Strength and durability characteristics of polymer-modified carbon fiber concrete

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ABSTRACT: Carbon-fiber concrete (CFC) materials are gaining momentum due to the reduction of carbon fiber cost and also to the sensing performance of carbon fiber reinforced concrete based structures. For carbon fiber concrete electrical resistance increases with tensile stress and decreases upon compression. Therefore CFC can act as self-monitoring strain sensor. Nevertheless, fiber incorporation is responsible for a loss in concrete workability, and also for a slightly compression strength reduction related to an increase in air content. Although short-term mechanical properties of these materials are well documented, durability issues still need further investigations efforts. This paper reports some results on the strength and durability characteristics of several concrete mixtures made with different polymer and carbon fiber addition percentage. Results show that carbon fiber addition decreases strength and increases water penetration under pressure and also increases chloride diffusion, while the polymer addition reduces water penetration and concrete permeability.

1 INTRODUCTION

Ordinary Portland Cement (OPC) concrete structures deterioration is a very common phenomenon. The number of premature cases of OPC structures disintegration is overwhelming. Beyond the durability problems originated by imperfect concrete placement and curing operations, the real issue about OPC durability is related to the intrinsic properties of that material. It presents a higher permeability that allows water and other aggressive elements to enter, leading to carbonation and chloride ion attack resulting in corrosion problems (Glasser et al. 2008, Bentur & Mitchell 2008). That scenario is exacerbated by the fact that concrete structure inspections and conservation actions are expensive. Therefore investigations over smart structural materials are needed. Sensing is a fundamental aspect of a smart structure. According to Chung (2000) structural composites which are themselves sensors are multifunctional materials.

So far concrete structures assessment required the use of several devices that are attached to or embedded in the concrete elements. The procedure is expensive, and in the case of embedded devices may be responsible for property loss and may induce concrete degradation. Carbon-fiber cement-matrix composite materials are gaining momentum due to the reduction of carbon fiber cost and also to the sensing performance of carbon fiber reinforced concrete based structures.

The sensing ability of carbon fibers reinforced concrete is due to the electric conductivity provide by the carbon fibers. Cement paste is electrically conductive, with a DC resistivity at 28 of day curing around 5000 Ω.m at room temperature. The addition of short (5mm) carbon fibers, (0,5% by weight of cement) decreases the resistivity of carbon fiber concrete to just 200 Ω.m in the presence of silica fume which provides fiber dispersion (Chung, 2002). The resistivity of concrete reinforced carbon fibers is influenced by the volume and size of carbon fibers, and also by the saturation degree of the cement matrix (Wen & Chung 2001, Chen et al. 2004). CFC electrical resistance increases with tensile stress and decreases upon compression (piezo-resistivite property). The explanation for that behavior is related to the fact that tension leads to micro crack opening so it increases concrete resistivity. Therefore carbon fiber concrete can act as self-monitoring strain sensor (Gonzalez & Jalali 1999, Wen et Chung 2005).

CFC can also be used to assess its own damage because of electrical resistivity increase enabling structural health monitoring (Reza et al. 2003, Wen et Chung 2005). This ability can also be used to assess damage evolution (Cao et Chung, 2002). This property will enable real time monitoring, which is a crucial tool to avoid structural failure, like the one that took place in March of 2001 in Portugal (Entre-Rios bridge failure). Nevertheless, carbon fiber incorporation is responsible for a slightly compression strength reduction related to an increase in air content (Balaguru &Khajuria, 1996) and also for a loss in concrete workability. Although short-term mechanical properties of these materials are usually well documented, long-term durability issues about carbon fiber concrete still deserve further investigations. On the other hand it is well known that polymer modified concrete possesses a denser microstructure and increased durability (Shaker et al. 1997, Yang et al. 2008, Rossignolo 2009).

This paper reports some results on the strength and durability characteristics of several concrete mixtures made with different polymer and carbon fibber addition percentages.

2 EXPERIMENTAL PROGRAM

2.1 Materials, mix design and concrete mixing

The characteristics of the aggregates used to make the concrete mixtures are shown in Table 1.

Table 1: Characteristics of aggregates

Characteristics	Fine sand (0-1mm)	Sand (2-3 mm)	Coarse aggregates (5-15 mm)
Density (Kg/m^3)	2542	2538	2634
Water absorption by immersion (%)	1,2	0,9	1,4
Faury fineness modulus	1,644	3,478	4,873

An ordinary Portland cement (CEM II 42,5) was used. Styrene-butadiene polymer in a liquid form and pitch carbon fibber produced by Kureha Chemicals (reference KFC-100) were also used. The characteristics and properties of carbon fibers are shown in Table 3. Seven concrete mixes were designed using the Faury (1958) concrete mix design method. The concrete mixes are described in Table 4. A reference mixture (B_P0_F0) without carbon fibber or polymer addition and three mixtures with a polymer/cement mass ratio of 3,6% (B-P3,6) and three mixtures with a polymer/cement mass ratio of 5,4 % (B_P5,4). Two carbon fiber percentages by cement weight were used (0,5 and 1%). In order to avoid carbon fibber winding effect the mixing order goes as follow: first the water and the fibers are mixed during 30 s, only then Portland cement and the aggregates are placed in the mixer.

2.2 Compressive strength

The compressive strength was determinated following the ISO 4012. The specimens were conditioned at a temperature equal to 18 ± 1 ºC cured under water until they have reached the testing ages. Tests were performed on 100x100x100 mm^3 specimens. Compressive strength tests were carried out on 4 specimens for each curing age. Compressive strength for each mixture was obtained from an average of 3 cubic specimens determined at the age of 7,14, 28 and 56 days of curing.

2.3 Water penetration under pressure

The determination of water penetration under pressure was performed following the ISO 7031 test method. Water is applied under pressure on the surface of hardened concrete. The specimen is then split and the depth of penetration of waterfront is measured. Specimens were cured for 28 days under water at a temperature equal to 18 ± 1 ºC prior to testing and were tested in the saturated state.

2.4 Chloride diffusion test

This test method, first suggested by Luping (1996), consists of determining the depth of penetration of chloride ions through 50 mm thick slices of 110 mm nominal diameter cylinders. A potential difference of 30±0,2V is maintained across the specimen. One face is immersed in a sodium chloride and sodium hydroxide solution, the other in a sodium hydroxide solution. The duration of the test depends on the electric current passed through the concrete specimen. The test specimens are coated laterally and saturated in a sodium hydroxide solution under vacuum before being submitted to the described test method. The depth of penetration is measured by splitting the specimens, after exposure to migration of chloride ions. The surface of split concrete is sprayed with silver nitrate (NO_3Ag) and the penetration depth is measured by difference in the colour. The chloride diffusion coefficient can be calculated using the following equation:

$$D = (RTL/zFU).[X_d - (\alpha \sqrt{X_d})/t]$$

where:
$\alpha = 2\sqrt{(RTL/zFU)}.\ \mathrm{erf}^{-1}(1-2c_d/c_o)$
D: diffusion coefficient, m2/s; z: absolute valence of the ion involved, for chloride ion, z = 1; F: Faraday constant, F = 9.648 x 104 J/(V.mol); U: absolute potential difference, V; R: constant of ideal gases, R = 8.314 J/(K.mol); T: solution temperature, K; L: thickness of specimen, m; X_d: depth of penetration, m; t: duration of the test, seconds; erf^{-1}: inverse of error function; c_d: chloride ion concentration with which the colour changes; c_o: concentration of chloride ion in the sodium chloride solution.

3 RESULTS AND DISCUSSION

Compressive strength of polymer-modified carbon fiber concrete is shown in Fig. 1.

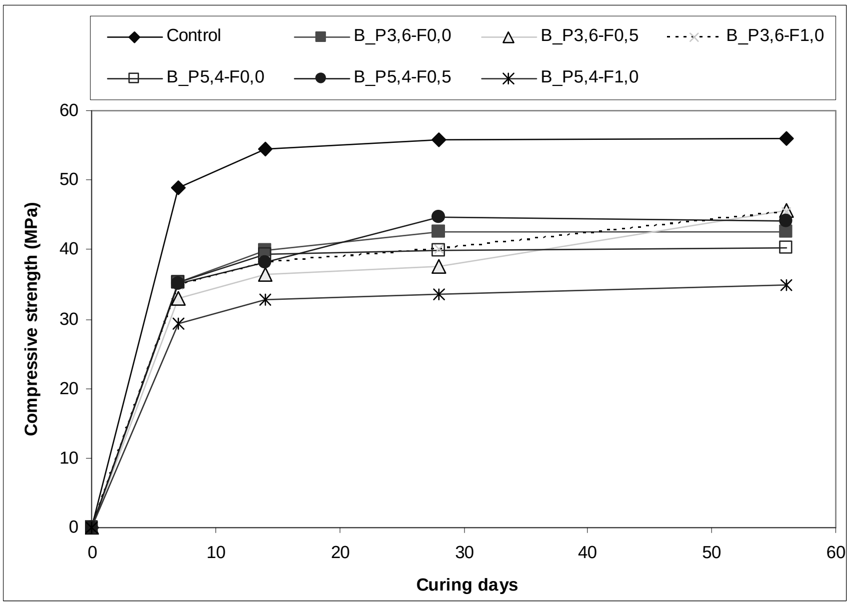

Figure 1: Compressive strength

Results show that polymer addition decreases compressive strength. Concrete with 3,6% of styrene-butadiene polymer lost 24% of its strength when compared to the compressive strength of control mixture. An increase in polymer percentage from 3,6% to 5,4% leads to a strength loss of 28%. The strength loss seems to stabilize after 28 days curing. Neelamegan et al., (2007) confirm that polymer addition leads to a compressive strength loss .

Chmielewska (2007) mentioned a compressive strength loss of 16% for a polymer/cement ratio of 5%. But the same author reported that when a polymer percentage of 20% was used compressive strength loss was only 2,7%. It seems that below a certain polymer percentage a major strength loss takes place but above that optimum percentage strength loss reach a minimum level. Further investigations about this subject should be carried out in the future. As for mixtures with carbon fiber incorporation, results show that using a fiber percentage of 1% with 5,4% polymer addition leads to a strength loss of 37,7%. That’s the largest compressive strength loss for all the mixtures studied. Using the same fiber percentage and 3,6 % polymer addition leads to a strength loss of 18,9%. Almost half of the strength loss of the 5,4% polymer addition.

When a fiber addition of 0,5% is used compressive strength is almost the same for 56 days curing for both polymer addition of 3,6% and 5,4%. For the same fiber percentage addition the compressive strength behavior for 28 days curing is rather different for the two percentages of styrene-butadiene polymer. Being that the 5,4% percentage has a compressive strength of 44,7MPa against 37,6MPa of the concrete mixture with a 3,6% polymer percentage. According to the integrated Beeldens-Ohama-Van Gemert model, polymer film formation begins only when a dry curing take place (Gemert et al., 2005), the water saturated conditions means that polymer particles remain in the pore solution. Since all the concrete mixtures were cured in water one can assume that polymer formation had not taken place by the time of testing. This may indicate that compressive strength behavior is not influence by polymer film formation. Further investigations over the influence of the curing type on carbon fiber concrete durability should be carried out. Water penetration under pressure is shown in Fig. 2.

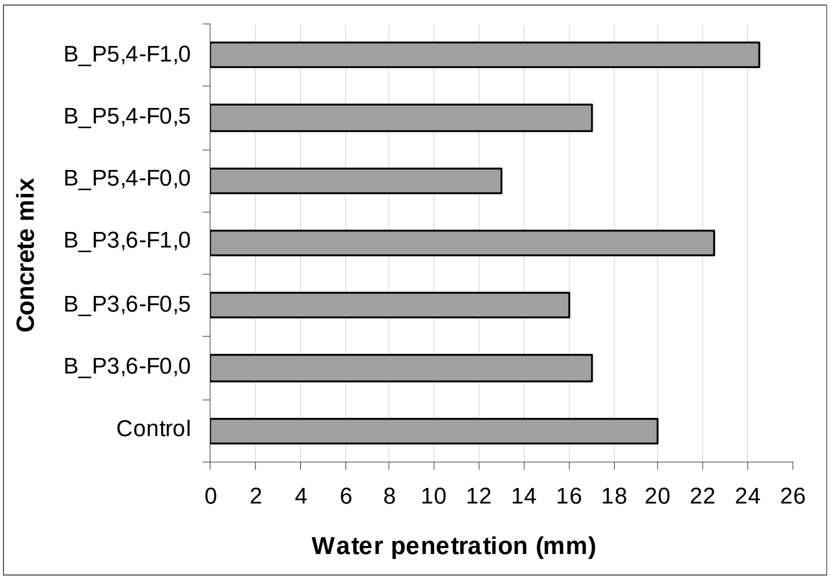

Figure 2: Water penetration

Only the concrete mixes with a carbon fibber content of 1% performed worst than the control mix. Which means that styrene-butadiene polymer addition leads to a denser microstructure and increases concrete durability for low carbon fibber additions. Nevertheless, for the mixtures with 1% of carbon fibers increasing polymer content from 3,6 to 5,4% increases water penetration by 9%. The concrete mix with the best performance (water penetration of 13mm) has a polymer percentage of 5,4% and no carbon fibbers (B_P5,4_F0,0). This mixture achieved a 35% reduction of water penetration compared to that of the control mixture. It seems that fibber addition leads to better water penetration results for low polymer addition percentages. Results of chloride ion diffusion are shown in Fig. 3.

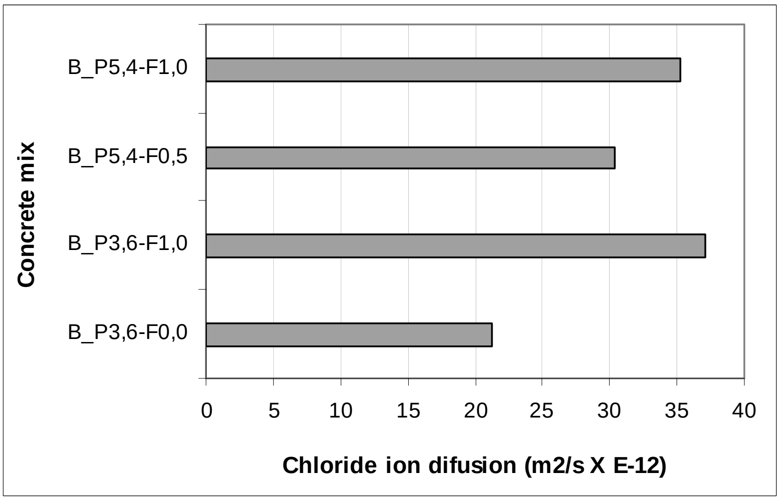

Figure 3: Chloride diffusion

Mixtures without carbon fibers and polymer addition have low chloride ion diffusion. Fibber incorporation has a negative impact over the durability of carbon fiber concrete. However, this effect is reduced when polymer addition increases from 3,6 to 5,4%. These results confirm results reported by Yang et al. (2009), indicating that styrene-butadiene addition increases ionic transport resistance.

4 CONCLUSIONS

The following conclusions can be drawn from this study:
Results show that carbon fibber addition decreases strength and increases water penetration under pressure and also increases chloride diffusion, while the polymer addition increases concrete durability. Further investigations for determining the optimum amount of polymer percentage that leads to a minimum strength loss of polymer-modified carbon fiber concrete (PMCFC) and the influence of the curing conditions on PMCFC durability are needed.

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