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MECHANICAL PROPERTIES OF FRC WITH VARIOUS FIBER TYPE AND CONTENT

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Abstract: *The paper presents results of a study focused on the mechanical properties of fiber reinforced concrete with different fiber type and content. Original experiments are compared to results available from the literature. Conclusions on the dependence of the fracture energy on the fiber type and content are drawn.*

Keywords: ***Fiber reinforced concrete, fracture energy, strain-rate effect***

1. Introduction

Fiber reinforced concrete (FRC) is because of its mechanical properties much more suitable for the use in structures subjected to higher strain rates, e.g. blast or impact loading. The value of fracture energy is the decisive material characteristics for assessment of the damage of concrete structures by loadings with higher strain rates. This paper summarizes the results of the tests focused on fracture energy of fiber reinforced concrete of different strength classes, different fiber types and fiber contents subjected to different loading rates.

2. Methods of assessing the fracture energy of FRC

The fracture characteristics of FRC are usually tested on beams subjected to three-point bending or on specimens subjected to uniaxial tension. The value of the fracture energy is equal to the area under the force-deflection diagram (F-δ):

$$G_f = \frac{W}{B.H} \tag{1}$$

$$W = \int F.d\delta \tag{2}$$

where W is the area of under the force-deflection diagram and $B.H$ [m] are the cross-sectional dimensions of the crack of the specimen, F [N] is the force which loads the specimen and δ [m] is the deflection the force is causing in the middle of the span of the specimen. The area under the force-deflection diagram is taken for a limited deflection. When the loading of the specimen continues until the collapse, the value B.H is equal to the area of the concrete specimen.

According to the RILEM recommendations, the fracture characteristics of FRC are assessed using the three-point bending test of notched specimens, dimensions 150x150x650mm. The height of the notch is 25mm. The three-point bending together with the notch clearly defines the position of the crack. The results of the experiments have smaller scatter in comparison to the tests without notch.

The value of fracture energy according to this arrangement can be obtained from the following formula:

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$$G_f = \frac{W}{B.(H-a)} \tag{3}$$

where W is the area of under the force-deflection diagram until the complete collapse of the specimen, B [m] is the width of the specimen, a [m] is the height of the notch and H [m] is the height of the specimen.

The tests described in this paper were not performed according to the RILEM recommendations but according to the recommendations published in TP FC 1-1 (2007). The specimens are beams, 150x150x700mm with the span of 600mm. No notch is used for the definition of the position of the macro-crack. The specimen is loaded by four-point bending, the forces divide the span into thirds. The benefit of this test arrangement is the constant value of the bending moment in the middle third of the specimen and elimination of the effect of the shear force. At the specimens without the notch, the macro-crack propagates at the weakest cross-section, i.e. the cross-section with the smallest fiber content, which is subjected to the biggest bending moment. The scatter of the results is bigger in comparison to the tests on notched specimens.

The layout of the experiments can be seen in Fig. 1.

Fig. 1: Layout of the experiments

All other technical arrangements are similar to the experiments described in (Drahorád et al., 2012).

3. Available results

The fracture energy is a key material constant which defines its resistance high strain-rate loadings like blast or impact. Nevertheless, not much results are available in the literature.

Steel fiber reinforced concrete specimens (SFRC) with varying notch height were tested in (Kazemi et al., 2004). The fiber content was taken 80 and 120 kg/m3 (0.1% and 1.5%).

SFRC specimens with fiber content of 30, 60 and 90 kg/m3 were studied in Barros & Cruz (2001). (Bencardino et al., 2010) studied fracture energy of various mixes of high performance fiber reinforced concrete (HPFRC).

Lee & Barr (2003) studied the differences in the behaviour of notched and not notched SFRC specimens.

4. Results of the experiments

The experiments were performed on two different strength classes of concrete and varying fiber type and content. The strength classes of concrete were chosen C30/37 and C55/67. For both types of concrete, two different materials of fibers with two different fiber contents were tested. The poly propylene (PP) 54mm long fibers were used in dosages of 4,5 and 9 kg/m3 (0.5% and 1%), the steel fibers were used in dosages of 40 and 80 kg/m3 (0.5% and 1%). In total, 8 options were used.

Every material option was tested at three speeds of deformation to verify the dynamic increase factor and the influence of the loading rate on the fracture energy. The speeds of deformation were chosen 0.2 mm/min (approximately static loading), 2mm/min and 6 mm/min. The corresponding strain rates are summarized in Table 1.

Tab. 1: Mean values of strain rate for the defined speed of deformation before and after crack propagation

Speed of deformation υ	**Strain rate** $\dot{\varepsilon}$ **Before crack propagation**	**Strain rate** $\dot{\varepsilon}$ **After crack propagation**
[mm/min]	[s^{-1}]	[s^{-1}]
0,2	8,696E-06	2,286E-05
2	8,696E-05	2,286E-04
6	2,609E-04	6,856E-04

The outputs of the experiments are the force-deflection diagrams. Outputs of the tested options are plotted in Figure 2 to 9 and summarized in Table 2.

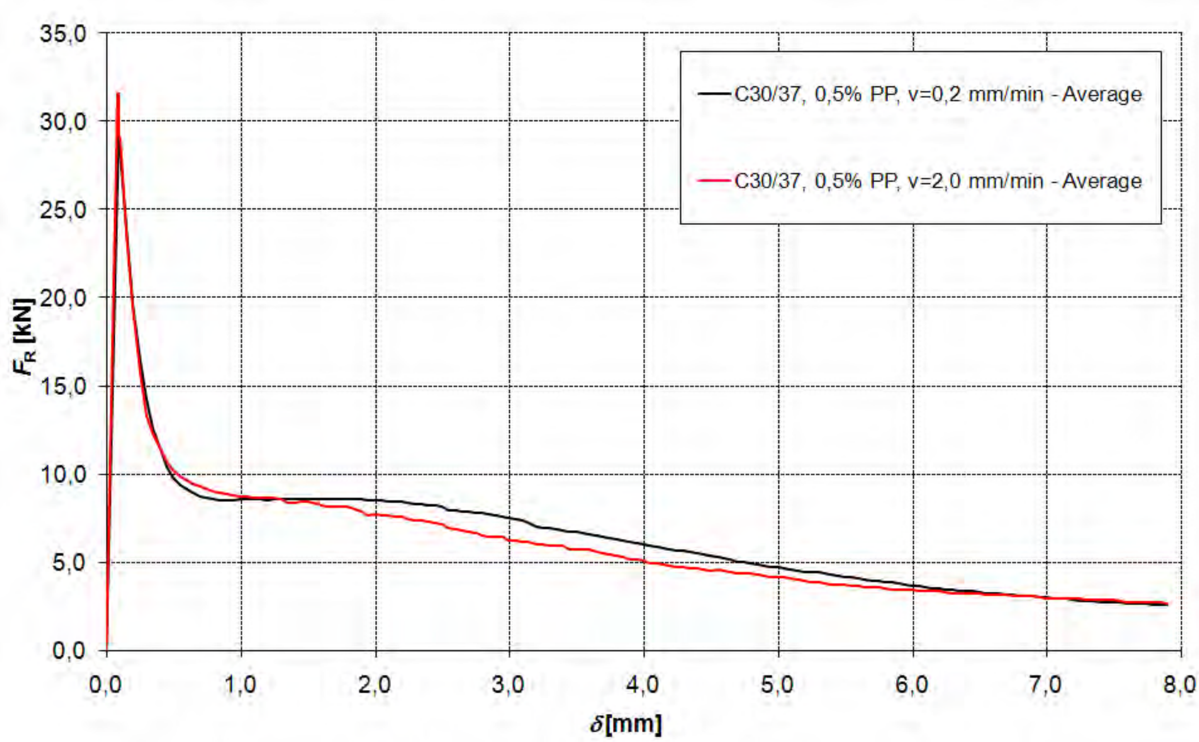

Fig. 2: Force-deflection (F-δ) diagram for concrete C30/37 with 0.5% PP fibers

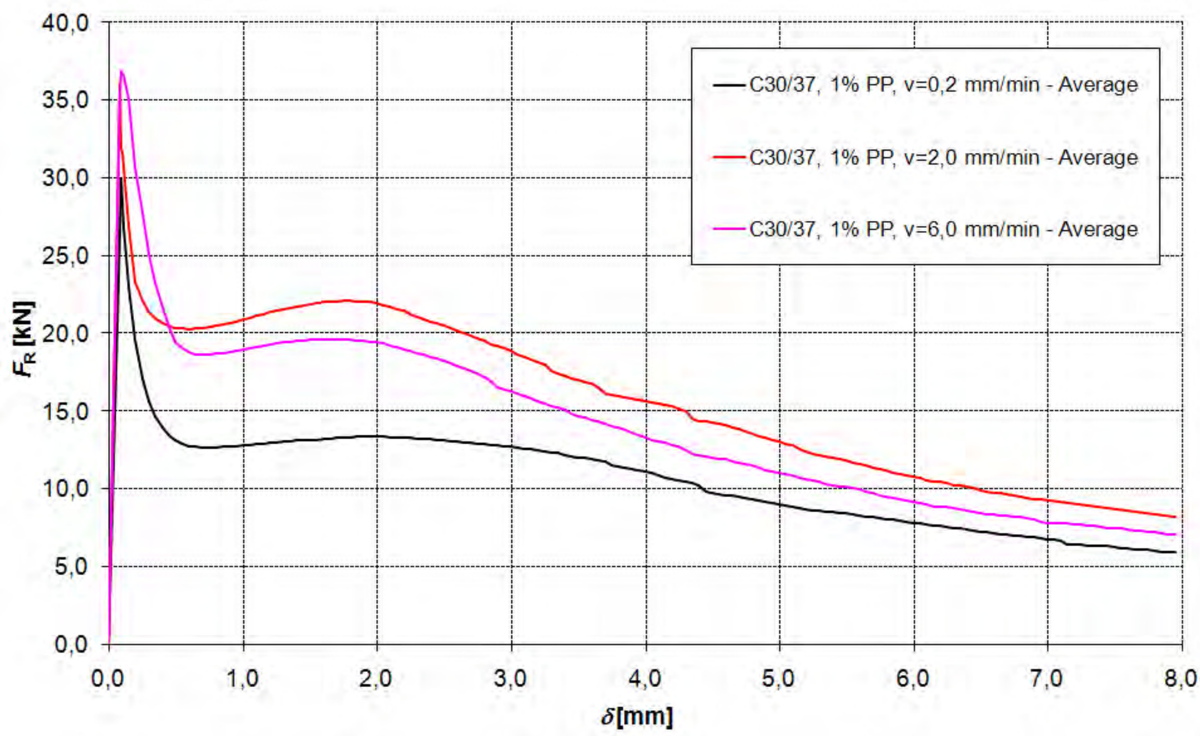

Fig. 3: F-δ diagram for concrete C30/37 with 1% PP fibers

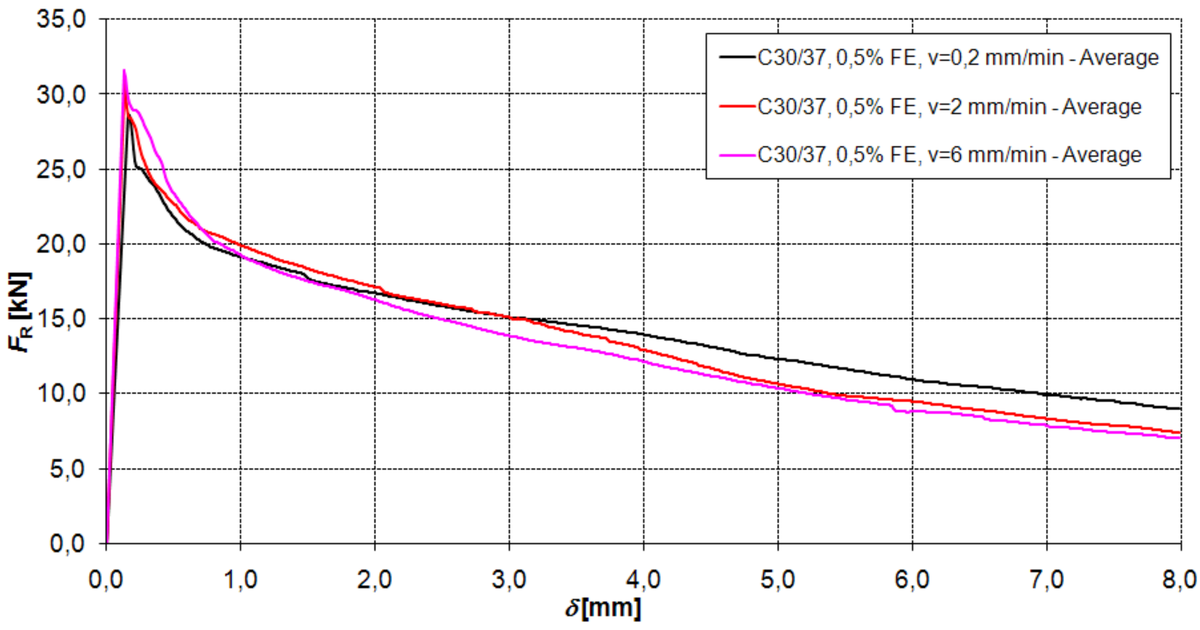

Fig. 4: F-δ diagram for concrete C30/37 with 0.5% FE fibers

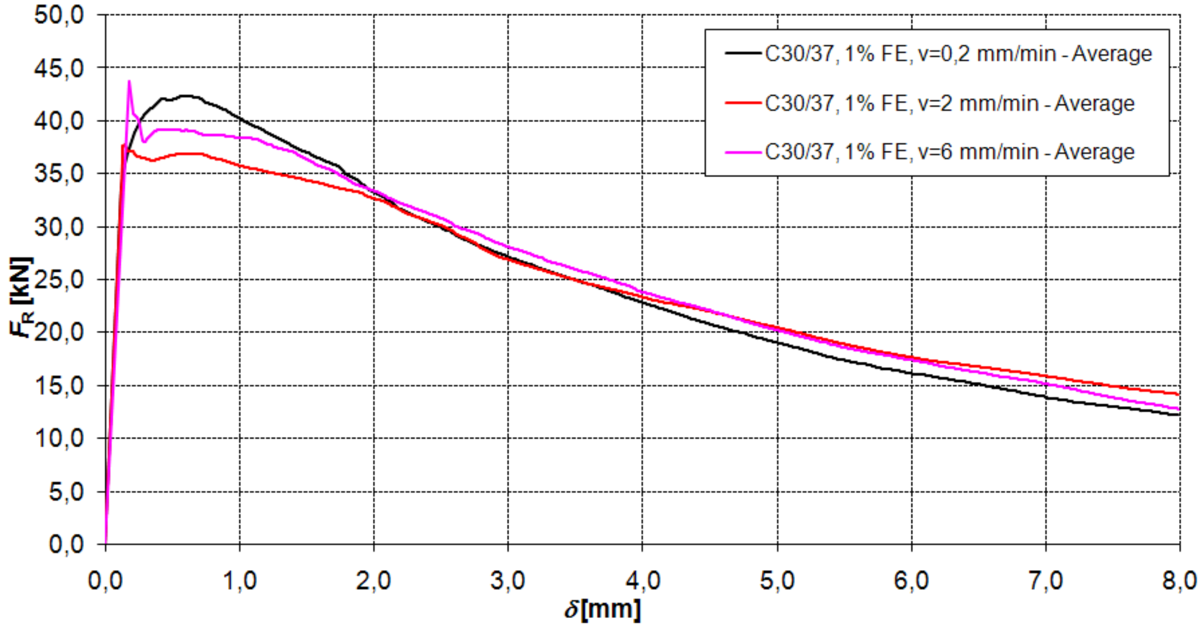

Fig. 5: F-δ diagram for concrete C30/37 with 1% FE fibers

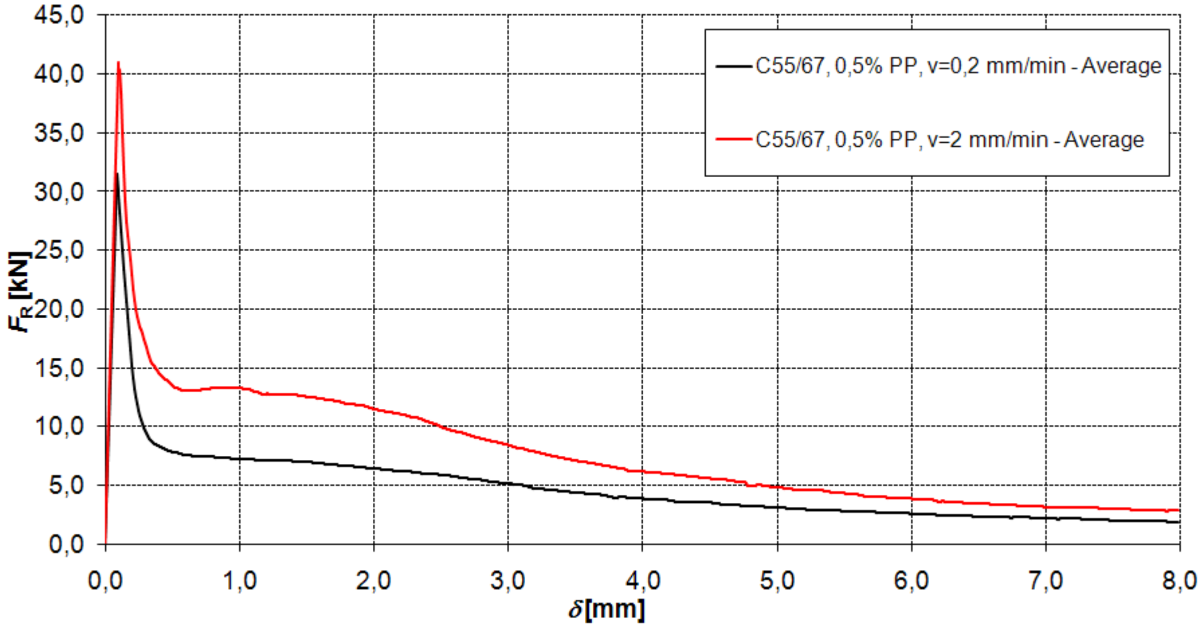

Fig. 6: F-δ diagram for concrete C55/67 with 0.5% PP fibers

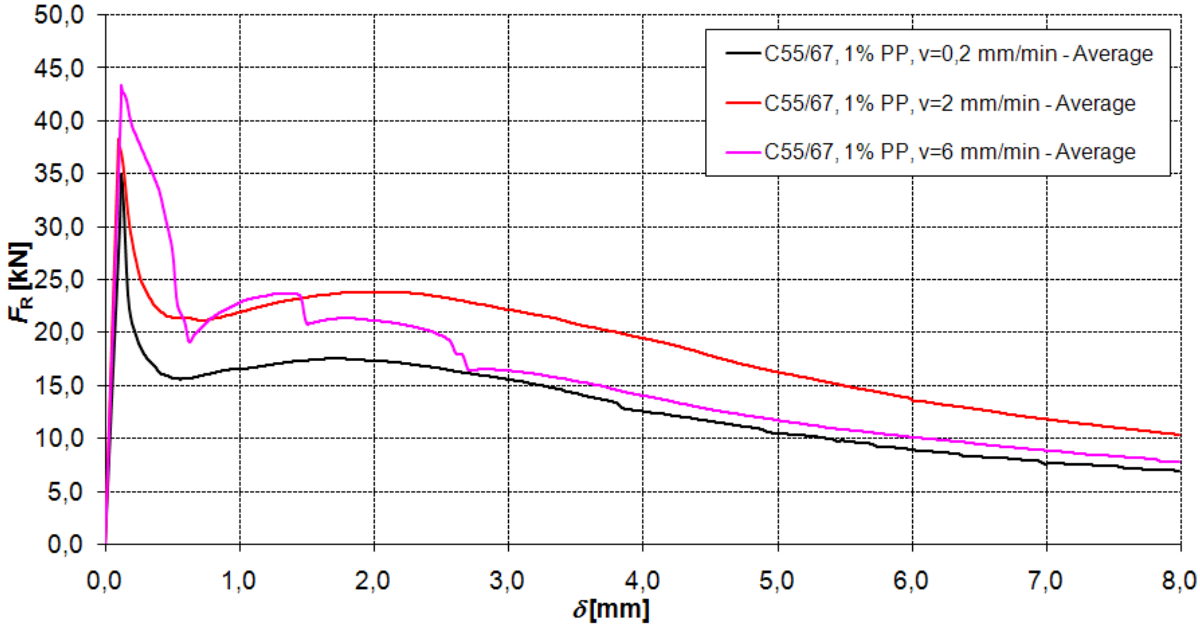

Fig. 7: F-δ diagram for concrete C55/67 with 1% PP fibers

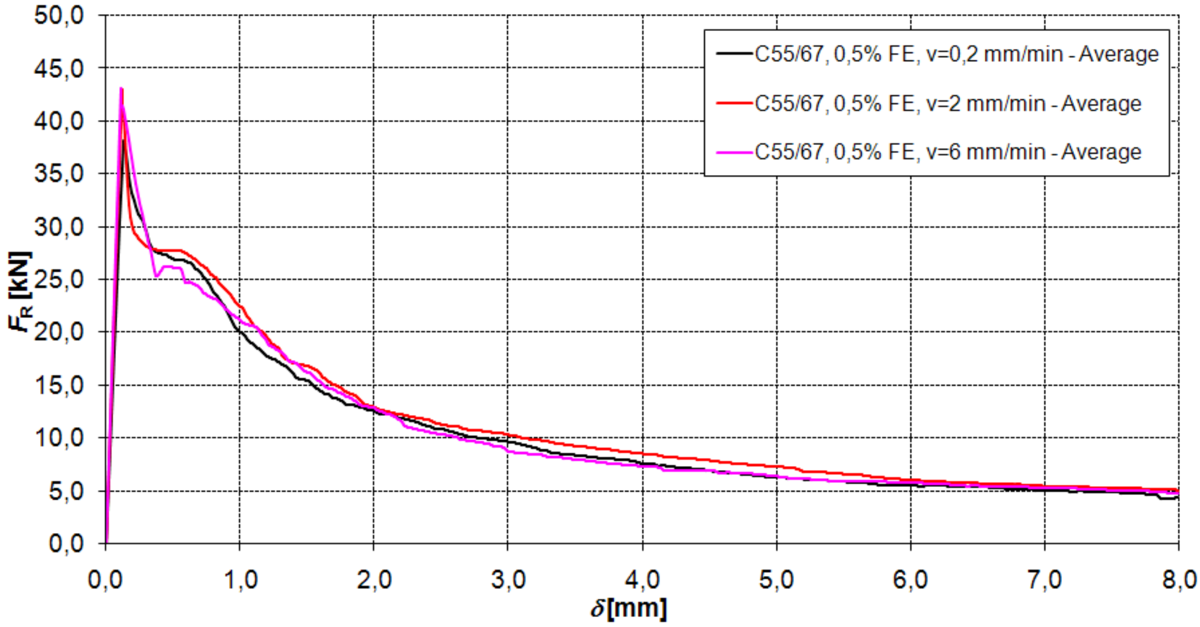

Fig. 8: F-δ diagram for concrete C55/67 with 0.5% FE fibers

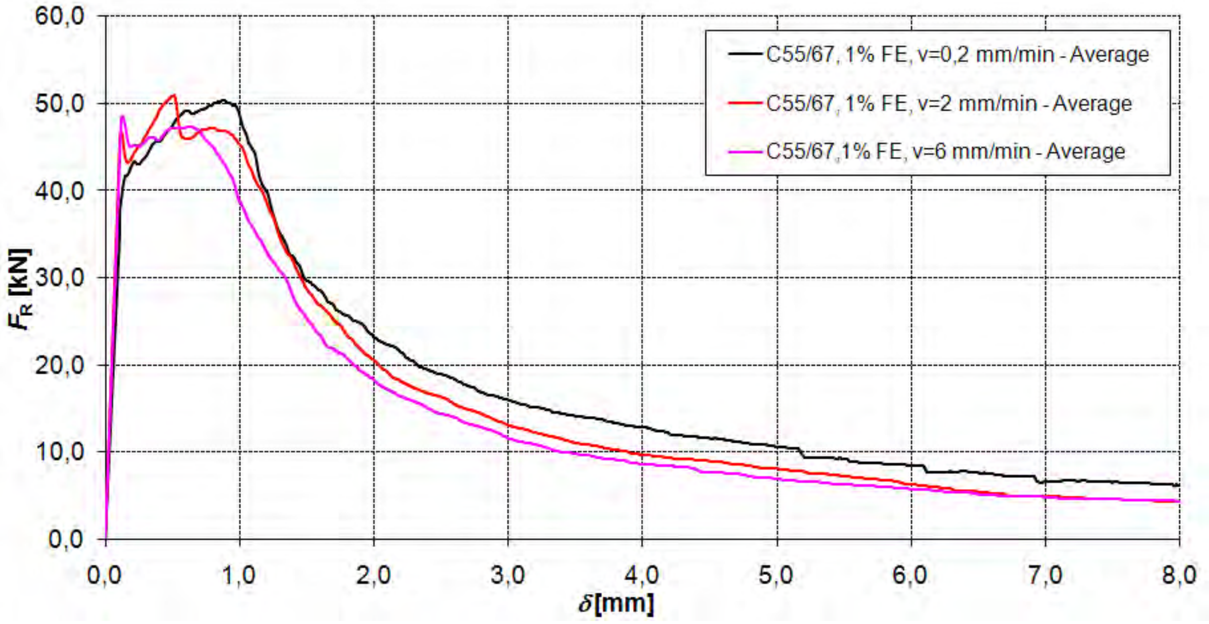

Fig. 9: F-δ diagram for concrete C55/67 with 1% FE fibers

The value of the force at the crack opening increases with the speed of deformation, this effect is called the strain rate effect. The basic is the value of the concrete tensile strength subjected to static loading, ε = 10-6. In this case, the lowest speed of deformation 0,2mm/min was taken as the reference value, i.e. static loading. Figure 10 shows a plot of the strain rates of the specimens into the trend lines compared in (Drahorád et al., 2012).

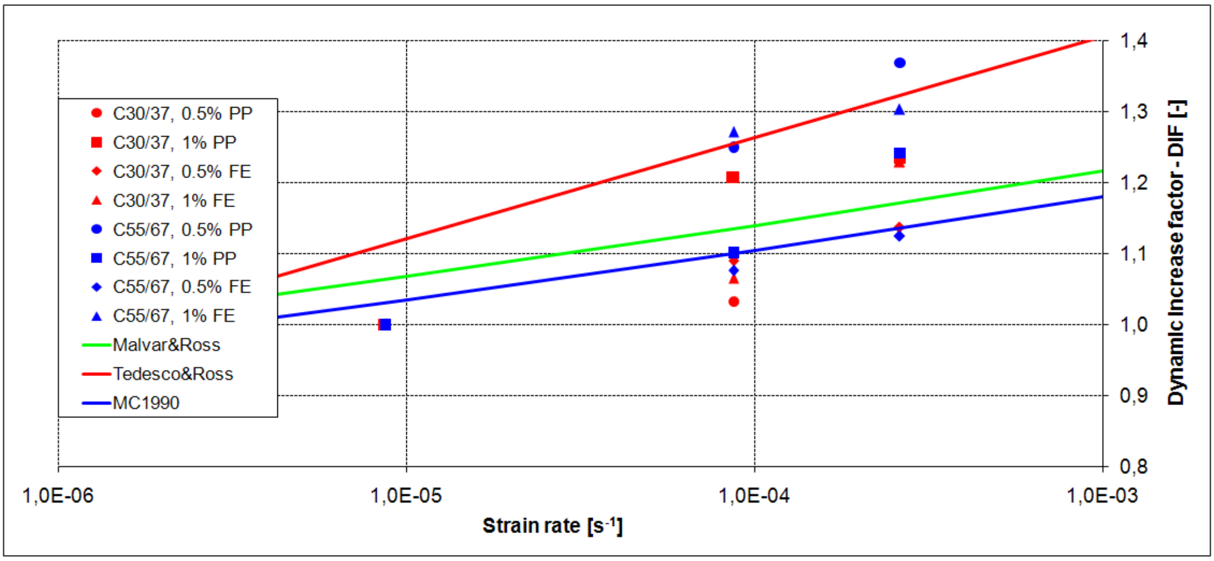

Fig. 10: The dynamic increase factor for different fiber concrete specimens

Tab. 2: Comparison of the fracture properties of the tested FRC

Speed of deformation υ	C30/37, PP, $\rho = 0.5\%$			C30/37, PP, $\rho = 1.0\%$		
	Crack opening		Fracture energy	Crack opening		Fracture energy
	F_{CLS}	δ_{CLS}		F_{CLS}	δ_{CLS}	
[mm/min]	[kN]	[mm]	[N/m]	[kN]	[mm]	[N/m]
0.2	30,6	0,09	2615	29,9	0,10	5007
2.0	31,6	0,09	2451	36,1	0,09	7405
6.0	-	-	-	36,9	0,12	6610

Speed of deformation υ	C30/37, FE, $\rho = 0.5\%$			C30/37, FE, $\rho = 1.0\%$		
	Crack opening		Fracture energy	Crack opening		Fracture energy
	F_{CLS}	δ_{CLS}		F_{CLS}	δ_{CLS}	
[mm/min]	[kN]	[mm]	[N/m]	[kN]	[mm]	[N/m]
0.2	28,0	0,152	6628	35,4	0,153	11467
2.0	30,5	0,130	6351	37,7	0,129	11453
6.0	31,8	0,128	6119	43,5	0,179	11667

Speed of deformation υ	C55/67, PP, $\rho = 0.5\%$			C55/67, PP, $\rho = 1.0\%$		
	Crack opening		Fracture energy	Crack opening		Fracture energy
	F_{CLS}	δ_{CLS}		F_{CLS}	δ_{CLS}	
[mm/min]	[kN]	[mm]	[N/m]	[kN]	[mm]	[N/m]
0.2	32,0	0,084	2100	34,4	0,117	6129
2.0	40,0	0,100	3440	37,9	0,097	8807
6.0	43,8	0,107	-	42,7	0,116	7452

Speed of deformation υ	C55/67, FE, $\rho = 0.5\%$			C55/67, FE, $\rho = 1.0\%$		
	Crack opening		Fracture energy	Crack opening		Fracture energy
	F_{CLS}	δ_{CLS}		F_{CLS}	δ_{CLS}	
[mm/min]	[kN]	[mm]	[N/m]	[kN]	[mm]	[N/m]
0.2	37,2	0,121	4559	37,6	0,099	7634
2.0	40,0	0,116	4899	47,8	0,120	7571
6.0	41,8	0,113	4612	49,0	0,126	7227

5. Comparison of the results

The results of the experiments are compared in Table 3 and 4. The results are compared based on the material of the fibers, fiber content, strength class of concrete and the speed of deformation.

The compared quantities characterize the fracture properties of the composite material: the force at crack opening and the fracture energy.

Tab. 3: Comparison of the fracture properties of FRC specimens (material of the fibers, fiber content, strength class)

Influence of the fiber content	F_{CLS}		G_f	
C30/37, 0,2mm/min	0,5% PP	1% PP	0,5% PP	1% PP
	1,00	**0,97**	1,00	**1,91**
	0,5% FE	1% FE	0,5% FE	1% FE
	1,00	**1,26**	1,00	**1,73**
C55/67, 0,2mm/min	0,5% PP	1% PP	0,5% PP	1% PP
	1,00	**1,08**	1,00	**2,92**
	0,5% FE	1% FE	0,5% FE	1% FE
	1,00	**1,01**	1,00	**1,67**

Influence of the material of the fibers	F_{CLS}		G_f	
C30/37, 0,2mm/min	0,5% PP	0,5% FE	0,5% PP	0,5%FE
	1,00	**0,92**	1,00	**2,53**
	1% PP	1% FE	1% PP	1% FE
	1,00	**1,18**	1,00	**2,29**
C55/67, 0,2mm/min	0,5% PP	0,5% FE	0,5% PP	0,5%FE
	1,00	**1,16**	1,00	**2,17**
	1% PP	1% FE	1% PP	1% FE
	1,00	**1,09**	1,00	**1,24**

Influence of the concrete strength class	F_{CLS}		G_f	
0,5%PP, 0,2mm/min	C30/37	C55/67	C30/37	C55/67
	1,00	**1,05**	1,00	**0,80**
1%PP, 0,2mm/min	C30/37	C55/67	C30/37	C55/67
	1,00	**1,15**	1,00	**1,22**
0,5%FE, 0,2mm/min	C30/37	C55/67	C30/37	C55/67
	1,00	**1,32**	1,00	**0,69**
1%FE, 0,2mm/min	C30/37	C55/67	C30/37	C55/67
	1,00	**1,06**	1,00	**0,67**

Tab. 4: Comparison of the fracture properties of FRC specimens (speed of deformation)

Influence of the speed of deformation		F_{CLS}			G_f	
υ [mm/min]	0,2	2	6	0,2	2	6
C30/37, 0,5%PP	1,00	**1,03**	**-**	1,00	**0,94**	**-**
C30/37, 1% PP	1,00	**1,21**	**1,23**	1,00	**1,48**	**1,32**
C30/37, 0,5% FE	1,00	**1,09**	**1,14**	1,00	**0,96**	**0,92**
C30/37, 1% FE	1,00	**1,06**	**1,23**	1,00	**1,00**	**1,02**
C55/67, 0,5%PP	1,00	**1,25**	**1,37**	1,00	**1,64**	**-**
C55/67, 1% PP	1,00	**1,10**	**1,24**	1,00	**1,44**	**1,22**
C55/67, 0,5% FE	1,00	**1,08**	**1,12**	1,00	**1,07**	**1,01**
C55/67, 1% FE	1,00	**1,27**	**1,30**	1,00	**0,99**	**0,95**

6. Conclusions

The experiments showed great influence of the fiber type and content on the fracture energy of FRC.

The fracture energy rises with the increasing fiber content.

The increase of the speed of deformation from 0.2 mm/min to 2 mm/min caused an increase of the fracture energy. Yet, the further increase of the speed of deformation to 6 mm/min did not cause further increase of the fracture energy.

The increase of the strength class of concrete causes increase of the fracture energy of the PP-fiber FRC. The increase of the strength of concrete did not cause increase of the fracture energy of the FRC.

The increase of the concrete tensile strength was shown with the increased speed of deformation.

Fiber reinforced concrete (FRC) is because of its bigger ductility much more suitable for the use in structures subjected to higher strain rates, e.g. blast or impact loading. The value of fracture energy is the decisive material characteristics for assessment of the damage of concrete structures by loadings with higher strain rates and is used for calibration of material models.

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References

M. Drahorád, M. Foglar, P. Veselý, S. Smiřinský, Užití dynamického faktoru nárůstu pevnosti betonu pro zkrácení doby trvání zkoušek vláknobetonových vzorků. *BETON-technologie, konstrukce, sanace*. 1/2012, 74-79 (2012).

TP FC 1-1. Technické podmínky 1: Vláknobeton - Část 1 : Zkoušení vláknobetonu. Praha, Českomoravský beton, a.s., , 34 (2007).

M.T. Kazemi, M. Naraghi, F.V. Shahvari, Fracture energy determination of SFRC from notched beam tests, *6th International RILEM Symposium on Fiber Reinforced Concretes*, 359-368 (2004).

J. A. O. Barros, J. Sena Cruz, Fracture Energy of Steel Fiber-Reinforced Concrete, *Mechanics of Composite Materials and Structures*, Vol. 8, Iss. 1, 29-45 (2001).

F. Bencardino, L. Rizzuti, G. Spadea, R.N. Swamy, Experimental evaluation of fiber reinforced concrete fracture properties, *Composites Part B: Engineering*, Volume 41, Issue 1, 17-24 (2010).

M.K Lee, B.I.G Barr, Strength and fracture properties of industrially prepared steel fiber reinforced concrete, *Cement and Concrete Composites*, Volume 25, Issue 3, 321-332 (2003).