Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2009, Valencia
Evolution and Trends in Design, Analysis and Construction of Shell and Spatial Structures
28 September – 2 October 2009, Universidad Politecnica de Valencia, Spain
Alberto DOMINGO and Carlos LAZARO (eds.)

Structural behavior of self-compacting and fiber reinforced concrete under shear loading

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Abstract
Shear behavior of concrete elements made with traditional concrete (TC), self-compacting concrete (SCC) and fiber reinforced concrete (FRC) was analyzed. Three reinforced concrete beams were tested using three different kinds of concrete: TC, SCC and FRC, and two prestressed reinforced beams with SCC and FRC. Minimum traditional shear reinforcement was fixed so that a shear failure took place. Displacements, load and crack width were measured during the tests. Subsequently, the values obtained during the tests were analyzed by comparing the results of the different kinds of concrete. By means of video recording and subsequent image analysis, crack widths in beams were measured. Crack opening was controlled at the fixed control points. Shear experimental strength and behavior were compared. A safety margin was obtained for the analyzed cases.

Keywords: Self-Compacting Concrete, Fiber Reinforced Concrete, Shear, Steel Fibers.

1. Introduction
SCC is becoming more and more important especially in precast industry. Bonen *et al.*,[2] showed that SCC is a new technology and the market share of its products is rapidly growing because of the economic opportunities and improvements of the quality of the concrete and the working environment. SCC is an innovative concrete that does not require vibration for placing and compaction. It is able to flow under its own weight, completely filling formwork and achieving full compaction, even in the presence of congested reinforcement [12]. Choulli *et al.*, [4] showed that shear strength of SCC beams is lower than TC beams because of the reduced aggregate interlock between crack faces as a consequence of a minor size aggregates or/and aggregates volume and, also by the smooth surfaces that are produced. So, it is necessary to know the behavior of SCC against shear.

On the other hand, the interest on FRC structures is continuously growing [13]. In prefabrication, FRC is particularly appealing for facilitating the industrialization of the production and introducing an improvement in the overall characteristics and durability of the products [10]. Dupont *et al*. [8], showed that addition of steel fibers to concrete improves its postcrack behavior in tension. As a consequence one could expect that steel fibers contribute to the shear capacity of a concrete beam. Shear tests on steel fiber reinforced concrete beams without stirrups have shown that if the fiber dosage is high enough no other transverse reinforcement is necessary to achieve the desired shear capacity [8]. Casanova *et al*. [3], proposed that fibers act as transverse reinforcement, the parameters relevant to the structural part have the same effects as in reinforcement concrete and that the various parameters relevant to fibers can be taken into account globally through the post-cracking tensile behavior of the fiber reinforced concrete used. Meda *et al*. [10] concluded that the beams reinforced only with steel fibers showed a similar, or even better, post-cracking behavior than the beams with the minimum amount of transverse reinforcement. When fibers are used in addition to conventional transverse reinforcement the shear strength significantly increases. Steel fibers also reduce the width of shear cracks, thus improving durability.

2. Research significance.

This experimental program has been carried out in order to study the shear behavior of SCC and FRC beams and to compare it to the shear behavior of TC beams. Reinforced and prestressed beams were tested.

Shear ultimate load, deflections, cracking pattern and crack width evolution were analyzed. A comparative study on the safety margins of shear values determined according to annex 14 of EHE-08 [9], based on RILEM [11], versus experimental values was carried out.

3. Experimental program.

3.1. Materials and elements geometry.

The objective of this research was to verify at the precast factories that SCC beams have the same structural reliability than TC beams. Also, FRC beams behavior under shear loading was compared with the Annex 14 of EHE-08 [9]. The analysis was specially focused on the study of aggregates interlocking, since one of the most criticized aspects is that SCC has a smoother surface than TC. Furthermore, 5 beams were tested: 3 of them reinforced (TC, SCC and FRC) and the other 2 prestressed (SCC and FRC).

The length of reinforced concrete beams was 7.88m, whereas the length of prestressed beams was 6.66m.

TC and SCC mixture were daily utilized at precast industry. FRC were adapted from the SCC. Fibers were 80/50. 80 is the aspect ratio of fiber (length / diameter) and 50 is the length of the fiber (L in mm). Concrete mix proportions are shown in *Table 1*.

Beam	A	B	C	D	E
Date	05/March/2008	06/March/2008	07/March/2008	01/April/2008	02/April/2008
Concrete	TC	SCC	FRC	SCC	FRC
Reinforcement	Reinforced	Reinforced	Reinforced	Prestressed	Prestressed
Cement CEM I-52,5R (kg)	296	344	331	410	398
Natural River Sand (kg)	846	-	-	-	-
Crushed Sand (kg)	-	978	1030	1028	1029
Limestone 6/10 (kg)	952	844	854	793	793
W/C	0,48	0,5	0,51	0,41	0,44
Fiber (kg)	-	-	60	-	60
Superplasticizer (Kg)	4	8,6	8,5	9,5	9,5
Slump (cm)	17	-	-	-	-
Slump Flow (cm)	-	66	70	60	40
fc (Mpa)	50,5	53,8	50,6	51,3	54,3
fR,3,k (Mpa)	-	-	8,544	-	8,224

Table 1 : Concrete mix. Constituents (kg/m^3) [6]

The geometry of the full scale reinforced beams is shown in Figure 1.

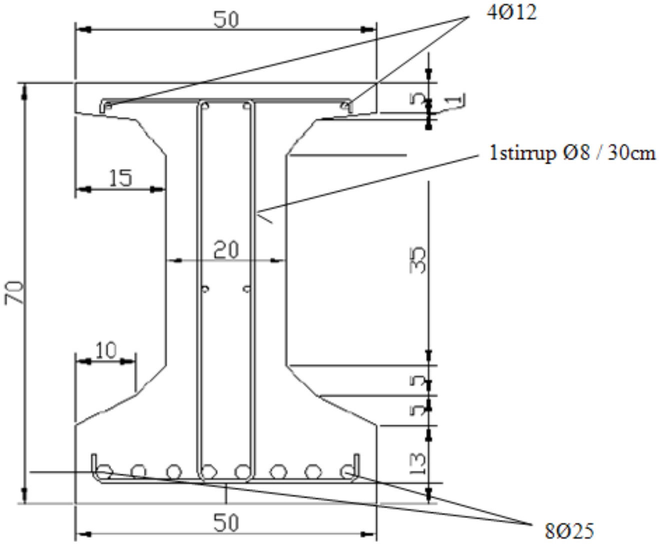


Figure 1: Geometry of reinforced beams (cm) [7].

B 500 SD steel was used for the reinforcement. Minimum shear reinforcement was fixed so that a shear failure took place. Beams were overestimated in flexure. The reinforcement was the same for the three reinforced beams as shows Figure 1.

The geometry of the full scale prestressed beams is shown in Figure 2.

25 prestressed tendons (Y 1860 S 7) separated 5 cm one to each other were disposed at bottom flange of the prestressed beams, and 2 tendons were disposed at top flange, at shows Figure 2. Total prestressed force was 3726 KN.
Transversal reinforcement of prestressed beams is showed at Figure 3. Several areas of transversal reinforcement were distinguished as shows Figure 4.

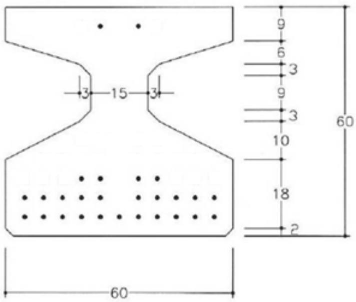


Figure 2: Geometry of prestressed beams (cm).

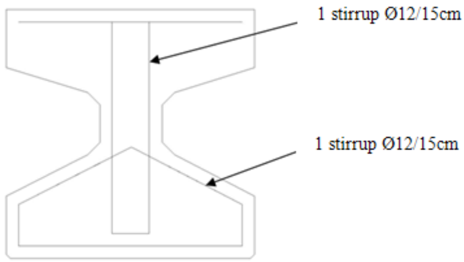


Figure 3: Transversal reinforcement of prestressed beams.

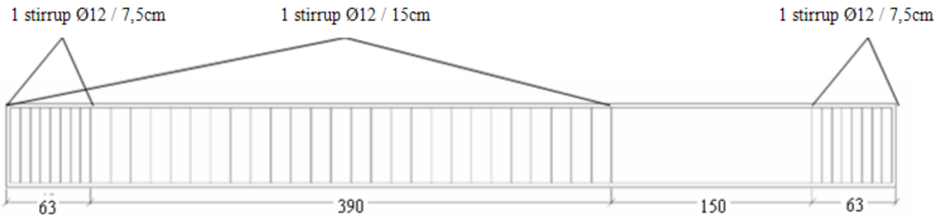


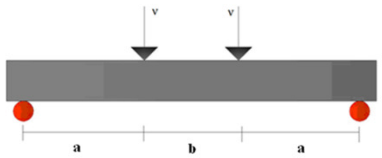
Figure 4: Distribution of transversal reinforcement of prestressed beams (cm).

3.2. Test procedure.

Beams were produced at a precast industry. 2 cylinder for all mixes and 2 prismatic specimens for each FRC mix were casted with the same concrete of each beam. Then, compression, according to UNE 83304 and residual flexural strength, according to EN14651, were determined. Results are showed at Table 1.

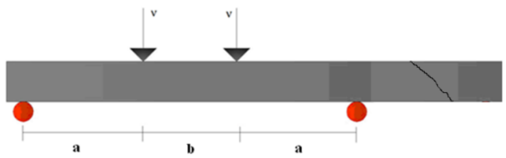
Beams were disposed for testing simply supported (Figures 5 and 6). Prestressed beams failed by shear in the area without shear reinforcement (1^{st} phase). Then, the area with shear reinforcement in prestressed beams was tested (2^{nd} phase) as shows Figure 6.
In all the beams the shear span ratio (a/d) at the failure zone was 3, where: a= shear span; d=depth.

Deflection was measured in three points of each beam: mid span and mid shear span. Also, load and crack widths were measured.
Tests were recorded by video, and after tests, crack pattern and evolution crack widths were analyzed at the shear span surface.
Loads were applied by a 1000 KN hydraulic jack for beams A and B, and two for beam C.



Reinforced beams (A, B, C): a=2,1m; b=1,8m
Prestressed beams (D, E) (1st phase): a=1,8m; b=2,4m

Figure 5: Supports and loads distribution for beam tests.



Beam D (2nd phase): a=1,76m; b=0,46m
Beam E (2nd phase): a=1,22m; b=0,46m

Figure 6: Distribution of supports and loads of prestressed beams (cm). 2nd phase.

4. Results and discussion.

4.1. Ultimate loads and failure modes.

Figures 7 to 13 show the appearance of the shear span after failure.

Figure 7: Beam A

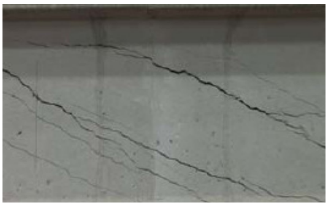


Figure 8: Beam B

Figure 9: Beam C

Figure 10: Beam D (1st phase)

Figure 11: Beam E (1st phase)

Figure 12: Beam D (2nd phase)

Figure 13: Beam E (2nd phase)

Ultimate shear loads and failure modes are showed at Table 2.

Beam	Ultimate Shear Load (KN)	Failure Mode
A	358	Shear
B	365	Shear
C	549,6	Shear
D (1st phase)	426,30	Shear
E (1st phase)	693,6	Shear
D (2nd phase)	873	Crash concrete (top flange)
E (2nd phase)	1186,5	Bond

Table 2: Ultimate Shear loads and Failure modes.

Beams A, B, C, D (1st phase) and E (1st phase) failed by shear. Beams C and E (1st phase) failed by shear, without brittleness. It confirms the capacity of steel fibers to control shear cracking. Beams D (2nd phase) and E (2nd phase) didn't fail by shear, but there were small shear cracks.

4.2. Reinforced beams.

4.2.1. Shear strength values.

Experimental and theoretical shear strength values were compared. Theoretical value was calculated by using the EHE-08 Code [9], specifically using the 14th EHE-08 Annex for fiber concrete beams (based on RILEM [11]). Table 3 shows both, theoretical and experimental values, for TC (Beam A) and SCC (Beam B), and the safety margin between both values.

Theoretical strength was evaluated with the actual properties (compression and residual flexural strength) of the concrete without any reducing factor.

In all the analyzed cases, experimental values of ultimate shear were higher than theoretical values.

Codes are highly conservative, since theoretical value is higher than the experimental value, which is logical because of fragile failure of shear, as show Table 3.

Fibers avoid the appearance of generalized cracks, and lead to ductile behavior. Shear resistance increase due to fibers was 184,6 KN as show Table 3.

Analyzing fibers contribution separately, flange factor (K_f) gives no conservative results. Probably, flange design too slender is ineffective.

4.2.2. Deflections.

Beams deflection was analyzed, specifically in mid span. For loads less than 300 KN, deflection behavior was similar for beams A and B. Differences were for failure loads; in this case, deflection of Beam B was lower than Beam A as shows Figure 14. Also, the same ultimate load was reached for both beams. Beam C reached ultimate loads bigger than beams A and B and had a more rigid behavior at the cracked state. Failure mode was more ductile at beam C, which is deduced by the horizontal end previous at failure. And, for the same level of load, deflection of Beam C was smaller than beams A and B. Beam C had a ductile behavior because of fibers.

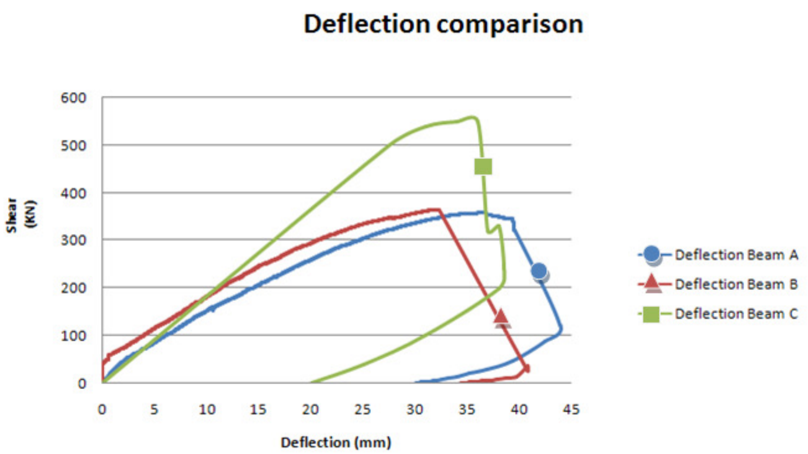


Figure 14: Deflection comparison. Beams A, B and C at mid span [7].

4.2.3. Crack width evolution.

By means of video recording and image analysis software developed at ICITECH, crack widths in beams were measured. Several points were identified in the early pictures and its separation length was evaluated in consecutive pictures during the load process to evaluate the crack evolution in an eventual crack between two control points. Crack width was measured in each beam at different control points, in points that one crack crosses a stirrup or points with a crack between stirrups. Figure 15 shows crack evolution.

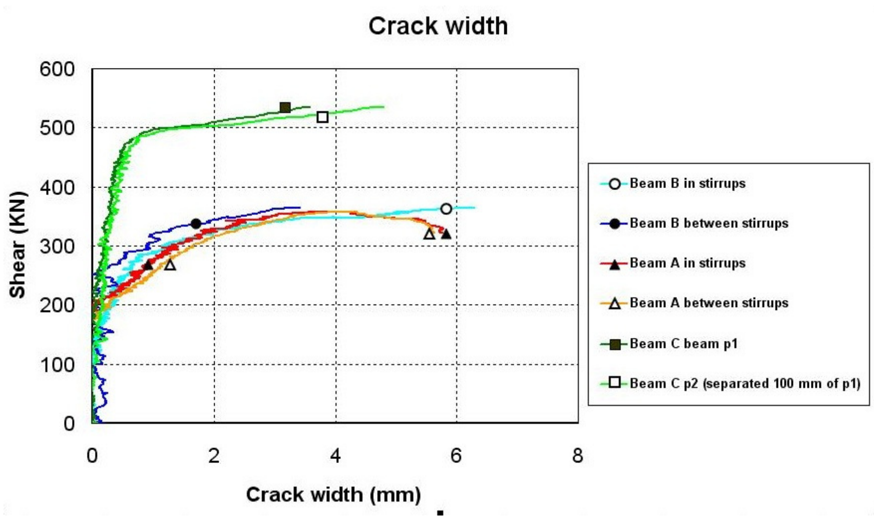


Figure 15: Crack width versus load [6].

At serviceability state, cracking behavior of beams was very similar for every beam and measured point, only differences were observed at ultimate state, when beam are near to fail. Nevertheless, when crack width of Beam B, made of SCC, was slightly bigger than Beam A, made of TC. For loads nearby to failure, the contribution of aggregate interlock to shear wasn't effective because of crack width, so this different is not important because beams A and B reached similar crack opening at ultimate load, as shows Figure 15.

Crack width in FRC shows an elastoplastic behavior, clearly more rigid than TC or SCC, even close to the failure which means a more ductile behavior.

Cracks widths were slightly bigger between stirrups than in stirrups. An evident stirrups influence wasn't observed.

4.3. Prestressed beams.

Prestressed beams were tested, and their behavior is showed at Figure 16. When zone without stirrups was tested, both beams had a shear failure, and Beam E reached higher loads than Beam D because of fibers.

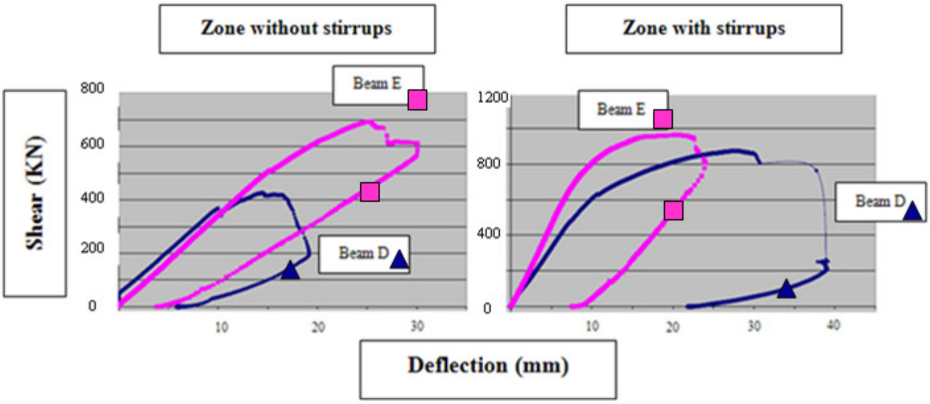


Figure 16: Deflection comparison between Beam D and Beam E [1].

Table 3 shows ultimate shear in both beams: D and E. Experimental and theoretical values were compared.

When zone with stirrups was tested, in Beam D the failure was by crash concrete at the top flange. Failure of Beam E occurred by bond failure. FRC beams showed a ductile behavior.

4.4. Safety factor of shear theoretical values.

Failure values of tested beams and shear values calculated by using the 14th EHE-08 Annex without safety factor are at Table 3. A safety margin (SM) was determined. This margin is the ratio between experimental and theoretical shear strength.

Beams D and E (2nd phase) didn't failure by shear, failure was by compression at top flange and by bond failure respectively; so if these beams had failure by shear, SM would have been bigger, which means more conservative.

For an exhaustive analysis, contribution of fibers (V_{fu}) was determined too, and this value was compared with the difference between experimental values of SCC beam and a FRC beam with the same geometry and reinforcement. V_{fu} was obtained considering a K_f multiplier coefficient which consider the contribution of flanges at "T" sections. Also, K_f was evaluated without the flanges contribution (K_f=1).

Theoretical shear values were too conservative, because the safety margin was bigger than one. EHE-08 Code [9] was especially conservative for prestressed beams.

In conclusion, Table 3 shows that:

a) Beams with traditional shear reinforcement made of TC or SCC showed similar SM values (1,34 to 1,39). These cases are beams A, B and D (2nd phase).

b) Beams without traditional shear reinforcement (Beam D, 1st phase) had a high SM (1,8), because of the fragile failure.
c) The evaluation of fiber contribution to shear strength according to EHE-08 Code [9] (14th Annex) at prestressed beams showed SM higher than elements with traditional shear reinforcement.
d) Fiber contribution at reinforced beams was evaluated with a maximum SM=1. In this case, flanges contribution wasn't evident due to their slenderness.

		PC	SCC	FRC			
						Increase because of fibers (Vfu)	
				With Kf	Without Kf	With Kf	Without Kf
REINFORCED CONCRETE	Theoretical value (KN)	269,4	272,85	568,69	468,96	Vfu=299,175	Vfu=199,45
	Experimental value (KN)	358	365	549,6		184,6	
	SM	**1,33**	**1,34**	**0,97**	**1,17**	**0,62**	**0,93**
PRESTRESSED CONCRETE (Without TR)	Theoretical value (KN)		237,22	427,42	364,73	Vfu=188,07	Vfu=125,38
	Experimental value (KN)		426,3	693,6		267,3	
	SM		**1,8**	**1,62**	**1,9**	**1,42**	**2,13**
PRESTRESSED CONCRETE (With TR)*	Theoretical value (KN)		629,27	819,09	756,4	Vfu=188,07	Vfu=125,38
	Experimental value (KN)		873	1186,5		313,5	
	SM		**1,39**	**1,45**	**1,57**	**1,67**	**2,5**

Table 3: Comparison between theoretical and experimental shear values (KN) [6].
Where: TR= Transversal Reinforcement; SM=Safety Margin= (V_{exp}/V_{theo}).
* : These cases didn't reach shear failure.

5. Conclusions.

- Beams made of TC or SCC with an identical concrete compression strength showed identical shear behavior. No difference was found in shear strength and load-deflection behavior.

-Only a slight difference was found in shear crack evolution for high loads levels. This difference wasn't apparent at serviceability state load levels. As a consequence, the effect of a possible less contribution of aggregate interlock won't determine the structural shear design.

-FRC beams had a more ductile behavior because of fibers at serviceability and ultimate states. Fibers controlled the appearance and propagation of cracks.

-Fibers are able to contribute to the shear strength. Beams with fibers reached higher shear ultimate loads.

-Fiber contribution is well evaluated with the formula proposed in the EHE-08 Code [9] with a wide safety margin SM= (V_{exp}/V_{theo}).

Acknowledgements

Funding from the Spanish Ministry of Education and Science, through grants BIA2006-15471-C02-01 and PSE 11-2005, PSE-380000-2006-4, PSE-380000-2007-1: "HABITAT 2030", is greatly appreciated.

This research project was financed by PREVALESA (Collaborator Precast industry) and IMPIVA (Instituto de la Pequeña y Mediana Industria Valenciana)-2008.

References

[1] Beltrán A., *Aplicación práctica del anejo de hormigón con fibras de la nueva EHE al cálculo a cortante en vigas prefabricadas para puentes.* , PFC, UPV, 2008.

[2] Bonen, D., Shah, Surendra P., *Fresh and hardened properties of self-consolidating concrete*. Prog. Struct. Engng. Mater. 2005; 7. 14-26.

[3] Casanova, P., Rossi, P., Schaller, I., *Can Steel Fibers replace transverse reinforcements in reinforced concrete beams?*. ACI Materials Journal no. 94-M41. September-October 1997.

[4] Choulli, Y., Marí Bernat, A.R., Cladera Bohigas, A., *Shear behaviour precast prestressed high strength self compacting concrete beams*., Hormigón y acero, ISSN 0439-5689, Num. 244, 2007. 47-56.

[5] CNR-DT204, Guidelines for the design, construction and production control of fiber reinforced concrete structures.

[6] Cuenca E., *Comportamiento a cortante de elementos constructivos fabricados con hormigón autocompactante y hormigón reforzado con fibras.* , Master thesis, UPV, 2008.

[7] Cuenca E., *Estudio del comportamiento frente a esfuerzo cortante de elementos constructivos de hormigón autocompactable. Aplicación a vigas prefabricadas de hormigón armado para edificación industrial.*, PFC, UPV, 2008.

[8] Dupont, D., Vandewalle, L., *Shear capacity of concrete beams containing longitudinal reinforcement and steel fibers*. Proceedings ACI Fall Convention 2000, ACI-SP, American Concrete Institute, Detroit, USA, 2000.

[9] Ministerio de Fomento. Gobierno de España. EHE-08. Instrucción del Hormigón Estructural. 2008.

[10] Meda, A., Minelli, F., Plizzari, G.A., Riva, P., *Shear behaviour of steel fibre reinforced concrete beams*. Materials and Structures, 38, April 2005. 343-351.

[11] RILEM TC 162-TDF: *"Test and design methods for steel fibre reinforced concrete. σ-ε- design method. Final Recommendation".* Materials and Structures, Vol. 36, October 2003, 560-567.

[12] *The European Guidelines for Self-Compacting Concrete. Specification, Production and Use*. EFNARC. May 2005.

[13] Walraven, J., *The evolution of Concrete*, Structural concrete 1, 1999. 3-11.