Twin Covilhã International Conferences
5th Int'l Conference on The Concrete Future
26-29 May 2013, Covilhã, Portugal

DURABILITY OF STEEL FIBER REINFORCED SELF-COMPACTING CONCRETE

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Keywords: Durability, steel fiber reinforced self-compacting concrete, corrosion.

Abstract. *For conventional concrete without steel fibers, although still an aspect under discussion, there are some commonly used durability indicators. However, for steel fiber reinforced self-compacting concrete (SFRSCC) literature is sparse and the aspects of durability, particularly corrosion resistance, still deserve deeper research, mainly the corrosion of the fibers, since its influence on the appearance and on the serviceability limit states of a SFRSCC structure can be a concern. Therefore, in the ambit of an ongoing research project dealing with the development of SFRSCC sandwich panels, durability tests were executed to compare the performance of SFRSCC and self-compacting concrete (SCC) specimens. Nine different tests were performed, applied to SFRSCC and SCC in order to characterize their mechanical properties (elasticity modulus, compressive strength and flexural behaviour) and to evaluate its durability indicators normally used for plain concrete, namely: water absorption by immersion and by capillarity, permeability to air, electrical resistivity, chloride diffusion by migration under non-steady state and carbonation. The results for the different concretes and curing times up to 28 days are presented and analyzed.*

1 INTRODUCTION

Durability is one of the most important aspects of concrete due to its fundamental incidence in the serviceability life of structures. The structures must be able to resist the mechanical actions, the physical and chemical aggressions they are submitted during their expected service life. In this respect, cracking plays a key role in the durability of concrete structures. Due to this fact it is necessary to establish measures in order to maintain the cracks under limit that imply a non-significant risk for the durability of structural elements [1]. In this context, steel fibers are presented as a solution for this problem, since due to fiber reinforcement mechanisms the concrete ductility and post-cracking resistance can be significantly improved. Though much research has been performed to identify, investigate, and understand the mechanical traits of steel fiber reinforced concrete (SFRC), little research has concentrated on the transport

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properties of this material. Material transport properties, especially permeability, may affect the durability and integrity of a structure [2]. The increase in concrete permeability, due to the initiation and propagation of cracks, provides ingress of water, chlorides and other corrosive agents, facilitating deterioration [3]. Rapoport *et al.* [2] examined the effects of different steel fiber volumes (0%, 0.5%, 1%) in fiber reinforced cracked concrete. Specimens were cracked to specified crack mouth opening displacement (0, 100, 200, 300, 400, and 500 μm). After the cracks were induced, the specimens were unloaded and the cracks relaxed. Later the cracked specimens were tested for low pressure water permeability. There are two major conclusions from this research: at larger crack widths, steel fibers might stitch the cracks, shortening the length of the crack, and reducing crack area for permeability. The higher steel volume of 1% has reduced the permeability more than the low steel volume of 0.5%, which permitted to conclude that the SFRC permeability decreases with the fiber content. This is probably due to the crack stitching and multiple cracking effects of steel fiber reinforcement. For crack width lower than 100 μm, steel fibers do not seem to affect the permeability.

Research on the durability of SFRSCC is still sparse, particularly corrosion resistance, which is treated in an incipient form, giving doubt, for example, whether the corrosion of the fibers may or may not lead to cracking and subsequent spalling of the surrounding concrete. Thus, the durability of SFRC is still a subject with lack of knowledge, and therefore the need to obtain durability indicators is of paramount importance for a large acceptation of this composite material. Under the framework of a research project on the development of sandwich panels with outer layers in SFRSCC connected by GFRP connectors, some indicators on the durability performance of SFRSCC are compared to those obtained in equivalent SCC. For this purpose, nine different tests were performed with SFRSCC and SCC specimens in order to characterize their mechanical properties (elasticity modulus, compressive strength and flexural behaviour) and to evaluate durability indicators normally used to assess the durability performance of conventional concrete, namely: water absorption by immersion and by capillarity, permeability to air, electrical resistivity, chloride diffusion by migration under non-steady state and carbonation. The results for the different concretes and curing times up to 28 days are presented and analysed in this work.

2 CORROSION RESISTANCE OF SFRSCC

It is widely reported that in case of SFRC, steel fiber corrosion is much less severe as compared with steel rebar reinforcement of concrete structures [4]. Due to large surface area to volume ratio, steel fibers are more effectively screened by the lime rich layer than the large diameter bars used in conventional reinforced concrete. However, the corrosion of fibers can produce micro-spalling of concrete, as well as the reduction of the sectional area of the fibers that arise some concerns on the long term material and structural performances of SFRC structures [5].

The corrosion resistance of SFRC is governed by the same factors that influence the corrosion resistance of conventionally reinforced concrete. Processes such as carbonation, penetration of chloride ions and sulphate attack are related to the permeability of the cement matrix. As long as the matrix retains its inherent alkalinity and remains uncracked, deterioration of SFRC is not likely to occur.

In the case of SFRC, the fibers are dispersed in all the volume of the material. The fibers that are close to the surface can have a very small cement matrix cover thickness [4].Thus the corrosion can be viewed in two aspects. The fibers corrosion can promote the formation of cracks that can affect the structural performance. The corrosion at surface can be described as appearance of rust spots at the surface on the exposed concrete structures. Balouch *et al.* [4] investigated the dependence of surface corrosion risk versus the W/C ratio of the concrete. With W/C=0.78 concrete matrix, all the fibers embedded less than 1 mm have caused corrosion spots at the surface. Using smooth, oiled and impermeable formwork the necessary minimum cover of the fibers to prevent surface corrosion is dropped to less than 0.2 mm when W/C is decreased to about 0.5. Further decrease of W/C did not give significant extra benefits.

Mangat *et al*. [6] reported that the generated expansive forces during the corrosion of fibers are insufficient for the detachment of concrete because, due to its reduced diameter, the increase in volume produced by the oxides resulting from corrosive process is not sufficient to split the surrounding concrete.

3 EXPERIMENTAL PROGRAM

3.1 Materials and mix composition

In the current experimental program, two different concrete mixtures were produced using CEM I 42.5 R Portland cement (C), limestone filler (LF), three types of aggregates (fine river sand (FS), coarse river sand (CS) and crushed granite 5-12 mm (CA)), water (W), superplasticizer (SP) based on ether polycarboxylate (ViscoCrete 3005) and hooked ends steel fibers of a length (l_f) of 35 mm, a diameter (d_f) of 0.50 mm, an aspect ratio (l_f/d_f) of 70 and a yield stress of 1300 MPa.

Table 1 includes the composition that has best fitted self-compacting requirements for the adopted fiber content, (C_f).

	C(kg)	LF(kg)	FS(kg)	CS(kg)	CA(kg)	W(L)	SP(L)	C_f(kg)	W/C
SCC	413	353	127.8	198	722	648	7.83	0	0.31
SFRSCC	413	353	127.8	195	713	640	7.83	60	0.31

Table 1: Compositions for 1 m^3 of concrete

3.2 Test procedures

In order to characterize the concrete behaviour in fresh state, slump flow tests were performed according to EN 12350-2 [7], L-Box tests according to EN 12350-10 [8] and tests to achieve density and air content according to EN 12350-6 [9] and EN 12350-7 [10], respectively with. The mechanical characterization of the produced mixtures was focused on the study of variation over time (7, 28 and 90 days) of elasticity modulus, compressive strength and bending behaviour. In addition to the evaluation of mechanical properties, the properties in the hardened state of the mixtures were also assessed through durability test indicators. The durability tests were performed on specimens of SFRSCC and SCC at 28 days of age, and were focused on the determination of water absorption by immersion and by capillarity, permeability to air, electrical resistivity, chloride diffusion by migration under non-steady state and carbonation.

Two days after have been manufactured all specimens were demoulded and kept immersed in water at 20ºC until testing: elasticity modulus (prEN 12390-13 [11]) and compressive strength (EN 12390-3 [12]) - 4 cylindrical specimens (150 mm diameter and 300 mm in height); flexural behaviour (RILEM TC162-TDF [13]) - 4 rectangular prisms (150x150x600 mm^3); water absorption by immersion and by capillarity (LNEC E394 [14] and LNEC E393 [15]) - 6 cubic specimens of 100 mm edge; permeability to air (LNEC E392 [16]) – 4 cylindrical specimens (50 mm diameter and 40 mm in height) extracted from a slab; electrical resistivity (RILEM TC 154-EMC [17]) – the same specimens used for the elasticity modulus and compressive strength (before these tests); diffusion of chlorides by migration under non-steady state (LNEC E463 [18]) – 3 cylindrical specimens (100 mm diameter and 50 mm height); carbonation (FprCEN/TS 12390-12 [19]) - 1 rectangular prism (100x100x600 mm^3).

4 RESULTS AND DISCUSSION

4.1 Fresh State

Regarding the properties in fresh state, workability was assessed using the slump-flow test, and the L-Box test. Density and air content were also achieved. The results are shown in Table 2.

Concrete	Slump flow		L-Box			density (g/cm^3)	air content (%)
	spread (mm)	T_{500} (s)	H_2/H_1	T_{200} (s)	T_{400} (s)		
SCC	673	10.2	0.88	2.5	5.3	2.38	0.83
SFRSCC	667	15.6	0.81	5.3	10.1	2.40	0.80

Table 2: Fresh properties of SFRSCC and SCC

As expected, addition of fibers to fresh concrete results in a loss of workability, mainly when self-compacting requirements are based on time indicator. However, both compositions presented almost equal results in terms of spread and H_2/H_1 parameter.

4.2 Hardened State

4.2.1 Mechanical Properties

4.2.1.1 Compressive Behaviour

The modulus of elasticity and the compressive strength of each specimen were assessed at 7, 28 and 90 days of age. In terms of compressive tests, the procedure adopted consisted on determining the compressive strength in one specimen, at each age, in order to establish the correct maximum load value of the load-unload cycles to be carried out for the modulus of elasticity determination (Figure 2). For the 3 remaining specimens, the modulus of elasticity was determined in a first phase and then tested up to failure in order to determine the stress-strain response of the materials in a second phase (Figure 3).

Figure 2: Test setup for Modulus of Elasticity

Figure 3: Test setup for stress-strain in compression

The stress-strain diagrams obtained for the SCC and SFRSCC are depicted in Figure 4, while average modulus of elasticity, E_{cm}, and compressive strength, f_{cm}, at 7, 28 and 90 days of age are included in Table 3. The corresponding coefficients of variation, CoV, are also presented in this table.

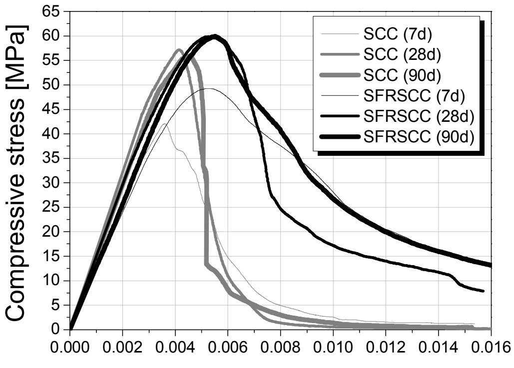


Figure 4: Compressive stress-axial strain relationships at different ages

	SCC			SFRSCC		
	7 days	28 days	90 days	7 days	28 days	90 days
E_{cm} (MPa)	31.16	35.79	36.65	31.58	36.88	37.80
CoV (%)	8.62	1.16	6.96	7.62	6.71	6.38
f_{cm} (MPa)	43.23	60.28	63.85	50.17	61.90	66.13
CoV (%)	8.29	1.27	2.05	6.92	6.34	9.99

Table 3: Summarized results of compression tests

As expected, Figure 4 demonstrates that the addition of steel fibres has mainly contributed for the increase of the compressive strength in the post peak phase of the material, with a favourable effect in terms of its energy absorption capability.

4.2.1.2 Flexural Behaviour

The flexural tensile strength of SFRSCC was obtained according to the recommendations of RILEM TC 162 TDF [13]. The tests were performed in displacement control by imposing a deflection rate of 0.2mm/min in the transducer positioned at midspan of the beam (Figure 5).

Figure 6 represents the average force-deflection response (F-u) registered in the SCC and SFRSCC at the three considered ages.

Figure 5: Test setup for the bending test

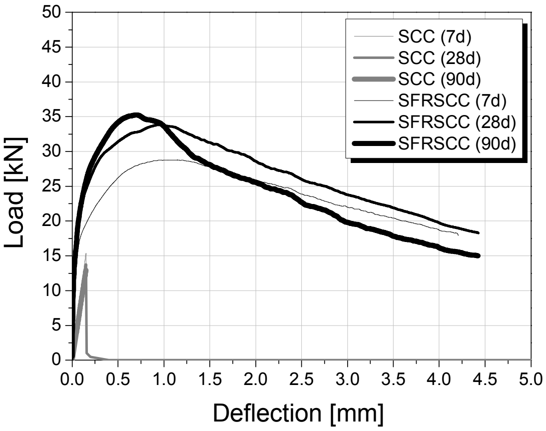


Figure 6: Flexural load-deflection relationships at different ages

Table 4 presents the average values and corresponding coefficients of variation of the flexural tensile strength, $f_{ctm,fl}$, and energy absorbed up to a deflection of 4 mm, G_{fm}, which represents the area under the F-u curves up to this deflection. The fibers were very effective in terms of increasing the flexural strength and the energy absorption.

	SCC			SFRSCC		
	7 days	28 days	90 days	7days	28 days	90 days
$f_{ctm,fl}$ (MPa)	4.90	4.83	4.67	9.44	10.92	11.73
CoV(%)	5.19	7.54	9.15	19.39	13.76	15.84
G_{fm} (N/m)	211.46	209.35	183.49	6248.32	7245.16	6678.39
CoV(%)	21.97	7.80	10.23	33.34	9.32	12.99

Table 4: Summarized results of the flexural tensile strength and energy dissipated

Based on the recommendations of RILEM TC 162 TDF [13], and considering the F-u obtained in the tests, the equivalent (f_{eq2} and f_{eq3}) and the residual (f_{R1} and f_{R4}) flexural tensile strength parameters were calculated. The obtained values are presented in Table 5.

	F_L (kN)	$f_{ct,L}$ (MPa)	$f_{eq,2}$ (MPa)	$f_{eq,3}$ (MPa)	$f_{R,1}$ (MPa)	$f_{R,4}$ (MPa)
AVG (7d)	15.919	5.094	8.337	8.512	8.247	7.085
CoV(%)	5.27	5.26	20.28	19.41	19.00	27.29
AVG (28 d)	19.967	6.389	10.122	9.721	9.915	7.629
CoV(%)	7.58	7.58	19.73	15.25	19.37	13.03
AVG (90 d)	21.90	7.008	10.105	7.944	9.822	7.546
CoV(%)	5.75	5.75	4.50	12.85	3.62	4.97

$F_{ct,L}$ - proportionality limit

Table 5: Summarized results of flexural tests

The results in Table 5 shows that both f_{eq} and f_R increase up to 28 days, and for 90 days a decrease was registered, mainly for the parameters evaluated at larger deflection/crack width, which means that due to the relatively high strength of the matrix some fibers would have failed by rupture.

4.2.2 Durability Indicators

4.2.2.1 Water absorption by immersion

Figure 7 presents the test results of water absorption by immersion, which indicates that the open porosity of SFRSCC was slightly higher than of SCC. The average porosity of the SCC was 10.7% and 11.3% of SFRSCC, therefore about 5.6% higher.

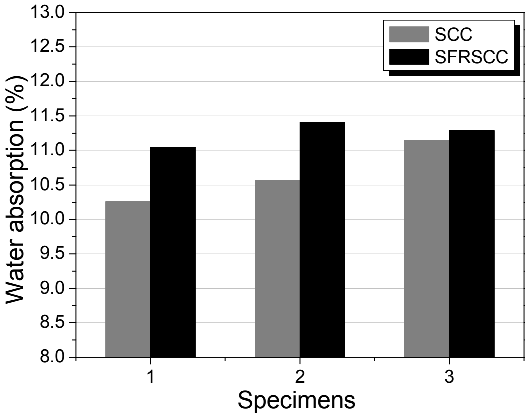


Figure 7: Absorption of water by immersion at atmospheric pressure

4.2.2.2 Water absorption by capillarity

Regarding water absorption by capillarity, the results obtained and presented in Figures 8 and 9 demonstrate that the total amount of water absorbed is greater in SCC, but the coefficient of water absorption by capillarity action is similar to SFRSCC (0.1272 mg/mm^2/min$^{0.5}$ to SCC and 0.0941 mg/mm^2/min$^{0.5}$ for SFRSCC).

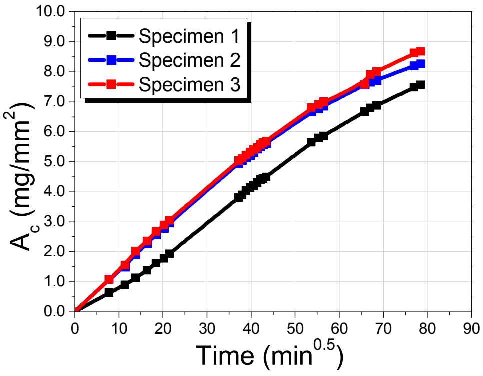


Figure 8: Absorption of water by capillarity of SCC

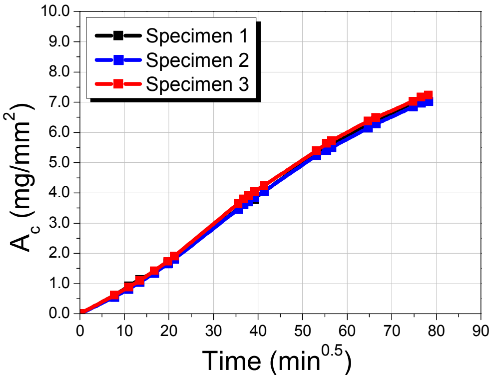


Figure 9: Absorption of water by capillarity of SFRSCC

4.2.2.3 Air Permeability

For the determination of air permeability, the Leeds cell was used. This device ensures that the specimen is subjected to a steady state flow of the fluid that passes through the sample under a given pressure during a certain period of time.

Figure 10 presents the air permeability coefficients of the tested specimens. The average of air permeability coefficient was 0.483x10^{-16} m^2 to SCC and 0.443x10^{-16} m^2 to SFRCCC. These results are similar because the variation of 8.3% between them is the order of magnitude of the test error, which usually has a high dispersion.

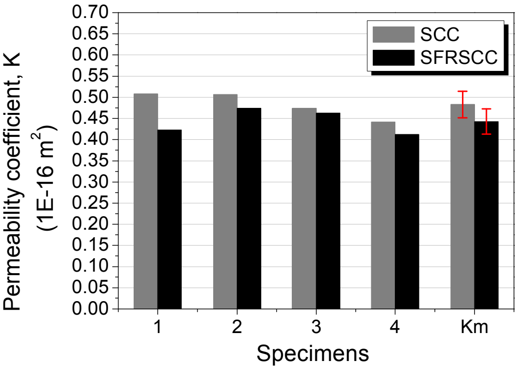


Figure 10: Air permeability coefficients for the specimens

4.2.2.4 Electrical resistivity

The average electrical resistivity, ρ_m, of the tested concretes is presented in Table 6. The difference between SCC and SFRSCC (reduction of 63% in SFRSCC) was obtained due to the high electrical conductivity of steel fibers which decrease the electrical resistivity of concrete. The high CoV obtained in SFRSCC at 7 and 28 days is justified by the presence of steel fibers that can significantly influence the electrical field generated by Wenner resistivimeter.

	SCC			SFRSCC		
	7 days	28 days	90 days	7days	28 days	90 days
ρ_m (kΩ.cm)	7.3	10.1	11.4	2.6	3.7	4.5
CoV (%)	2.71	1.64	3.46	22.75	21.47	4.01

Table 6: Summarized results of the electrical resistivity tests

4.2.2.5 Diffusion of chlorides by migration under non-steady state

In order to test the resistance against chloride penetration, an accelerated non-steady state migration test method was applied according to LNEC E463 [18] (Figure 11). The average diffusion coefficient of chlorides by migration, D_m, is shown in Table 7.

	SCC	SFRSCC
D_m ($\times 10^{-12}$ m²/s)	11.97	11.91
CoV (%)	11.27	32.09

Table 7: Summarized results of chloride migration test

Figures 11: Rapid chloride migration test

In table 7 it is possible to see that the resistance to penetration of chlorides is apparently the same in SCC and in SFRSCC, since they are endowed with similar diffusion coefficient. However, the comparison between the SCC and SFRSCC in migration test may not be immediate, since the presence of the steel fibers can cause the setting of chloride ions preferably on the fibers and thus may delay, or even prevent, penetration of ions into the matrix. During the test was possible to observe the formation of corroded material in the cathodic solution of the tests of SFRSCC and it was increased with the duration of the test (Figure 11).

4.2.2.6 Carbonation

Figure 12 shows the average carbonation depths (mm^2) measured on SCC and SFRSCC. Applying a linear regression analysis, the carbonation resistance, R_{c65}, was calculated by the slope of the linear equation following the recommendations of LNEC E465 [20]. The obtained carbonation resistance of SCC (1898.7 $kg.ano/m^5$) is only 4.8% higher than for SFRSCC (1806.9 $kg.year/m^5$), which means they have a similar resistance to carbonation in uncracked stage.

For SCC and SFRSCC there is a low increase of depth of carbonation over time of exposure to CO_2 due to the reduced permeability of the concrete. In the SCC mixes, the near-surface concrete is denser and more resistant than in the traditional vibrated concrete, which caused this higher resistance to carbonation.

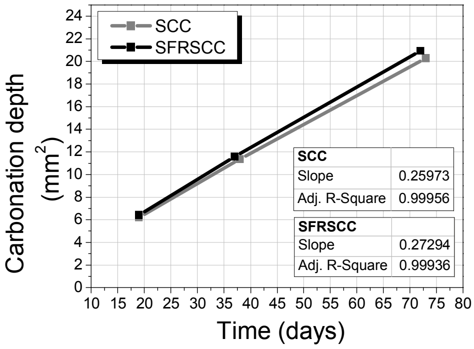
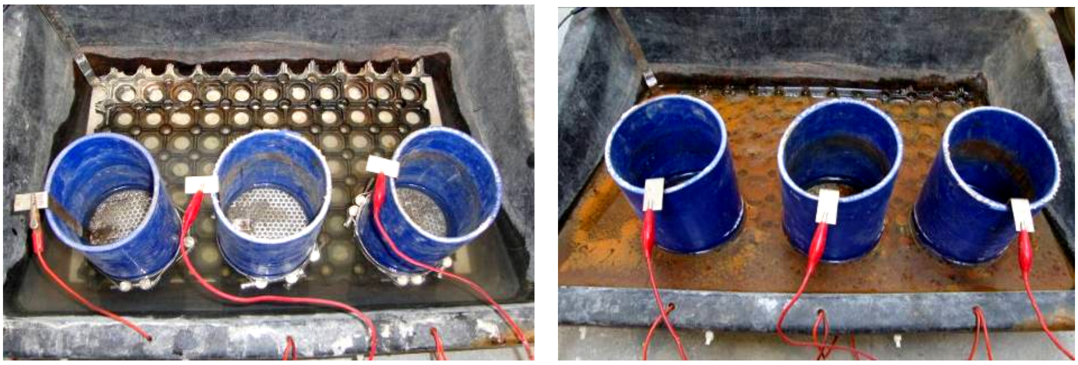


Figure 12: Carbonation depth along exposed time

4.2.3 Corrosion of steel fibers

With the purpose of verifying if the corrosion of the fibers may or may not lead to cracking and subsequent spalling of the surrounding concrete, SFRSCC specimens were submitted to the migration test of chlorides LNEC E463 [18], in order to induce severe corrosion in steel fibers. For this purpose, some samples were subjected to a potential difference of 30 V for 72 hours, and others at 45 V for 72 hours. With the development of this chlorides migration test under extreme aggressiveness conditions, it was detected that the cathodic solution showed increasing signs of corrosion of steel fibers (Figures 13). After 72 hours of testing, the SFRSCC specimens showed strong evidence of corrosion on the surface, as intense as more aggressive the environment (Figure 14 left). The cross section of the steel fibers has decreased along the chloride penetration length in the specimen (Figure 14 right). It was also noted that after migration test, SFRSCC specimens showed micro-cracks along the outer surface (Figure 15 left). This might have been caused by the increase in fiber volume associated with the corrosion of the fibers since, as known, the formation of iron oxide involves an increase in fiber volume.

After the exposure period, it was determined the tensile strength by diametral compression according with NP EN 12390-6 [21]. At the section fracture of the specimens it was observed an intense corrosion of steel fibers (Figure 15 right).



Figures 13: Chloride migration test of SFRSCC at the beginning (left) and at the end (right)

Figures 14: SFRSCC specimens after and before chloride migration test (left) and after tensile test by diametral compression (right)

Figures 15: Micro-cracking observed in SFRSCC specimens after chloride migration test (left) and section fracture after tensile strength test by diametral compression (right)

The results from three tests of tensile strength by diametral compression f_{ct}, are presented in table 8.

	SFRSCC (without corrosion)	SFRSCC (30V – 72h)	SFRSCC (45V – 72h)
f_{ct} (MPa)	5.59	5.67	3.13
CoV (%)	16.71	15.81	9.12

Table 8: Summarized results of tensile strength tests by diametral compression

The results shown in table 8 indicate that the tensile strength by diametral compression of SFRSCC was not significantly affected by steel fibers corrosion when these fibers were partially corroded (30V). When the fibers were fully corroded (45V), the corrosion of the fibers caused micro-cracks with a consequent reduction in tensile strength by diametral compression of SFRSCC (44%) compared to concrete without fibers corrosion.

The tests conducted in extreme aggressiveness allowed to evidence that corrosion of steel fibers may induce the formation of micro-cracks in surrounding concrete and subsequent micro-spalling.

Evaluating the weight of the specimens before and after the test, it was observed an increase in mass of 0.80% in the first case (30V) and 1.51% in the second case (45V). However, it should be noted that this damage was obtained for extreme aggressiveness conditions, with unexpectable occurrence in real environment conditions.

5 CONCLUSIONS

Based on the results obtained from durability indicators, t the following observations can be pointed out:

- Addition of steel fibers resulted in a very slightly increase of open porosity;
- Adding steel fibers did not change significantly the water absorption by capillarity, indicating that the capillarity pore size was not substantially changed;
- The air penetrability was not substantially affected by the steel fibers, although a slightly reduction in SFRSCC was observed;
- The presence of steel fibers reduce the electrical resistivity of concrete;
- Determining the diffusion coefficient from the chloride migration test under non-steady state may not be feasible for a SFRSCC since the methodology can cause significant corrosion of steel fibers

and chlorides may tend to settle in steel fibers. However, the results obtained in both concretes were similar;

- Due to the relatively high compactness of SCC mixes, they presented good resistance to carbonation;

The study concluded also that, in extremely aggressiveness conditions, corrosion of steel fibers can induce cracking in concrete and decrease tensile strength of concrete.

ACKNOWLEDGEMENTS

This work is part of the research project QREN number 5387, LEGOUSE, involving the Companies Mota-Engil, CiviTest, the ISISE/University of Minho and PIEP**.** The first author acknowledges the research grant under this project. The support provided by Maccaferri and Radmix for the supplying of the fibers, Sika for the superplasticizer, Secil for the cement and Omya Comital for the limestone filler.

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Proceedings of the

5th International Conference on
The CONCRETE FUTURE
26–29 May 2013

Venue

University of Beira Interior,
Engineering Faculty, 6200-001 Covilhã, Portugal

Editors

Castro Gomes, Sérgio Lopes, Luís Bernardo

Twin Covilhã International Conferences on

Civil Engineering

(Towards a Better Environment)

and

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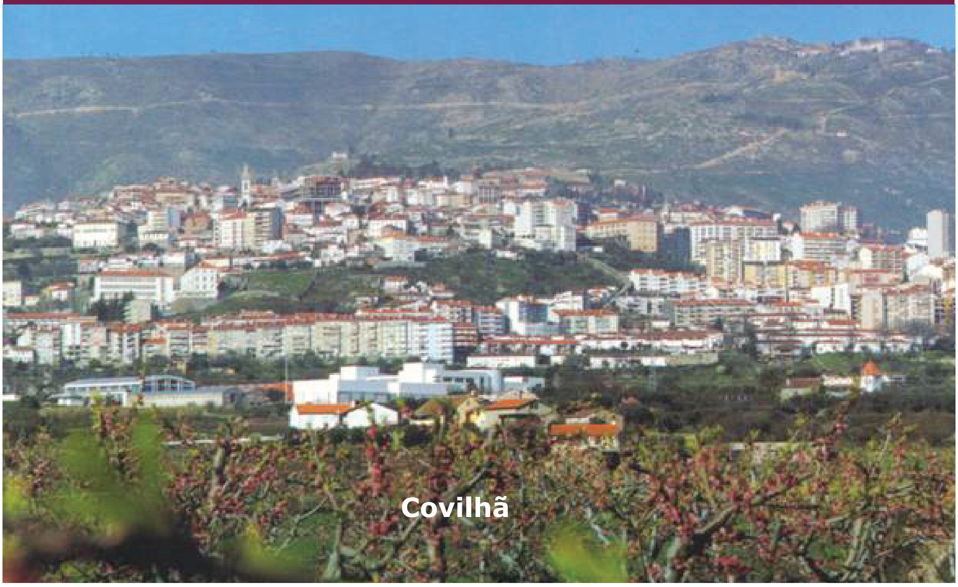

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and

The Concrete Future

26-29 May 2013
Covilhã, Portugal

Organisers:

- University of Beira Interior, Portugal
- University of Coimbra, Portugal
- CI-Premier Conference, Singapore

ISBN: 978-981-07-6067-0

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Published by:
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PREFACE

The 2nd International Conference on Civil Engineering towards a Better Environment (CE13) and the 5th International Conference on the Concrete Future (CF13) are held at the University of Beira Interior, in the city of Covilhã, Portugal, from 26 to 29 of May, 2013. These events are organized by the University of Beira Interior, the University of Coimbra and CI Premier.

CE13 aims at promoting a discussion on the role of Civil Engineering on the environmental aspects of the construction activities. This conference is of interest for researchers and professionals related with design and construction activities, among others. This is an excellent opportunity for people from different professional sources to meet and to share experiences and to discuss new ideas and development trends on this subject. CE 13 is the second conference of the series and is a consequence of the success of the first conference previously organized in Coimbra.

CF13 is the fifth conference of the series with the previous ones taking place in Malaysia, China and Portugal. It aims at discussing the challenges that concrete constructions are faced in the coming years. Energy efficiency and carbon emission rates are issues that are setting some requirements that are more difficult to be met. The professionals or researchers who are involved on the construction of concrete structures need to find alternative technologies to adapt the concrete to such new requirements so that the material could continue to be competitive. This conference is an excellent opportunity for researchers and professionals to discuss such aspects.

The coincidence of these two conferences is also a positive point, since there are some overlapping topics that can be discussed by a broader audience. People with different viewpoints can give their opinion on particular aspects and this will certainly enriches the discussion. To encourage a broad discussion, special few joined sessions are planned. For the rest of the sessions, the conferences will run separately.

The technical programme also includes a visit to an earth dam in River Coa, complemented with more relaxed visits to the medieval village of Sortelha and to museums in the city of Belmonte, including the Discoveries Museum and the Jewish Museum.

The technical sessions will include approximately 40 oral presentations, whose articles are included in this proceedings book. In the name of the local organising committees the chairs of the conferences would like to express their gratitude to the authors who presented their manuscripts for consideration and to the Scientific Committee for the referring work of the manuscripts. They also want to thank the presenters of the articles, the colleagues that were willing to chair the sessions, the sponsors and all the people that have collaborate in some way for the success of these conferences.

Victor Cavaleiro
Isabel Pinto
Luis M. Ferreira Gomes

Castro Gomes
Sergio Lopes
Luis Bernardo

TWIN COVILHÃ INTERNATIONAL CONFERENCES
26 – 29 May 2013, Covilhã, Portugal

2ND CIVIL ENGINEERING – Towards a Better Environment

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TWIN COVILHÃ INTERNATIONAL CONFERENCES
26 – 29 May 2013, Covilhã, Portugal

5TH CONCRETE FUTURE

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