

Vibrated and self-compacting fibre reinforced concrete: experimental investigation on the fibre orientation

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Abstract. In addition to the fibre type and content, the residual properties of fibre reinforced concrete are influenced by fibre orientation. Consequently, the performance fibre reinforced concrete can be affected by its fresh properties (workability, flowing capacity) and by casting and compaction processes adopted. This paper focuses on the study of the orientation of steel or macro-synthetic fibres in two materials characterized by very different fresh properties: vibrated and self-compacting concrete. Four rectangular slabs 1800 mm long, 925 mm wide and 100 mm high were produced changing concrete and fibre type. From each slab, eighteen small prisms (550 mm long) were firstly cut either orthogonal or parallel to casting direction and, secondly, notched and tested in bending according to EN 14651. Experimental results showed that the toughness properties of a thin slab significantly varies both in vibrated and self-compacting concrete, even if in case of self-compacting concrete this variation resulted higher. Steel fibres led to greater variability of results compared to polymer one, underlining a different fibre orientation. A discussion on the relative residual capacity measured on the prisms sawn from the slabs and the parameters obtained from standard specimens is performed.

1. Introduction

It is well known that the residual properties of Fibre Reinforced Concrete (FRC) are directly related to the number of fibres crossing the fracture surface. Many studies confirm that fibres are oriented in concrete due to and different factors [1, 2, 3], being the casting and compaction processes [4], the geometry and type of the fibres and the wall effect some of the more relevant; very fluid mixtures more susceptible and in self-compacting FRC it was proved the existence of significant flow effect [5, 6, 7, 8, 9]. The influence of these factors increases if thin elements are considered [10, 11].

As a consequence, the *fib* Model Code 2010 takes into consideration the fibres orientation in the design of FRC elements [12]. In a similar way German standard DadStb [13] considers orientation factors which varying from 0.5 to 1.

This paper shows the results of an experimental study performed with the aim to analyse the orientation of fibres on 100 mm depth slabs and its influences on the residual properties of FRC. Vibrated and self-compacting FRC mixtures are compared; in addition the fibre type (steel or macro-synthetic) is also considered as a variable. A comparison of the relative residual capacity measured on the prisms sawn from the slabs and the parameters obtained from standard specimens is performed.



2. Experimental program

2.1. Materials

Four Fibre Reinforced Concretes (FRC) were produced incorporating a same volume (0.5 %) of steel (s) or polymer (p) fibres. Table 1 shows the characteristics of the selected fibres which have similar aspect ratio.

With each fibre, one FRC compacted by vibration (V) and one self-compacting FRC (SC) were prepared; the fibre dosages were 40 kg/m³ and 4.6 kg/m³ for steel and polymer fibres respectively.

Table 2 shows the mixture proportions, the identifications and fresh properties of each FRC.

Table 1. Characteristics of steel and macro-synthetic fibres.

Fibre designation	s	p
Type	Steel	Polypropylene
Shape	Hooked-end	Embossed
Length l [mm]	50	54
Diameter Ø [mm]	0.80	0.81
Aspect Ratio l/Ø	63	67
Tensile Strength [MPa]	> 1100	> 552
Elastic Modulus [GPa]	210	6
Relative density [kg/m ³]	7.85	0.91

Table 2. Fiber Reinforced Concretes.

Concrete identification	Vs	Vp	SCs	SCp
Concrete type	Vibrated (V)		Self-compacting (SC)	
Fibre type	s	p	s	p
Mixture proportions				
Portland cement CEM II/A-LL 42.5R [kg/m ³]	430		400	
Calcium carbonate filler [kg/m ³]	-		200	
Natural sand 0-4 mm [kg/m ³]	990		860	
Coarse aggregate 4-12 mm [kg/m ³]	725		725	
Water/cement ratio	0.46		0.44	
Superplasticizer (% of cement content)	0.2%		1.1%	
Fibre content [kg/m ³]	40	4.6	40	4.6
Fresh properties				
Slump [mm]	80	75		
Slump flow: diameter [mm] / flow time [s]			720 / 2.9	700 / 4.6

2.2. Test details

One 925 x 1800 x 100 mm slab, three 150 x 600 x 100 mm prisms as reference samples (RS) and four cubes 150 mm side were cast with each concrete. Slabs Vs and Vp were compacted by internal vibration, while the corresponding RS were compacted by external vibration. Slabs SCs and SCp were cast from the smaller side flowing along the 1800 mm length; the related RS were cast from its centre as it is indicated in the EN14651 standard [14].

All specimens were kept protected to avoid water evaporation during 1 day. After demoulded the specimens, moist curing was applied during 2 weeks and then they remains in outdoors conditions (relative humidity 70 ± 10 %, temperature 15 ± 10 °C).

With the aim of comparing the linear shrinkage of different mixtures, one RS of each concrete was introduced in a dry room (relative humidity 50 ± 3 %, temperature 20 ± 2 °C) at the age of 14 days; a mechanical length comparator with a precision of 0.00254 mm was used to perform the measurements.

Prisms of 100 x 150 x 550 mm were sawn from each slab in orthogonal (O) and parallel (P) directions of the flow one as it is indicated in Figure 1 (the arrow represents pouring point and casting direction). The samples were identified by a progressive number followed by cutting direction (O or P). These sawn prisms and the RS were notched and tested in bending following the guidelines of the EN 14651 Standard [14]. The specimens were turned on 90° for testing, thus the depth was 150 mm and the unique difference with the standard prisms was the beam width (100 mm instead of 150 mm). Bending tests were performed at 3 months. As results the limit of proportionality (f_L), and the residual flexural tensile strengths $f_{R,1}$, $f_{R,2}$, $f_{R,3}$ and $f_{R,4}$ corresponding to a Crack Mouth Opening Displacement (CMOD) value of 0.5, 1.5, 2.5 and 3.5 mm respectively were calculated. Figure 2 shows the instrumentation details of bending tests. At the end of bending tests, the number of fibres on the fracture surfaces was counted to determine the density of fibres.

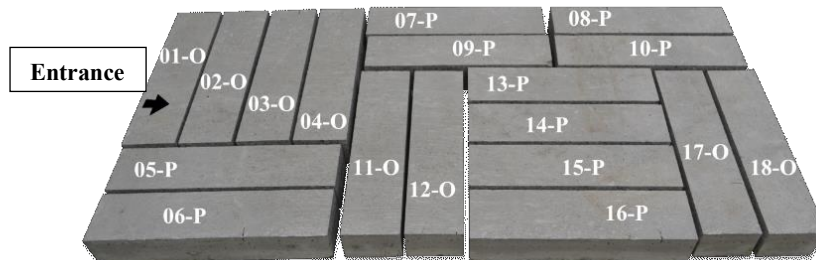


Figure 1. Schema of slabs and sample identification.



Figure 2. Bending tests.

3. Experimental results and discussion

As expected, no significant differences in drying shrinkage were found as the coarse aggregate volume was equal in all mixtures (see Figure 3).

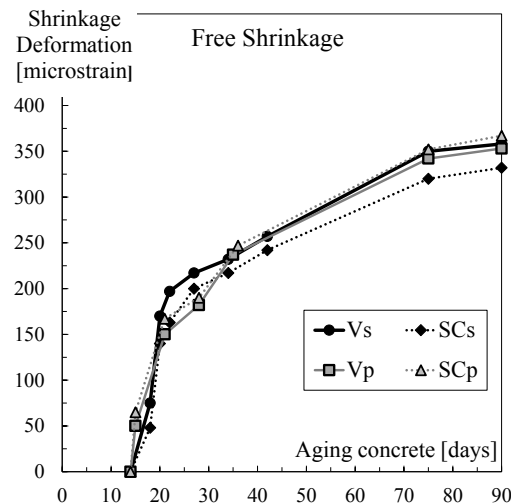


Figure 3. Free shrinkage deformation for vibrated (V) and self-compacting (SC) FRC.

Table 3 presents the mechanical properties of each FRC in terms of the mean values of cube compressive strength and flexural tensile properties measured on the reference specimens (RS), the limit of proportionality (f_L) and the residual strengths $f_{R,1}$ and $f_{R,3}$; the coefficients of variation (CV) are provided between brackets). In addition, and based on the bending properties, the FRC class according to the *fib* Model Code 2010 [12] were indicated. As it can be seen, vibrated FRC were characterized by a cube compressive strength near 61 MPa, while in the case of self-compacting FRC it was approximately 66 MPa. As expected, while the fibre type and content has no significant effect on compressive strength, the bending properties are strongly modified. However, for the same type and content of fibre, the post-cracking response is almost similar in vibrated and self-compacting FRC although the FRC had very different workability properties; when the FRC classes are considered no differences were found when V or SC FRC are compared.

Table 3. Mechanical properties of each concrete measured on standard specimens.

FRC	$f_{c,cube}$ [MPa]	f_L [MPa]	$f_{R,1}$ [MPa]	$f_{R,3}$ [MPa]	FRC class
Vs	62.7 (0.01)	5.74 (0.02)	6.71 (0.09)	6.16 (0.15)	6c
SCs	67.8 (0.06)	5.55 (0.04)	6.25 (0.19)	6.03 (0.20)	6c
Vp	59.5 (0.01)	5.64 (0.01)	1.94 (0.33)	2.76 (0.32)	1.5e
SCp	65.8 (0.03)	5.46 (0.07)	1.91 (0.14)	2.87 (0.23)	1.5e

As is well known the residual properties of FRC are directly related to the number of fibres crossing the fracture surface. With the aim of analysing the effect of fresh concrete properties on the orientation of fibres, Figure 4 compares the stress - CMOD curves obtained from the prisms sawn in orthogonal (O) and parallel (P) directions for the case of steel FRC (Vs and SCs). In a similar way, Figure 5 presents the stress - CMOD curves obtained on the prisms sawn from the slabs cast with macro-synthetic FRC (Vp and SCp). As a reference the stress - CMOD curves of the standard prisms (RS) are included in each plot.

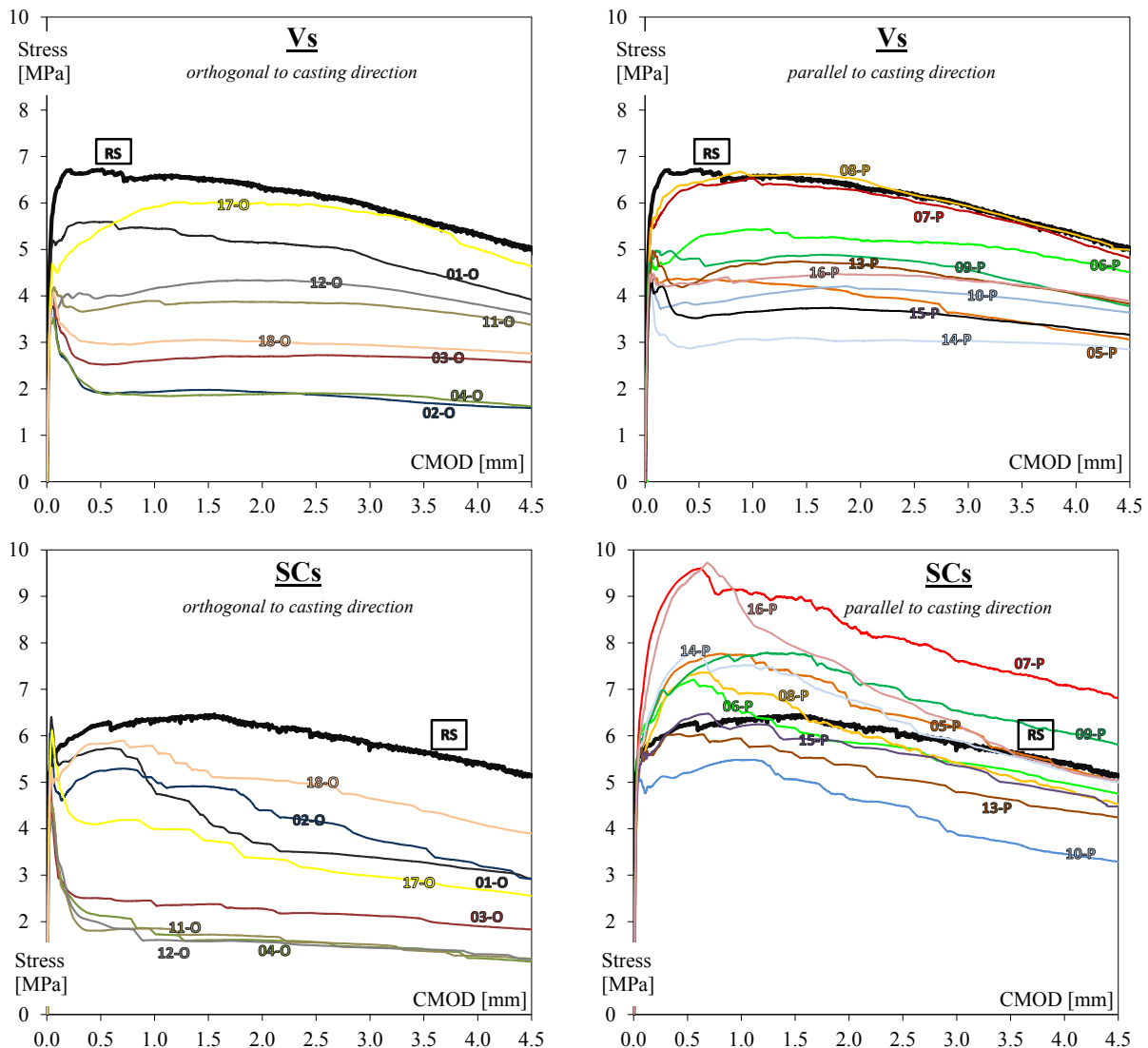


Figure 4. Nominal stress vs. CMOD curves for Vs and SCs.

It can be seen a great variability in the post-peak response of FRC, which is higher than the own variability usually found between standard specimens. In this case the orientation of fibres is strongly affected by wall and flow effects. Analyzing the results from steel FRC slabs, it appears that generally parallel (P) prisms show better residual properties than orthogonal (O) ones. In vibrated FRC all stress vs. CMOD curves are equal or lower than those corresponding to the RS indicating that the standard tests can be assumed as an optimal performance. The low performances can be associated to a lower content of fibres crossing the fracture surfaces. Although again in self-compacting FRC P prisms show better residual properties than O ones, the differences are significantly increased and in this case most parallel prisms shows better performance than RS prisms; this fact clearly demonstrates the contribution of flow effects on fibre orientation. The curves of lower residual capacity correspond to O prisms obtained from the zone of higher flow rate or P prisms close to the end of the mould, where the wall effect of the end modifies the orientation of the fibres.

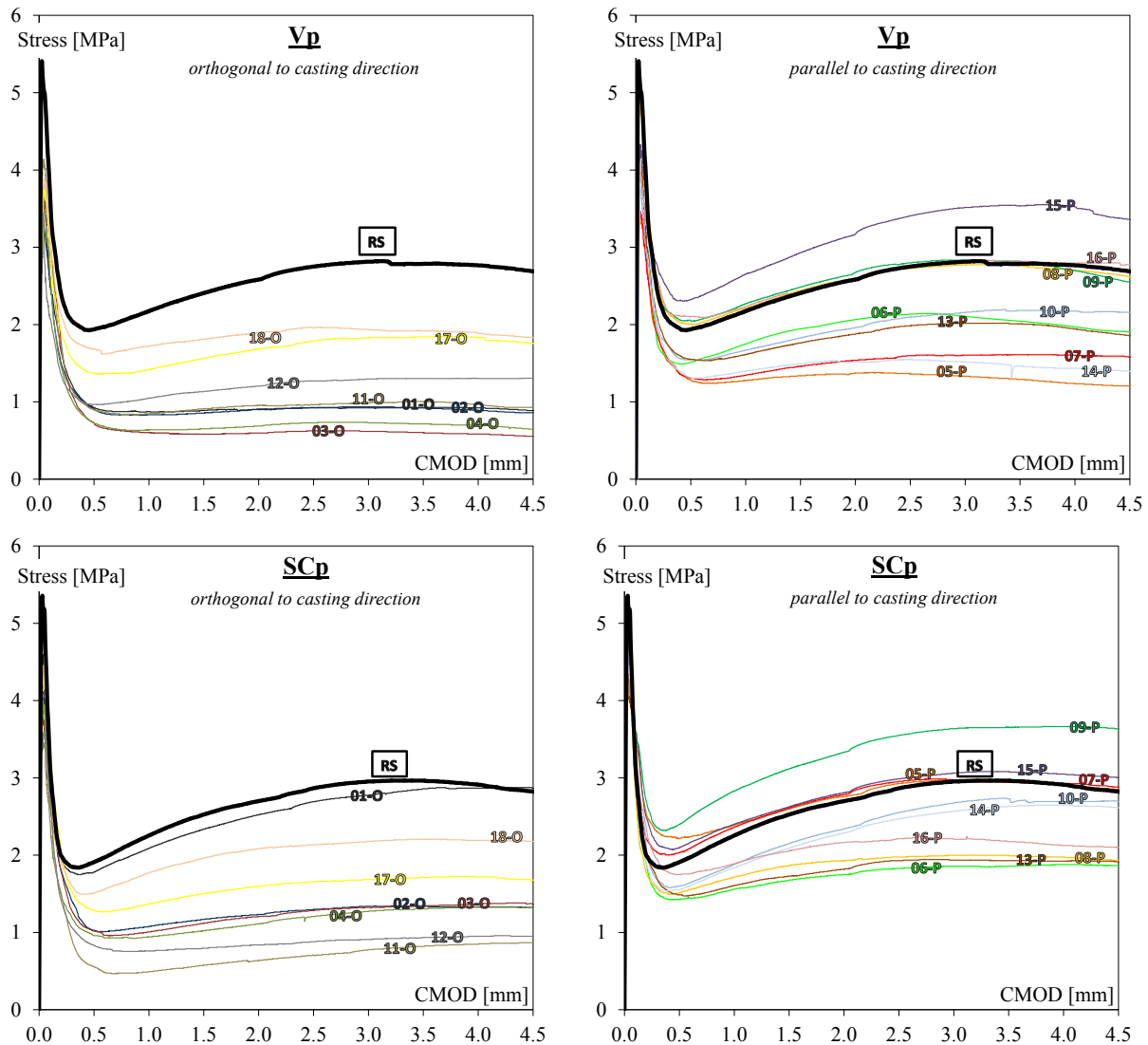


Figure 5. Nominal stress vs. CMOD curves for Vp and SCp.

Regarding polymer FRC, Figure 5 also shows a better post-peak performance of P-prisms than O-prisms. Nevertheless there are not strong differences when Vp and SCp curves are compared. In both cases the RS curves show the highest residual capacity in orthogonal specimens and near the middle post-peak behaviour in the case of parallel prisms.

Table 4 shows compares the values of the residual flexural tensile strength $f_{R,3}$ measured on the prisms sawn from the slabs with the results obtained from the reference specimens (RS); the mean values corresponding to orthogonal and parallel samples (O-prisms, P-prisms) are also given as relative values of RS. The CV are expressed between brackets. As it can be seen, the variability in sawn prisms results increases when comparing with RS results as wall and flow (mainly in the case of SC) effects modify the orientation of fibres in different sectors of the slabs. The lowest CV correspond to P-prisms and no significant differences in variability were found between the four FRC studied. Analysing the relative values it appears that the overall performance is near 70 % of the residual stresses measured on standard beams; O-prisms show $f_{R,3}$ near 50 % of RS and in the case of P-prisms

it can be clearly seen that the residual capacity is higher in SC FRC than in V FRC making evident the flow effect mainly in the case of steel fibres.

Table 4. Mean values of the residual flexural tensile strength $f_{R,3}$ of samples obtained from the slabs.

Samples	$f_{R,3}$ [MPa]			
	Vs	SCs	Vp	SCp
RS	6.16 (0.15)	6.03 (0.20)	2.76 (0.32)	2.87 (0.23)
O-prisms	3.57 (0.41)	2.81 (0.47)	1.15 (0.47)	1.48 (0.44)
P-prisms	4.56 (0.21)	6.08 (0.16)	2.24 (0.30)	2.54 (0.22)
Mean (O, P)	4.12 (0.31)	4.62 (0.43)	1.75 (0.44)	2.07 (0.40)
Relative values				
O/RS	0.58	0.47	0.42	0.52
P/RS	0.74	1.01	0.81	0.89
Mean/RS	0.67	0.76	0.63	0.72

As it is well known, the residual properties of FRC are directly related to the number of fibres crossing the fracture surface. Figure 6 shows the variation of $f_{R,1}$ and $f_{R,3}$ with the fibre density measured on the fracture surfaces of the prisms after bending tests, for steel FRC (Vs, SCs). It can be seen that there is a wide range of variation of fibre density between 0.3 and 1 fibres/cm². Both Vs and SCs specimens follow similar tendencies being the variability a bit higher in the case of SCs.

Analogous conclusions can be obtained from Figure 7, which shows the variation of $f_{R,1}$ and $f_{R,3}$ with the fibre density for polymer FRC (Vp, SCp); in this case the fibre densities varied between 0.2 and 0.8 fibres/cm², and no differences can be appreciated between vibrated or self-compacting FRC.

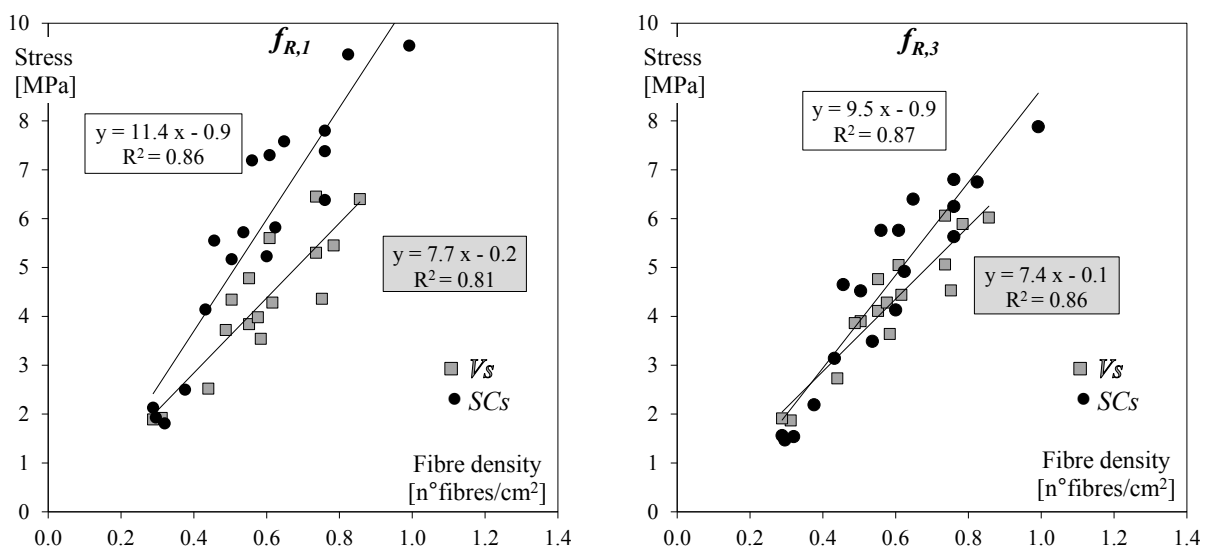


Figure 6. Residual strength $f_{R,1}$ and $f_{R,3}$ vs. fibre density on sample fracture surface for Vs and SCs.

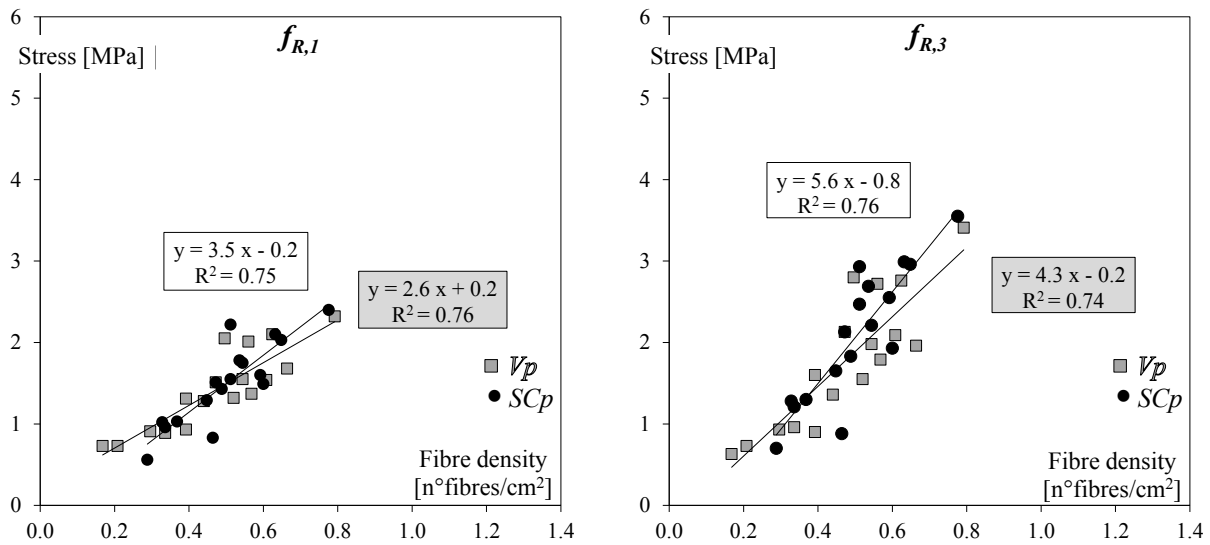


Figure 7. Residual strength $f_{R,1}$ and $f_{R,3}$ vs. fibre density on sample fracture surface for Vp and SCp.

Figure 8 and Figure 9 show the variation of $f_{R,3}$ for steel and polymer fibres in orthogonal ($f_{R,3y}$) and parallel directions ($f_{R,3x}$) respect to casting one. The residual mechanical properties of FRC slabs are different in the two considered directions, and these differences increase in SC-FRC and in the case of steel fibres. Wall effects always appeared in both directions (more evident in prisms orthogonally oriented to casting direction ($f_{R,3y}$)). As expected, a flow effect appeared in SC-FRC, leading to higher performance of $f_{R,3x}$ compared to V-FRC, mainly in the case of steel fibres.

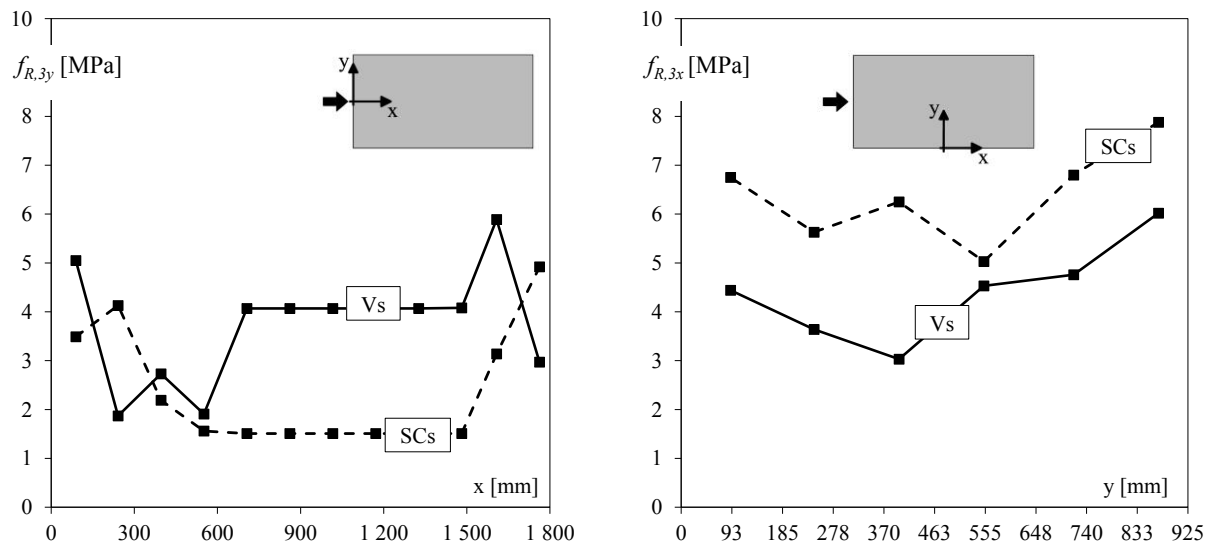


Figure 8. Variation of the residual flexural tensile strength $f_{R,3}$ in Vs and SCs slabs.

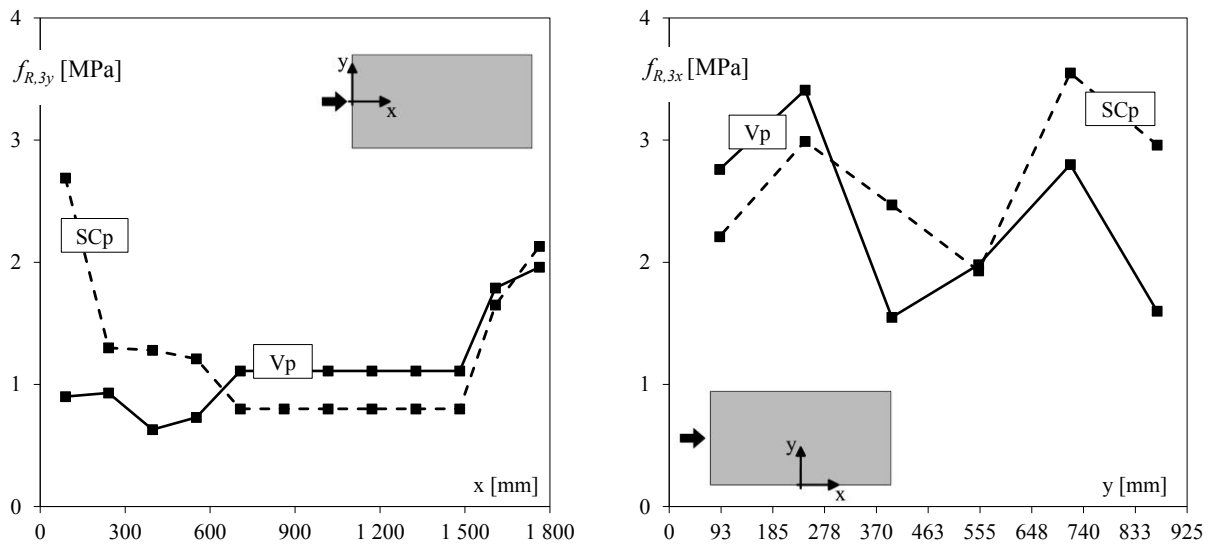


Figure 9. Variation of the residual flexural tensile strength $f_{R,3}$ in Vp and SCp slabs.

Finally, Figure 10 compares the residual bending parameters obtained from the sawn prisms with those obtained from the reference samples. In the case of steel FRC increases the variability in test results between V-FRC and SC-FRC, mainly in terms of the maximum values, which means that the flow effect is more pronounced with rigid fibres. On the contrary, both minimum and maximum values are similar in the case of macro-synthetic FRC for vibrated and self-compacting FRC.

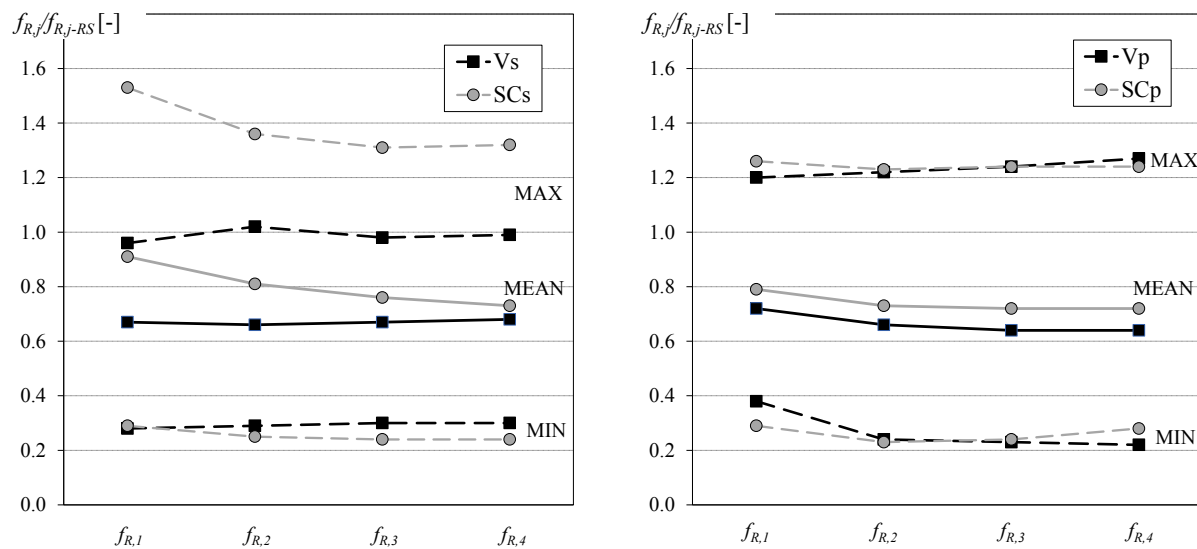


Figure 10. Comparison between residual properties of slabs and reference samples.

4. Concluding remarks

The orientation of fibres in 100 mm depth slabs cast with vibrated (V-FRC) and self-compacting (SC-FRC) steel and macro-synthetic FRC was studied. The following conclusions might be drawn:

- Wall and flow effects that modify the orientation of fibres along the slabs were verified. As a consequence, a great variability in the residual bending capacity in different directions and sectors of the slabs was found.
- Differences in fibre orientation increase in the case of SC-FRC, mainly if steel (more rigid) fibres are used.
- The mean values of the post-peak capacity found for the prisms sawn from the slabs were near 70% of the residual strengths measured on standard specimens.
- The residual properties were greater in the prisms parallel to the casting direction. In the prisms orthogonally oriented with respect to the casting direction the mean residual capacity decrease near 50% when compared to that obtained from standard specimens.

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