DURABILITY OF SCC REINFORCED WITH POLYMERIC FIBERS: INTERACTION WITH ENVIROMENT AND BEHAVIOUR AGAINST HIGH TEMPERATURES

M. C. ALONSO[1], M. SÁNCHEZ [1], C. RODRIGUEZ [1], B. BARRAGÁN [2]
1 "Eduardo Torroja" Institute of Construction Structures (IETcc) – CSIC C/ Serrano Galvache 4, 28033 Madrid
2 School of Civil Engineering, Universitat Politécnica Catalunya, Spain
Email address: mcalonso@ietcc.csic.es

ABSTRACT

In last years there is a great interest in developing materials with enhanced performance in construction, as for instance the Self Compacting Concrete (SCC). The addition of fibers to concrete considerably improves its structural properties such as static flexural strength, impact strength, tensile strength, ductility and flexural toughness. However, it is necessary assuring that this enhancement on the mechanical properties is not accompanied by a detrimental effect on the durability properties.

Self-Compacting Concrete reinforced with polymeric fibers (Polypropylene fibers, PPF) has been considered in present work. First, the mechanical and microstructural characterization has been determined. Further the influence of the presence of the PPF in the SCC durability properties of the material has been studied at laboratory, using different indicators.

Finally, the response of both types of material with respect to resistance at high temperature was evaluated through microestructural analyses and mechanical properties changes suffered for the material.

KEYWORDS

Self-compacting concrete; polymeric fibers; durability; high temperature

INTRODUCTION

In last decades the development of concretes with enhanced mechanical performance and durability has become an aspect of great concern, to fulfil new challenges and long service lives of constructions. The addition of fibers to concrete has contributed to the improvement of mechanical properties of concrete. On the other hand, many efforts have been made in building up concrete with improved workability by application of self-compacting concrete (SCC) technology. Then, a SCC reinforced with polypropylene fibers (SCC+PPF) results a very interesting technologic material with many advantages associated to durability and mechanical properties [Persson, 2003, Persson, 2001]. The workability properties of self-consolidating concrete (SCC) leads to an important potential for the application of this material, however, even though multiple advantages are associated to the use of SCC, its real market in situ application is much lower than what it would be expected [Assié, S, 2007]. In some way, this limitation is a consequence of the lack of knowledge related to durability and degradation mechanisms with time [Domone, 2006, Barragan et al., 2005, Sanchez et al., 2008].

The addition of fibers to reinforced self compacting concrete (SCC) improves compressive strength or strain, the impact resistance, reduces the cracking and spalling risk at high temperatures. Although the behaviour of SCC against fire is still under debate, the addition of polymeric fibers to this material should have a synergic effect, reason why polypropylene fibers (PPF) are well considered as an effective method to improve the response of concrete to high temperatures.[Alonso et al., 2008,Ye, et al., 2007, Janson and Boström, 2007, Suhaendi and Horiguchi, 2007, Khoury, 2007].

Present work focuses on the evaluation of the durability and mechanical properties of self compacting concrete (SCC) with addition of polymeric fibers (PPF) in order to improve the mechanical properties of concrete. Also, the effect of fibers on the behaviour of SCC when exposed to high temperatures has been analysed.

EXPERIMENTAL PROGRAM

Materials

Self-Compacting Concrete beams of 40x10x10cm and cylinders of 7.5x10 cm were manufactured with and without addition of 3 kg/m^3 of PPF (54 mm of length and 0.05 mm of diameter), adding 426 kg/m^3 of Ordinary Portland Cement (OPC) (CEM I 52.5 R), 963 kg/m^3 of crushed limestone aggregates with a grading of 0-5 mm for the sand and 5/12 mm for the gravel, 647 kg/m^3 of limestone filler, obtained from the crushing of aggregates, and 6.40 kg/m^3 of polycarboxylate-based superplasticizer. A water/cement ratio (w/c) of 0.45 was added for the preparation of the mix.

The casting specimens were stored in a curing chamber at 20±1ºC and 98±2%RH until testing. The tests were carried out with the cast cylinders and cores of 7.5x10 cm taken from the beams.

Mechanical characterization

Compression and indirect strain tests were performed for mechanical characterization of the concretes after curing. Cores and cylinders were used for characterization to confirm the homogeneity of the material.

Microstructural characterization

SEM: observation using Back-Scattering microscopy mode were carried out to study the interface concrete-PPF.

The total porosity and pore size distribution were carried out with mercury porosity in concrete samples from both type of SCC.

Characterization of the influence of PPF in durability performance of SCC

The durability of plain and fiber-reinforced SCC has been evaluated by obtaining different durability indicators defined from laboratory methods, to determine the resistance to the transport of fluids. The samples were obtained from cast cylinders:

- *Capillary absorption coefficient*: The test method defined in standard PrUNE 83982 for "determination of water absorption by capillarity of concrete wetted by Fagerlund Method" has been used. The Committee Euro International du Beton [CEB, 1998] proposes a classification of concrete in three different classes depending on the capillary absorption coefficient .
- *Chloride diffusion coefficients*: the effective (Deff) and the apparent (Dapp) chloride diffusion coefficients have been obtained both from natural diffusion and accelerated (migration) tests [Castellote et al., 2001]. These tests have been widely considered for characterization of conventional vibrated concretes, but less experience exists in SCC application.
- *Carbonation resistance*: Accelerated tests have been used to evaluate the carbonation resistance of the concretes. The concretes were put in a carbonation chambers at 20 ± 2 ºC and 60% RH, flowing a gas containing 1% CO2 for 56 days and 100% CO2 for 64 days. The carbonation profile was measured by the phenoftaleine colorimetric test, (UNE 112-011-94).

Determination of the influence of PPF in SCC at high temperatures*:*

SCC cores taken from the beams with and without polymeric fibers were exposed to elevated temperatures in a furnace at a heating rate of 2ºC/min until the temperature selected and maintained for two hours. Then, the cooling of the samples was inside the furnace, following a cooling rate <1ºC/min. Changes in microstructure and mechanical properties of heated concrete were measured after exposure of the cores at different temperatures (in residual state).

The temperatures considered were: 20ºC (as initial), 200, 300, 500 and 700ºC: After heating, each specimen was introduced in a plastic bag and then in a desiccator in order to avoid any contact with the atmosphere before testing.

- *Pore structures:* Mercury porosimetry measurements were obtained for the concretes exposed to different temperatures
- *TG/DTA:* A sample of fiber was heated to 5ºC/min, and the transformations taking place were identified.
- *Residual mechanical properties*: Compressive strength and indirect strain were performed.

RESULTS

Influence of PPF in micro and macrostructural properties of the SCC

Interfacial transition zone PPF-Concrete

The study of the interface PPF-Concrete was made by observation with SEM, as show in Figure 1. The interface fiber-cement paste matrix shows that there is not a chemical interaction between both materials, but a good physical adhesion between the fiber and the surrounding paste is observed, similarly to that of the interface paste/aggregate.

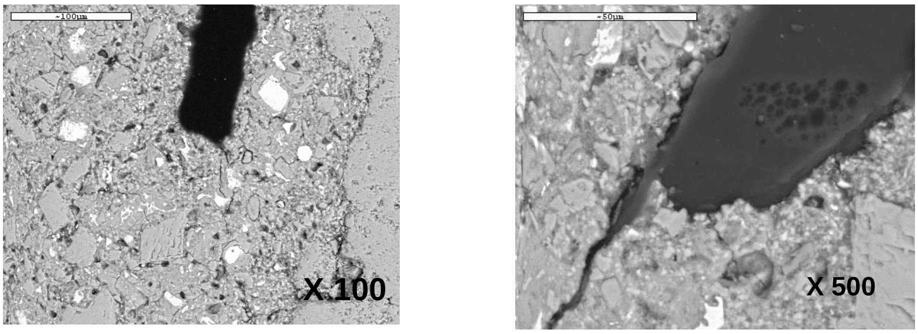

Figure 11 – Interface PPF SCC concrete matrix

Mechanical properties

The compressive strength values obtained for both type of concretes are around 57.4±0.3 MPa for SCC without fibers and 57.4±0.8 MPa for SCC with fibers; (figure 2-left). No differences in compressive strength due to the presence of the fibers were observed. Besides, similar response for concrete samples, either using cores from the beams or cast cylinders are obtained, witch confirms the homogeneity of the material. However the indirect strain test (figure 2-right) gives higher values with the presence of PPF (5.3 MPa for plain SCC with respect to 6.9 MPa with PPF, aprox. 30% higher). This improvement in tensile performance demonstrates the consequence of the good joint of the PPF with the concrete, as seen with SEM (figure 1).

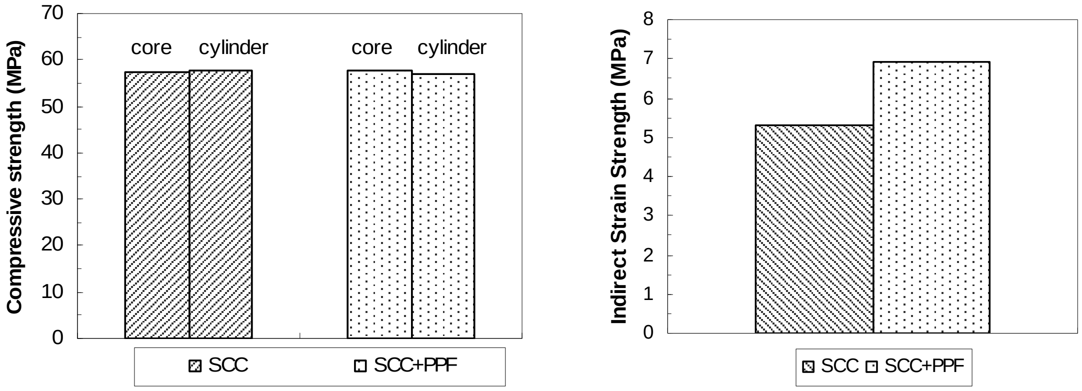

Figure 2 – Compressive strength (left) and indirect strain strength (right)

Porosity

The presence of the polymeric fiber (PPF) in the SCC, does not imply an increase in total porosity due to the disturbance introduced by the presence of the fiber in the matrix of the concrete (Figure 3-left), being 9.63 ± 0.74% for SCC without fibers and 8.76 ± 0.61% with fibers, the differences considering an admissible error of 10% for the technique are no relevant, and can be said that the fiber has no create new connected spaces, which is also noticed in the pore size distribution (figure 3-right).

Differential intrusion versus pore diameter is drawn in figure 3-right. Most of the pores are among 0.01-0.1μm for both concretes, although in lower amount in SCC+PPF indicating that the presence of fibers does not affect the pores connectivity of the SCC. Pore size distribution was similar for each type of concrete using different samples, either from cores and cast cylinders which confirms again the homogeneity of the material.

These results also contribute to demonstrate the adequate distribution of the fibers within the mass of fluid concrete to fulfil the self-compacting requirements.

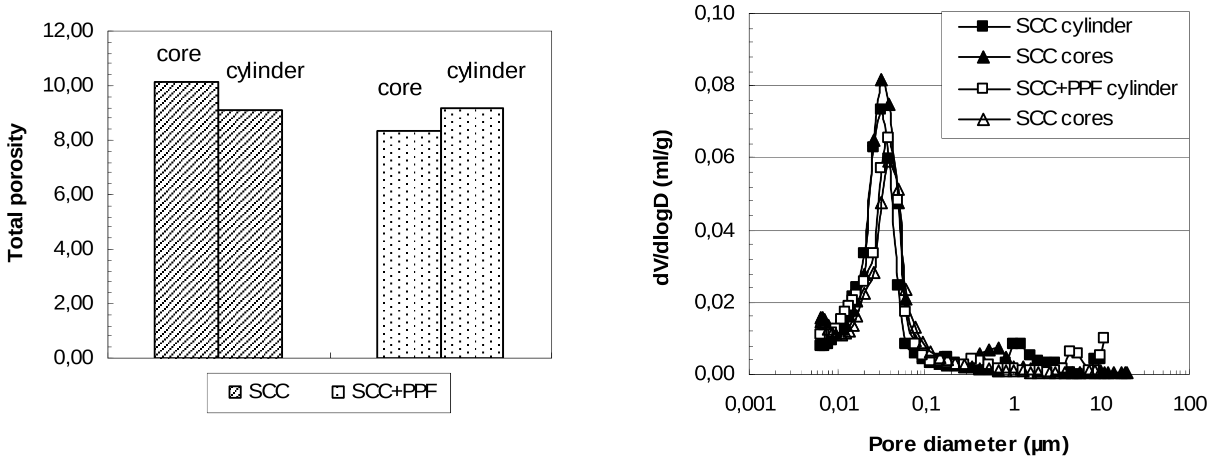

Figure 3 – Total porosity and pore size distribution of SCC with and without fibers

Influence of the Polypropylene fibers in the transport of aggressive in SCC

Transport of water: Capillary suction:

In figure 4 the results of capillary suction tests are represented, in the form of weight increment in the concrete versus time due to the entrance of water. The same increment for concrete with and without fiber is measured. The values of porosity accessible to water and capillary absorption coefficient are given in table 1, where no differences are obtained between SCC with and without fibers.

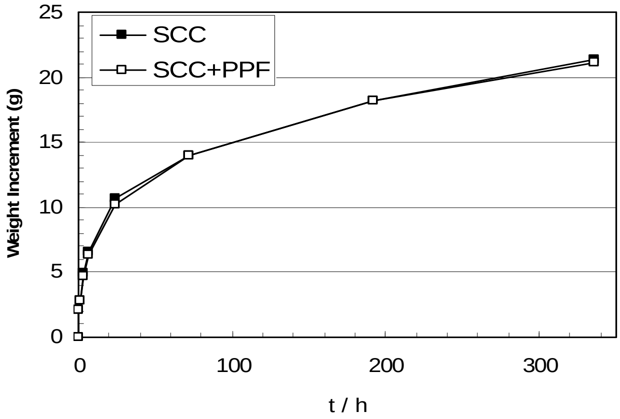

Figure 4 Weight increment versus time

Table 1

	SCC	SCC+PPF
Porosity accessible to water	8,22	8,26
Capillary absorption coefficient / mm·min$^{--0.5}$	0.07	0.06

The water porosity measured by this method is in the same order to that determined using mercury porosimetry. The low values of capillary absorption coefficient in both concretes allow classifying as good quality concretes with respect transport properties [CEB, 1998]. Besides, the similar values of capillary absorption coefficient confirm again that the introduction of the PPF does not disturb the connectivity of pore structure.

Transport of Chlorides

The data obtained in the laboratory, for test in stationary and non-stationary conditions, are shown in Figure 5. The effective diffusion coefficients, D_{eff} , (stationary test) are given in figure 5-left, for accelerated and natural transport, calculated considering the first Fick law. The apparent diffusion coefficient, D_{app}, (non-starionary conditions), obtained from accelerated tests, is included in figure 5-rigth. Both type of diffusion coefficients, D_{eff} and D_{app}, independent of the presence of fibers, have values indicating good quality of both type of concretes (lesser than 5·10-8) [Baroghel-Bouny, 2006]. Thus, no relevant influence associated to the presence of the fiber can be deduced, even when the transport of Cl- takes place by migration, accelerated by an electrical field.

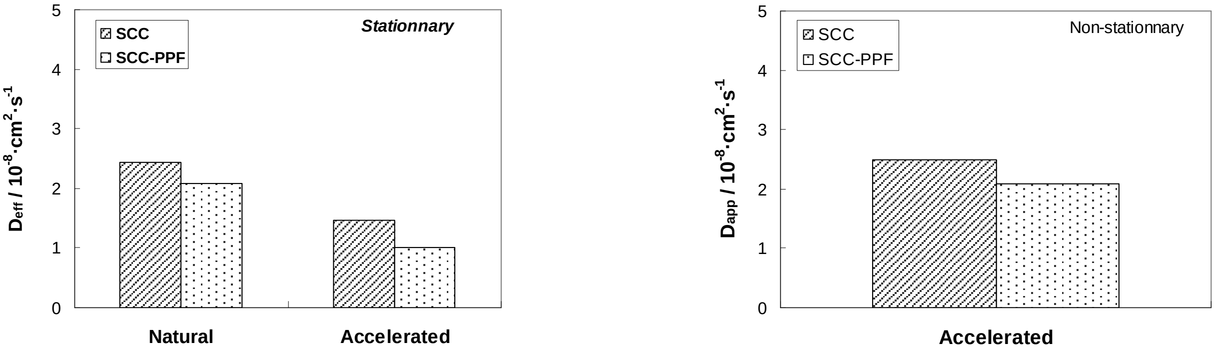

Figure 5 D_{eff} (left), D_{app}(right) for SCC and SCC+PPF

Accelerated carbonation

Figure 6 shows the carbonation depths for both SCC with and without fibers. These values were obtained by measuring the depth of the carbonation front at different points of the samples, calculating the average value and the standard deviation. The average values for both SCC show no significant differences and have similar response taking into account the standard deviation of both tests.

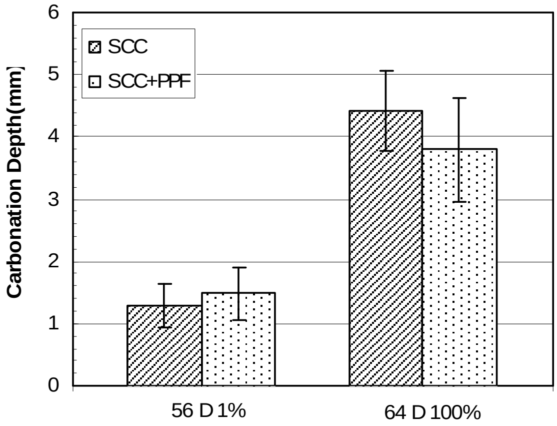

Figure 6. Carbonation depth in SSC and SSC+ PPF at 1% and 100% CO_2

Influence of the Polypropylene fibers in the resistance of concrete under fire

Stability of PPF at high temperatures

The polypropylene fiber used melted at 133ºC and turn into vapour al 444ºC, as determined from the thermogravimetric (TG) and differential thermal analyses (DTA), figure 7. This ability of the PPF to melt at relatively low temperatures, affects the transport process of vapour release from the dehydration of the concrete. This fact could be observed in samples heated at 200ºC, where the PPF are melted and absorbed into the matrix of cement paste. However, at temperatures above that of combustion, the fiber decomposes leaving small spaces in the mass of the concrete.

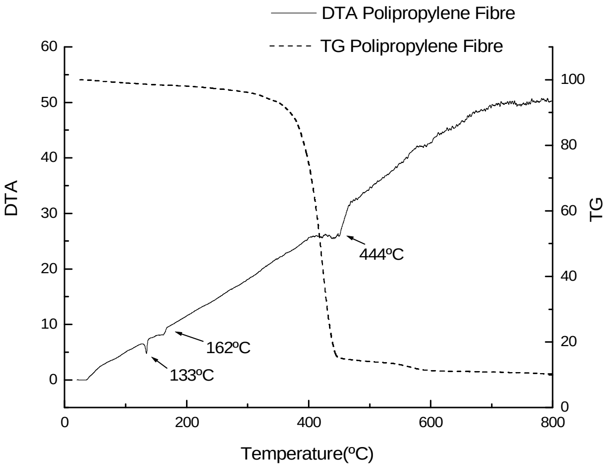

Figure 7. Differential thermal analysis (DTA) and thermogravimetric analysis (TG) of polypropylene fiber

Influence of PPF in the evolution of porosity of SCC at high temperatures

The pore structure of the concretes undergo some changes due to heat action, associated with the dehydration of the cement paste components and thermal stresses of the paste, aggregates, filler and PPF, creating open pores, microcracks and empty spaces [Alonso, 2007].

The presence of the PPF, which melt at 133ºC but its combustion is from 444ºC, does not increase the pore structure at low temperatures. The changes appear more clearly in capillary pores, decreasing those of smallest size, from less than 0.01 to 0.1μm, being the pore structure changes more evident at 500ºC.

Small pores, <0.01µm, decrease more intensively in SCC+PPF than for the plain SCC but this does not represent a higher increase in higher capillary pore size, the reason is that the fibers melt and close small pores. The efficiency of the PPF is noticed latter when the PPF evaporates, which confirms that previously found by [Alonso et al., 2005, Kalifa et al., 2002]. This could be also the reason why recent results of some authors did not found correlation between PPF content and pore pressure decrease and also spalling is not always guarantee. Probably a critical balance between pore size increase due to dehydration and the pore sealing due to the fiber melt is needed.

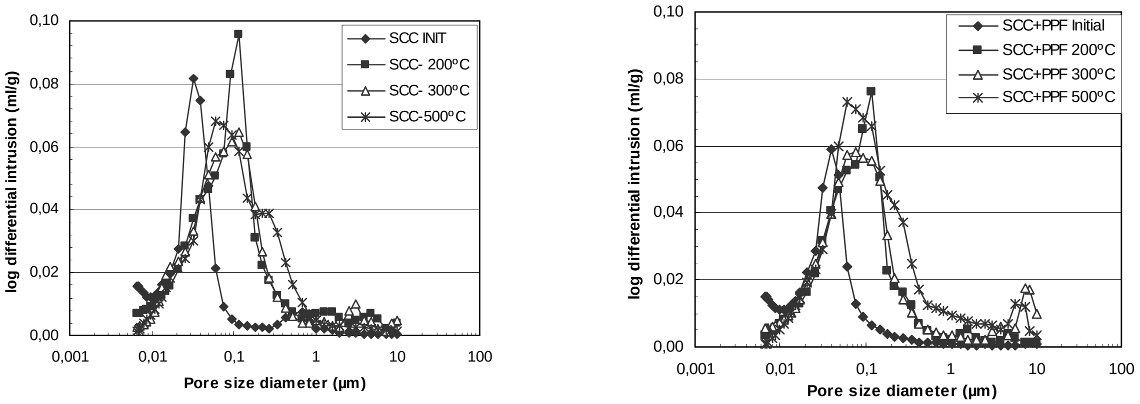

Figure 8 Mercury intrusion porosimetry of SCC and SCC+PPC

Influence of PPF in mechanical properties of SCC at high temperatures

The compressive strength and indirect strain after exposure at 20, 300, 500 and 700ºC were also determined, and the relative values are given in figure 9. Compressive strength does not show important differences between SCC with and without fiber, but indirect strain decreases more quickly for SCC+PPF than SCC, this is attributed, first due to loss of beneficial effect of PPF in the strain response after melting and at higher temperatures due to the empty spaces created by the combustion and evaporation of the fiber.

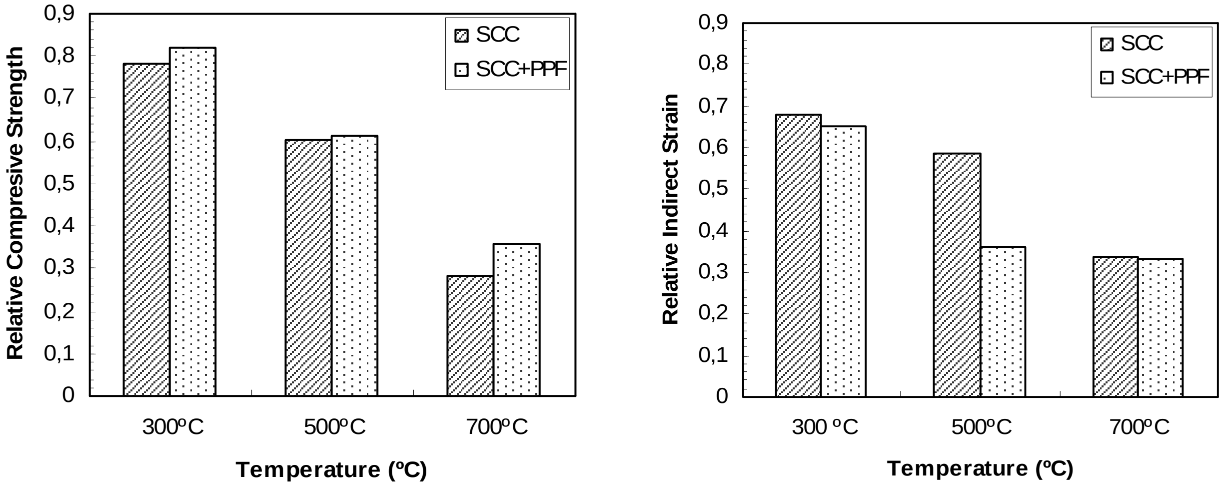

Figure 9 Compressive Strength and indirect strain for SCC and SCC+PPF

This response of PPF at high temperatures is important because it is believed that the use of PPF in concrete avoids the risk of explosion under fire due to its ability to melt at the temperature where the risk of explosion is higher up to 300ºC [Janson and Boström, 2007, Suhaendi and Horiguchi, 2007, Khoury, 2007] due to the increase of empty spaces leaved by the heat decomposition of the fibers, that relax the high pore pressures generated during heating from dehydration of cement paste.

However, recent studies have demonstrated that the risk of spalling due to vapour released still remains even in presence of PPF; the reason can be attributed to the close of pores at temperatures lower than 200ºC that could not be compensated by the increase in pore size due to dehydration of cement paste, so the beneficial effect of PPF in concrete at high temperatures with respect to spalling will also depend on the pore size distribution of concrete, what means adequate content of polypropylene fibers and w/c ratio, or use fibers with adequate temperature range for melting and combustion.

CONCLUSIONS

The properties studied for self compacting concrete with and without fibers determine that their behaviour for porosity, capillary suction, transport of chloride and depth of carbonation are very similar.

The behaviour at high temperatures, the porosity and compressive strength are also similar in both concretes at high temperature, but SCC+PPF loss faster the strain resistance properties gained with the addition of the fibers.

ACKNOWLEDGEMENTS

The authors acknowledge the funding received from the Spanish Ministry of Education and Science PSE-380000-2006-4 / PSE-380000-200681, HABITAT 2030.

REFERENCES

Alonso, C., Fernandez-Municio, L.2007. “Dehydration and Rehydration processes in cementitious materias after fire. Correlation between micro and macrostructural transformations”. International Workshop “Fire Design of concrete structures- From materials modelling to structural performance”, University of Coimbra, Portugal, 69-78.
Alonso, C., Andrade, C., Gallo, E. and Menendez, E. 2005. Microstructural changes in high and ultra high strength concrete exposed to high temperatures environments, ACI Internacional, SP-229(2005) 289-302.
Alonso, C., , Rodriguez, C., Andrade, C. and Arlaud, J. 2008. “Microstructural analysis of high performance concrete under fire. Improving resistance through the use of fibers” ECOMAS, Venice, July 2008.
Barragán, B., Zerbino, R., Gettu, R., De La Cruz, C., Bravo, M. 2005. “Durability properties of SCC thin walls”, In Proc. fib Symposium “Structural Concrete and Time”, (Eds. A. Di Maio and C.J. Zega), V.2, La Plata, Argentina, 897-904. (in Spanish).
Baroghel-Bouny, V. 2006. Durability indicators: relevant tools for performance-based evaluation and multi-level prediction of RC durability. Proceedings of the International RILEM Workshop on Performance Based Evaluation and Indicators for Concrete Durability, Madrid, España, pp. 1 – 30.
Castellote, M. Andrade, C. Alonso, C. 2001. “Measurement of the steady and non-steady-state chloride diffusion coefficients in a migration test by means of monitoring the conductivity in the anolyte chamber. Comparison with natural diffusion tests”, Cement and Concrete Research 31, 1411-1420.
CEB-FIP, 1998. “Strategies for Testing and Assessment of Concrete Structures, Guidance Report”, Bulletin 243 CEB, Comité Euro-International du Beton, 33-34.
Domone, P. L. 2006. “Self-compacting concrete: An analysis of 11 years of case studies”, Cement and Concrete Composites, 2., 197-208.

Jansson, R. and Boströn, L. 2007**.** “Experimental study of the influence of polypropylene fibers on material properties and fire spalling of concrete”. Proceedings of the international workshop fire design of concrete structures from materials modelling to structural performance. University of Coimbra, Portugal. 177-188.

Kalifa, P. Chéne, G. and Cálle, C. 2001. **“**High-temperature behaviour of HPC with polypropylene fibers. From spalling to microstructure” Cement and Concrete Research, 31(10), 1487-1499.

Kalifa P, Pardon D., Menneteau, F., Callé C., Chené, G. and Pimienta, P. 2002. “Comportament a haute temperature des betons a hautes performances: de l´eclatement á la microstructure”. Cahiers du CSTB.8.

Khoury, G.A., Majorana, C., 2007. “Polypropylene fibers and explosive spalling” Proceedings of the international workshop fire design of concrete structures from materials modelling to structural performance. University of Coimbra, Portugal. 211-224.

Persson, B. 2003. “Self-Compacting concrete at fire temperatures” TVBM-3110 Lund Lund Institute of Technology. Lund University. Division of Building Materials.

Persson, B. 2001. “A comparison between mechanical properties of self-compacting concrete and the corresponding properties of normal concrete” Cement and Concrete Research 31, 193-198.

PrUNE 83987, 2007**. “**Durability of concrete. Determination of the chloride ion migration. Multi-regime method” (in Spanish).

Sanchez, M., Alonso, C. and Barragán, B. 2008. **“**Durabilidad de hormigones autocompactantes expuestos a atmosferas agresivas naturales”, 1º Cong español sobre el Hormigón autocompactante, Valencia.

Suhaendi, S. and Horiguchi ,T. 2007. “Explosive spalling mitigation mechanism of fiber reinforced high strength concrete under high temperature condition” Proceedings of the international workshop fire design of concrete structures from materials modelling to structural performance. University of Coimbra, Portugal. 189-197.

Ye G., Liu X., De Schutter, Taerwe L., Vanndevelde P. 2007. “Phase distribution and microstructural changes of self- compacting cement paste at elevated temperature”. Cement and Concrete Research, 37, 978-987.