論文 INFLUENCE OF STRESS ON CHLORIDE PENETRATION INTO FIBER REINFORCED CONCRETE

Antoni *1, Takashi HORIGUCHI *2, Noboru SAEKI *3

ABSTRACT: In order to have better prediction of the service life of structures against chloride penetration and starting time of corrosion, more study should be performed for chloride penetration on concrete under loading condition. In this study, effect of chloride penetration on fiber reinforced concrete and plain concrete under several compressive and tensile stresses are studied and compared. By using modified migration test which include application of stress on concrete, the relation between diffusion coefficient and stress on plain concrete and fiber reinforced concrete was obtained.
KEYWORDS: Chloride, migration, penetration, diffusion, stress effect, polypropylene fiber, service life

1. INTRODUCTION

Prediction of service life of concrete structures exposed to chloride laden environment has become increasingly important as it determines the life cycle cost of the structure. Chloride penetration in concrete is mostly determined by the chloride diffusion coefficient of concrete without macro defect. Loading can affect the chloride penetration in concrete, and this can affect lifetime prediction of concrete structure. Therefore the effect of stress on the penetration of chloride into concrete should be studied as it represents chloride penetration in real concrete structures where load is always present.

Fiber reinforced concrete can improve the properties of concrete material and with the combination of fiber reinforced concrete with steel reinforcement, concrete structure with crack resistance, high ductility and high energy absorption can be made [1]. However the durability properties of the structure need to be checked. Fiber reinforced concrete can significantly alter crack development in concrete members under loading condition. Fiber reinforced concrete is much more likely to develop multiple cracking as the result of crack-bridging across the fibers. This condition can also alter the chloride penetration in concrete. To ensure that fiber reinforced concrete structure will be durable and have a long service life, the properties of chloride penetration in fiber reinforced concrete and loading effect should also be investigated.

2. EXPERIMENTAL PROCEDURES

2.1 MODIFIED MIGRATION TEST

The chloride migration test used in this study is based on Standard of NordTest Build 492 - Non-steady state migration test [2]. This test method was initially proposed by Tang and Nilsson [3] as CTH Rapid Test. The principle of the test is to subject concrete to external electrical

*1 Division of Structural and Geotechnical Eng., Hokkaido University, Ph.D. Student. Member of JCI
*2 Division of Structural and Geotechnical Eng., Hokkaido University, Assoc. Professor, Member of JCI
*3 Division of Structural and Geotechnical Eng., Hokkaido University, Professor, Member of JCI

potential applied across the specimen and to force chloride ions to migrate into the specimen. After certain test duration, the specimen is split and a silver nitrate solution is sprayed on the freshly split section. At the chloride penetrated area, silver ions will react with chloride ions and change into white color. Chloride penetration depth thus can be determined from this white precipitation of silver chloride. The rapid migration test is considered to be a better test method compared to other test methods. As it gives more consistent results and it overcomes drawbacks of Rapid Chloride Permeability Test (RCPT) such as rise of temperature and lower precision. The results obtained from the migration test can be used directly for service life prediction.

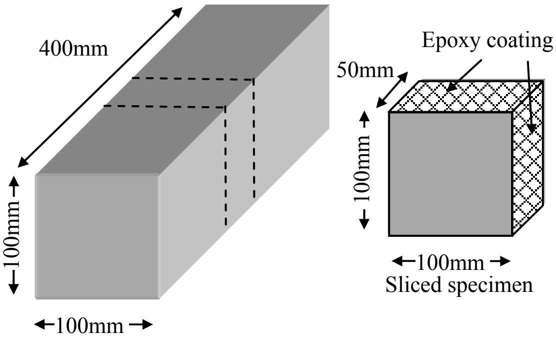
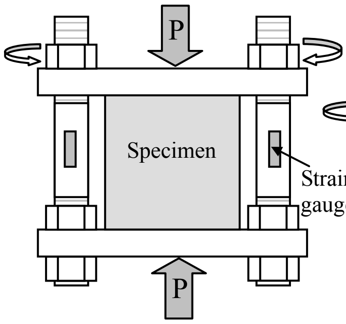


Fig.1 Specimen preparation



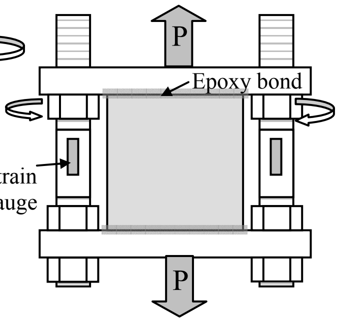


Fig.2 Compressive loading **Fig.3** Tensile loading

In this research, chloride diffusion coefficients of plain concrete and fiber concrete were measured while load was constantly applied on the specimen. Thus migration test setup was modified by addition of external steel frame to induce axial stress on the concrete. In this setup, the shape of the specimen used was rectangular prism of 100×100×50 mm cut from 100×100×400 mm specimen as shown in **Fig.1**. The specimen was loaded using two stainless steel plates connected by bolts. For compressive loading, as illustrated in **Fig.2**, the outer bolts were tightened up and the strain at the steel bolt was measured to determine the magnitude of load applied on the specimen. As for the tensile loading illustrated in **Fig.3**, two steel plates were attached to the specimen by epoxy bonding and then the inner bolts were tightened up until the desired tensile load was achieved.

2.2 MIXTURE PROPORTION AND SPECIMENS

The materials used for the test specimen were ordinary portland cement, river sand and 20 mm maximum size river gravel. Polypropylene fiber (Mesh type) with a length of 12 mm was used in making the fiber concrete. For both cases, the water to cement ratio (w/c) used was 0.5. The mix proportion and the resulting physical properties are shown in **Table 1**.

Table 1 Mix proportions and physical properties

Type	Fiber type & Vf (%)	w/c	s/a (%)	Water (kg/m^3)	AE agent (%C)	Air Content (%)	fc' at 28 days (MPa)	Bulk density (kg/m^3)
PC	-	0.5	45	165	0.044	5.2	39.77	2406.6
FC	PP-12mm 0.1	0.5	43	165	0.044	7.0	37.33	2367.3

Fresh concrete was cast into 100×100×400 mm rectangular prism specimen for migration test while cylindrical specimen of ϕ100x200 mm was used for compressive test. The molds were removed after 24 hours and the specimens were cured in water for 28 days. After water curing, the prismatic specimens were cut by water-cooled concrete cutter perpendicular to its axis into 50±2 mm thick specimens with 100×100 mm cross section (**Fig.1**). All specimens were then placed in room condition (20±5°C) for additional 60 days before migration test. This additional time was intended to reduce age effect of the specimen [4].

2.3 TESTING PROCEDURES

Epoxy coating was applied on the 50 mm sides of the specimen to prevent chloride penetration in these sides since using the silicon rubber sleeve recommended by NordTest standard was not feasible with the addition of steel frame. The specimen was then loaded to the selected condition by the method described earlier. Axial stresses were chosen to be 80%, 50%, 30%, 0%, -3% and -5% of the maximum compressive strength at 28 days. The negative mark means that the specimen was subjected to tensile load. Three replicates were made for each loading condition. After loading, a hollow plastic box of 100×100 mm cross-section and 150 mm height was attached to the face of specimen by using silicon glue to make an anolyte reservoir for the migration test as shown in **Fig.4**. The specimen was then left overnight for the silicon sealant to dry.

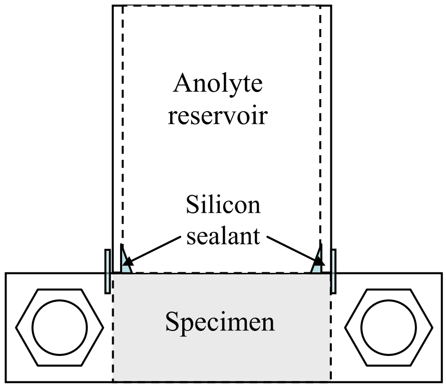


Fig.4 Attaching anolyte reservoir

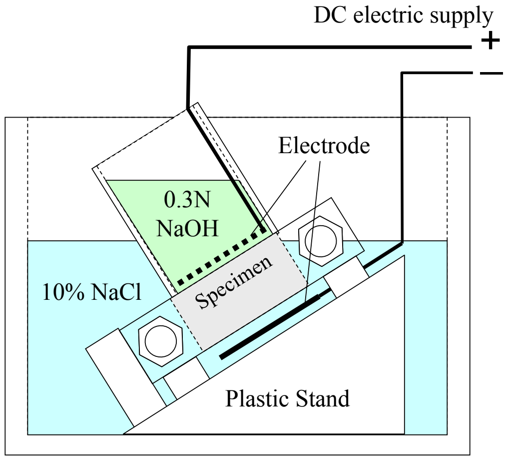


Fig.5 Migration test setup

Preconditioning the specimen was done according to NordTest standard. The specimen and the frame were placed in vacuum desiccators with both test surface exposed. The pressure inside the desiccators was reduced to 1-5 kPa for 3 hours and the vacuum desiccators was then filled with saturated calcium hydroxide solution so that all the surfaces were immersed. Vacuum condition was kept for one hour before allowing air to reenter the desiccators. Specimen was left in the solution for additional 18±2 hours.

In the migration test, a catholyte reservoir using plastic box with a size of 400×300×250 mm was filled with 15 liters of 10% sodium chloride solution. The specimen was taken out from the desiccators and excess calcium hydroxide was removed by rinsing it with tap water. Next, the specimen and cathode electrode made from 80×80×0.5 mm stainless steel plate were placed on top of inclined plastic stand as shown in **Fig.5**. The inclined position allows any hydrogen gas forming at the bottom electrode to escape. The anolyte reservoir was subsequently filled with 0.3 N sodium hydroxide solution and a perforated 0.5 mm thick stainless steel plate was inserted. The electrodes were connected to a 0 to 60 V DC power supply. The current was initially measured at 30 V setting and then the potential was adjusted so that it would allow reasonable chloride penetration. The temperature of the solution and initial current were also measured.

After the specified test duration (usually 24 hours), the frame was opened and the specimen was split along the loading axis. The freshly split surface was immediately sprayed with 0.1 M silver nitrate solution. After 15 minutes, white silver chloride precipitation was clearly visible. To eliminate the edge effect, the area 20-mm from the two edges were excluded in measuring the average chloride penetration.

3. RESULTS AND DISCUSSION

Three replicates of plain concrete and fiber reinforced concrete were tested by the modified migration test for chloride penetration for each loading condition. After spraying silver nitrate solution, chloride penetration depth in each specimen was measured. Typical split surface after spraying is shown in **Fig.6**. The average penetration depth was calculated by measuring the area of penetration and divided by the width of specimen excluding 20 mm from both sides.

The chloride non-steady state migration coefficient was then can be calculated from the following equations given in NT Build 492[2]:

$$D_{nssm} = \frac{RT}{zFE} \cdot \frac{x_d - \alpha\sqrt{x_d}}{t} \qquad (1)$$

where $$E = \frac{U-2}{L} \qquad (2)$$

and $$\alpha = 2\sqrt{\frac{RT}{zFE}} \cdot \mathrm{erf}^{-1}\left(1 - \frac{2c_d}{c_0}\right) \qquad (3)$$

D_{nssm} is the non-steady state migration coefficient (m^2/s), R is the gas constant (R=8.314 J/(K.mol)), T is the average temperature in the solution (K), z is absolute value for ion valence (for Chloride, z=1) F is the Faraday constant (F=9.648×10^4 J/(V.mol)), U is the applied potential (V), L is the specimen thickness (m), x_d is the average value of penetration depth (m), t is the test duration (seconds), erf^{-1} is the inverse error function, c_d is the concentration at which the color changes ($c_d \approx$ 0.07N for OPC) and c_0 is the chloride concentration at catholyte solution ($c_0 \approx$ 2N).

The calculated non-steady state migration coefficient for plain concrete and fiber concrete specimens under compressive and tensile stresses are provided in **Table 2**.

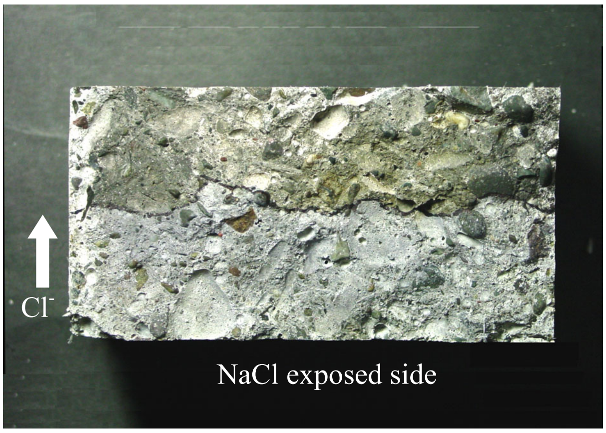


Fig.6 Typical Split surface

Table 2 Diffusion coefficient of plain concrete and fiber concrete for selected stress level

Stress ratio (%)	Plain Concrete D_{nssm} ($*10^{-12}m^2/s$)		Fiber Concrete D_{nssm} ($*10^{-12}m^2/s$)	
0	15.67	16.92	24.66	25.76
	17.39		25.91	
	17.69		26.71	
30	20.23	18.54	21.95	25.34
	17.79		27.89	
	17.59		26.19	
50	16.66	20.90	19.97	24.96
	23.44		28.02	
	22.61		26.89	
80	31.32	31.93	30.75	34.06
	31.22		31.82	
	33.24		39.60	
-3	29.01	27.70	23.56	24.69
	28.83		24.76	
	25.27		25.76	
-5	26.59	27.46	25.30	24.72
	27.35		21.62	
	28.43		27.23	

For the chloride penetration under free stress condition, fiber concrete showed higher diffusion coefficient. The chloride diffusion for fiber concrete is about 1.5 times higher compared to plain concrete even though the compressive strength is about the same. This condition could be due to the addition of fiber into concrete causing an increase in the air void content of concrete. The air contents of the fresh concrete were measured at 5% and 7% for plain concrete and fiber concrete, respectively. The interfacial transition zone of fiber and concrete might have also caused higher penetration of chloride. Chloride ions could penetrate into fiber concrete by interconnection of fiber along the interfacial transition zone. Further study is needed to confirm this, since this study was limited to only one type of fiber concrete.

The effect of compressive stress on chloride penetration into plain concrete and fiber concrete are shown in **Fig.7**. Chloride penetration in fiber concrete is higher compared to plain concrete at lower stress level. Chloride penetration into plain concrete at 30% and 50% of stress level increased 1.1 times and 1.23 times, respectively. At higher stress level of 80%, chloride penetration has increased nearly 1.9 times compared to concrete without loading. As for fiber concrete, chloride penetration did not show any significant change up to 50% stress level and at 80%, chloride penetration of fiber concrete increased 1.3 times compared to zero loading condition.

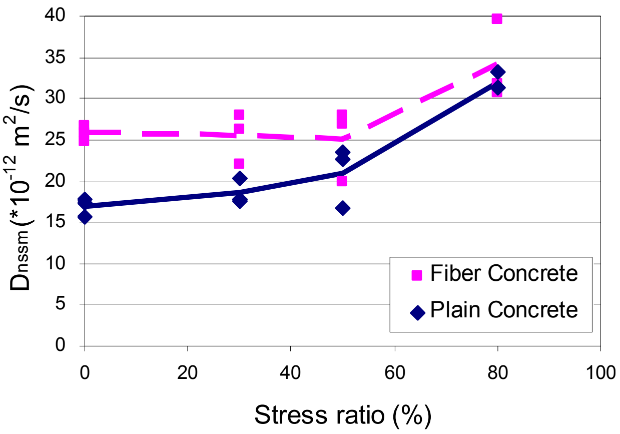


Fig.7 Chloride penetration of plain concrete and fiber concrete under compressive stress

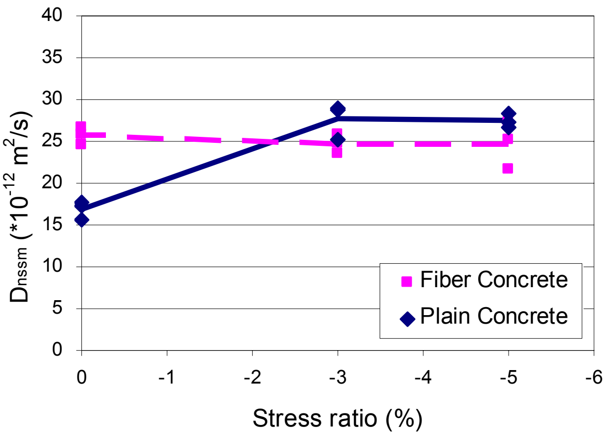


Fig.8 Chloride penetration of plain concrete and fiber concrete under tensile stress

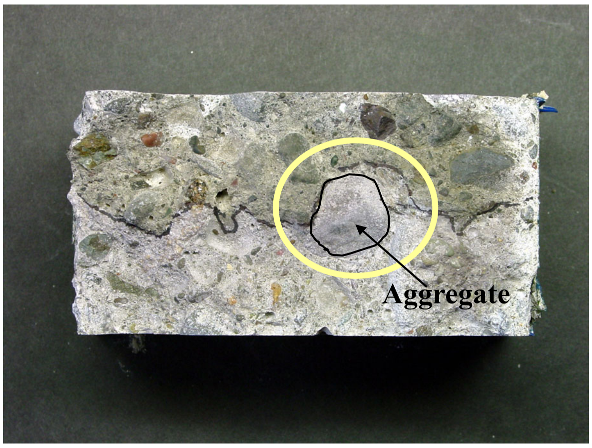


Fig.9 Interfacial influence between aggregate and mortar under tensile loading

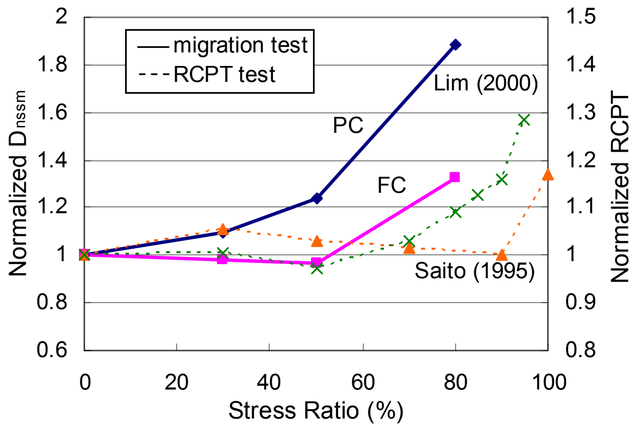


Fig.10 Comparison of increase of chloride penetration against stress ratio of migration test and RCPT

Chloride penetration in plain concrete and fiber concrete under tensile stress is shown in **Fig.8**. Plain concrete at -3% stress ratio already showed increase in chloride penetration while fiber concrete did not show any changes under tensile loading. This shows that penetration of chloride into concrete is more severe on concrete subjected to tensile loading. Under tensile loading, crack can easily open especially at the interfacial transition zone of aggregate and mortar. This effect can be seen in one of the specimen tested at -5% stress ratio as shown in **Fig.9**. Because of the tensile loading in concrete, the bond between the aggregate and mortar becomes weaker and chloride ions could penetrate faster in this area.

From the previous study by Saito and Ishimori [5], it was found that after subjecting plain concrete to compressive loading at about 90% of the ultimate strength, chloride permeability did not show any significant increase. Similar test was done by Lim et al.[6] with more consideration on microcracks. In their test, chloride permeability of concrete did not show any significant increase until the load reaches 70% of the ultimate strength and as the stress ratio increase, chloride permeability is also increasing. At 90% of the ultimate strength, chloride permeability increased about 1.3 times compared to unloaded specimen. The mentioned previous studies used RCPT test where the chloride permeability is measured by the amount of charge passing through the specimen. **Fig.10** shows the normalized non-steady state diffusion coefficient obtained from present study and normalized charge pass of RCPT in the previous studies**.** In the figure, the trend of chloride penetration increase against stress ratio is shown. The insignificant increase in chloride permeability at lower stress ratio was mostly influenced by the test setup where concrete was tested after the loading was removed. As mentioned by Lim [6], until 50% of the ultimate strength, the microcracks in concrete close back almost completely upon unloading of concrete and chloride permeability showed small changes. Therefore, the method of measuring chloride permeability by considering only residual strain is not adequate.

In the comparison of the performance of fiber concrete and plain concrete, it was shown that plain concrete without stress had higher chloride penetration resistance, whereas in the presence of load, the chloride penetration increases. Fiber reinforced concrete could have better performance when the concrete is loaded.

4. CONCLUSIONS

Chloride penetration in plain concrete and fiber reinforced concrete under compressive and tensile loading was investigated. The following conclusions were drawn from this study.

1. The effect of loading on chloride penetration in concrete should be considered in the prediction of service life as the penetration of chloride changes when concrete was under loading.
2. Chloride penetration into concrete increases when the concrete is loaded. The increase is more profound for concrete member under tensile stress.
3. Fiber reinforced concrete shows better performance under compressive and tensile loadings compared to plain concrete. Chloride penetration in fiber concrete does not show significant changes under loading. However, at zero loading condition, chloride diffusion coefficient of fiber concrete is higher compared to plain concrete.
4. Chloride penetration in concrete under loading could also be affected by the weaker portions of the interfacial transition zone of aggregate and mortar.

ACKNOWLEDGEMENTS

The authors would like to thank Wescot, Japan and Sho-Bond Corporation, Japan for providing the materials used in this experimental study.

REFERENCES

1. Swamy, R.N., “FRC for Sustainable Infrastructure Regeneration and Rehabilitation”, 5th RILEM Symposium on Fiber Reinforced Concrete, Sept. 2000, pp. 3-18.
2. Nordtest NT BUILD 492, “Chloride Migration Coefficient from Non-Steady State Migration Experiment”, Nordtest, Finland, 1999.
3. Tang, L. and Nilsson, L. O., “Rapid Determination of the Chloride Diffusivity in Concrete by Applying an Electrical Field”, ACI Materials Journal vol.89, No.1,Jan.-Feb. 1992, pp.49-53.
4. Nilsson L.O. et al. “Comparison of Chloride Profile Predicted by ClinCon and Measured by NT Build 443”, HETEK Report No.83, The Danish Road Directorate, 1997, pp. 25-32.
5. Saito, M. and Ishimori, H., “Chloride Permeability of Concrete under Static and Repeated Loadings”, Cement and Concrete Research Vol.25 No.4, 1995. pp. 803-808.
6. Lim, C.C., Gowripalan, N., Sirivivatnon, V., “Microcracking and Chloride Permeability of Concrete under Axial Compression”, Cement and Concrete Composite 22, 2000, pp. 353-360.