Third International Conference on Sustainable Construction Materials and Technologies   http://www.claisse.info/Proceedings.htm

The Rheological and Mechanical Properties of the *SRCC* Composites

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ABSTRACT

The main problem of *SRCC* (safe rope effect cement composite) are poor rheological properties of the mix. This paper presents the attempt to use fiber reinforcement to ensure that *SRCC* composites maintain similar rheological properties to those of self consolidating concrete *SCC*. The search was concentrated on finding the compromise between mechanical and rheological properties. The hybrid reinforcement was also proposed to maximize mechanical properties of *SRCC*. The rheological properties of the mixes were controlled by *D*-cube test (flow, slump, cone immersion and electrical resistance). This method makes it possible to observe the sedimentation of aggregates and fibers and to optimize different admixtures and additives and the rheological properties of cement mixes.

Keywords. *SRCC***,** hybrid reinforcement, fibers, rheology, electrical resistance

INTRODUCTION

The mechanical properties of cement composites are often determined by the rheological parameters of the mix. Sedimentation or not homogeneously dispersed fibers may provide wrong conclusions, therefore the information about rheological properties of the mix is very important, [Banfill et al., 2006; Ozyurt et al. 2007; Martinie et al, 2010; Ding et al, 2010].

There are different methods of controlling rheological properties such as: the slump test, *Ve-Be*, flow table, *L*-box, *J*-ring test, *V*-funnel, Abrams cone test, cone for mortars, viscomates and rheometers and others. A development of cement composites causes changes in the methods of measurement of rheological properties. As it was noticed, [Logoń,2012], the main problem is that there is no one simple method to control the rheological properties of paste, mortar and concrete mixes.

The first attempts to control the rheological properties with *D*-cube tests were made [Logoń,2012]. It was found that it is a good method for liquid mixes but not good enough for concrete mixes with very poor rheological properties. A review of the remaining relevant literature shows that there are no established methods to measure the resistivity of fresh mixes in order to control rheological properties of cement mixes [Ciao et al, 2008; Salem, 2002; Xiao et al, 2007]. The electrical resistance *D*-cube test in this paper was limited to the measurement of resistance in the upper and lower part of the mix, which enables the assessment of homogeneous dispersion of the components or their sedimentation.

The *SRCC* (safe rope effect cement composite) requires a high amount of long fibers which decrease significantly rheological properties [Logoń, 2011]. The paper presents that too many fibers prevent homogeneous dispersion in the matrix and decrease mechanical properties. It is necessary to search for fibers with such a modified surface, flexibility and geometry that worsen the rheological properties of the mix to the smallest extent.

An attempt to obtain *SRCC* with the rheological properties corresponding to *SCC* (self consolidating concrete) was made. The replacement of half of the maximum volume of long fibers with high-strength short flat smooth steel ones enables to improve significantly rheological properties and increase the load corresponding to the firs crack. The results are quite good but it is necessary to find compromise between rheological and mechanical properties.

EXPERIMENTAL

Materials. The materials for preparation of the cement composites: Portland cement (*c*) *CEM I 42,5R* – 550 kg/m^3, silica fume (10%c), fly ash (20%c), sand and coarse aggregates <16 mm -1475kg/m^3, superplasticizer (*SP*), tap water (*w*), w/c = 0.35.
The composites were reinforced with randomly dispersed fibers:
- synthetic structural polypropylene (*R*) fibers (compliance with *ASTM C-1116*): specific weight 0.91 kg/dm^3, flexural strength f_t = 620-758 MPa, E = 4.9 GPa, l = 54 mm, equivalent diameter 0.48 mm, l / d = 113.
- steel flat (*S*) fibers (compliance with *ASTM C-1116*): specific weight 7.85 kg/dm^3, flexural strength f_t = 1100 MPa, E = 210 GPa, l = 3 mm, diameter 0.175 mm, l/d = 17.1

Mixture proportions and specimen fabrication. To reduce the influence of uncontrolled factors on the properties of fresh mixes, all steps in the procedure of mix preparation and rheological measurements were kept the same.

Table 1. Specimens: concrete *C* and paste *P*

Composite	Components
C	*C* (matrix - concrete)
C1Sp	*C+ sup.(Sp* 1%*c)*
C2Sp	*C + sup.(Sp* 2%*c)*
C3Sp	*C + sup.(Sp* 3%*c)*
C2R	*C + fib.*$(R=2\%V_f)$*+Sp2%c*
C1S1R	*C+fib.*$(S=1\%V_f, R=1\%V_f)$*+Sp2%c*
C1S2R	*C+fib.*$(S=1\%V_f, R=2\%V_f)$*+Sp2%c*
P6R	*P (paste)+ fib.*$(R=6\%V_f)$*+Sp2%c*

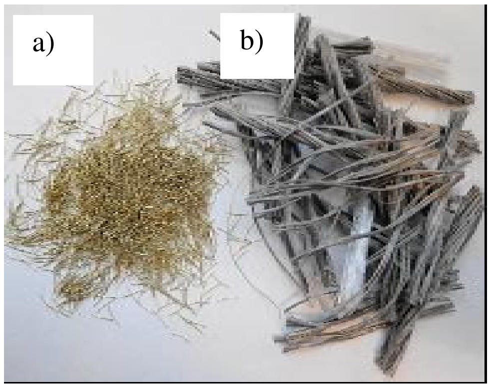

Figure 1. Fibers: a) steel flat (*S*) 6 mm, b) structural polypropylene (*R*) 54 mm

Electrical resistance test. For electrical resistance measurements an *ELC-3131D* meter and two copper electrodes were used (ϕ 6 mm), fig.2. Directly after filling the cube (150x150x150mm) with the mix, the bar (ϕ 15 mm) was plunged 15 times in the mix, then the surface was smoothed and measurement was conducted. For sedimentation the measurement was at upper and lower part of the cube R_1 and R_2.

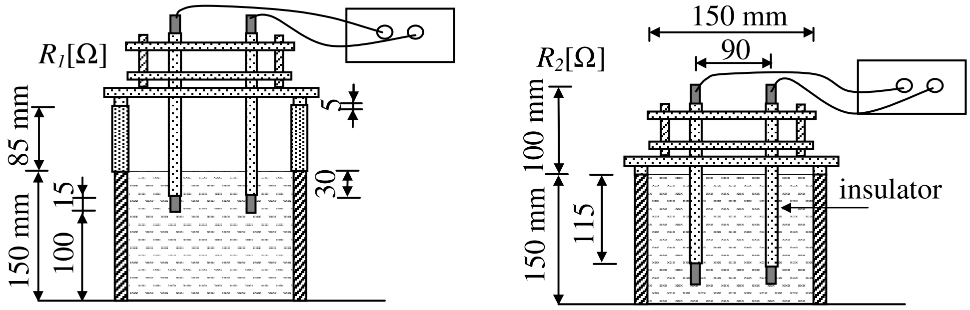

Figure 2. Electrical resistance measurement at upper R_1 and lower part R_2

***D*-cube test.** Directly after filling the cube with the mix, the bar was plunged 15 times in the mix and the immersion of Novikov (I_N) cone and *D*-cone (I_D) in the mix placed in the cube was used (*D*-cone = Novikov cone+200g). After raising the cube the slump h_c, flow diameter d_c, and the distance between the edge of the flow and the additives d_x were measured. The assessment of the homogeneity of the fibers dispersion and water bleeding b_L was also possible (in the case of poor rheological properties the slide of the mix can be noticed).

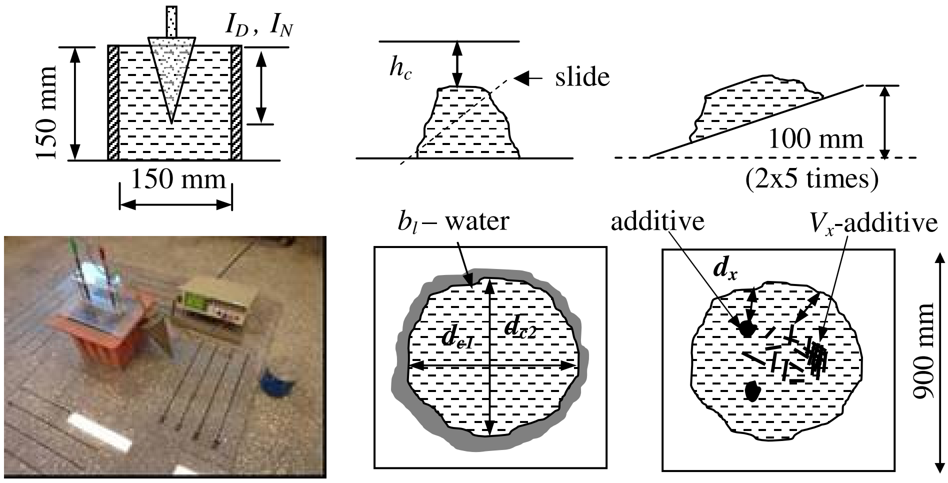

Figure 3. The measurement of rheological parameters using cube flow test

The polycarbonate plate (specific weight 1.2 Mg/m^3) with a diameter of 900x900 mm (thickness 10 mm) can be used for the *D*-cube test, fig.3. Additionally, the measurements of *D*-cube slump and flow were repeated after one of the four edges of the plate was lifted 10cm high and then dropped (on a concrete floor) 5 and 10 times. Additionally, in order to compare the results a slump of Abrams cone was measured (slump h_A , flow d_A) as well as the immersion of Novikov cone (I_N).

Bending test. Four-point bending tests were carried out on the testing machine with closed-loop servo control displacement, fig.4. The load-deflection curves were obtained according to *ASTM C* 1018 but the test was based on the measurement of the displacement of crosshead. More details about bending test and mechanical results are shown in [Logoń, *SCMT3* 2013, *Hybrid Reinforcement in SRCC Concrete.*].

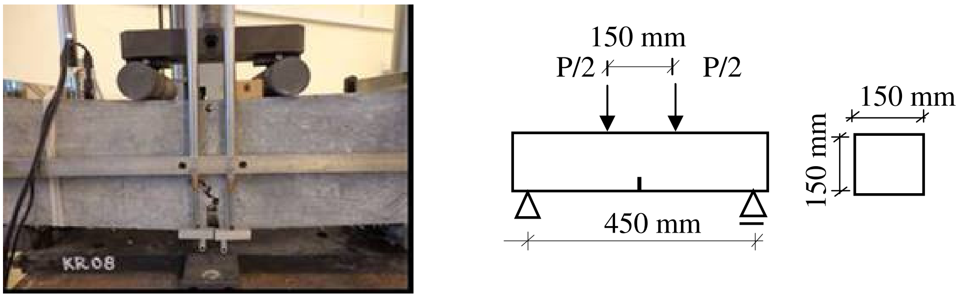

Figure 4. Four-point bending test

TESTS RESULTS

The rheological properties of cement mixes are shown in tab.2 and in fig.5. The influence of the amount of superplasticizer was tested on concrete with 1% - *C1Sp*, 2% - *C2Sp* and 3% - *C3Sp*. As it can be noticed 1% *Sp* in concrete *C1Sp* corresponds to the lowest class *SCC* mix (Abrams *SF1*=550mm). Two percent of *Sp* improves rheological parameters and this amount was kept in mixes with randomly dispersed fibers.

Table 2. Influence of superplasticizer and fibers volume on the rheological parameters

Composite	Resistance	Abrams		Nov.	*D* cube - test				
	R_1 ; R_2	h_A	d_A	I_N	I_D	$h_c/h_{c5}/h_{c10}$	$d_c/d_{c5}/d_{c10}$	d_f/b_l	disp
	[Ω]	10 [mm]			10 [mm]				
C1Sp	179 ≈177	-	55	8.5	11	9.5/10/11	33/35/37	0/0	+
C2Sp	160 ≈161	-	73	12	13	12/12.5/13	44/43/44	0/0	+
C3Sp	185 > 155	-	80	>14	>14	12/13/13	55/68/62	0/0	+
C1S1R	80 ≈ 83	18	26	5.5	6.3	4/6/10	19.5/22/24	0/0	+/-
**C 1S1R*	97 > 82	21	50	8	9.5	6.5/8/10.5	39/47/50	1/1	+/-
C2R	170 ≈ 170	6	0	1.5	3.3	2/3.5/7.5	16.5/19/20	0/0	-
C1S2R	100 ≈ 99	4	0	1	3	1/3/4.5	15.3/16/18	0/0	-
P6R	Not possible to measure								

* addition of 3% *Sp*

As it can be observed in fig.5, 3% of *Sp* are too much for the matrix and result in the irregular edge of the mix *C3Sp* and the differences in resistance R_1=185Ω and R_2=155Ω indicate sedimentation of the components.

The maximum volume of long fibers in concrete *C2R* was 2% and in paste *P6R* 6%. It is difficult to mix fibers with maximum V_f. Whereas the rheological test for concrete was possible, it could not be done for paste.

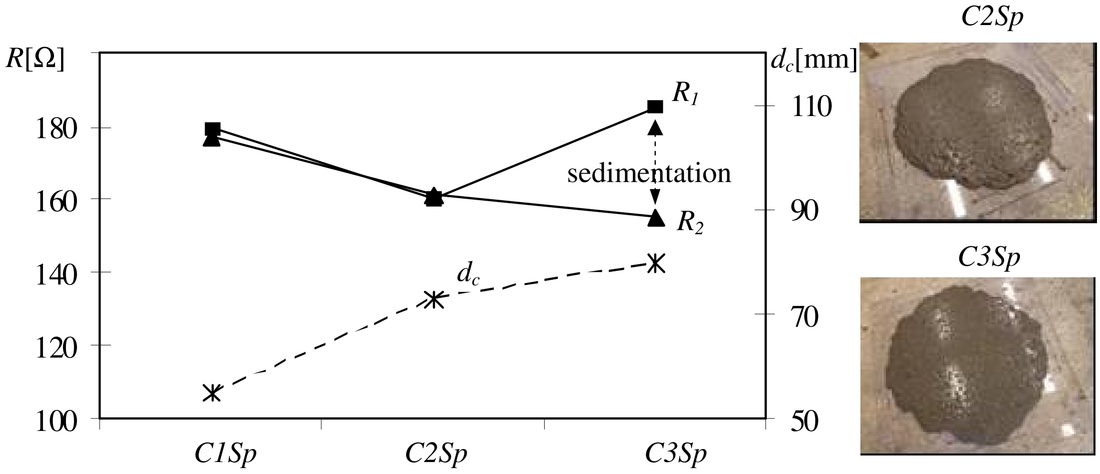

Figure 5. The *D*-cube resistance R_1,R_2 test and flow test d_c of concrete (matrix) with 1, 2 and 3%*Sp*

The replacement of 1% structural polypropylene long fibers with short steel ones improves significantly the rheological parameters (compare *C2R* with *C1S1R*), tab. 2. The addition of 3% of *Sp* to **C1S1R* results in rheological properties corresponding to *SCC* (*SF1*=550mm) but 10mm paste bleeding was observed. Better results can be achieved by using 10% of fly ash instead of 20%, which reduces viscosity of the mix; the amount of *Sp* should not exceed 2%.

The surface of *C1S1R* and *C2R* composites after bending test is shown in fig.6. A high fibers volume can be noticed in *C2R* concrete. There is no place for more fibers and there is not enough paste to anchor reinforcement. In *C1S1R* composite, where there are fewer fibers, they can be better dispersed and anchored; the better dispersing of fibers is confirmed by the rheological parameters in tab.2

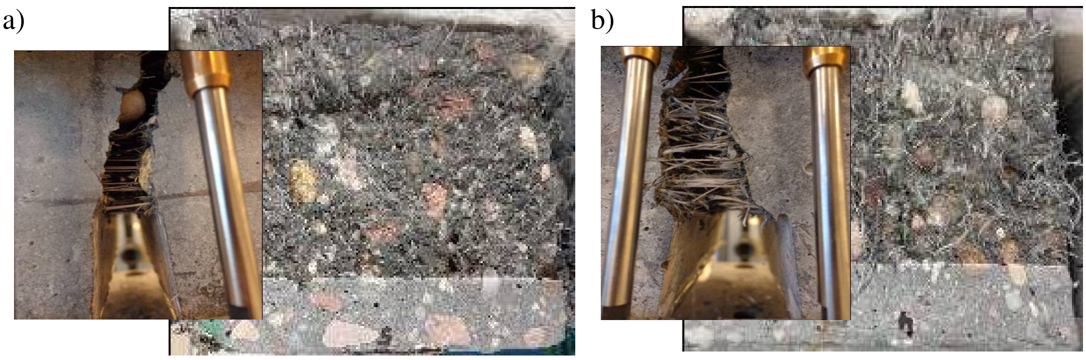

Figure 6. The surface of the composites after bending test: a) *C1S1R*, b) *C2R*

The bending tests results are presented in figure 7 and 8. More information on mechanical properties is presented in [Logoń, *ACMT3* 2013]. Fig. 7 shows displacement in relation to the neutral axis. It can be noticed (fig. 7a and 7b) that in the case of strong deflection each edge of the beam is displaced differently. The best results of displacement are found in paste with the maximum fiber volume V_f=6%. As it can be observed there are too many fibers in the volume of the mix, fig. 7c. Two macrocracks were observed in the multicracking stage of paste *P6R* bending test, fig. 7a. Macrocracks are stopped and microcracking increases up to the maximum load, fig.7b.

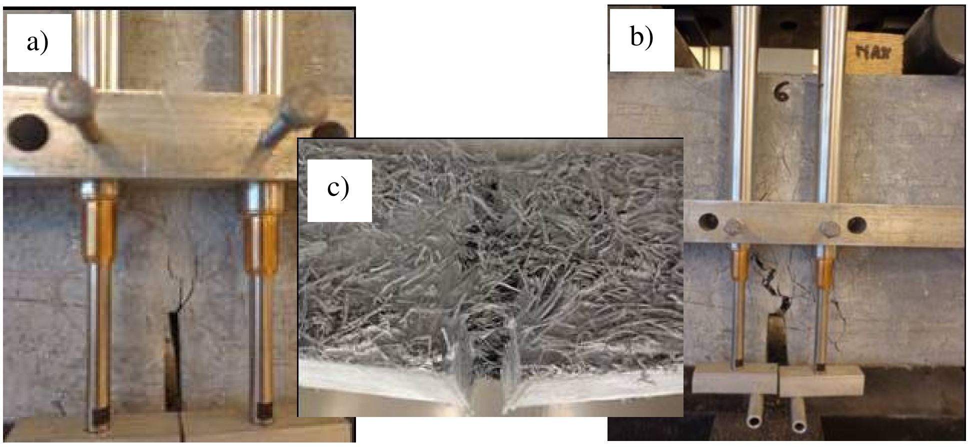

Figure 7. Four-point bending test for paste V_f=6%, *P6R*: a) the multicracking stage, b) the maximum load c) after test (the opposite side)

The load deflection curves of tested composites are shown in fig.8. The *C*, *C2R* are characterized by the same first crack load f_{cr}. Higher strength of the matrix in pastes increases f_{cr} but rheology of the mix is poor.

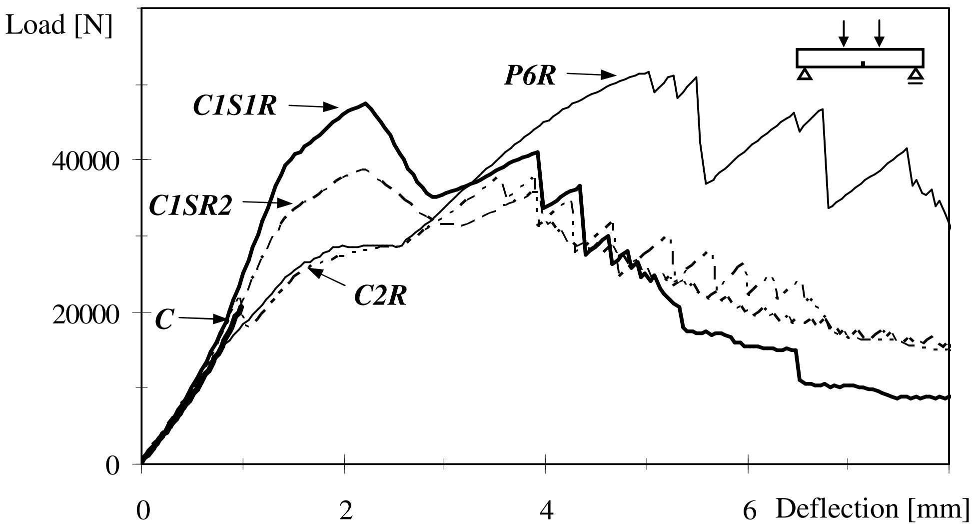

Figure 8. The load-deflection curves for tested composites

The addition of 1% of short steel fibers also increases f_{cr} but keeps maximum load the same as in *C1SR2* though with lower deflection. The best results of tests analyzing mechanical and rheological properties of the mix are achieved in the case of *C1S1R*.

DISCUSSION

The main problem of cement composites with randomly dispersed fibers are the rheological properties of the mixes. Sedimentation or poor dispersion of fibers results in an incorrect interpretation of mechanical properties. Rheological properties of the *SRSS* matrix should correspond to those of *SCC* composites. The presented methods of controlling rheological properties enable the optimization of the composition of the mix. The differences in resistance in *D*-cube test indicate sedimentation in composites. The Abrams and *D*-cube tests, especially corresponding to high viscosity mixes, give insufficient information about this phenomenon. As it can be noticed an irregular circle of the flow (*C3Sp*, fig. 5) is the information about possible sedimentation, which was confirmed by *D*-cube resistance test. The visual assessment of the dispersion of aggregates, fibers and additives on the plate (using Abrams and *D*-cube flow tests) is not sufficient to asses sedimentation over a longer period of time. *D*-cone immersion test is a supporting method of assessment of consistency which can also be used while forming concrete in moulds at a construction site. The proposed methods (*D*-cube test) of assessing fibers dispersion are very simple, inexpensive and do not require experience to conduct the measurements. The majority of researchers agree that the interpretation of mechanical effects without rheological properties of the mix may lead to wrong conclusions but only few give this information in their papers.

The *SRCC* requires optimum fiber volume $V_{min}<V_f<V_{max}$. The V_f is determined by the mechanical and rheological properties. The results of an attempt to find a compromise between rheological and mechanical properties were quite good. Fibers require good fiber-matrix bond particularly in *SRCC,* therefore an insufficient amount of paste in the concrete or an excessive amount of reinforcement decreases mechanical and rheological properties and makes it impossible to mix the fibers. The addition of short steel fibers increases f_{cr} and does not increase bending strength. The replacement in *C2R* composite of half of the long fibers *R* with the short ones *S* improves significantly rheological properties (comparison of *C2R* and *C1S1R,* tab.2). Using 3% of *Sp* enables to obtain mix **C1S1R* corresponding to the lowest class of *SCC* concrete (flow *SF1*=550mm). Such a high amount of *Sp* in matrix causes sedimentation and in hybrid reinforced composite – small water bleeding, and separation of the paste from the mix can be observed. The replacement of long dispersed reinforcement with short *HP* fibers with smooth surface (pitch–based carbon fibers can improve f_{cr} and multicracking effect but decrease rheological ones) facilitates the dispersion of fibers, increases f_{cr}, and ensures good compromise between rheological and mechanical properties. This work is the first step to find rheological-mechanical compromise and there are many possibilities to improve it. More details on mechanical results are presented in [Logoń, *SCMT3* 2013].

The maximum fibers volume *R* in cement pastes is about 6 % (*P6R*) while for concrete it is 2% (*C2R*). The *P6R* composite is characterized by the best deflection and maximum load. This composite was reinforced with the maximum fiber volume and rheological parameters were impossible to determine. The results obtained in concrete indicate that similar effects can be achieved in paste, where the replacement of half of long fibers with HP short ones will also increase load corresponding to the first crack and the maximum load with lower deflection as well as significantly improve rheological properties. The highly deflected specimens make it difficult to measure displacement of *SRCC* beams; each of the four edges of a beam are displaced differently, therefore the deflection until the first crack appearance should be measured in relation to the neutral axis (corresponding to *ASTM C 1018*) and after that in relation to the threshold movement.

CONCLUSIONS

The Abrams cone and *D*-cube flow tests are not sufficient to assess sedimentation of cement mixes. It was confirmed that differences R_1, R_2 (exceeding 10%) in electrical resistance *D*-cube test indicate sedimentation or heterogeneous dispersion of components.

The replacement of long fibers with shorter ones in *SRCC* (with smooth surface) improves significantly rheological properties and increases mechanical properties (with lower deflection).

The compromise between rheological and mechanical properties can result in *SRCC* cement mixes with good rheological properties approximately corresponding to the lowest class of *SCC* concrete.

To achieve good rheological properties and mechanical effects of *SRCC* it is necessary to have the optimum volume of fibers $V_{min} < V_f < V_{max}$ that have to be properly dispersed, which requires a higher amount of binder in concrete.

Too many fibers make dispersion of fibers impossible and decrease the fiber–matrix anchor and mechanical effects in *SRCC*.

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