Performance of Polymer-Concrete Composites Exposed to Harsh Environment

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ABSTRACT

This paper presents an extensive experimental investigation on the durability of the polymer-concrete composites exposed to severe environment. In the last three decades, the premature deterioration of various reinforced concrete structures has been a widely recognized problem in the world due to its excessive costs of maintenance and repair, and also environmental impacts. Based on the literature review, diffusion of chloride into the concrete structures was found to be the major cause of the corrosion of steel reinforcement to promote their deterioration. Reinforced beam specimens were exposed to simulated marine environment for 24 months. Then, by utilizing accelerated chloride-induced corrosion test, the time to crack initiation was collected. The results revealed that the polymeric fibre-concrete composites not only increase the durability of the concrete, but also improve the mechanical properties of the concrete.

Keywords. Polymer-concrete composites, Concrete durability, Corrosion of steel in concrete, Chloride diffusion, Accelerated chloride-induced corrosion

INTRODUCTION

Premature deterioration of reinforced concrete (RC) structures exposed to aggressive environment such as marine and salt de-icing has become a worldwide problem with serious economic consequences regarding to maintenance, repair, and replacement of the RC structures and also environmental impact and safety issue (Ann, Ahn & Ryou 2009; Song & Kwon 2009). According to the vast investigations, it is found out that the dominant factor of this process is the chloride-induced corrosion of the steel reinforcement in concrete (Costa & Appleton 1999; Zornoza et al. 2009).

Chloride diffusion into the concrete occurs through the concrete interconnected pores and surface cracks resulted from different sources such as loading and shrinkage. Increasing the number and the width of cracks will not only accelerate the diffusion process but also enhance the probability of the steel corrosion leading to decreasing the service life of structures. When the concentration of chloride ions around the steel reinforcement surface reaches to the chloride threshold level, depassivation of high alkaline protective layer leads to corrosion initiation (Ann & Song 2007; Koleva et al. 2007). The surface of the corroding steel functions as a mixed electrode that is a composite of anodes and cathodes electrically connected through the body of steel itself, upon which coupled Anodic and Cathodic reactions take place. Concrete functions as an aqueous medium, i.e., a complex electrolyte. Therefore, a reinforcement corrosion cell is formed (Maruya et al. 2007).

Since concrete in the corrosion process contributes as an electrolyte (solid electrolyte), then electrical resistivity (or conductivity) of concrete is of importance to certain diffusion of aggressive ions and corrosion process(Hansson 1984).

Corrosion products occupy approximately four to five times more space than the original state of steel. This expansion generates tensile stresses in concrete. Consequently, tensile stresses cause the crack initiation in concrete cover and then spalling of concrete and strength reduction of the concrete element. Generation of cracks relates to low tensile strength and strain of the conventional concrete. To help overcome to these imperfections, there has been a steady increase in use of the fibre reinforced concrete (FRC) over the last 40 years. The main role of short monofilament fibres is to control the numbers and width of cracks in the concrete (Brandt 2008).

Synthetic fibres have become increasingly important to the civil and structural engineering over the last decade and now have a broad range of applications. Different kinds of synthetic fibres like polypropylene, aramid, polyvinyl alcohol etc. are utilized in cementitious materials to enhance mechanical properties of concrete such as tensile and flexural strengths, toughness, impact load resistance, and fracture energy (Zheng & Feldman 1995). Among the various types of fibres, polypropylene fibres (PP) have become more and more important in engineering application due to their low cost, light weight, good bond with matrix and high corrosion resistance.

It has been shown earlier that the cracks resulted from plastic shrinkage and differential settlements during the fresh state can be effectively inhibited by monofilament type of polypropylene (PP) fibres reinforcement. Because of the large numbers involved, fibres can be properly distributed throughout the mortar matrix, around the coarse aggregate particles, and even in boundary layers of concrete elements.

In this paper, the mechanical properties and durability assessment of FRC incorporating PP fibres exposed to simulated marine environment utilizing Accelerated Chloride-Induced Corrosion Test are investigated.

MATERIALS

1) Portland cement type General Purpose (GP) based on Australian Standard which is equivalent to ASTM C 150 Type (I) was used in this study. (2) Monofilament type of PP fibres with length of 18 mm and a diameter of 24 μm were employed.(3) Crushed coarse aggregate with maximum size of 20 mm, specific gravity of 2.71, and water absorption capacity of 1.48% was used. Table 1 shows the sieve analysis of coarse aggregate based on Australian Standard (AS2758.1).

Table 1. Coarse aggregate grading

Sieve Size(mm)	26.5	19	9.5	4.75
Passing (%)	100	91.30	9.21	0.34

(4) Natural fine aggregate with specific gravity of 2.62 and water absorption capacity of 1.67% was used. Table 2 presents sieve analysis of fine aggregate according to Australian Standard (AS2758.1).

Table 2. Fine aggregate grading

Sieve Size (mm)	Passing (%)
9.5	99.74
4.7	93.64
2.3	82.33
1.18	55.20
0.600	34.27
0.300	16.67
0.150	6.74

METHODS

Mechanical Properties. In this investigation, Conventional Concrete (CC) as a reference specimen; and Fibre Reinforced Concrete (FRC) specimens with various proportions of PP Fibres, were cast and examined. According to Australian standard (AS4997), “Guidelines for Design of Maritime Structures”, a minimum characteristic compressive strength of 40 MPa, minimum cement content (400kg/m^3) and maximum water to cement ratio of 0.4 were taken into account as the basic and initial assumptions of concrete mix design.

Mix Design. The mean concrete compressive strength of 60 MPa and water-cement ratio of 0.35 with a cement content of 400 kg/m^3 and slump between 60-80 mm were fixed to design of the concrete mix. The concrete mix design is reported in Table 3.

Table 3.Mix design for conventional concrete

Material	Magnitude (kg/m3)
Cement	400
Water	140
Coarse aggregate	1173
Fine aggregate	781

The Characteristics of Fibre Reinforced Concrete Specimens. Fibre reinforced concrete specimens with three different proportions of polypropylene fibres were made to be investigated. The PP fibres proportions of 0.1%, 0.2%, and 0.3 % by the volume of concrete were selected. Increasing the proportion of PP fibres in the mix causes the reduction of the concrete workability. Table 4 displays the characteristics of these PP fibre reinforced concrete samples.

Table 4.Fibre reinforced concrete characteristics

Concrete Category	Fibre Content (%)*	Superplasticizer (%)**
CC	0.0	0.6
FRC1	0.1	1.0
FRC2	0.2	1.3
FRC3	0.3	1.8

*by the volume of concrete
**by the weight of cement

Mixing Procedure. The mixing process for the conventional concrete was conducted in accordance with Australian Standard (AS 1012.2). For FRCs, the same process was performed and after completing the mixing time PP fibres were added to the freshly concrete mix. Since the monofilament PP fibres must uniformly be dispersed and distributed throughout the whole matrix body, four minutes more was considered for mixing process time after accomplishing the conventional concrete mixing process. Increasing the proportion of fibres causes the reduction of the workability of freshly mixed concrete leading to use more Superplasticizer.

Geometry of the specimens. A rectangular (400 ×100×100 mm) reinforced concrete beam shape consisting embedded reinforcing steel of 12 mm diameter fixed in the centre of cross sectional area was selected for the casting of all specimens.

Curing Method and Exposure Conditions. The wet curing system was utilized to all specimens for 28 days. Then, all reinforced concrete specimens were exposed to a simulated marine environment consisting of high concentrated Sodium Chloride solution (15%) with equal time interval (seven days) wetting and drying cycles at about 23$\pm$ 3ºC for the period of 24 months.

Accelerated Chloride-Induced Corrosion Test. Since the corrosion of reinforcing steel bars is a long term electrochemical process, the electrochemical accelerated methods can help to obtain the results in relatively shorter time for laboratory investigations (Ha et al. 2007; Saetta 2005). Thus, the Accelerated Chloride-Induced Corrosion Test method with constant impressed voltage was performed to identify the time to crack initiation in the concrete cover (corrosion time) for FRCs and references specimens. The corrosion time of reinforcing steel bars was considered as a criterion for durability assessment of the concrete. The greater corrosion time indicates the more durable concrete.

After 24 months of marine simulated exposure conditions, the specimens were tested under Accelerated Chloride-Induced Corrosion Test to measure the corrosion time of each category of the concrete. In this electrochemical test, the embedded steel in concrete acts as an anode and steel bar performs as a cathode and the electrolyte is Sodium Chloride solution with 15% concentration. During the test a 30 V constant voltage is applied from the external DC source between anode and cathode. The intensity of electrical current versus time is continuously recorded by using high resolution digital data logger. Based on the concept of this method, any impulsive raise in electrical current indicates corrosion-induced cracking in concrete cover. The time correspond to this raise of current is considered as corrosion time. The schematic of the test arrangement is shown in Figure 1.

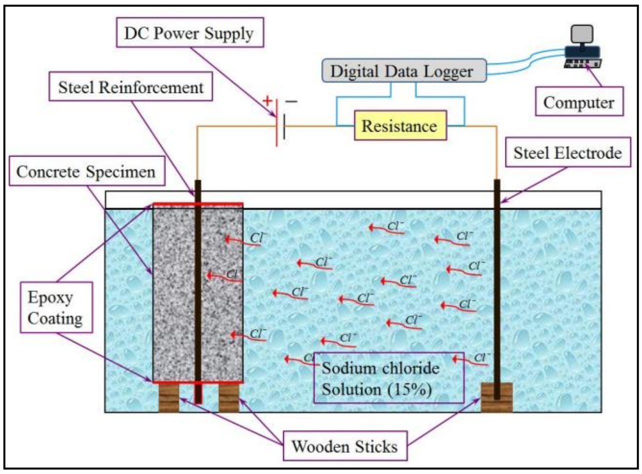

Figure 1. Accelerated chloride-induced corrosion test set up

RESULTS AND DISCUSSION

Compressive Strength. Compressive strength test is carried out based on Australian Standard (AS 1012.9) after 7 days and 28 days of casting time. Compressive strength test results are reported in Table 5.

Table 5.Compressive strength test results

Concrete Category	7-day MPa	Average MPa	28-day MPa	Average MPa
CC1	40.5		61.7	
CC2	41.4	41.0	62.8	62.3
CC3	41.2		62.5	
FRC1-1	43.6		64.8	
FRC1-2	45.3	44.5	65.3	64.7
FRC1-3	44.6		63.9	
FRC2-1	46.8		68.3	
FRC2-2	45.3	46.5	67.9	67.9
FRC2-3	47.4		67.4	
FRC3-1	49.2		68.4	
FRC3-2	47.8	48.5	70.5	69.4
FRC3-3	48.8		69.2	

The results confirm that PP fibres can improve the compressive strength of concrete due to bridging effect after cracks generated. Increasing the amount of fibres increases the compressive strength. Fibre proportions of 0.1, 0.2, and 0.3% by the volume of concrete improved the compressive strength by 4, 9, and 13%, respectively.

Also, Figure 2 represents the comparisons between the averages of 7-day and 28-day compressive strength for CC and FRCs.

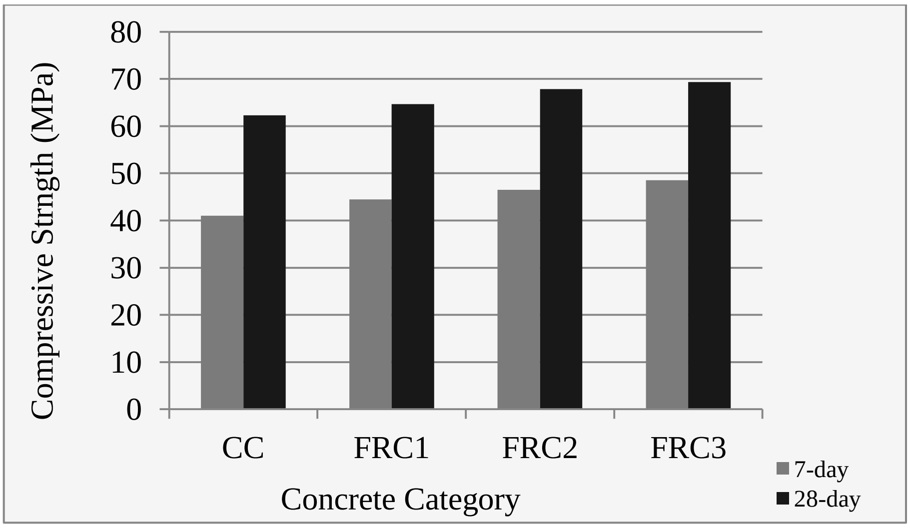

Figure 2. The average of 7-day and 28-day compressive strength test results

Flexural Test. Flexural test- flexural test was carried out in accordance with Australian Standard (AS 1012.11). The results of the maximum load and maximum deflection and the modulus of rupture (MOR) for all types of concrete have been summarized in Table 6.

Table 6. Flexural strength and maximum central deflection results

Specimen Code	Max. Load (kN)	Average (kN)	Deflection (mm)	Average (mm)	MOR (MPa)	Average (MPa)
CC1	22.596		0.462		6.78	
CC2	22.353	22.464	0.402	0.433	6.71	6.74
CC3	22.443		0.435		6.73	
FRC1-1	22.683		0.534		6.80	
FRC1-2	23.132	22.866	0.577	0.553	6.94	6.86
FRC1-3	22.784		0.548		6.84	
FRC2-1	23.883		0.584		7.16	
FRC2-2	24.361	24.084	0.623	0.603	7.31	7.23
FRC2-3	24.008		0.602		7.20	
FRC3-1	26.086		0.712		7.83	
FRC3-2	25.495	25.752	0.637	0.676	7.65	7.73
FRC3-3	25.674		0.678		7.70	

The results regarding to modulus of rupture for all categories of concrete are represented in Figure 3. Considering the results, it can be stated that by increasing the proportion of Polypropylene up to 0.2% by the volume of concrete, MOR will be enhanced by approximately 16%. But, by increasing the amount of fibre more than 0.2% in the concrete, the MOR compare to other PP FRC will be reduced but it is still around the modulus of rupture for CC. The average results of the maximum central deflection and modulus of rupture are shown in Figure 3 and Figure 4, respectively.

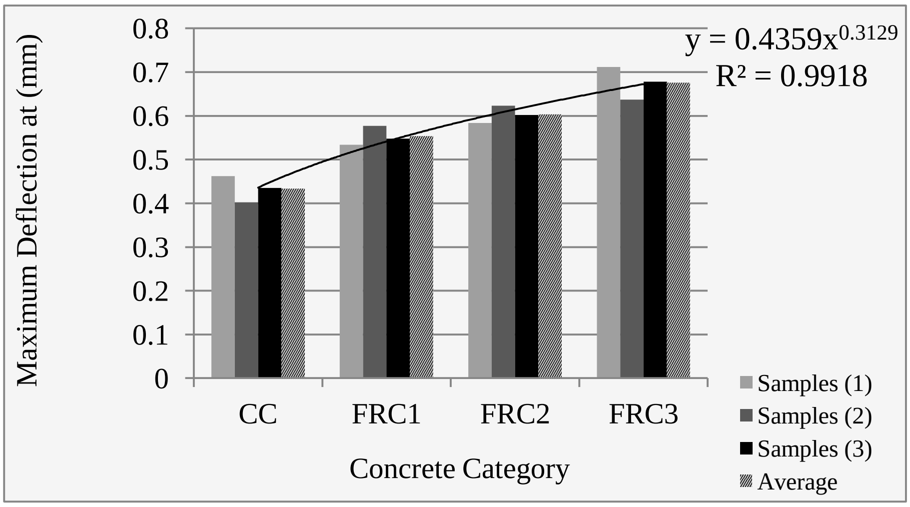

Figure 3.Maximum deflection in Flexural test

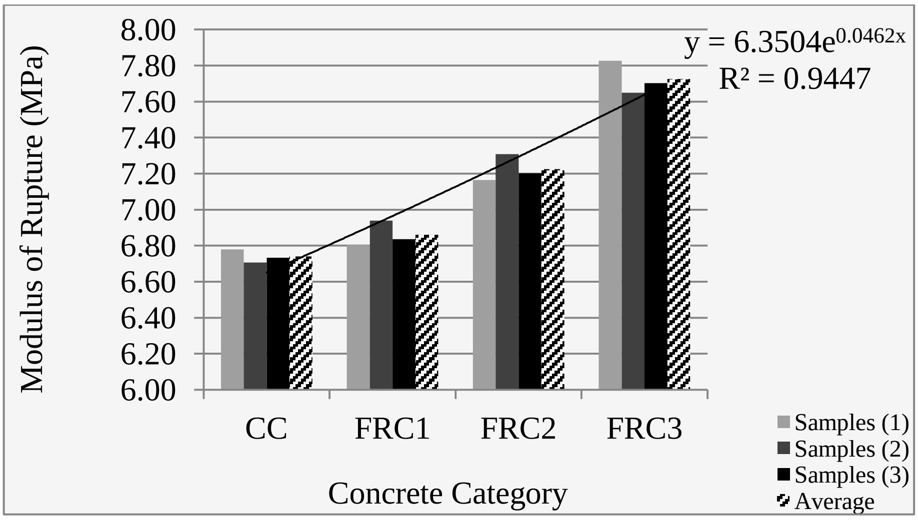

Figure 4. MOR for different concrete category

Accelerated Chloride-Induced Corrosion Test Results. The results presented in Table 7 indicate that generally FRC has a greater time to crack initiation which proves that the chloride diffusion coefficient of FRC is less than CC. Also, it can be stated that by increasing the fibres proportion, the time to cracking is increased. For instance, adding 0.1% PP fibres to the concrete mix can improve the time to corrosion by approximately 16% and using 0.3% of fibre proportion can enhance the time to cracking up to approximately 45% compare to CC which can be considered as a high improvement of the service life of reinforced concrete. For better comparison, the time to crack initiation results are illustrated in Figure 5.

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Table 7. Time to crack initiation (end of service life)

Concrete Category	Time to Cracking (h)	Average (h)
CC1	120	
CC2	126	123
CC3	122	
FRC 1-1	139	
FRC 1-2	141	143
FRC 1-3	148	
FRC 2-1	165	
FRC 2-2	171	168
FRC 2-3	168	
FRC 3-1	178	
FEC 3-2	181	178
FRC 3-3	175	

The summarized of time to cracking results are illustrated in Figure 5.

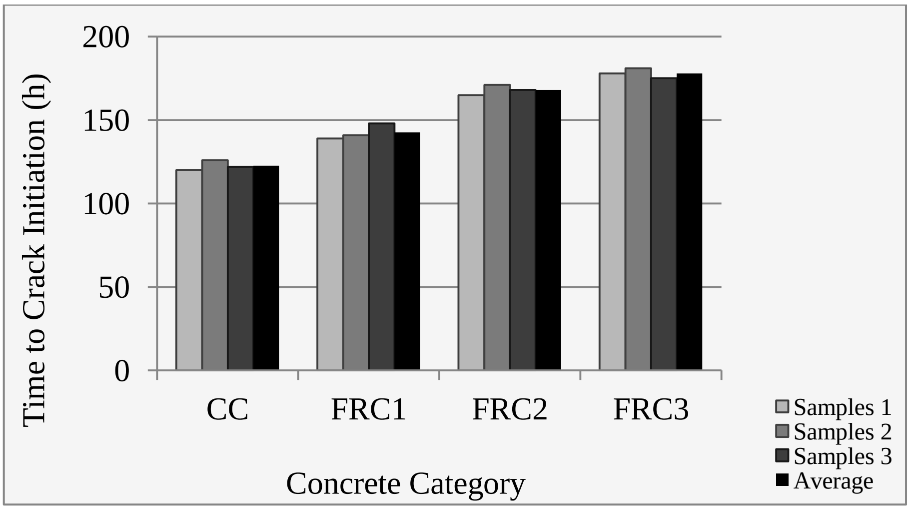

Figure 5. Comparison of the time to crack initiation in different samples

The maximum values of anodic current intensity for all concrete categories are expressed in Table8. As can be seen, FRCs shows lower electrical conductivity than CC. By adding 0.2% of PP fibres to the CC, the conductivity reduces to 30%.The anodic current can be considered as a criterion to judge about the concrete conductivity (resistivity). The lower anodic current value shows the higher concrete resistivity property. Based on the results, FRCs show more electrical resistivity compare to CC. Besides, it can be noted that increasing the fibre proportion in the FRC improves the concrete electrical resistivity.

This discussion is more comprehensive by comparing the results displayed in Figure 6.

Table 8. Maximum of anodic current intensity

Concrete Category	Current Density mA	Average mA
CC1	273	
CC2	282	272
CC3	261	
FRC 1-1	240	
FRC 1-2	226	230
FRC 1-3	224	
FRC 2-1	182	
FRC 2-2	191	191
FRC 2-3	199	
FRC 3-1	175	
FEC 3-2	178	172
FRC 3-3	162	

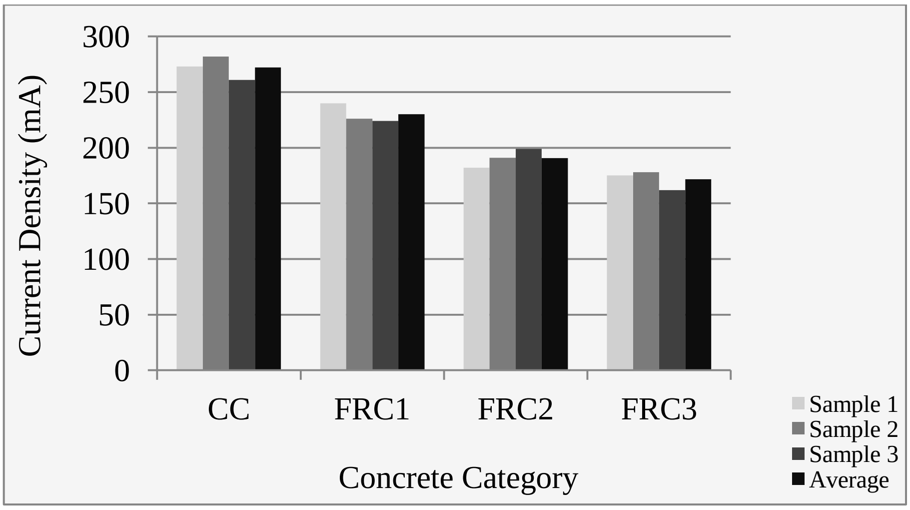

Figure 6. Maximum anodic current intensity for CC and FRCs

CONCLUSIONS

In this experimental study the mechanical properties and durability assessment of polypropylene fibre reinforced concrete exposed to marine environment have been investigated and outcomes can be derived as follows:

(1) Increasing the proportion of PP fibres decreases the workability of freshly concrete mix.

(2) PP fibres with proportion of 0.3% increase the concrete compressive strength approximately by 13%. But, flexural test results present that the magnitude of MOR beyond 0.2% of fibres proportion is decreased

The electrochemical experiment results obtained from measuring the anodic current indicate that PP fibre reinforced concrete shows lower concrete conductivity.

(3) PP FRC shows reduction in permeability compare to CC considering results of time to crack initiation. Increasing the amount of PP fibres increases the time to cracking remarkably.

(4) By obtaining less maximum current intensity and more time to crack initiation in PP fibre reinforced concrete, it can be declared that the PP fibres increasing the durability of concrete which consequently prevents the premature deterioration of structure or in another hand, extends the structure service life of RC structures considerably.

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