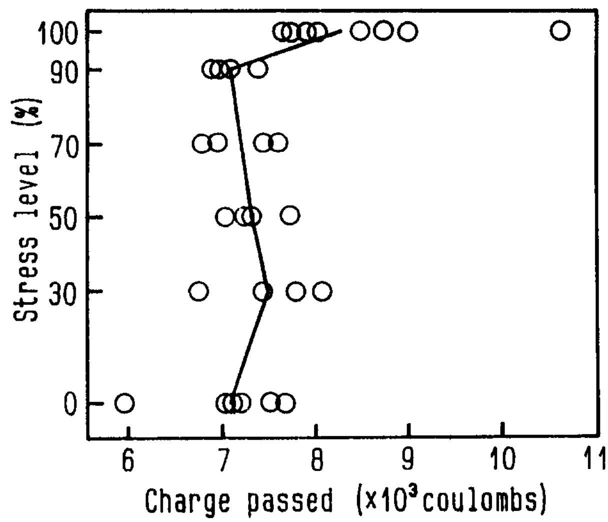

FIG. 2
Relationship Between Stress Level and Charge Passed Through Concrete under Static Compressive Loading

Chloride permeability of concrete under repeated compressive loading

The results of chloride permeability tests for concrete subjected to repeated compressive loading are given in Table 3. Comparison between the results in Table 3 and the plots in Fig. 2 shows that there is little difference in the charge passed between concrete loaded repeatedly with the maximum stress level of 50 % and that before loading. Even high-cycle load repetitions of more than one million cycles at this stress level result in little increase in the chloride permeability. On the other hand, the results of concrete tested under the maximum repeated stresses of 60 to 80 % of the ultimate strength indicate that load repetitions up to 33,000 cycles give rise to a significant increase in the chloride permeability. In particular, a remarkable increase in the charge passed is found in some specimens loaded with the maximum stress level of 70 %.

Bennett and Raju (6) observed microcracking on the surfaces of concrete prisms loaded statically to about 95 % of the ultimate strength and those loaded repeatedly with the maximum stress level of 75 %. They found that the course of crack development under repeated tests was

TABLE 3
Chloride Permeability Test Results for Concrete under Repeated Compressive Loading

Rank of specimen	S = 50 %		S = 60 %		S = 70 %		S = 80 %	
	N	C	N	C	N	C	N	C
1	20,000	7,027	18,000	8,509	1,000	7,814	50	8,994
2	20,000	7,069	20,000	8,393	3,300	14,596	200	8,896
3	20,000	7,778	20,000	9,420	4,000	18,170	220	8,452
4	300,000	8,801	20,000	12,118	7,000	10,553	300	9,652
5	1,234,000	7,511	33,000	9,256	20,000	8,574	370	9,146
6	—	—	33,000	10,049	20,000	9,983	—	—
7	—	—	—	—	20,000	19,237	—	—

S=maximum stress level, N=number of cycles, and C=charge passed(coulombs).

different from that under static tests, being characterized by the appearance of more microcracks. Raju (7) reported that the decrease of pulse velocity through specimens in repeated tests with the maximum stress levels ranging from 67 to 85 % was nearly three times that observed in static tests, but that the specimen loaded repeatedly with the maximum stress level of 53 % to 3 million cycles showed no significant decrease in the pulse velocity. He maintained that the large amount of bond cracks accounted for the large decrease in the pulse velocity observed in the repeated tests with the maximum stress levels not less than 67 %. Shah and Chandra (8) also observed microcracking in concrete subjected to repeated compressive stresses with the maximum stress levels of 60 to 85 %. They found that the load repetitions resulted in a significant increase in microcracking with the passage of time. The above findings manifest that the repetitive nature of loading brings about a conspicuous increase in the total amount of microcracking in concrete, when the concrete is tested under the relatively high maximum repeated stresses. This supports the idea that the significantly high chloride permeabilities for the maximum stress levels of 60 to 80 % as indicated in Table 3 are attributable to the extensive and additional formation of microcracking caused by the repeated loading.

It is found from Table 3 that the chloride permeability test results for the 60 and 70 % maximum stress levels scatter widely. That is, when loaded repeatedly to 20,000 cycles, the values of charge passed for the maximum stress levels of 60 and 70 % fall in the range of 8,393 to 12,118 coulombs and of 8,574 to 19,237 coulombs, respectively. The results in Table 3 also show that the chloride permeability for a certain maximum stress level does not always increase with the number of cycles of load application. These may be caused by a complicate nature of microcrack growth in concrete under repeated loading. At any rate, the loading conditions such as the maximum stress levels and the number of cycles are of little use in predicting the chloride permeability of concrete subjected to repeated loads. The values of charge passed given in Table 3 are plotted against the values of residual strain of specimens immediately after the repeated tests, as shown in Fig. 3. Fig. 3 indicates that the charge passed increases with incresing

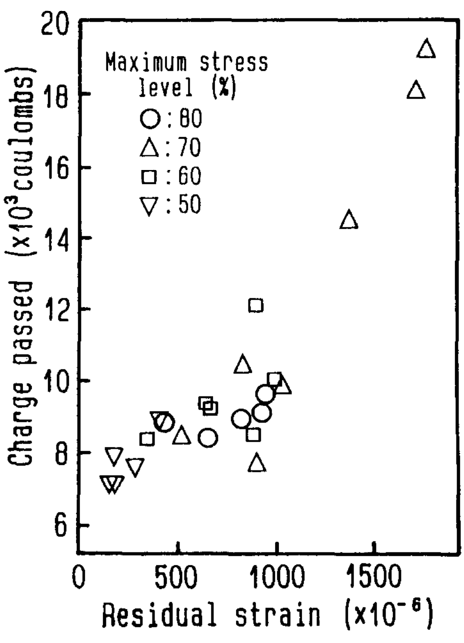

FIG. 3
Relationship Between Charge Passed and Residual Strain for Concrete under Repeated Loading

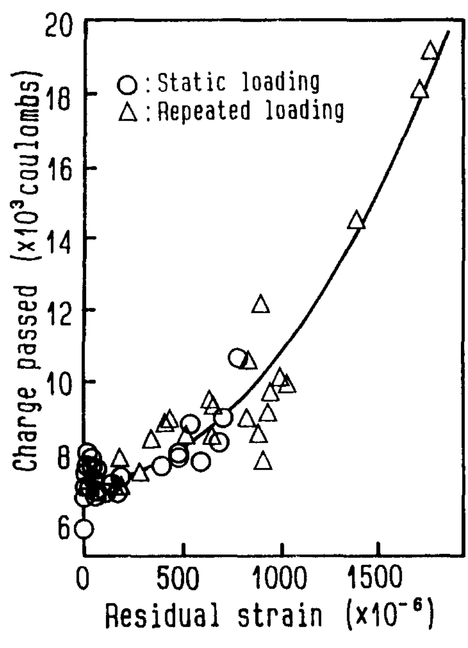

FIG. 4
Relationship Between Charge Passed and Residual Strain for Concrete Loaded Statically and Repeatedly

residual strain. The charge passed versus residual strain plots for all specimens loaded statically and repeatedly are also given in Fig. 4. It can clearly be seen from Fig. 4 that the chloride permeability increases at an increasing rate as the residual strains increase. This fact shows that the chloride permeability of concrete under static and repeated compressive loading can be estimated from the residual strains.

Conclusions

The following conclusions were drawn from this study.

1. The chloride permeability of concrete subjected to static compressive stresses up to 90 % of the ultimate strength is nearly equal to that of concrete before loading. Even concrete after reaching the ultimate strength only exhibits a comparatively small increase in the chloride permeability. Microcracking in concrete caused by static compressive loading appears to have less effect on its chloride permeability.

2. Compressive load repetitions at the maximum stress levels of 60 to 80 % give rise to a significant increase in the chloride permeability of concrete, whereas those at the maximum stress level of 50 % up to more than one million cycles have little influence on the chloride permeability. It seems that the former result is attributable to the extensive and additional formation of microcracking caused by the repeated loading.

3. The chloride permeability of concrete under static and repeated compressive loading increases at an increasing rate as the residual strains increase.

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