- Technical paper -

PERFORMANCE OF FIBER REINFORCED CONCRETE AGAINST CHLORIDE PENETRATION UNDER LOADING

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ABSTRACT: This paper presents an experimental study on chloride penetration in fiber reinforced concrete (FRC) under compressive and tensile loading. The addition of short fiber into concrete is known to improve its mechanical properties, however the durability aspect of FRC should also be considered when designing its service life. The variations in fiber type, fiber length, fiber content and air content were investigated to determine its relationship to chloride penetration. Furthermore, three different types of polypropylene FRC (PFRC) were tested under compressive and tensile loading. The results showed that PFRC could provide good resistance against chloride penetration under loading.
KEYWORDS: Chloride, migration, diffusion, stress effect, loading, polypropylene fiber, mesh type, mono-filament type, volume fraction, service life

1. INTRODUCTION

The durability of concrete structure has become a very important factor in designing its service life especially for concrete under salt-laden environment. During its service period, concrete is subjected to various conditions such as loading and also damage that can reduce the resistance of concrete against chloride penetration. Microcracks due to stress could influence the chloride penetration. Some studies have shown that concrete under loading conditions, especially under tensile loading, reduce the resistance of concrete against chloride penetration [1,2]. In order to measure the effect of loading on the chloride penetration into concrete, a test method is developed in this study to measure the changes in the chloride penetration under compressive and tensile loading. When changes in the chloride penetration into concrete under loading are known, the changes in the service life of the structure with regard to the loading effect could be assessed.

The inclusion of discontinuous fibers into concrete could improve the properties of concrete such as crack resistance and increase its ductility and energy absorption. Short and fibrillated fibers could reduce the shrinkage crack and microcracks due to loading while longer and stiffer fibers could improve the tensile strength of concrete. The development of microcracks in fiber reinforced concrete under loading condition is altered also by the bridging effect of the fiber. The chloride penetration into concrete may also be affected by the inclusion of fiber. In this study, the mesh type and mono-filament type of polypropylene fiber were used to make fiber reinforced concrete. The performance of fiber reinforced concrete is tested under several compressive and tensile loading conditions. The relationship of fiber type and fiber volume fraction to the chloride migration coefficient under zero loading were investigated. The effect of different casting direction of fiber reinforced concrete on the chloride penetration was also examined in this study as it could be affected by the orientation of the fiber. Effect of orientation could especially be true for long and stiff fiber such as steel fiber.

2. MATERIALS AND METHODS

2.1 FIBER TYPES

Three types of fiber were used to make fiber reinforced concrete in this study. **Fig. 1** shows mesh

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type 12 mm polypropylene fiber (PP12M), mono-filament type 10 mm polypropylene fiber (PP10S) and mono-filament type 30 mm stiffer polypropylene fiber (PP30S) used. Fiber diameters are 0.31 mm (equivalent), 0.23 mm and 1.0 mm for PP12M, PP10S and PP30S, respectively.

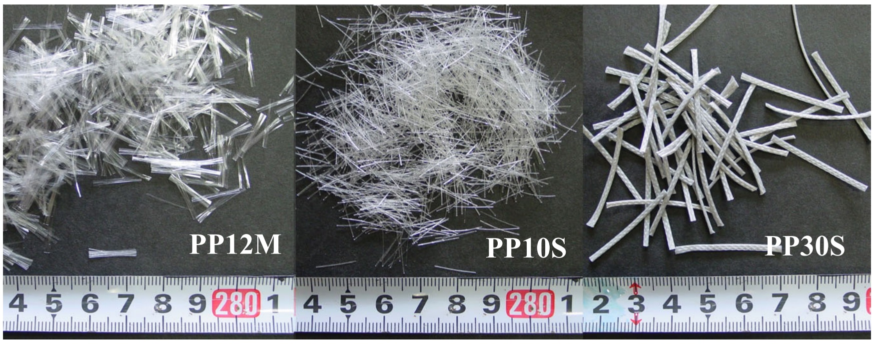


Fig. 1 Fiber types and designations

2.2 PREPARATION OF TEST SPECIMEN

The materials used for the test specimen were ordinary Portland cement, river sand and river gravel. For all cases, the water to cement ratio (w/c), water content and sand by aggregate volume fraction were fixed at 0.5, 175kg/m^3 and 0.52 respectively. The maximum aggregate size used was 12 mm. Addition of superplasticizer was used to achieve target slump of 8 to 12 cm and addition of air entrainment admixture to achieve target air content of 3% to 7%. The properties investigated and the physical properties of concrete are shown in **Table 1**.

Table 1 Properties investigated and physical properties of concrete

Effect	Type	Fiber (%V)	Air (%)	Bulk (kg/m^3)	fc'$_{28days}$ (MPa)
Fiber type, volume fraction and casting direction	PC	0	3.0	2,461	50.07
	PP12M	0.1	2.7	2,440	41.80
		0.3	3.7	2,450	42.27
		0.5	2.9	2,425	35.62
	PP10S	0.3	3.0	2,408	41.45
		0.5	3.2	2,446	41.52
		1.0	4.3	2,372	36.30
	PP30S	0.5	2.4	2,435	47.45
		1.0	2.0	2,453	48.95
		1.5	2.0	2,446	46.65
Air content	PC	0	3.0	2,461	50.07
			4.9	2,385	42.85
			7.3	2,331	34.41
	PP12M	0.1	2.7	2,440	41.80
			5.9	2,409	39.04
			7.6	2,329	38.82
Loading	PC	0	4.9	2,383	42.24
	PP12M	0.1	5.9	2,397	39.04
	PP10S	0.5	6.8	2,367	35.89
	PP30S	1.0	6.2	2,358	37.36

The inclusion of fiber in concrete could also cause different chloride penetration due to the orientation of fibers. To investigate this effect, the fiber reinforced concrete specimens were cast into vertical and horizontal mold with cross section of 100×100 mm for chloride migration test as shown in **Fig.**

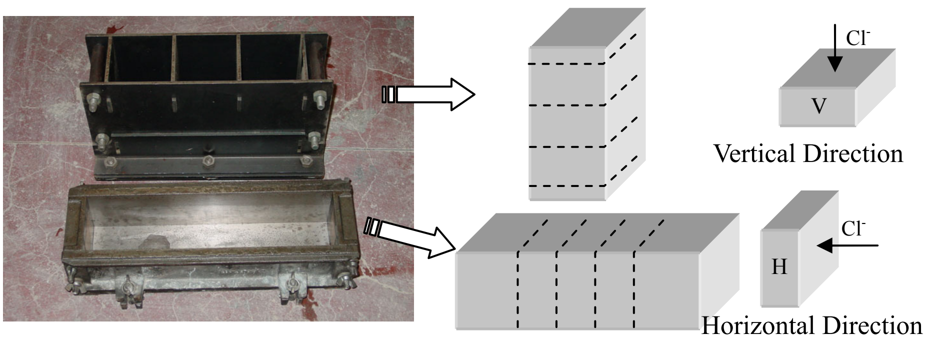


Fig. 2 Concrete mold and casting

2. The specimens were later cured in water for 60 days. After water curing, the prismatic specimens were cut by water-cooled concrete cutter perpendicular to its axis into 50±2 mm thick specimens. All specimens were then placed in room condition for additional 30 days before performing the chloride migration test.

2.3 NON-STEADY STATE MIGRATION TEST

The chloride migration test used in this study is based on the standard of NordTest Build 492 - Non-Steady State Migration test [3]. The principle of the test is to subject the concrete to external electrical 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 whitish color.

The chloride non-steady state migration coefficient can then be calculated from the following equation given in NT Build 492 [3]:

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

where $E = \dfrac{U-2}{L}$ and $\alpha = 2\sqrt{\dfrac{RT}{zFE}} \cdot \mathrm{erf}^{-1}\left(1 - \dfrac{2c_d}{c_0}\right)$ (2) & (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 of the solution (K), z is the absolute value of ion valence (for Chloride, z=1), F is the Faraday's 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 effect of loading on the chloride penetration is conducted by using Modified NT Build 492 test that introduces loading at the time of testing. The concrete was loaded by using external frame as shown in **Fig. 3** and tested for chloride migration under loading (**Fig. 4**). The detailed explanation of this test method can be found in [1]. Loading variations performed in the experiment were 30%, 50% and 80% of ultimate compressive strength for compressive loading and 3% and 5% of ultimate compressive strength for tensile loading.

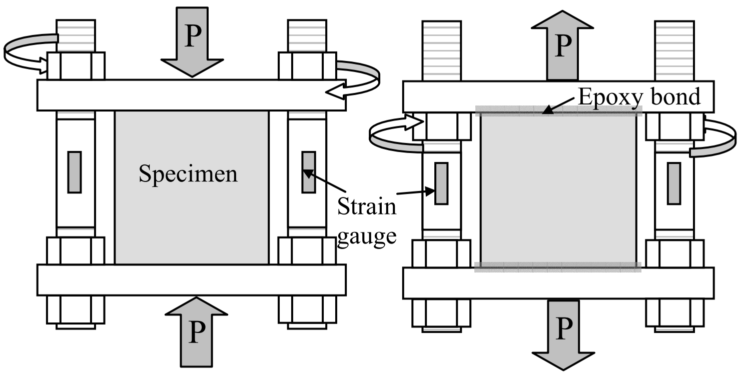


Fig. 3 Application of loading on concrete

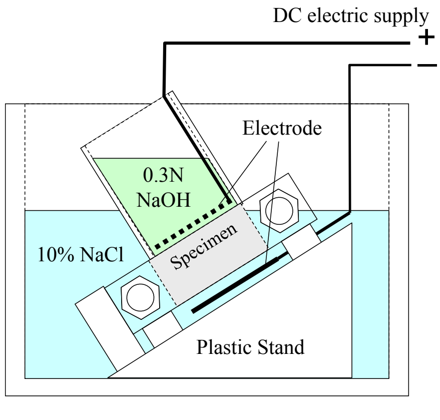


Fig. 4 Migration test setup

3. RESULTS AND DISCUSSIONS

3.1 EFFECT OF FIBER CONTENT

The results of non-steady state chloride migration tests with different types of fiber and volume fraction are shown in **Fig. 5**. Three replications were done for each type of condition. The results showed that the chloride penetrations for PP10S and PP30S did not change with the increase in fiber content, while for PP12M, at volume fraction of 0.5%, the chloride penetrability increased significantly. This increase was caused by the reduction of the compactness due to difficulties in casting concrete when excessive fiber volume is used. The recommended volume fraction of mesh type PP12M is 0.1% as compared to 0.5% volume fraction used in this study. The use of mono-filament type fiber, PP10S and

PP30S, in this case showed no changes in chloride penetration. However, with the increased fiber content, the fiber distribution becomes more important. The use of excessive fiber could lead to local defect such as "balling" and large entrapped air void that could reduce chloride resistance significantly. The result showed that the inclusion of fiber up to a certain volume fraction do not cause a detrimental effect to the durability properties of concrete.

3.2 EFFECT OF CASTING DIRECTION

Fiber reinforced concrete cast in horizontal and vertical directions as specified in Section 2.2 were tested for chloride penetration. The results are shown in **Fig. 6**, **Fig. 7** and **Fig. 8** for PP12M, PP10S and PP30S, respectively. The casting direction had little effect on the short fiber type of PP12M and PP10S with the exception of PP12M-0.5% which as stated earlier included excessive amount of fibers. This means that the effect of casting direction to the chloride penetration is insignificant for shorter fiber. This could be due to the random orientation of short fibers. However, for PP30S, the vertical casting direction showed higher resistance to chloride penetration. For long and stiff fiber [4], the fibers are mostly oriented in the horizontal plane and the orientation of the fibers in the horizontal plane is quite random. In the case of vertical specimens, the fiber direction is perpendicular to the direction of chloride penetration as shown in **Fig. 9(a)**. The chloride movement into concrete is therefore reduced by the presence of fiber as the interfacial transition zone of the fiber provides easier path for the chloride to migrate in direction along the fiber and mortar interface. **Fig. 10** shows a sample of PP30S-1.5%-V. It can be clearly seen from this

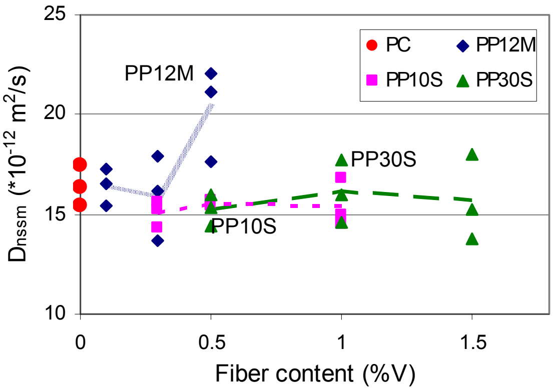


Fig. 5 Fiber content effect on chloride penetration

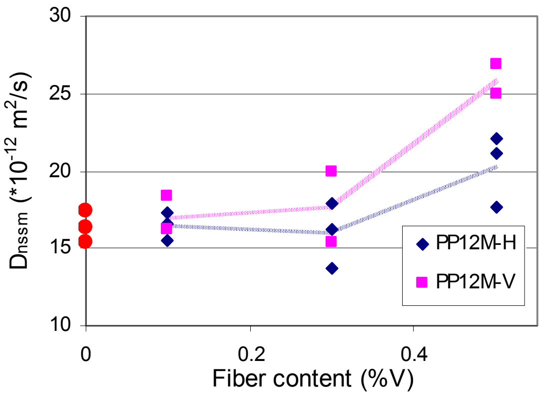


Fig. 6 Direction effect of PP12M

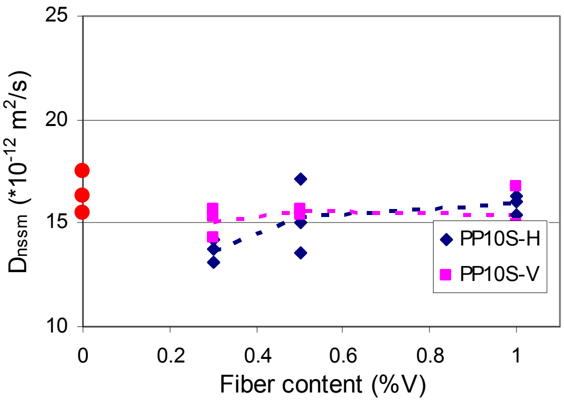


Fig. 7 Direction effect of PP10S

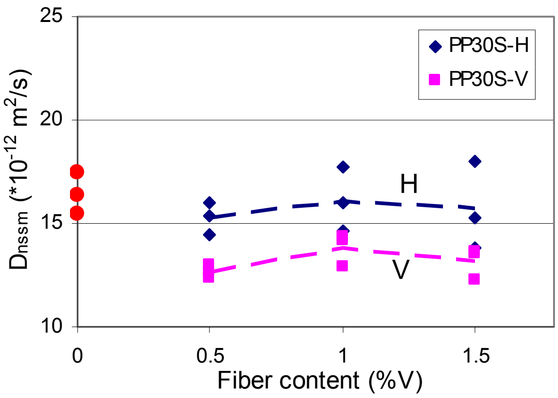
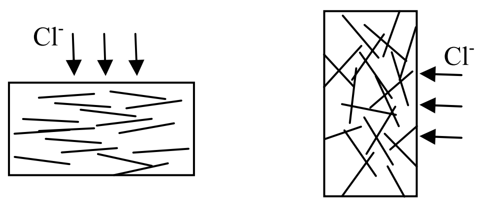


Fig. 8 Direction effect of PP30S



(a) V-specimen (b) H-specimen

Fig. 9 Cross section of specimen showing the orientation of long and stiff fibers

Fig. 10 Split specimen of PP30S-1.5%-V

figure that most of the fibers were oriented in the horizontal direction. For the horizontal casting direction **(Fig. 9(b))**, the random orientation means that some fiber could resist chloride penetration while some could increase it. On the average, the chloride penetration in PP30S-H is about the same as the plain concrete.

3.3 EFFECT OF AIR CONTENT

The effect of different air content on chloride penetration into plain concrete (PC) and fiber reinforced concrete (PP12M) was also investigated. **Fig. 11** shows the relationship between air content and chloride penetration. It is shown that an increase in the air content in PC does not lead to an increase in chloride penetration. On the contrary, at 7% air content, the chloride penetration was slightly lower than the one at 3%, even though the compressive strength was greatly reduced. Better performance of 7% air entrained concrete is mostly attributed to better dispersion of fine air bubble in concrete causing an increased workability at casting time thereby improving the quality of concrete. This result shows that the assessment of the effect of chloride penetration could not solely be based on the concrete compressive strength. For PP12M fiber reinforced concrete, the result showed similar trend in chloride resistance but the reduction of strength was not as pronounced as that of plain concrete. The use of air entrainment to increase air content in concrete could give a good resistance against chloride penetration while performing well under freezing and thawing exposure.

3.4 EFFECT OF LOADING

The result of chloride penetration into plain concrete and three types of fiber reinforced concrete under compressive loading are presented in **Fig. 12**. The results show a trend similar to the previous study [1]. Plain concrete showed an increased chloride penetration under compressive loading, while fiber reinforced concrete showed a small increase in chloride penetration at a stress ratio of 80%. At compressive loading, PP10S and PP30S showed lower values of migration coefficient compared to PC for all cases, while PP12M showed higher value. However, at stress ratio of above 50%, the PP12M performed better than PC. The PC, PP10S and PP30S showed some reduction in chloride penetration at loaded condition until 30% stress ratio. This could be attributed to the increase in the density of concrete due to loading before any cracks could occur. However, at the stress ratio of 50% to 80% there is some increase in the chloride penetration for all specimen types.

For the tensile loading, the chloride migration coefficient is shown in **Fig. 13**. Plain concrete showed higher increase in chloride penetration under tensile loading compared to fiber concrete at 3% of loading. However at 5%, there was a slight reduction. This could be due to release of the tensile loading due to cracking in the concrete. PP12M also show similar behavior with PC showing that the fiber content was not enough to change the behavior of concrete under loading. PP10S and PP30S also showed an increase in the chloride penetration but to a lesser degree. The changes in chloride penetration of fiber reinforced concrete showed a different behavior when they are subjected to tensile loading. For the mono-filament type fiber, it appears that as the cracks are initiated, they will be eventually bridged by the fibers, thereby stopping crack propagation. This could then lead to a reduced increase in chloride penetration. From tensile stress ratio of 3% to 5%, PP10S showed a reduced increase in chloride penetration while PP30S still showed almost the same increase as that from 0 to 3%.

The normalized value of non-steady state migration coefficient under compressive loading is shown

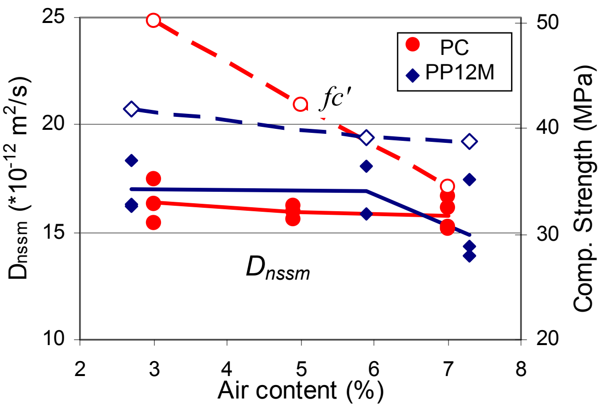


Fig. 11 Effect of air content on chloride penetration

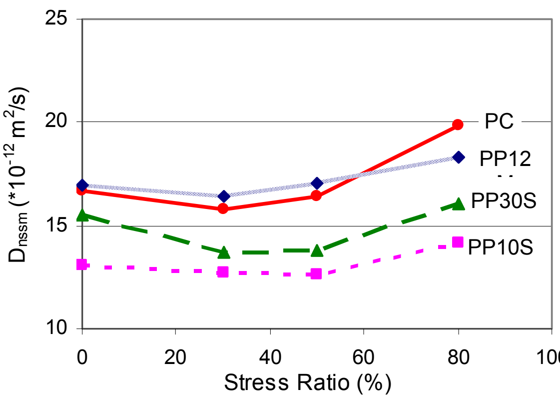


Fig. 12 Effect of compressive loading

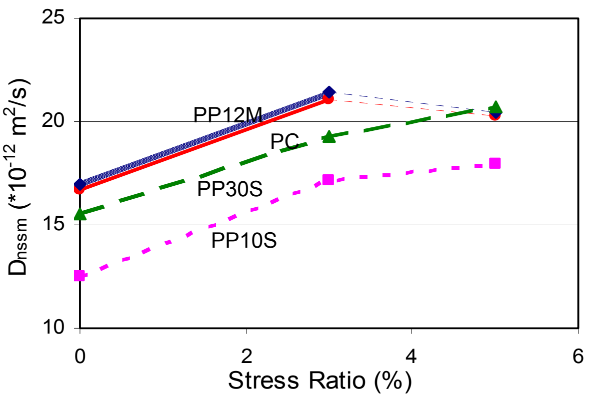


Fig. 13 Effect of tensile loading

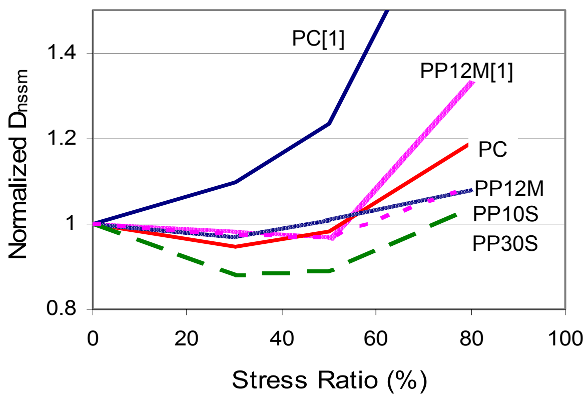


Fig. 14 Normalized value of chloride migration

in **Fig.14** where the results of the previous study [1] are also included. The increase in chloride penetration under loading for PC in the current experiment is not as large as the previous one. The difference in the concrete materials used was the maximum aggregate size (G_{max}). In [1], the G_{max} used was 20 mm, while current experiment used 12 mm. This difference obviously has large influence on the durability performance under compressive loading. It is shown that for G_{max} of 20 mm, the critical stress is at 30% stress ratio while for G_{max} of 12 mm, critical stress is at 50% stress ratio. Larger aggregate size has more significant negative influence when microcracks occur.

Comparing the performance of polypropylene fiber reinforced concrete to plain concrete, it appears that all types of fiber performs better under compressive loading, while the monofilament type fiber gives better performance under tensile loading.

4. CONCLUSIONS

The performance of several types of fiber reinforced concrete against chloride penetration under loading was investigated and the conclusions drawn from this study are as follows:

1. The chloride penetration resistance of fiber reinforced concrete under loading is better compared to plain concrete. The inclusion of fibers in concrete increases its resistance to chloride penetration under compressive and tensile loading with the shorter fiber giving better performance based on the fiber type used in this study.
2. Plain concrete shows large increase in chloride penetration when it is subjected to tensile loading and also shows some increase in chloride penetration under high compressive loading. On account of this, special consideration should be given to structural members under tensile stress.
3. Maximum aggregate size appears to have great influence on the chloride penetration when concrete is subjected to loading.

For fiber reinforced concrete under zero loading condition, the following conclusions are obtained:

4. The inclusion of fiber into concrete at a certain volume fraction does not show any reduction in the chloride penetration resistance.
5. The effect of fiber orientation should also be considered when using long and stiff fiber as it could also affect the resistance to chloride penetration.
6. The increase in air content does not lead to an increase in chloride penetration in concrete. On the contrary, at higher levels of air content, there is a slight reduction in the chloride penetration due to improved workability at the fresh concrete stage.

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