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SENSITIVITY OF THE FLEXURAL PERFORMANCE OF GLASS AND SYNTHETIC FRC TO FIBRE DOSAGE AND WATER/CEMENT RATIO

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ABSTRACT

A comparative analysis of the flexural performance of FRC mixes with either glass or synthetic fibers is presented in this paper. The data used for such analysis were obtained from an experimental programme which comprised 42 notched prismatic specimens, produced and tested to EN 14651 at the age of 28 days. Different fibre dosages up to 15 kg/m^3 were considered in two series of mixes with water/cement ratios of 0.26 and 0.39, which yielded average compressive strength values of 65 MPa and 50 MPa respectively. A direct correlation between fibre content and residual flexural strength was confirmed. However, statistically significant differences were observed between the two fibre types considered. FRC mixes with glass fibre contents up to 5 kg/m^3 failed immediately after the first crack and showed no residual flexural strength. In general, specimens reinforced with synthetic fibres showed better levels of residual flexural strength and toughness than their glass fibre counterparts. The ratio between the residual flexural strength and the limit of proportionality provides a good illustration of such observations: it was 61% on average for FRC mixes with synthetic fibers at 10 kg/m^3, whilst it was only 33% for FRC mixes with the same amount of glass fibers.

KEYWORDS: Synthetic fibres, glass fibres, residual flexural srength.

1. INTRODUCTION

Fibre reinforced concrete (FRC) is well suited for a variety of structural as well as non-structural applications, as concrete performance in the hardened state is generally enhanced by the fibres role in bridging cracks, which results in improved crack control and enhanced properties in the cracked state [1, 2]. For applications where the structural contribution of fibres is intended to be significant, steel fibres are generally preferred [3, 4]. Fibres made with other materials have lower tensile strength and elastic modulus than steel fibres, and they are typically considered for applications where their main contribution is concerned with restraining the plastic cracks, and shrinkage cracking control. However, there is no clear-cut separation that restricts non-steel fibres to non-structural applications, and this, together with current trends favouring materials with lower carbon footprint, has motivated increasing interest in the mechanical performance of FRC with synthetic or glass fibres.

Fibres partially counterbalance the brittleness which is intrinsic to concrete as a material [5, 6], but their positive influence on flexural toughness varies greatly depending on the type of fibre material, its dimensions, and the fibre dosage. A number of studies [7-9] have investigated the flexural performance and toughness of FRC made with different types of fibres, and there is clear consensus that the addition of increasing fibre contents improves residual flexural strength and toughness.

To characterise, specify and design with FRC, the residual flexural strength parameters or toughness as obtained from the bending test are used as reference, in addition to the compressive strength at 28 days. In this study, the flexural response of different FRC mixes with either glass or synthetic fibres was characterised by testing notched prismatic specimens under three point bending test conditions, following the standard EN 14651 [10]. Different fibre dosages were considered. Also, to evaluate the influence of water-to-cement (*w/c*) ratio on flexural toughness, and how this modifies the contribution of fibres to residual flexural strength, two reference concrete mix designs were considered.

2. EXPERIMENTAL PROGRAMME

2.1. Variables considered

The factors considered in this study were: *w/c* ratio, type of fibre, and fibre content. Cement type CEM I 52.5N was used, and the superplasticiser was Sika Viscocrete 25MP. Two different values were considered for the *w/c* ratio: 0.26 and 0.39, leading to the definition of two reference mix designs, which were adjusted for a slump value of 120-150 mm so they could incorporate different fibre contents without further adjustments. These reference mix designs are summarised in Table 1, and were intended to be representative of a range of specified compressive strengths between 45-60 MPa approximately.

Table 1. Reference mix designs (kg/m^3)

	w/c = 0.39	w/c = 0.26
Cement	440	510
Water	175	130
Fine aggregate	825	950
Coarse aggregate (10 mm)	637	580
Coarse aggregate (20 mm)	317	300
Superplasticiser	8	11

The two types of fibres considered in this study were: synthetic fibrillated macro-fibres and alkali-resistant glass macro-fibres, and they are shown in Figure 1. The synthetic fibres were high-modulus 54-mm long polymeric fibres and had a tensile strength of 600 MPa. The glass fibres, on the other hand, were 36 mm long and their tensile strength was 1700 MPa. Synthetic fibres were used in dosages of 5, 7.5, and 10 kg/m^3, whilst the dosages considered for the glass fibres were 2.5, 5, and 15 kg/m^3.

Figure 1. Samples of the glass fibres (left) and synthetic fibres (right) used in this study.

2.2. Production of FRC mixes

Taking as reference the two mix designs presented in Table 1, either glass or synthetic fibres were incorporated in different dosages, leading to the combinations summarised in Table 2.

Table 2. Summary of the FRC mixes considered in this study.

Fibre type	*w/c* ratio	Fibre content (kg/m^3)
(None)	0.26	0.0
	0.39	0.0
Glass	0.26	2.5
		5.0
		15.0
	0.39	2.5
		5.0
		15.0
Synthetic	0.26	5.0
		7.5
		10.0
	0.39	5.0
		7.5
		10.0

The same mixing sequence was followed in the production of all mixes. In preparation before the mixing of every batch, the total amount of water to be added was separated in two buckets: one containing 80% of the water, and the other containing the mixture of the remaining 20% of the water and the required amount of superplasticiser. First, cement and all aggregates were all poured into the mixer and dry-mixed for 2 minutes. After that, 80% of the water was added and mixed with the cement and aggregates for 3 minutes. During this time, the fibres were poured gradually into the mixer. Finally, the remaining 20% of the water with the superplasticiser predispersed in it was added, and the mixing continued for 4 minutes. In all cases, a uniform distribution of the fibres in the mix was observed.

2.3. Characterisation of FRC mixes

For each of the combinations presented in Table 2, one batch of 70 litres was produced, and this material was used to cast 3 cubes, 3 cylinders, and 3 prismatic specimens. All specimens were tested at the age of 28 days. Prior to this, all specimens were kept in a fog room with a controlled temperature of 20C and a relative humidity of 90%. The cubes were 100-mm side and were used to determine the compressive strength, whilst the 150x300 mm cylinders were used to determine the splitting tensile strength following the standard EN 12390-6:2009 [11].

The prismatic specimens were produced and tested in flexure, according to the standard EN 14651 [10], and were 150 mm side and 600 mm long. They were all notched with a notch depth of 25 mm and 5 mm width using a wet sawing machine, and cured for a minimum of 3 days after sawing according to EN 12390-2 [12] until the age of testing. For the flexural strength test, a three point bending scheme was used, an image of which is shown in Figure 2. The tests were carried by imposing a constant rate of 0.05 mm/min for the increasing CMOD until the CMOD reached 0.1 mm, after which the rate was increased to 0.2 mm/min. CMOD values were monitored by means of LVDTs placed right under the notch, and a K7500 service controller was used for the data acquisition and control signal.

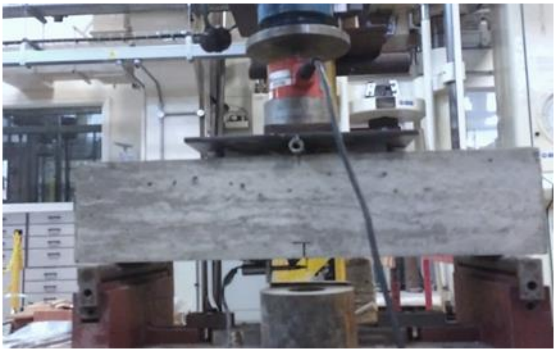

Figure 2. Set up for tested specimen

3. TEST RESULTS AND DISCUSSION

3.1 Compressive and splitting tensile strength

The results of the compressive strength and splitting tensile strength tests are presented in Table 3. The average compressive strength was 67 MPa and 50.4 MPa for the reference mixes without fibres and *w/c* ratios of 0.26 and 0.39 respectively.

Table 3. Compressive and splitting tensile strength results.

Fibre type	*w/c* ratio	Fibre content (kg/m^3)	Compr. strength (MPa)		Split. tensile strength (MPa)	
			Average	Std. dev.	Average	Std. dev.
(None)	0.26	0.0	67.0	1.0	4.2	0.2
	0.39	0.0	50.4	0.6	3.8	0.6
Glass	0.26	2.5	66.6	1.5	3.9	0.6
		5.0	66.8	0.6	4.0	0.6
		15.0	67.5	0.7	4.0	0.4
	0.39	2.5	50.8	1.9	3.6	0.5
		5.0	51.3	1.4	3.7	0.8
		15.0	52.2	0.8	3.8	0.5
Synthetic	0.26	5.0	67.3	0.9	4.1	0.4
		7.5	67.5	0.6	4.1	0.3
		10.0	67.6	0.3	4.0	0.3
	0.39	5.0	51.3	1.4	3.7	0.4
		7.5	52.4	0.8	3.7	0.7
		10.0	52.2	0.8	3.6	0.4

The addition of glass or synthetic fibres, at the dosages considered in this study, did not introduce significant variations in terms of average compressive strength, and the same can be said in relation to splitting tensile strength. Although fibres have been reported to sometimes increase the compressive strength of concrete by up to 15%, ACI 544 [13] , these results are in agreement with those other studies that reported no significant improvements in compressive strength due to the presence of fibres [14, 15]. In terms of variability, low fibre contents were observed to increase the standard deviation of compressive strength values with respect to the reference mixes without fibres. However, increasing fibre contents were associated with decreasing standard deviation values, for both types of fibres and *w/c* ratios.

3.2 Bending test results

For each of the FRC mixes as per the combinations listed in Table 2, three prismatic specimens were tested under flexure to EN 14651[10], and the corresponding load-CMOD curves were obtained. From these curves, the equivalent stress corresponding to the limit of proportionality, f_L, and the residual strength parameters f_{R1}, f_{R2}, f_{R3}, and f_{R4} (corresponding to CMOD values of 0.5, 1.5, 2.5, and 3.5 mm, respectively) were obtained. Their average values are given in Table 4.

Table 4. Bending test results: average values, expressed in MPa.

Fibre type	Fibre content (kg/m^3)	*w/c* ratio	f_L	f_{R1}	f_{R2}	f_{R3}	f_{R4}
Glass	2.5	0.26	5.68	0.00	0.00	0.00	0.00
		0.39	5.69	0.00	0.00	0.00	0.00
	5	0.26	6.96	0.00	0.00	0.00	0.00
		0.39	6.31	0.00	0.00	0.00	0.00
	15	0.26	5.41	2.49	2.00	2.00	1.93
		0.39	5.67	2.61	1.74	1.61	1.57
Synthetic	5	0.26	7.45	2.66	2.56	2.53	2.42
		0.39	6.24	2.12	2.08	2.14	2.18
	7.5	0.26	7.48	3.10	2.84	2.79	2.75
		0.39	6.79	2.53	2.50	2.44	2.39
	10	0.26	6.68	3.17	3.10	3.09	3.08
		0.39	7.43	2.78	2.60	2.61	2.58

All specimens produced with FRC mixes containing glass fibres at dosages of 2.5 and 5.0 kg/m^3 failed without exhibiting any residual load-bearing capacity in flexure, regardless of the *w/c* ratio. A softening response was observed in specimens where the glass fibres dosage was 15 kg/m^3. A graphical comparison of the f_L values corresponding to the FRC mixes with glass fibres, and the stress-CMOD curves corresponding to specimens with a glass fibre dosage of 15 kg/m^3 are shown in Figure 3.

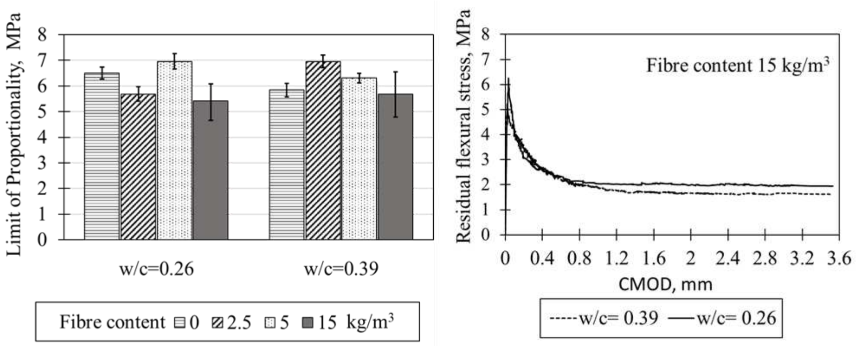

Figure 3. Flexural test results for glass FRC mixes: limit of proportionality values (left) and stress-CMOD curves for 15 kg/m^3 fibre content.

On the other hand, specimens with synthetic fibres presented comparatively better performance than their glass fibres counterparts, as residual flexural capacity was developed for all fibre dosages and *w/c* ratios considered. Figure 4 shows the average stress-CMOD curves for the different dosages of synthetic fibres and *w/c* ratios considered. Furthermore, comparing the results corresponding to those mixes where fibres were added at the maximum dosages considered in this study (10 kg/m^3 for synthetic fibres, 15 kg/m^3 for glass fibres), synthetic fibres did better than glass fibres in terms of the level of residual flexural strength achieved. The incorporation of synthetic fibres at a dosage of 10 kg/m^3 led to f_{R1}/f_L ratios between 0.42 and 0.61, for *w/c* ratios of 0.39 and 0.26 respectively, as opposed to 0.26 and 0.33, corresponding to specimens with 15 kg/m^3 of glass fibres.

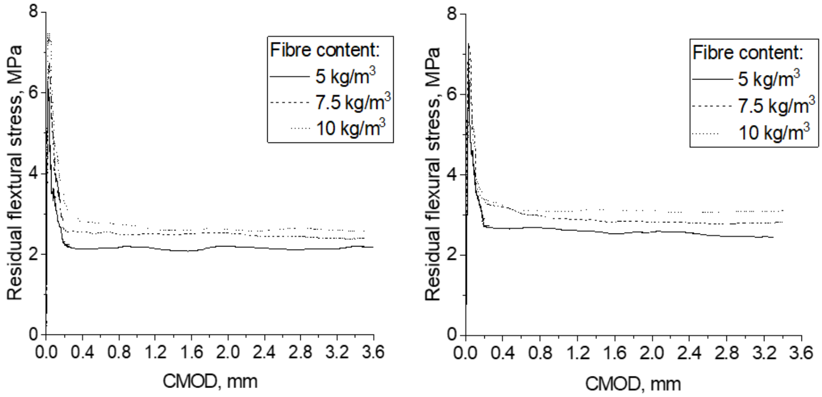

Figure 4. Flexural test results for glass FRC mixes with *w/c*=0.39 (left) and *w/c*=0.26 (right).

3.3 Residual flexural strength

In order to better quantify the differences in the flexural response of FRC introduced by changes in the variables considered in this study, a regression analysis was done and equations for the residual flexural strength parameters were obtained. In the regression analysis, the interactions between fibre content, fibre type and *w/c* ratio were also considered, with the purpose of determining whether these synergies were statistically significant. The equations obtained are presented in Table 5, where C_f is the fibre content in kg/m^3. The R-squared values ranged between 0.91 and 0.97, which indicated a very accurate fit with the experimental results.

Table 5. Regression equations obtained for the residual flexural strength parameters.

FRC with glass fibres	FRC with synthetic fibres
$\mathrm{Ln}(f_{R1}) = -3.845 + 0.380C_f - 3.31w/c$	$\mathrm{Ln}(f_{R1}) = 1.733 + 0.044C_f - 3.31w/c$
$\mathrm{Ln}(f_{R2}) = -3.557 + 0.314C_f - 1.89w/c$	$\mathrm{Ln}(f_{R2}) = 1.258 + 0.041C_f - 1.89w/c$
$\mathrm{Ln}(f_{R3}) = -4.097 + 0.305C_f$	$\mathrm{Ln}(f_{R3}) = 0.647 + 0.040C_f$
$\mathrm{Ln}(f_{R4}) = -4.650 + 0.335C_f$	$\mathrm{Ln}(f_{R4}) = 0.628 + 0.041C_f$

Unsurprisingly, fibre content and the fibre type were found to have a statistically significant effect on all residual flexural strength parameters. In addition to that, the interaction between fibre type and fibre content was found to be statistically significant. That is, the effect that a certain increase in the fibre content had on residual flexural strength was modified depending on the type of fibre considered. Regarding the effect of the *w/c* ratio, it was found that it had a statistically significant effect on f_{R1} and f_{R2}. However, the regression analysis showed that varying the *w/c* ratio did not introduce statistically significant variations in f_{R3} and f_{R4}.

The equations presented in Table 5 were useful in visualising the sensitivity of the different residual flexural strength parameters to changes in *w/c* ratio, fibre type, and fibre content.

Figure 5 shows the contour plots for f_{R1} values corresponding to mixes reinforced with either glass fibres (left) or synthetic fibres (right), as a function of *w/c* ratio and the fibre content. For the mixes with glass fibres, a theoretical minimum for the fibre content could be identified in order for the material to present residual flexural capacity. This minimum glass fibre content was in the range of 10 to 12 kg/m^3 and was slightly dependent on the *w/c* ratio.

The effect of *w/c* ratio was much more marked in mixes with synthetic fibres. As the contour plot in Figure 5 (right) shows, reducing the *w/c* ratio could lead to improvements in f_{R1} comparable to those which would be achieved by increasing the amount of synthetic fibres in the mix. Contour plots for f_{R2} are not shown in this paper because they were very similar to those obtained for f_{R1} and led to similar conclusions.

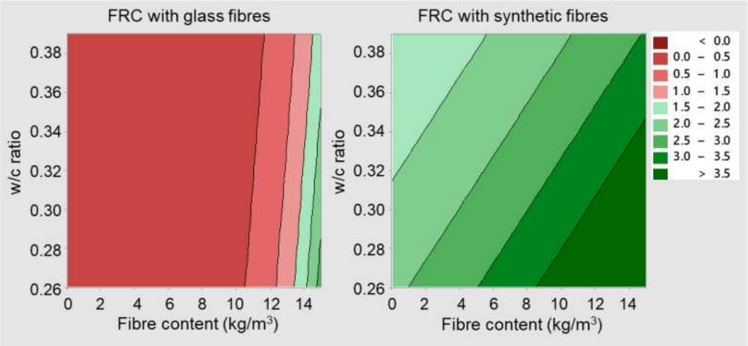

Figure 5. Contour plots for f_{R1} (in MPa) as a function of *w/c* ratio, type of fibre, and fibre content.

Figure 6 shows the trend followed by f_{R3} and f_{R4} values with respect to increasing fibre contents, for the two types of fibres considered. As mentioned before, f_{R3} and f_{R4} were not sensitive to variations in the *w/c* ratio within the range considered in this study. It can be seen that, for the mixes with synthetic fibres, the relationship between f_{R3} or f_{R4} values and the fibre content was practically linear. Also, in all cases considered in this study there was almost no difference between f_{R3} and f_{R4} values.

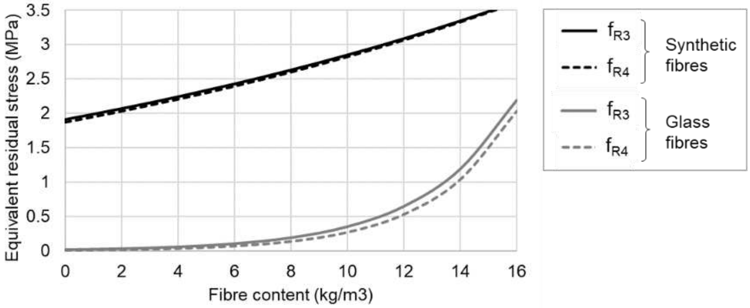

Figure 6. Regression lines for f_{R3} and f_{R4} as a function of fibre content.

3.4 Flexural toughness

In order to obtain an indication of the flexural toughness from the bending test results, the areas under the stress-CMOD curves up to a CMOD value of 3.5 mm were calculated. The average toughness values obtained for each case considered in this study are summarised in Table 6. Values for glass fibre contents lower than 15 kg/m^3 are not presented, as those cases exhibited a brittle failure.

Table 6. Toughness (mm.MPa)

Fibre type	Fibre content (kg/m^3)	$w/c = 0.39$	$w/c = 0.26$
Glass	15.0	6.95	8.03
Synthetic	5.0	7.78	9.52
	7.5	9.26	10.57
	10.0	10.52	11.51

The toughness values corresponding to synthetic FRC mixes were analysed by means of an analysis of variance, and this showed that the interaction between the fibre content and the *w/c* ratio had a statistically significant effect. The response surface shown in Figure 7 was obtained, and the significance of such interaction is clearly noticeable: the trend followed by toughness values with respect to the fibre content changes depending on the *w/c* ratio, and vice versa.

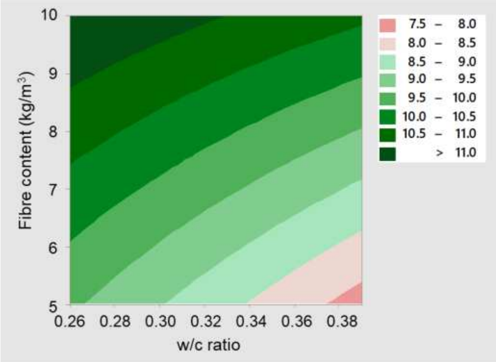

Figure 7. Contour plot for toughness values (area under stress-CMOD curve, in mmMPa).

Reducing the *w/c* ratio from 0.39 to 0.26 increases toughness values by 22% if a fibre content of 5 kg/m^3 is considered; however, this increase is 14% or 9.5% if the fibre content is 7.5 kg/m^3 or 10 kg/m^3, respectively. In consequence, it was concluded that mixes with higher synthetic fibre contents were less sensitive to changes in the *w/c* ratio, in terms of their flexural toughness. Conversely, increasing the synthetic fibre content led to increased toughness values, but the magnitude of such an increase was found to depend on the *w/c* ratio. For instance, for a *w/c* ratio of 0.39, toughness values were increased by 35% as a result of increasing the fibre content from 5 kg/m^3 to 10 kg/m^3; but this increase was 21% instead of 35% if the *w/c* ratio was 0.26 instead of 0.39.

4. CONCLUSIONS

Different FRC mixes were produced and tested in order to evaluate the sensitivity of their mechanical properties to changes in the following parameters: w/c ratio (0.26 or 0.39), type of fibre (glass or synthetic macrofibres), and fibre content (up to 10kg/m^3 or 15 kg/m^3 for synthetic or glass fibres, respectively). The following conclusions were obtained:

- The addition of the glass or synthetic fibres considered in this study, irrespective of their dosage, did not cause statistically significant changes to the average compressive strength or splitting tensile strength. However, increasing the fibre content was found to reduce the standard deviation of compressive strength values.

- FRC specimens with glass fibres in dosages of 2.5 kg/m^3 and 5 kg/m^3 presented brittle failure in flexure, and only those with 15 kg/m^3 of glass fibres showed residual flexural capacity. Based on the results obtained, it was estimated that glass fibres need to be added in contents of at least 10-12 kg/m^3 in order to achieve residual flexural capacity.
- No cases of brittle failure in bending were observed amongst the FRC specimens with synthetic fibres. They all presented a softening post-peak behaviour, irrespective of the *w/c* ratio and fibre content.
- When glass and synthetic fibres are compared at the maximum contents considered in this study, synthetic FRC specimens clearly outperformed their glass FRC counterparts. The level of residual flexural strength, represented by the ratio f_{R1}/f_L, varied between 0.42-0.61 for synthetic fibres, as opposed to 0.26-0.33 for glass fibres.
- The residual flexural strength parameters f_{R1} and f_{R2} were found to be sensitive to changes in *w/c* ratio, fibre type and fibre content. It was concluded that reducing the *w/c* ratio could lead to improvements in f_{R1} and f_{R2} comparable to those achieved by increasing the fibre content.
- Flexural toughness was evaluated through the area under the stress-CMOD curves up to a crack opening of 3.5 mm. Increasing the synthetic fibre content was found to decrease the sensitivity of this parameter to variations in the *w/c* ratio.

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REFERENCES

[1] Biolzi, L., Cattaneo, S. and Guerrini, G.L., 'Fracture of plain and fiber-reinforced high strength mortar slabs with EA and ESPI monitoring', Applied Composite Materials. **7**(1) (2000) 1-12.

[2] Kazemi, M.T., Golsorkhtabar, H., Beygi, M.H.A. and Gholamitabar, M., ‘Fracture properties of steel fiber reinforced high strength concrete using work of fracture and size effect methods’, Construction and Building Materials. **142** (2017) 482-489.

[3] Soutsos, M.N., Le, T.T. and Lampropoulos, A.P., ‘Flexural performance of fibre reinforced concrete made with steel and synthetic fibres’, Construction and building materials. **36** (2012) 704-710.

[4] Cho, B., Lee, J.H. and Back, S.Y., ‘Comparative study on the flexural performance of concrete reinforced with polypropylene and steel fibers’, Journal of The Korean Society of Civil Engineers. 34(6) (2014) 1677-1685.

[5] Olivito, R.S. and Zuccarello, F.A., ‘An experimental study on the tensile strength of steel fiber reinforced concrete’. Composites Part B: Engineering. **41**(3) (2010) 246-255.

[6] Thomas, J. and Ramaswamy, A., ‘Mechanical properties of steel fiber-reinforced concrete’. Journal of materials in civil engineering. 19(5) (2007) 385-392.

[7] Simoes, T., Costa, H., Dias-da-Costa, D. and Júlio, E.N.B.S., ‘Influence of fibres on the mechanical behaviour of fibre reinforced concrete matrixes. Construction and Building Materials. **137** (2017) 548-556.

[8] Lee, J.H., ‘Influence of concrete strength combined with fiber content in the residual flexural strengths of fiber reinforced concrete’, Composite Structures. **168** (2017) 216-225.

[9] Buratti, N., Mazzotti, C. and Savoia, M., 'Post-cracking behaviour of steel and macro-synthetic fibre-reinforced concretes', Construction and Building Materials. **25**(5) (2011) 2713-2722.

[10] BS EN 14651, 'Test Method for Metallic Fibre Concrete-Measuring the Flexural Tensile Strengh, British Standard Institute', UK, (2007) 1-20.

[11] BS EN 12390-6, 'Testing Hardened Concrete. Tensile Splitting Strength of Test Specimens'. British Standard Institution, London, (2009).

[12] BS EN 12390-2, 'Testing hardened concrete-Part 2: Making and curing specimens for strength tests', European Committee for Standardization, Brussels, (2009).

[13] ACI committee, ACI 544.1 R-96, 'State-of-the-art report on fiber reinforced concrete-Technical report', ACI Farmington Hills, Michigan, (2003).

[14] Mazaheripour, H., Ghanbarpour, S., Mirmoradi, S.H. and Hosseinpour, I., 'The effect of polypropylene fibers on the properties of fresh and hardened lightweight self-compacting concrete', Construction and Building Materials. **25**(1) (2011) 351-358.

[15] Cifuentes, H., García, F., Maeso, O. and Medina, F., 'Influence of the properties of polypropylene fibres on the fracture behaviour of low, normal and high-strength FRC', Construction and Building Materials. 45 (2013) 130-137.