International Journal of Sustainable Engineering
2011, iFirst article, 1–5

Sustainable monitoring of concrete structures: strength and durability performance of polymer-modified self-sensing concrete[1]

F. Pacheco-Torgal[a]*, J. Gonzalez[b2] and S. Jalali[c3]

[a]*C-TAC Research Unit, University of Minho, 4800 Guimarães, Portugal;* [b]*Department of Civil Engineering, Polytechnic Institute of Guarda, Guarda, Portugal;* [c]*Department of Civil Engineering, University of Minho, 4800 Guimarães, Portugal*

(*Received 11 January 2011; final version received 18 June 2011*)

Concrete structures all over the world are reaching the end of their service life sooner than expected. This is due to the fact that ordinary Portland cement-based concrete deteriorates under environmental actions and also that structural inspections and conservation actions are expensive. Besides, as they consume energy and non-renewable resources, they have negative environmental impacts. Self-sensing concrete provides an alternative way of monitoring concrete-reinforced structures at a much lesser cost and with lesser environmental impact. Although the short-term mechanical properties of these materials are usually well documented, the long-term durability issues about carbon fibre concrete still deserve further investigations. This paper reports some investigation of the strength and durability characteristics of several concrete mixtures modified with different percentages of polymer and carbon fibre addition. The results show that the addition of carbon fibre decreases the strength and increases water penetration under pressure and also increases chloride diffusion, whereas polymer addition is responsible for a denser microstructure and higher concrete durability.

Keywords: self-sensing concrete; carbon fibre; polymer; chloride diffusion; water penetration

1. Introduction

Deterioration of ordinary Portland cement (OPC) concrete structures is a very common phenomenon. The number of premature cases of OPC structure disintegration is overwhelming. Mehta (1991) mentioned a case of pile foundation disintegration just after 12 years and also a similar case of a tunnel in Dubai, which was completed in 1975 and needed to be completely repaired in 1986. Gjorv (1994) mentioned a study of OPC bridges in Norway indicating that 25% of those built after 1970 presented corrosion problems. Another author mentioned that 40% of the 600,000 bridges in the USA were affected by corrosion problems and estimated the cost of the repairing operations to be $50 billion (Ferreira 2009). Beyond the durability problems that originate because of 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 (Bentur and Mitchell 2008, Glasser *et al.* 2008). This scenario is exacerbated by the fact that concrete structure inspections and conservation actions are expensive. Besides, if we increase the durability of concrete from 50 to 500 years, we would reduce the environmental impact by a factor of 10 (Mora 2007). Therefore, investigations on smart structural materials are needed. Sensing is a fundamental aspect of a smart structure. Structural composites, which are themselves sensors, are multifunctional materials (Chung 2000). Thus far, the assessment of concrete structures required the use of several devices that are attached to or embedded in concrete elements. The procedure is expensive and, in the case of embedded devices, may be responsible for property loss and might induce concrete degradation. The use of carbon fibre–cement matrix composite materials is gaining momentum due to the reduction of the cost of carbon fibre and also to the sensing performance of carbon fibre-reinforced, concrete-based structures. The sensing ability of carbon fibres-reinforced concrete is due to the electric conductivity provided by the carbon fibres. Cement paste is electrically conductive, with a DC resistivity at 28 days of curing around 5000 Ωm at room temperature. The addition of short (5 mm) carbon fibres (0.5% by weight of cement) decreases the resistivity of carbon fibre concrete to just 200 Ωm in the presence of silica fumes, which provide fibre dispersion (Chung 2002). The resistivity of concrete-reinforced carbon fibres is influenced by the volume and size of the carbon fibres, and also by the degree of saturation of the cement matrix (Wen and Chung 2001, Chen *et al.* 2004). As the presence of aggregates and admixtures, such as latex and silica fumes, also influences the properties of these types of concrete mixtures, further research is needed to better understand the combined effects of these factors on the resistivity of concrete-reinforced carbon fibres. Carbon fibre

*Corresponding author. Email: f.pachecotorgal@gmail.com

ISSN 1939-7038 print/ISSN 1939-7046 online

DOI: 10.1080/19397038.2011.599075
http://www.informaworld.com

concrete electrical resistance increases with traction stress and decreases on compression (piezo-resistive property). The explanation for this behaviour is related to the fact that tension leads to a microcrack opening so that it increases concrete resistivity. Therefore, carbon fibre concrete can act as a self-monitoring strain sensor (Gonzalez and Jalali 1999, Wen and Chung 2005). The applications for the piezo-resistive behaviour of carbon fibre concrete include weighing, traffic monitoring, building facility management, building security and structural vibration control. It also enables building facility management through the use of the occupancy of each room to control lighting, heating, cooling and ventilation. Carbon fibre concrete can also be used to assess its own damage because of electrical resistivity increase enabling structural health monitoring (Reza *et al.* 2003, Wen and Chung 2006). This ability can also be used to assess damage evolution (Cao and 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 2001 in Portugal (the Entre-Rios bridge failure). Nevertheless, carbon fibre incorporation is responsible for a slight reduction in compression strength related to an increase in air content (Balaguru and Khajuria 1996) and also for the loss of concrete workability. On the other hand, it is well known that polymer-modified concrete possesses a denser microstructure and increased durability (Yang *et al.* 2008, Rossignolo 2009, Pacheco-Torgal and Jalali 2009). Therefore, this paper reports some results on the strength and durability characteristics of several concrete mixtures made by the addition of different percentages of polymer and carbon fibre.

2. Experimental work

2.1 Materials, mix design and concrete mixing

The characteristics of the aggregates used to make the concrete mixtures are shown in Table 1. OPC (CEM II 42.5) was used (Table 2). Styrene–butadiene polymer in a liquid form (Sika Portugal, SA Vila Nova de Gaia Portugal) and pitch carbon fibres produced by Kureha Chemicals (reference KFC-100, Japan) were also used. The characteristics and properties of carbon fibre are shown in Table 3. Seven concrete mixes were designed using the Faury concrete mix design method (Faury 1958, Lourenço and Coutinho 1986). The concrete mixes described in Table 4 are reference mixture (B_P0-F0) without carbon fibres 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 fibre percentages by cement weight were used (0.5 and 1%). To avoid the winding effect of the carbon fibre, the mixing order is as follows: first the water and the fibres are mixed for 30 s, only then Portland cement and the aggregates are placed in the mixer.

Table 1. Characteristics of aggregates.

Characteristics	Fine sand (0–1 mm)	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

Table 2. Chemical, physical and mechanical properties of the OPC (CEM II 42.5).

Chemical composition (%)	
LOI[a]	4.95
SiO_2	18.50
Al_2O_3	5.00
Fe_2O_3	2.90
CaO (total)	62.80
MgO	1.40
Na_2O	0.30
NO_3	0.70
SO_3	2.75 (max. 3.5)
Cl	0.01
Physical characteristics	
IR[b] (%)	0.70
Blaine (cm^2/Kg)	3700
Setting time	
Initial	2 h 30 m
Final	3 h 49 m
Exp.	0 mm
Compressive strength (MPa)	
1 Day	19.0
2 Days	28.0
28 Days	52.0

[a] LOI - Lost on Ignition;
[b] IR - Insoluble Residue.

Table 3. Characteristics and properties of carbon fibres.

Diameter (μm)	18
Tensile strength (MPa)	590
Young modulus (GPa)	30
Elongation at break (%)	2.0
Resistivity (μΩm)	150
Density Rg/m^3	1.65
pH	6–8
Carbon content (%)	95

3. Experimental procedures

3.1 Compressive strength

Compressive strength was determined by following ISO 4012. The specimens were conditioned at a temperature of 18 ± 1°C and cured under water until they had reached the testing age. The tests were carried out on 100 × 100 × 100 mm^3 specimens. The compressive strength of each mixture was obtained from an average of three cubic

Table 4. Concrete mix proportions per cubic metre of concrete.

Components	Concrete mix						
	B_P0-F0 (control)	B_P3.6-F0.0	B_P3.6-F0.5	B_P3.6-F1.0	B_P5.4-F0.0	B_P5.4-F0.5	B_P5.4-F1.0
Cement II 42.5 (Kg)	343.0	343.0	343.0	343.0	343.0	343.0	343.0
Fine sand (0–1 mm) (Kg)	443.0	443.0	443.0	443.0	443.0	443.0	443.0
Sand (2–3 mm) (Kg)	443.0	443.0	443.0	443.0	443.0	443.0	443.0
Coarse aggregates (5–15 mm) (Kg)	886.0	886.0	886.0	886.0	886.0	886.0	886.0
Polymer (L)	0.0	34.3	34.3	34.3	51.45	51.45	51.45
Water (L)	171.0	171.0	171.0	171.0	171.0	171.0	171.0
W/C[a]	0.499	0.563	0.563	0.563	0.595	0.595	0.595
P/C[b]	0.0	0.036	0.036	0.036	0.054	0.054	0.054
Solid polymer (Kg)	0.0	12.3	12.3	12.3	18.5	18.5	18.5
Liquid (L)	0.0	22.0	22.0	22.0	32.9	32.9	32.9

[a] W/C - Water/Cement;
[b] P/C - Polymer/Cement.

specimens determined at the age of 7, 14, 28 and 56 days of curing.

3.2 Water penetration under pressure

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

3.3 Chloride diffusion test

This test method, first suggested by Luping (1996), consists in determining the depth of the penetration of chloride ions through 50 mm thick slices of 110 mm nominal diameter cylinders. A potential difference of 30 ± 0.2 V is maintained across the specimen. One face is immersed in solution containing sodium chloride and sodium hydroxide; the other is immersed 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 hydroxide solution under vacuum before being subjected to the test that has been described. The depth of penetration is measured by splitting the specimens after exposure to the migration of the chloride ions. The surface of split concrete is sprayed with silver nitrate ($AgNO_3$) and the penetration depth is measured by difference in the colour.

4. Results and discussion

4.1 Compressive strength

The compressive strength is shown in Figure 1. The results show that the addition of the polymer decreases the compressive strength. The strength concrete with 3.6% of the styrene–butadiene polymer of 24% reduced by when compared with the compressive strength of the control mixture. An increase in the percentage from 3.6% to 5.4% leads to a strength loss of 28%. The strength loss seems to be stabilized after 28 days curing. Other authors confirm that the addition of a polymer leads to a loss of compressive strength (Neelamegan *et al.* 2007). 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, the compressive strength loss was only 2.7%. It seems that below a certain polymer percentage a major strength loss takes place, but above that percentage the optimum strength loss reaches a minimum level. Further investigations about this subject should be carried out in the future. As for mixtures with carbon fibre incorporation, the results show that using a fibre percentage of 1% with 5.4% polymer addition leads to a strength loss of 37.7%. This is the worst compressive strength loss for all the mixtures studied. Using the same fibre percentage and 3.6% polymer addition leads to a strength loss of 18.9%. This is almost half of the strength loss of the 5.4% polymer addition. When a fibre addition of 0.5% is used, compressive strength is almost the same for 56 days curing for polymer addition of both 3.6% and 5.4%. For the same fibre percentage addition, the compressive strength behaviour for 28 days curing is rather different for the two percentages of the styrene–butadiene polymer. The 5.4% polymer percentage has a compressive strength of 44.7 MPa against 37.6 MPa 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 dry curing takes place (van Gemert *et al*. 2005), i.e. the water-saturated conditions mean that the polymer particles remain in the pore solution. As all the concrete mixtures were cured in water, one can assume that polymer formation had not taken place during

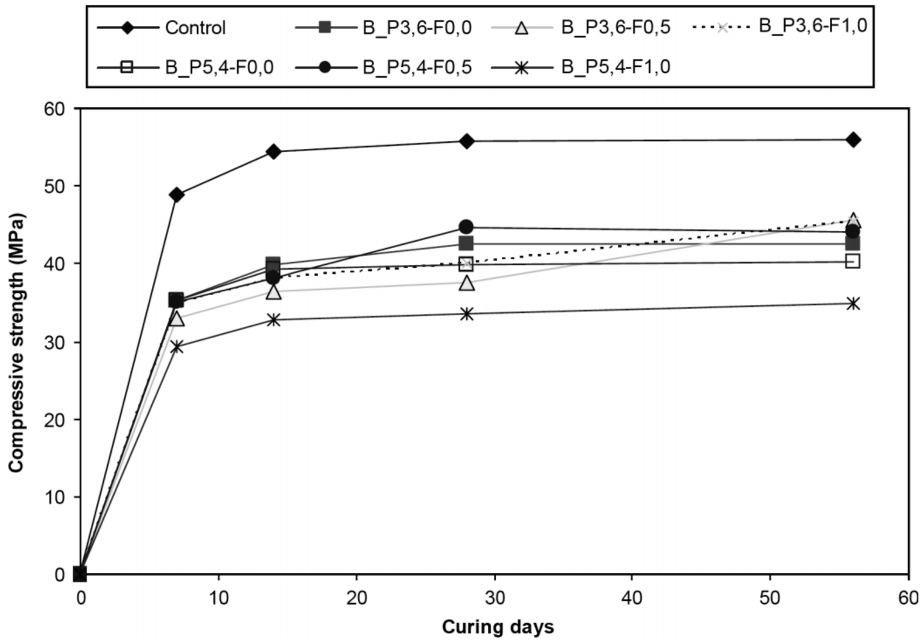

Figure 1. Compressive strength.

the time of testing. This means that compressive strength behaviour is not due to polymer film formation. Investigations of the influence of the curing type on concrete durability should be carried out in the future.

4.2 Water penetration under pressure

Water penetration under pressure is shown in Figure 2. The concrete mix having the best performance (water penetration of 13 mm) has a polymer percentage of 5.4% and no carbon fibres (B_P5.4-F0.0). This mixture achieved a 35% reduction in water penetration compared with the control mixture. Only the concrete mixes with a carbon fibre content of 1% performed worst than the control mix. For these mixtures, the water penetration is low with low polymer addition. For the mixtures with 1% of carbon fibres, increasing the polymer content from 3.6% to 5.4% increases water penetration by 9%. This means that the addition of the styrene–butadiene polymer leads to a denser microstructure and increases concrete durability for low carbon fibre addition and low polymer addition.

4.3 Chloride diffusion

Chloride ion diffusion is shown in Figure 3. Mixtures without carbon fibres and polymer addition have low chloride ion diffusion. Fibre incorporation has a negative effect on the durability of concrete. This effect is reduced when addition of polymer increases from 3.6 to 5.4% and the addition of styrene–butadiene. These results confirm the results of other authors (Yang *et al.* 2008). As the penetration of water, chloride and other aggressive ions into the concrete is the most important factor in the physical and chemical process of concrete deterioration (Pacheco-Torgal and Castro-Gomes 2006), this means

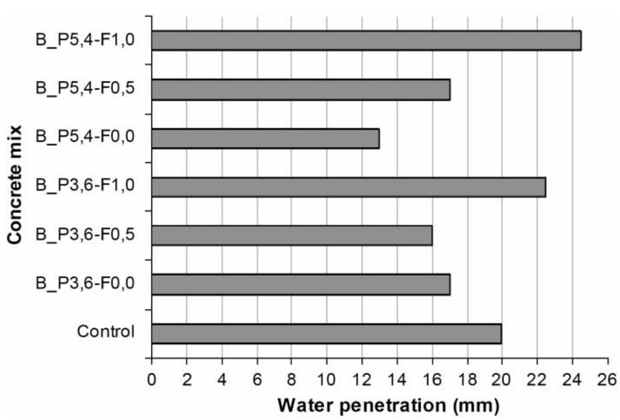

Figure 2. Water penetration of concrete mixtures.

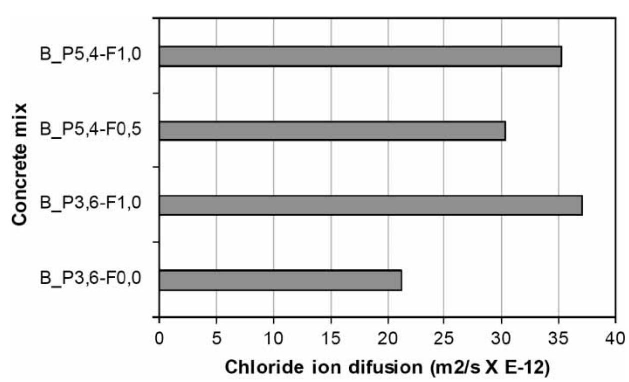

Figure 3. Chloride ion diffusion.

that polymer addition increases the durability of the self-sensing concrete.

5. Conclusions

This paper presents increases resistance to ionic transport the properties and the durability of self-sensing concrete. The following conclusions can be drawn from this study.

Polymer addition decreases compressive strength and also that the strength loss seems to stabilize after curing for 28 days.

The water absorption results show that polymer addition leads to a denser microstructure for low carbon fibre additions and low polymer addition.

Carbon fibre addition increases chloride diffusion, whereas polymer addition compensates this effect.

Further investigations about the polymer percentage, which leads to minimum strength loss, should be carried out in the future. Investigations on the influence of the curing type on durability are also needed.

Notes

1. The study described has not been submitted elsewhere for publication, in whole or in part, and all the authors listed have approved the manuscript that is enclosed.
2. Email: gonzalez@ipg.pt
3. Email: said@civil.uminho.pt

References

Balaguru, P., and Khajuria, A., 1996. Properties of polymeric fiber-reinforced concrete. *Journal of the Transportation Research Board*, 1532, 27–35.

Bentur, A., and Mitchell, D., 2008. Material performance lessons. *Cement and Concrete Research*, 38, 259–272.

Cao, J., and Chung, D., 2002. Damage evolution during freeze-thaw cycling of cement mortar studied by electric resistivity measurement. *Cement and Concrete Research*, 32, 1657–1661.

Chen, B., Wu, K., and Yao, W., 2004. Conductivity of carbon fiber reinforced cement-based composites. *Cement and Concrete Composites*, 26, 291–297.

Chmielewska, B., 2007. Adhesion strength and other mechanical properties of SBR modified concrete. *In*: K.-S. Yeon, ed. *Twelfth International Congress on Polymers in Concrete*, 157–166, Chuncheon, Korea.

Chung, D., 2000. Cement-matrix composites for smart structures. *Smart Materials and Structures*, 9, 389–401.

Chung, D., 2002. Electric conduction behavior of cement-matrix composites. *Journal of Materials Engineering and Performance*, 11, 194–204.

Faury, J., 1958. *Le Beton. Influence de ses constituents inerts. Regles á adopter pour sa meilheure composition. Sa confection et son transport sur les chantier*. 3rd ed. Paris: Dunod.

Ferreira, R., 2009. *Service-life design of concrete structures in marine environments: a probabilistic based approach*. VDM Verlag Dr. Muller Aktiengesellschaft & Co. KG, Saarbrücken, Germany.

Gjorv, O.E., 1994. Steel corrosion in concrete structures exposed to Norwegian marine environment. *ACI Concrete International*, 16, 35–39.

Glasser, F., Marchand, J., and Samson, E., 2008. Durability of concrete. Degradation phenomena involving detrimental chemical reactions. *Cement and Concrete Research*, 38, 226–246.

Gonzalez, J., and Jalali, S., 1999. Smart structures using carbon fibre reinforced concrete (CFRC). *In*: J. Holnicki-Szulc and J. Rodellar, eds. *Smart structures: requirements and potential applications in mechanical and civil engineering*. Netherlands: Kluwer Academic Publishers, 89–95.

Lourenço, J., and Coutinho, J., 1986. *Automatic calculations for concrete mix selection. Faury and Bolomey methods*. Technical documents, Coimbra.

Luping, T., 1996. *Chloride transport in concrete – measurement and prediction*, PhD Thesis. Chalmers University of Technology, Gotenborg, Sweden.

Mehta, P.K., 1991. *Concrete in marine environment*. New York: Elsevier Science Publishers.

Mora, E., 2007. Life cycle, sustainability and the transcendent quality of building materials. *Building and Environment*, 42, 1329–1334.

Neelamegan, M., Dattatreya, J., and Harish, K., 2007. Effect of latex and fibber addition on mechanical and durability. *In*: K.-S. Yeon, ed. *Properties of sintered fly ash light weight aggregate concrete mixtures. Twelfth International Congress on Polymers in Concrete*, 113–121, Chuncheon, Korea.

Pacheco-Torgal, F., and Castro-Gomes, J., 2006. Influence of physical and geometrical properties of granite and limestone aggregates on the durability of a C20/25 strength class concrete. *Construction and Building Materials*, 20, 1079–1088.

Pacheco-Torgal, F., and Jalali, S., 2009. Sulphuric acid resistance of plain, polymer modified, and fly ash cement concretes. *Construction and Building Materials*, 23, 3485–3491.

Reza, F., *et al.*, 2003. Resistant changes during compression of carbon fiber cement composites. *Journal of Materials in Civil Engineering*, 15, 476–483.

Rossignolo, J., 2009. Interfacial interactions in concretes with silica fume and SBR latex. *Construction and Building Materials*, 23, 817–821.

Van Gemert, D., *et al.*, 2005. Cement concrete and concrete-polymer composites: Two merging worlds. A report from 11th ICPIC Congress in Berlin, 2004. *Cement and Concrete Composites*, 27, 926–933.

Wen, S., and Chung, D., 2001. Effect of carbon fiber grade on electrical behavior of carbon-fiber reinforced cement. *Carbon*, 39, 369–373.

Wen, S., and Chung, D., 2005. Strain-sensing characteristics of carbon-fiber reinforced cement. *ACI Materials Journal*, 39, 244–248.

Wen, S., and Chung, D., 2006. Self sensing of flexural damage and strain in carbon fiber reinforced cement and effect of embedded steel reinforcing bars. *Carbon*, 44, 369–373.

Yang, Z., *et al.*, 2008. Effect of styrene-butadiene rubber latex on the chloride permeability and microstructure of Portland cement mortar. *Construction and Building Materials*, 23, 2283–2290.