FRACTURE PROPERTIES OF FIBER REINFORCED POLYMER CONCRETE UNDER MARINE ENVIRONMENT EXPOSURE

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Abstract. *Fracture properties of chopped fiber reinforced polymer concrete beams were investigated under marine exposure. Polymer Concrete, (PC), is a composite material formed by polymerizing monomer and an aggregate mixture. The polymerized monomer acts as the binder for the aggregates. The stress intensity factor* K_{Ic} *and the fracture energy* G_f *are measured for different exposure periods, Spring–Summer, Autumn–Winter and one year period. Specimens subjected to laboratory controlled environment were exposed to the same period for comparison. Results from outdoor exposure were compared to indoor. It was studied the influence of the period of the year and the exposure time on the fracture properties of epoxy concrete. The results show that the Spring–Summer exposure period brings strong deterioration in such fracture properties.*

Keywords*: Polymer Concrete, Fracture Mechanics, Environment Exposure*

1. Introduction

Polymer concrete is a composite material formed by combining mineral aggregates such as sand or gravel with a polymerizing monomer, where water is not present at all, unlike conventional cement where water is an important component. In recent years polymer concrete systems are being used increasingly more in the construction and repair of structures, structure reinforcement, chemical resistant pavements or marble imitations (Bubani *et al.* 2001 and El-Hawary *et al.* 1998). PC seems to be a good choice when a structure needs to be light and also to have high fracture toughness when compared to ordinary cement concrete.

Although three to five times stronger than conventional concrete, PC does display brittle characteristics that have limited its usefulness for load-bearing applications. According to the general classification of composites, both the portland cement concrete and polymer concrete can be considered as a particular composite with two main constituents: a matrix and dispersed particles of strengthening phases (Letsch, 2000).

Since PC is a relatively new material a need to establish the long-term properties of these types of materials when they are exposed to the environmental conditions likely to be encountered on site is very important for the success of these composite.

In this paper, the fracture properties of epoxy polymer concrete and fiber reinforced polymer concrete tested in three-point bending tests after exposure to weather atmosphere were investigated. Polymer Concrete consists in essence of an aggregate blend mixed with a polymer resin in convenient proportions studied were previously studied by the authors (Ferreira *et al*. 2000)

The method used to perform the fracture mechanic tests was the Two Parameter Fracture Model (TPFM) (Shah and Carpinteri, 1991) which proposes the critical stress intensity factor, K_{Ic}, and the critical crack tip opening displacement $CTOD_C$ as material fracture parameters. According to this RILEM proposal (RILEM, 1990), only one size three point bending specimen is needed for measure the K_{Ic} and $CTOD_C$. However, the testing procedure commands an unloading when 95% of the peak load is reached, but since this procedure is not accurate due to the difficult of unloading the machine exactly at 95% of the peak load, a continuum test is done. A decomposition of CMOD is done due to nonlinear effect (Shah and Carpinteri, 1991). The critical opening displacement of the original pre-crack tip, $CTOD_C$, is calculated from the maximum load registered and the value of the effective critical crack length, which is the initial notch depth plus the stable crack growth at peak load.

Another fracture parameter studied is the fracture energy, G_f. The ideal way of determining the fracture energy is by using a direct uniaxial tension test, since the direct tensile tests are not easy to perform in these materials, an alternative three point bending beam specimens is recommended by RILEM (RILEM 1995). In this method, the fracture energy is computed from the area under the load-deflection response of the specimen.

2. Experimental Program

2.1. Environmental Condition

The meteorological tower from Aveiro University, Portugal, was used to collect the temperature and humidity from Aveiro city, which is an excellent indication of the local weather condition during the year.

There is another significative issue on these tests, the weather condition in Aveiro, which has an overall similar temperature and humidity every combined season, registering the lowest temperatures in January, in the winter, and the hottest in the beginning of September, summer. According to the meteorological tower the lowest registered temperature was 5,9ºC in January and the highest was 20,3ºC in early September. The air humidity in that precise day was 77% and 66%, respectively. The range of air humidity during the year varies from 43% to 103%.

2.2. Test Samples

Polymer Concrete formulations were prepared by mixing an epoxy resin with siliceous sand with rather uniform granulometry.

Plain mortar formulations were prepared by mixing foundry sand with an unsaturated polyester and an epoxy resin. Resin content was 20% in mass and no filler was added in both formulations.

The polyester resin used in this investigation was S226E (NESTE®), an unsaturated orthophtalic polyester diluted in 44% styrene. The resin system is pre-accelerated by the manufacturer and the initiator used was methyl ethyl ketone peroxide (2 phr).

The epoxy resin system was EPOSIL 551 (SILICEM®), based on a diglycidyl ether of bisphenol A and an aliphatic amine hardener. This system has low viscosity, and is processed with a maximum mix ratio to hardener of 2:1.

Thermal and mechanical properties of both resins are presented at Table 1.

Table 1 – Thermal and mechanical properties of polyester and epoxy resins.

Resin properties (After one week at 25ºC)		Polyester resin (NESTE-S226E)	Epoxy resin (EPOSIL-551)
Glass transition temperature –DMA	ISO 6721-5	87ºC	45ºCº
Heat distortion temperature – HDT	ISO 75	50ºC	34ºC
Tear Strength[a]	ISO 527	58 MPa	40 MPa
Flexural Strength[a]	ISO 178	119 MPa	70 MPa

([a]) Mechanical properties given by the supplier.

Foundry sand used in this study was a siliceous one, with very uniform grain and a mean diameter, d_{50}, of 342 microns. The sand was dried before added to polymeric resins in an automatic mixer.

Both reinforced and plain polymer concrete, with these binder formulations and mix proportions, were mixed and moulded to specimens 30mm x 60mm x 280 mm, and then notched with 20mm depth using a 2mm diamond saw according to RILEM standard TC113/PC2 (RILEM 1995). All specimens were allowed to cure, for seven days at room temperature and then post-cured at 80ºC for three hours.

2.3. Experimental Procedure

The specimens were placed in the hoof of a house near “Aveiro”, a 60 kilometers far from “Porto”, nearby the ocean. The samples were faced Southwest with the notch free from touching any surface, for the fracture properties that were studied express a real situation. The material deterioration and structural performance were investigated in a real situation of exposure for a year period. The relationship between year period, exposure time and load-bearing capacity of deteriorated Polymer Concrete is studied and fracture mechanics of the specimens are discussed.

After the environmental exposure the samples were tested in laboratory conditions to determine its fracture properties. The tests set-up apparatus is displayed in figure 1. A decomposition of CMOD is done due to nonlinear effect.

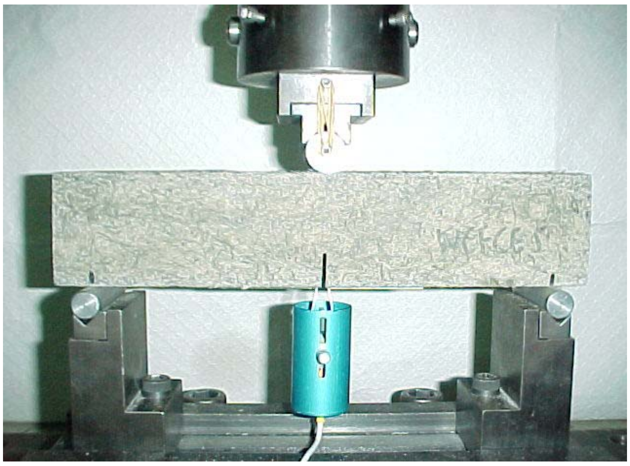

Figure 1 – Laboratory test set-up apparatus

The critical opening displacement of the original pre-crack tip, $CTOD_C$, is calculated from the maximum load registered and the value of the effective critical crack length, which is the initial notch depth plus the stable crack growth at peak load.

The fracture energy G_f of the polymer concrete can be calculated by the following equation (RILEM 1995):

$$G_f = \frac{W_0 + mg\delta_{max}}{A_{lig}} \qquad (1)$$

where W_0 is the area under the load–deflection curve (N m), mg is the self-weight of the specimen between supports (kg), δ_{max} is the maximum displacement (m), and A_{lig} is the fracture area [d(b – a)] (m^2); b and d are the height and width of the beam, respectively; a is the depth of the notch.

3. Results and discussion

The effect results of atmospheric exposure in a marine environment of unreinforced and fiber reinforced polymer concrete are presented in the following graphics and tables.

The application of the two parameter model and fracture energy to specimens exposed to season period, Autumn/Winter, Spring/Summer, and one year in the outside conditions are exposed from figures 2 and 3 for epoxy polymer concrete, in figures 4 and 5 for glass fiber reinforced polymer concrete and in figures 6 and 7 for carbon fiber reinforced polymer concrete. From Loas vs. CMOD, TPFM properties are obtained and the Load vs Mid-span Displacement curves are the reference to calculate the Fracture Energy, G_f. As can be seen from such results all samples were degraded.

Figure 2 and 3 displays a comparison of polyester polymer concrete tests results.

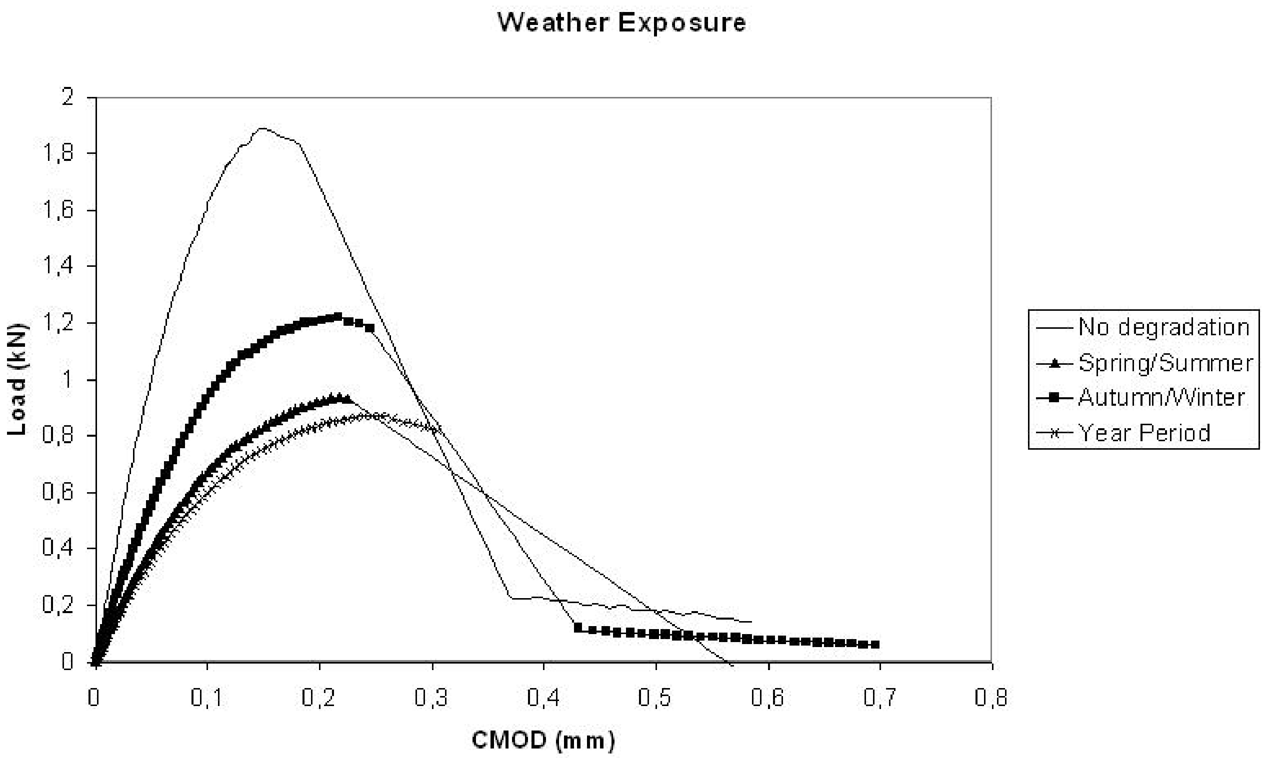

Figure 2.Load vs. CMOD test results of polyester polymer concrete

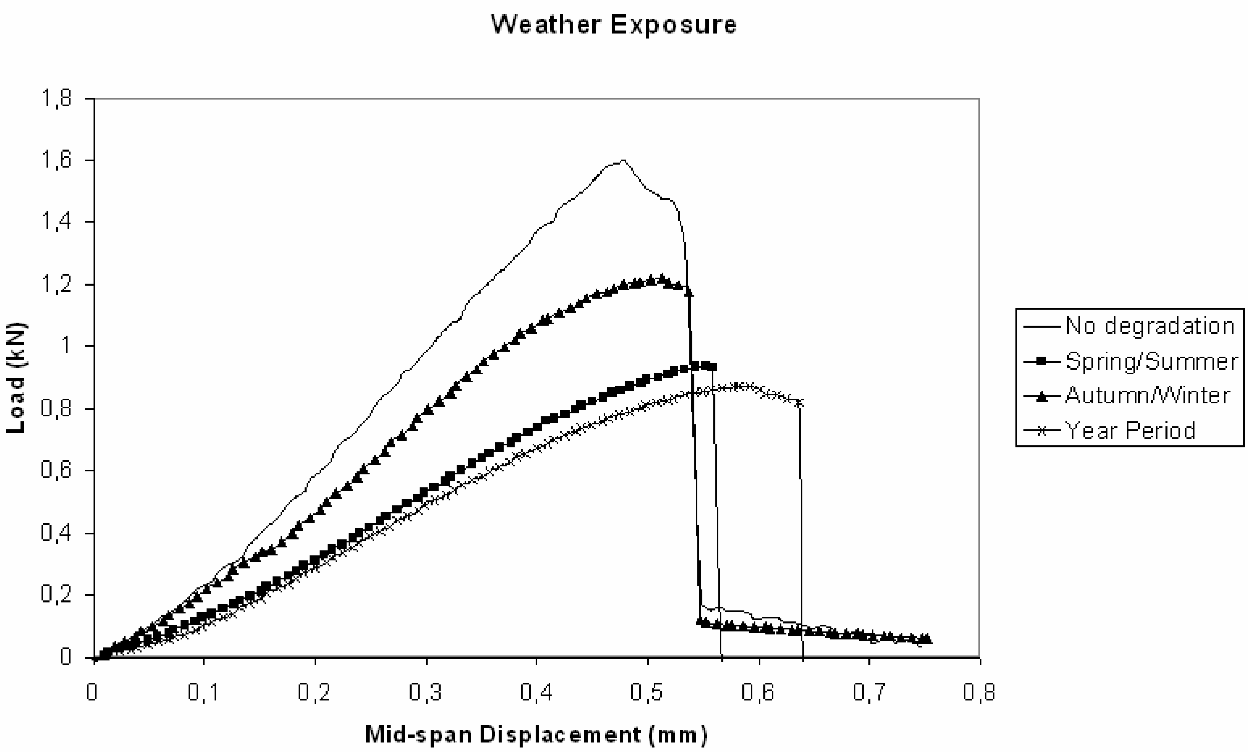

Figure 3.Three pt. bending test results of polyester polymer concrete

Figure 4 and 5 represents the tests results form glass fiber reinforced epoxy polymer concrete after exposed to certain period of degradation.

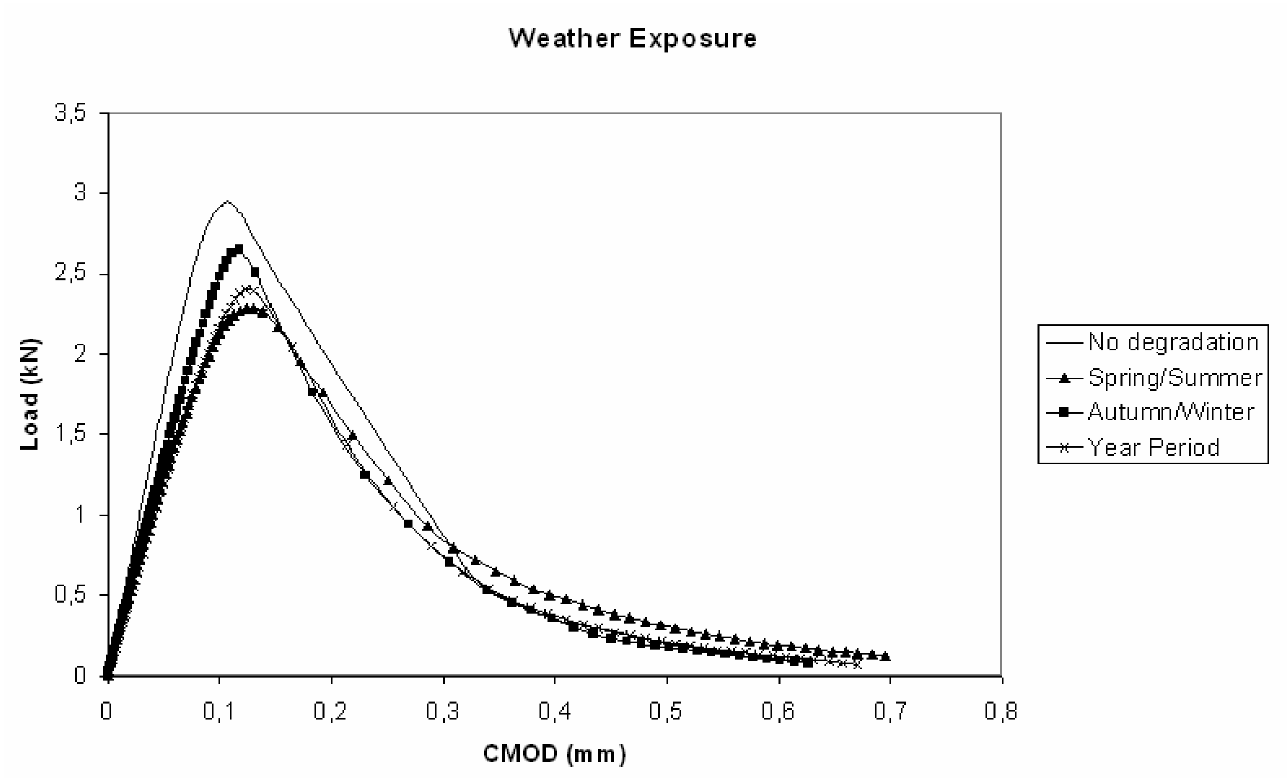

Figure 4.Load vs. CMOD test results of epoxy polymer concrete

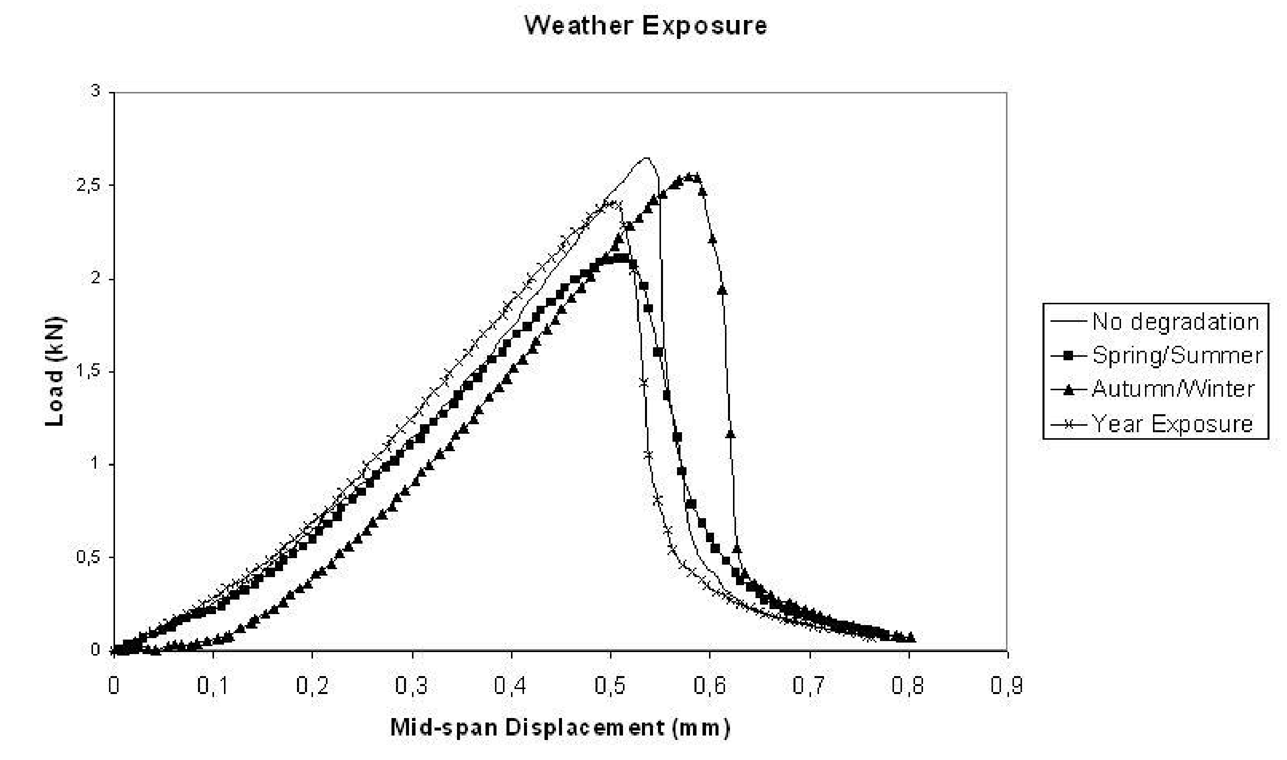

Figure 5.Three pt. bending test results of polyester polymer concrete

The carbon fiber reinforced polymer concrete reinforcement tests results are displayed in figures 5 and 6, where fig. 5 displays the results of Load vs. CMOD and fig. 6 represents the three point bending tests results.

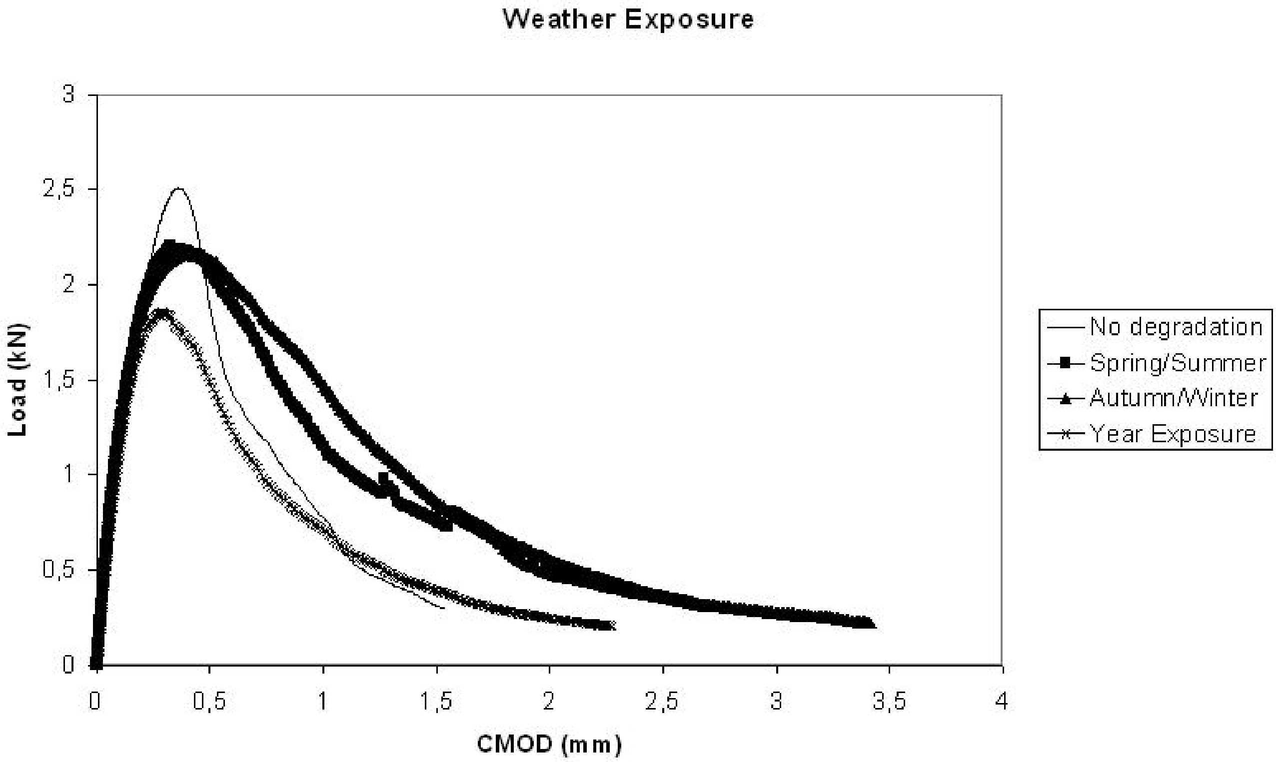

Figure 6.Load vs. CMOD test results of carbon fiber reinforced polymer concrete

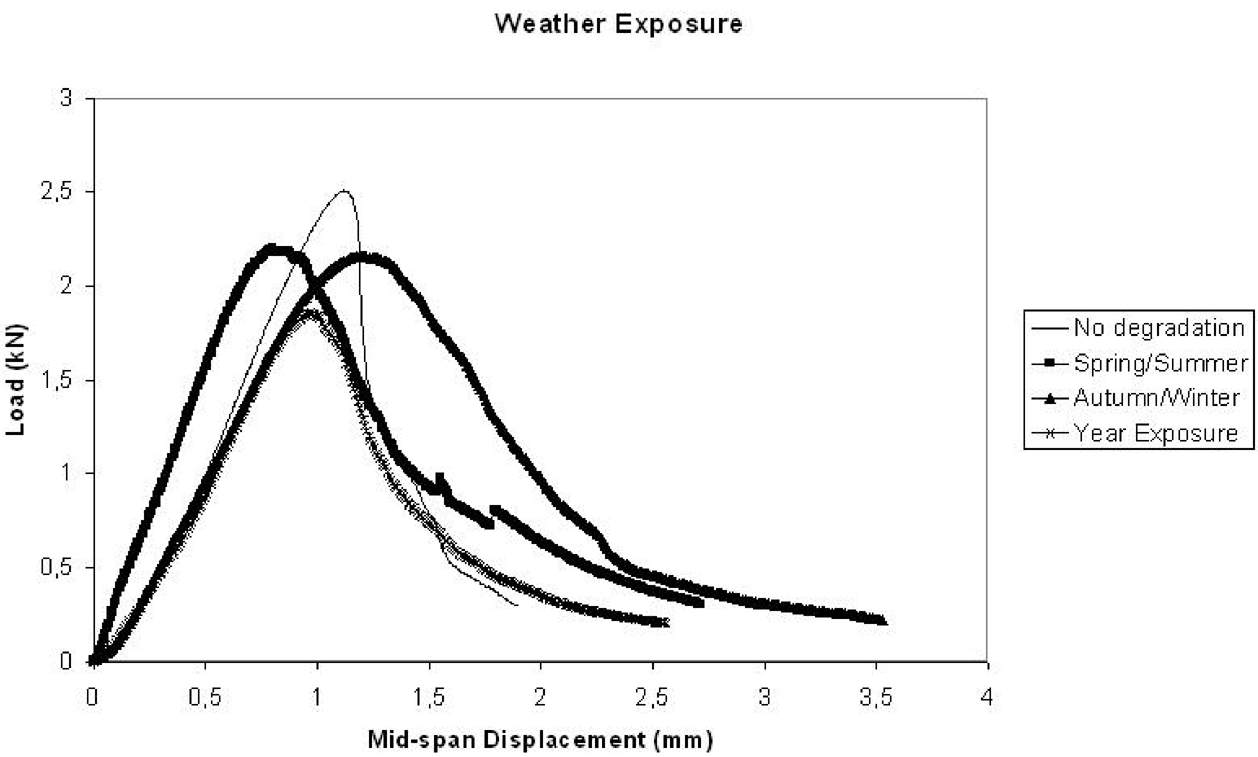

Figure 7.Three pt. bending test results of carbon fiber reinforced polymer concrete

Table 2 presents the results of polyester polymer concrete exposed under three different periods, Autumn/Winter, Spring/Summer and full year period.

Table 2 - Season Exposure Results for Polyester Polymer Concrete

Polyester Specimens	K_{ic} (MPa $\sqrt{m}$)	$CTOD_C$ (mm)	G_f (N/m)
Reference	1,112	0,039	8,492
	1,217	0,037	7,573
	1,122	0,046	5,986
Average	**1,150**	**0,040**	**7,350**
1 Year Weather Exposure	0,786	0,044	6,022
	0,812	0,046	5,896
	0,793	0,033	6,621
Average	**0,797**	**0,041**	**6,180**
Autumn/Winter Exposure	0,971		8,267
	1,063		8,715
	1,151		7,292
Average	**1,061**		**8,091**
Spring/Summer Exposure	0,791		6,781
	0,923		5,999
	0,790		5,992
Average	**0,834**		**6,254**

Comparing the results from table 2 it is clear that the period of the year containing hot weather degrades our material. The degradation of PC after 1 year exposed to weather condition in terms of K_{Ic} is 30,7% when compared to reference values. 27,5% decrease was observed after Spring/Summer period and 7,7% after Autumn/Winter period. When Fracture Energy, G_f, resuts were analysed a decrease of 15,9% and 14,9% after 1 year period and Spring/Summer, resctively were computed. After Autumn/Winter season 10,1% increase were calculated for G_f.

Table 3 displays the tests results of unreinforced epoxy polymer concrete and table 4 represents the carbon fiber reinforcement test results.

Table 3 - Season Exposure Results for Epoxy Polymer Concrete

Epoxy Specimens	K_{ic} (MPa $\sqrt{m}$)	$CTOD_C$ (mm)	G_f (N/m)
Reference	2,323	0,008	8,429
	2,344	0,023	7,012
	2,267	0,015	8,183
Average	**2,311**	**0,015**	**7,875**
1 Year Weather Exposure	2,005	0,019	8,107
	2,260	0,009	7,655
	2,138	0,013	7,901
Average	**2,134**	**0,014**	**7,888**
Autumn/Winter Exposure	2,376	0,005	8,695
	2,291	0,009	9,171
	2,254	0,007	8,904
Average	**2,307**	**0,007**	**8,923**
Spring/Summer Exposure	1,834	0,006	8,084
	1,953	0,014	8,373
	2,108	0,013	8,425
Average	**1,965**	**0,011**	**8,294**

As can be analysed from table 3 the stress intensity factor K_{Ic}, decrease in all different period of the year. After 1 year exposure a decrase of 7,65% is observed and a 14,97% decrease when exposed to Spring/Summer period. Almost no effect of degradation has been observed in terms of stress intensity factor after Autumn/Winter period. Values less than 1% was recorded for epoxy polymer concrete after the cold period of the year. An increase in fracture energy, G_f, was observed. After 1 year period epoxy PC has provide less than 1% in variation. When specific periods of the year were analysed the Autun/Winter display the best result, 13,3% and after Spring/Summer 5,3% increase, showing a good resistance of crack propagation form this formulation.

Table 4 - Season Exposure Results for Carbon Fiber Reinforced Polymer Concrete

Carbon Fiber Reinforced Specimens	K_{ic} (MPa $\sqrt{m}$)	$CTOD_C$ (mm)	G_f (N/m)
Reference	2,711	0,038	28,823
	2,586	0,059	28,857
	2,925	0,032	29,238
Average	**2,741**	**0,043**	**28,973**
1 Year Weather Exposure	1,443	0,059	21,687
	2,614	0,019	36,887
	2,192	0,034	34,551
Average	**2,083**	**0,037**	**31,042**
Autumn/Winter Exposure	1,954	0,007	37,464
	2,045	0,066	38,846
	2,141	0,015	28,181
Average	**2,046**	**0,029**	**34,830**
Spring/Summer Exposure	1,765	0,063	33,934
	1,916	0,030	27,373
	2,034	0,017	26,662
Average	**1,905**	**0,036**	**29,323**

When chopped carbon fiber were used to reinforce epoxy polymer concrete a decrease is also recorded in the results of stress intensity factor, K_{Ic}. 24, 25,3 and 30,5% decrease were observed after 1 year exposure, Autumn/Winter and Spring/Summer, respectively. Those results showed an evenly performance when carbon fiber were applied. Fracture Energy of carbon fiber reinforced epoxy polymer concrete displayed an increase of 7,1% after 1 year exposure, 20,2% after Autumn/Winter and 1% after Spring/Summer.

As can be analyzed from tables 2 to 4 after one year weather exposure the fracture toughness of Polymer Concrete are deteriorated when compared to reference values.

In all formulations the Fracture Energy increases its values, showing that after a period of time the material becomes tougher, less fragile to crack propagation.

During the outdoor exposure, visual inspection was performed. After exposure the specimens were measured and no change, cracks shrinkage or expansion, was observed in the tested Polymer Concrete.

Specimens containing Carbon fiber reinforcement presented a higher level of visual degradation since these fibers are UV radiations sensitive. Its color has change from black to a light brown showing after the tests that this is one of the reasons of Carbon Fiber Polymer Concrete has a lower comparative result to laboratory specimens.

4. Conclusions

Since polymer concrete reinforced and unreinforced is a material to be used in civil engineering conctruction, an approach to real situation of exposure has to be performed. Polymer concrete was exposed to real situation of weather and good results were obtained.

The marine environment, i.e. a place nearby the sea proves to be an excellent location to perform the required tests.

After 1 year exposure, polymer concrete deteriorates, but not as much as expected, proving that hottest is the environment involving Polymer Concrete higher the deterioration. Also Spring/Summer period highly degrades our material. This occurs due to the intensity of the sun and UV radiation. Since summer is the time of the year that average temperature is high compared to other season and polymer itself is heat sensitive, periods of exposure during this time was the hardest to support.

The Carbon fiber reinforcement proved to be an inappropriate reinforcement to use due to the loss of properties of carbon when exposed to weather conditions such as direct sunlight exposure, UV radiation. Carbon fiber these days are highly used as reinforcement to concrete structures, inside like steel or involving the concrete piles. These reinforcements are performed for inside structures with high rate of success but when carbon fiber are subjected directly specially to UV radiations the performance decrease drastically.

5. Acknowledgements

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