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Hybrid Reinforcement in *SRCC* Concrete

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ABSTRACT

The rapid destruction of brittle concrete can be limited by *SRCC* composites (safe rope effect cement composite). The rope effect results in a highly deflected damaged specimen with multicracking effect and with post-peak load at bending test exceeding that corresponding to the first crack. This enables to obtain cement composite with the ability to absorb additional energy corresponding to the rope effect after the appearance of the macrocrack. The *SRCC* cement composites - paste, mortar and concrete - were presented in the previous papers. This paper shows different effects of the strengthening of cement concrete with dispersed hybrid reinforcement. The possibility to control multicracking and the crack propagation process using hybrid fiber reinforcement effect for *SRCC* composites was presented. The assessment of the reinforcement effects was also proposed.

Keywords. *SRCC,* safe composite, the rope effect, hybrid fibers reinforcement

INTRODUCTION

The cement composites development results in the increase of compressive strength without significantly improving bending strength, [Brandt, 2009]. The brittleness of cement composites causes rapid destruction, which is particularly disadvantageous in high-strength cement composites. There are attempts to limit brittleness by increasing the flexural strength using various fibers and additives in *HPFRC* composites, [Glinicki, Brandt, 2007; Naaman, Reinhardt, 2003]. The reinforcement of cement composites with randomly distributed fibers improves the toughness of paste, mortar and concrete, [Bentur, Mindess, 1990]. It was noticed that the best results with respect to flexural strength and toughness were achieved with high-strength matrix and fibers. Various papers show that rheological properties influence mechanical ones. The influence of fiber orientation on mechanical properties was also noticed in previous papers [Logoń, 2011].

The destruction of *HPC* pastes, mortar and concrete can be limited by means of the multicracking effect, the rope effect and crack propagation control in *HPFRC*. The multicracking effect is achieved mainly with the use of short (but also long) fibers and the control of crack propagation after reaching maximum load - with the use of long ones, [Logoń, 2012]. The synergy effect resulting in toughness enhancement in the hybrid fibers system was noticed [Banthia, Soleimani, 2005]. The hybrid reinforcement causes better results due to the synergetic interaction of the fibers and the matrix, [Qian, Stroeven, 2000].

It was observed that the hybrid reinforcement (carbon short and steel long fibers) was the most effective for the improvement of strength and flexural toughness of concrete. These effects indicate that it is possible to increase mechanical effects in *SRCC* using hybrid reinforcement.

There are different methods of calculating flexural toughness: *JSCE* method [*JCI*, 2007], *ASTM C*1018 toughness indices [*ASTM 1018*, 1992] and *RILEM* recommendations. Despite a number of formulas for the calculation of the reinforcement effect, new methods and modifications of the existing ones are still being proposed.

This paper presents *SRCC* safe rope effect cement concrete. A damaged composite was obtained with significant deflection and flexural strength that equals or exceeds the strength corresponding to the first crack. This effect has already been presented for small beams of mortar paste and concrete with synthetic structural polypropylene fibers [Logoń, 20011/12]. This paper concentrates on hybrid concrete reinforcement in large beams. The suggested method of comparing reinforcement effects was presented earlier but is slightly modified in this paper. The main idea to compare different points or areas of the load-deflection curve is the same.

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.
The rheological properties of cement mixes are presented in [Logoń, *SCMT3* 2013, *The Rheological and Mechanical Properties of the SRCC Composites.*].

Table 1. Fiber volume in concrete

Composite	*S-fibers* V_f [%]	*R-fibers* V_f [%]
C – (matrix)	-	-
C2R	-	2
C1S1R	1	1
C1S2R	1	2

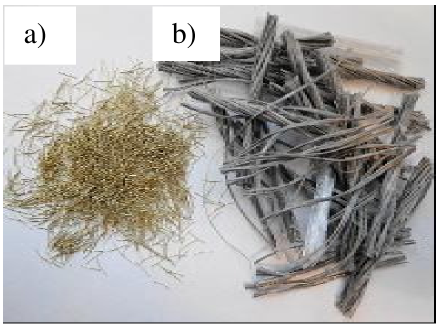

Figure 1. Fibers: a) steel flat (*S*) 6 mm, b) structural polypropylene (*R*) 54 mm

Beams (600x150x150 mm) were cast in slabs and then cured in water at 20 ± 2ºC. After 90 days of ageing, beams were prepared for bending test. Each specimen was turned over (90^o) and in the middle of its bottom side a 30 mm deep notch and 3 mm wide was sawn.

Tests. Four-point bending tests were carried out on the testing machine with closed-loop servo control displacement, figure 2. The load-deflection curves were obtained according to *ASTM C* 1018 but the test was based on the measurement of the displacement of crosshead and the following results were recorded:

- tensile strength at bending f_{tb} (*MOR*), tensile strength at first crack f_{cr} (*LOP*), and tensile strength corresponding to the rope effect f_R :
- deflection at maximum load ε_{tb}, first crack ε_{cr} and rope effect ε_R,
- energy (work) as proportional to the area under load-deflection curve up to the maximum load W_{tb}, up to the first crack W_{cr} and up to the rope effect W_R.

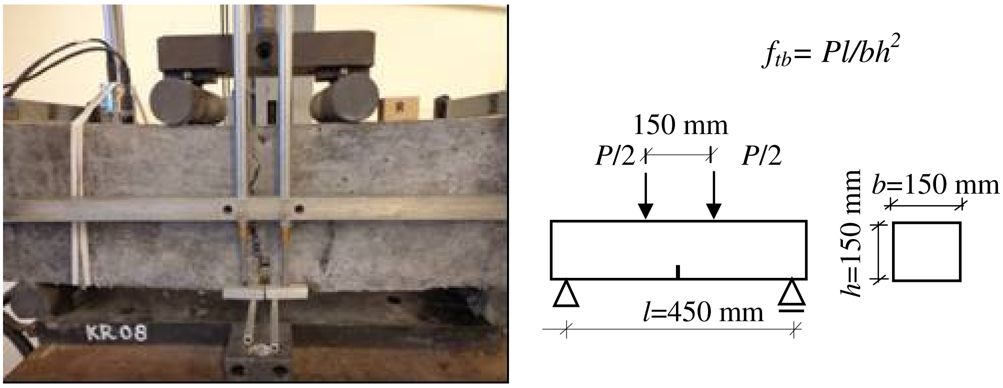

Figure 2. Four-point bending test

Tests were carried out on beams after 90 days of ageing. The presented results are for the most representative specimens selected from the tested beams. The results were confirmed on smaller beams 4x4x16mm and also plates 4x16x16mm. Although the results for smaller beams are different, the conclusions from the tests are the same.

Compressive strength f_c was tested on 4 cubes 100x100x100 mm using testing machine with closed-loop servo control displacement.

Calculation. The reinforced cement composites are determined by f_{tb} flexural (bending) and f_c compressive strength. The ratio $k=f_{tb}/f_c$ is the information about brittleness. The reinforced effect is presented by any point f_x(def.,load,work) where the work is the area under the load-deflection curve up to that point, fig.3.

The characteristic points on load-deflection curve, f_x (deflection, load, work):

f_{cr} - the first crack,

f_{tb} - the maximum load,

f_R - the end of the rope effect (post-peak load $F_R = F_{cr}$),

$f_{R/2}$ - the 50% load of the F_R.

The areas under the load-deflection curve between characteristic points A_x(def., load, work):

A_M - multicracking area (the difference between points f_{tb} and f_{cr}) ,

A_{Rp}, - the rope effect area (the difference between f_R and f_{tb}),

A_{Pr} - the crack propagation area (the difference between $f_{R/2}$ and f_R.),

A^{o}_{Rp} , A^{cr}_{Rp} - rope effect index: $A^{o}_{Rp} = A_{Rp}/A_o$ and $A^{cr}_{Rp}=A_{Rp}/A_{cr}$ respectively.

The influence of hybrid reinforcement in *SRCC* composites is presented in figure 3.

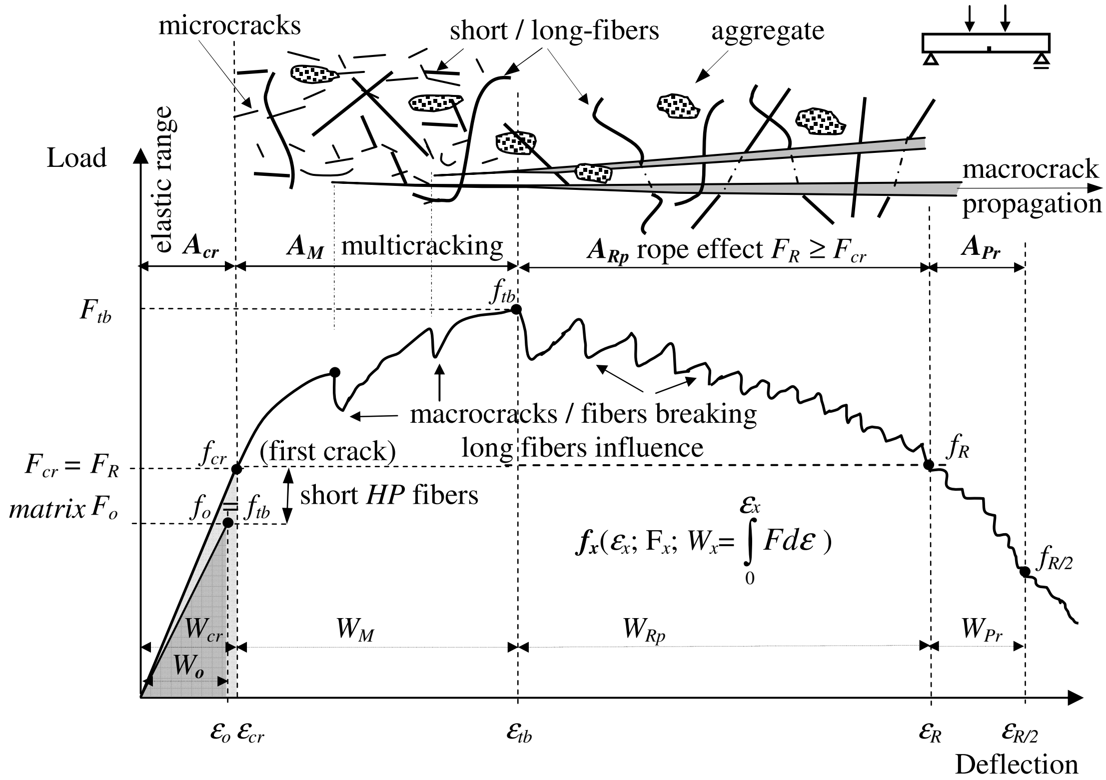

Figure 3. Load-deflection curve of the *SRCC* (multicracking and rope effect)

$f_{cr}(\varepsilon_{cr};F_{cr};W_{cr})$	$f_{tb}(\varepsilon_{tb};\ F_{tb};W_{tb})$	$f_R\ (\varepsilon_R;F_R,\ ;W_R)$	$f_{R/2}\ (\varepsilon_{R/2};F_{R/2};W_{R/2})$
first crack	multicracking	rope effect	crack propagation
$A_{cr}(\varepsilon_{cr};F_{cr};W_{cr})$	$A_M\ (\varepsilon_{tb}-\varepsilon_{cr};F_{tb};W_M)$	$A_{Rp}(\varepsilon_R-\varepsilon_{tb};F_R\ ;W_{Rp})$	$A_{Pr}(\varepsilon_{R/2}-\varepsilon_R;\ F_{R/2};W_{Pr})$
$W_{cr} = \int_0^{\varepsilon_{cr}} Fd\varepsilon$	$W_M = \int_{\varepsilon_{cr}}^{\varepsilon_{tb}} Fd\varepsilon = W_{tb}-W_{cr}$	$W_{Rp} = \int_{\varepsilon_{tb}}^{\varepsilon_R} Fd\varepsilon = W_R-W_{tb}$	$W_{Pr} = \int_{\varepsilon_R}^{\varepsilon_{R/2}} Fd\varepsilon = W_{R/2}-W_R$

$f^{x1}{}_{x2}$ - change of point f_{x2} compared to point f_{x1}: $f^{x1}{}_{x2}\,(\varepsilon_{x2}/\varepsilon_{x1}\,;\ F_{x2}/F_{x1};\ W_{x2}/W_{x1})$

$A^{x1}{}_{x2,x3}$ - change (area under the curve) between points f_{x3} *and* f_{x2} compared to point f_{x1}:

$$A^{x1}{}_{x2,x3}((\varepsilon_{x3}-\varepsilon_{x2})/\varepsilon_{x1}\,;F_{x3}/F_{x1};(W_{x3}-W_{x2})/W_{x1})$$

The assessment of reinforcement effects compared to the matrix f_o or to the first crack f_{cr}:

	point change:		area change:
first crack	$f^o{}_{cr}\,(\varepsilon_{cr}/\varepsilon_o\,;\ F_{cr}/F_o;\ W_{cr}/W_o)$	=	$A^o{}_{cr}\,(\varepsilon_{cr}/\varepsilon_o\,;\ F_{cr}/F_o\ ;\ W_{cr}/W_o)$
multicracking	$f^{cr}{}_{tb}\,(\varepsilon_{tb}/\varepsilon_{cr}\,;\ F_{tb}/F_{cr};\ W_{tb}/W_{cr})$		$A^o{}_M\,((\varepsilon_{tb}-\varepsilon_{cr})/\varepsilon_o\,;\ ;F_{tb}/F_o;((W_{tb}-W_{cr})/W_o)$
rope effect	$f^{cr}{}_R\ \ (\varepsilon_R\,/\varepsilon_{cr}\,;\ F_R/F_{cr};\ W_R/W_{cr})$		$A^o{}_{Rp}\,((\varepsilon_R-\varepsilon_{tb})/\varepsilon_o\,;\ F_R/F_o\ ;(W_R-W_{tb})/W_o)$
crack propag.	$f^{cr}{}_{R/2}\,(\varepsilon_{R/2}/\varepsilon_{cr}\,;\ F_{R/2}/F_{cr}\,;W_{R/2}/W_{cr})$		$A^o{}_{Pr}\,((\varepsilon_{R/2}-\varepsilon_R)/\varepsilon_o\,;\ F_{R/2}/F_o;(W_{R/2}-W_R)/W_o)$

RESULTS

The load-deflection curve for matrix - *HPC* high strength concrete are presented in fig. 4. The compressive strength and tensile strength are f_c = 86 [MPa], f_{tb} = 4.3 [MPa] respectively and the brittleness ratio is k_o=0.05. The point corresponding to the bending strength f_o(deflection, load , absorbed energy) is f_o (0.982[mm]; 20.62[kN]; 9.225[J]).

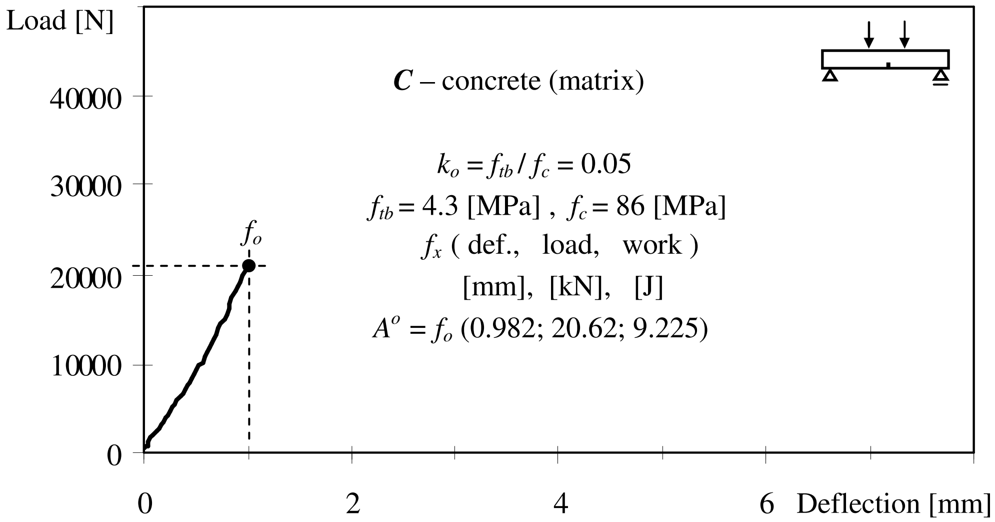

Figure 4. Load-deflection curve for concrete (matrix)

The influence of the addition of a high amount of long structural propylene fibers *(R)*, V_f= 2% is shown in figure 5. The bending strength increases significant up to f_{tb} = 7.8 [MPa] and compressive strength decreases to f_c = 79 [MPa]. The changes of the first crack load and deflection appearance are negligible $f^o{}_{cr}$(0.98;1.06;1.14).

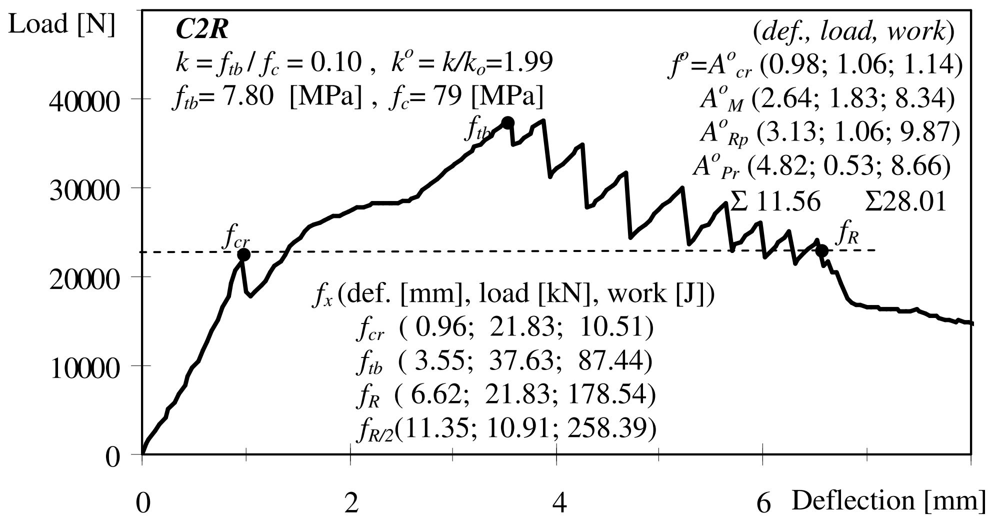

Figure 5. Load-deflection curve for concrete V_f=2% (*R*)

The areas corresponding to the multicracking $A^o{}_M$, rope effect $A^o{}_{Rp}$ and crack propagation $A^o{}_{Pr}$ (effects calculated to the matrix) are large. The rapid decrease of load indicates that macrocrack appears (A_M - area) or that one or a few fibers are broken (A_{Rp} - area).

The effects of 1% V_f *HP* short steel fibers (*S*) addition to *C2R* composite resulting in *C1S2R* are shown in fig.6. As it can be noticed short fibers increase the load corresponding to the first crack appearance from f_{cr} (21.8kN) up to f_{cr} (32,8kN). This higher load limits areas corresponding to multicracking and rope effect. Therefore, proper analysis of reinforcement effects should be conducted with respect to all the areas A_{cr}, A_M, A_{RP}, A_{PR}.

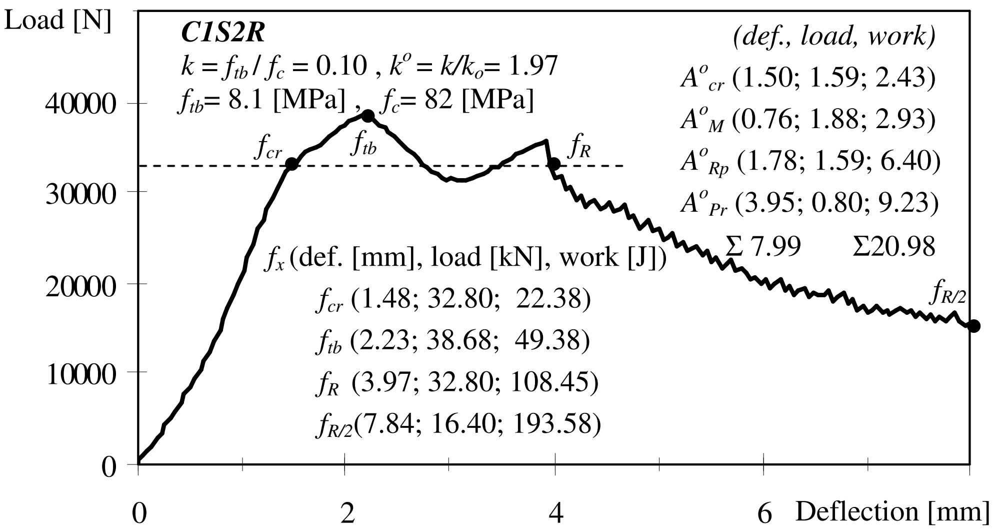

Figure 6. Load-deflection curve for concrete V_f=1% (*S*) and V_f=2% (*R*)

The replacement of 1%V_f (*R* -fibers) with 1%V_f *HP* short steel ones results in the highest bending and compressive strength f_{tb} and f_c , fig.7. This confirms that short fibers, as opposed to longer fibers, have a better influence on load f_{cr} and f_{tb} but worse on deflection.

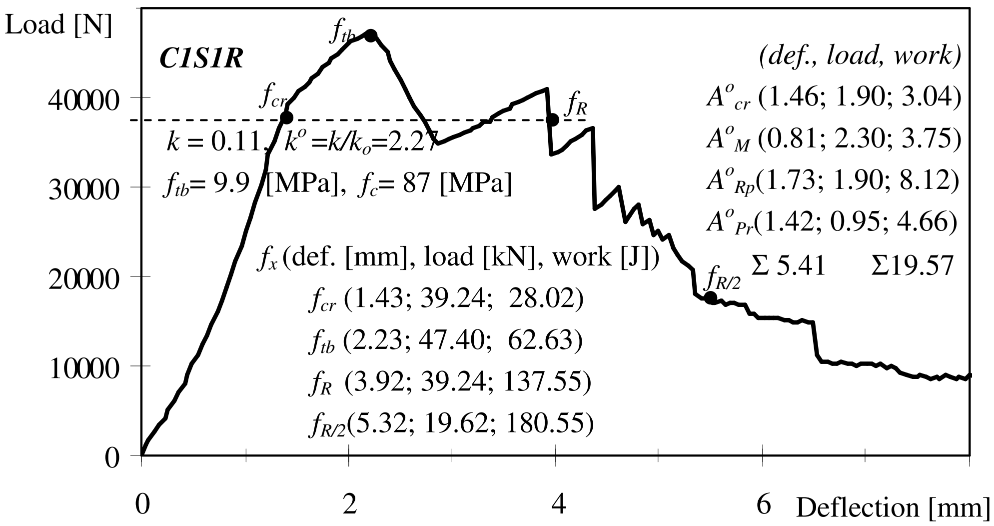

Figure 7. Load-deflection curve for concrete V_f=1% (*S*) and V_f=1% (*R*)

Similarly to *C1S2R,* the short fibers in *C1S1R* increase first crack load and limit the multicracking and rope effect areas; therefore A_{cr} area should be taken into account when analyzing A_M and A_{RP}.

DISCUSION

The influence of long structural polypropylene fibers on the first crack appearance is negligible (compare *C* and *C2R; A^{o}_{cr}* (0.98;1.06;1.14)), fig.8. This kind of reinforcement can stop the macrocrack – this results in stopping the rapid decrease of the load-deflection curve after first crack appearance and subsequently in an increase of the multicracking effect up to the maximum load A^{o}_{M} (2.64;1.83;8.34). As it was presented [Logoń, 2012], several macrocracks can be stopped in this area, particularly in the case of pastes and small beams. For concrete large beams there is usually one macrocrack. It is possible to increase the number of macrocracks to be stopped in this area using longer and stronger fibers (longer fibers, similarly as in the case of continuous reinforcement, will cause the appearance of several macrocracks). The rapid changes (decreasing and increasing of the load deflection curve in the rope effect area) indicate that fibers are broken and other fibers carry the stress. It can be concluded that stronger fibers (if fibers are too weak, they can be plated like a rope) with better ability to deflect can significant increase rope effect. After the multicracking and rope effect ends, the crack propagation control process still continues up to $f_{R/2}$ and then up to the end of the bending test where deflection is ca. 15-20 mm.

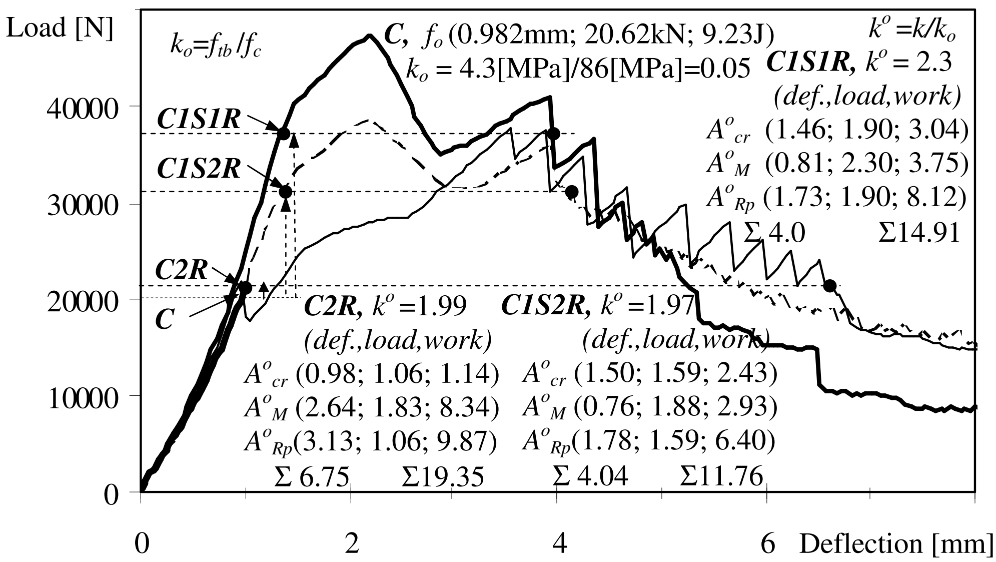

Figure 8. Load-deflection curves of the tested concrete composites

The *HP* (high strength f_t,E) short fibers control the multicracking effect and increase the load corresponding to the first crack. The short steel fibers were used due to fact that they ensure the best rheological properties of the mix from among the existing types of fibers (e.g. pitched-carbon fibers are also effective but they worsen the rheological properties of the cement mixes more significantly). As it can be observed, the increase of the load corresponding of the first crack appearance results in a decrease of the multicracking and rope effect area. Therefore, the reinforcement effects should be analyzed taking into account all the areas (A_{cr}, A_M, A_{Rp}). The reinforced effects can calculated in relation to both the matrix and the first crack appearance and the best *SRCC* results were achieved for hybrid reinforcement *C1S1R*. (In the future the standard matrix load-deflection curve may be determined for cement composites.) The best reduction of brittleness was for *C1S1R*, k^o=2.27, then for *C1S2R*, k^o=1.99 and *C2R*, k^o=1.97. The increase of the long fibers volume to 2%V_f decreases f_{cr} , f_{tb} with higher deflection, which is caused by lower fiber-matrix bond.

CONCLUSIONS

The optimum fiber volume $V_{min}<V_f<V_{max}$ is required for *SRCC*. Too many long fibers worsen the rope effect - too few don't cause the effect.

High strength short fibers in *SRCC* cause the multicracking effect which worsens the fiber-matrix bond of the longer fibers. Therefore, *SRCC* with hybrid reinforcement require longer and stronger fibers.

It is possible to increase the load corresponding to the first crack appearance in *SRCC* by using additionally high strength short fibers or increasing flexural strength.

The suggested method of describing the reinforcement effects f_x(def., load, work) enables the comparison of the effects in different composites tested in the same manner.

A deflection of the tested beams up to the load corresponding to the first crack can be measured in relation to the neutral axis and subsequently, due to high deflections, by means of measuring the crosshead displacement.

Unpublished own results indicate that it is possible to achieve *SRCC* composites in traditional concrete as well.

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