Early age behaviour of fibre reinforced shotcrete

J. Sustersic, A. Zajc, R. Ercegovic
IRMA Institute for Research in Materials and Applications, Ljubljana, Slovenia

V. Jovicic
Institute for Mining, Geotechnology and Environment, Ljubljana, Slovenia

ABSTRACT: In the paper, we show and discuss upon first results of research project with title Behaviour of Fibre Reinforced Shotcrete (FRS) Right After Construction. The results obtained on research field of primary lining of Dekani tunnel represent the starting-point of the project. The test method proposed by RILEM technical committee TC 148-SSC was used for evaluation of behaviour of young FRS. First obtained results of the research project show that added fibres have significant influence over behaviour of young FRS up to the age of 8 hours. We ascertain that the compressive strength of young FRS increases as well, besides ductility.

1 INTRODUCTION

The principle of improvement in the early age bearing capacity of tunnel lining made by fibre reinforced shotcrete (FRS) has been studied during the investigations on the research field in Dekani Tunnel, on the highway Ljubljana – Koper, as part of the research project: The Improvement of Tunnel Primary Lining in Rocks of Low Bearing Capacity by the Use of FRS [Sustersic et al, 2004]. The use of FRS practically eliminated the use of reinforcement mesh and the still arches from the primary lining. The effect of this was twofold: the savings were achieved both in the use of the material and time. Also, the safety on work has been improved, as there was less exposure of workers to the vicinity of the excavation face.

It seems that, bearing capacity of FRS tunnel lining improved, because of equivalent strengths at the selected crack widths were high enough at the early age of FRS, already and shortly after the placement of FRS lining, respectively. This statement is based on the results of observations and measurements of the lining deformations and convergence of tunnel profiles, respectively, as well as the results of investigations of FRS properties. Following properties of FRS were carried out: compressive strength, modulus of elasticity, ultimate flexural strength, and properties obtained by wedge splitting test (WST) method: ultimate strength, strength at the first crack and equivalent strengths up to selected crack width (CW = 0.1, 0.2, 0.3 and 0.4 mm). The measurements of these properties were carried out on 3, 7, 28 and 110-day-old specimens.

Increase of compressive strength at early age up to 2 hours, approximately was measured with penetrating needle on the fresh sprayed FRS in the test panels. Compressive strength of 1.0 MPa was obtained at 1 h and 40 min, on average after the placing of FRS. Further progress of compressive strength in regard to age of FRS is shown in Fig. 1.

Following ingredients were used for preparation of FRS constructed in the research field: cement (CEM II), high-range superplasticizer, accelerator, steel fibers with length of 16 mm and with diameter of 0.40 mm – 0.4 vol.%, polypropylene fibers with length of 10 mm – 0.05 vol.%, crushed limestone aggregate – fractions: 0-1, 0-4 an 4-8 mm.

Increase of compressive strength is relatively higher in early age (up to some days after construction) in comparison with increase of older FRS. So, average compressive strength of 1-day-old FRS is over 20 MPa what is already 50%, approximately of average compressive strength of 110-day-old FRS. Results of those investigations show increase of compressive strength in connection with time, but there is no evident how the FRC behaves when a compressive load is in action. First of all, there is a question whether FRC behaviour is ductile, as well at early age or right after construction, respectively. It means that we are interested in descending branch of stress – strain (σ – ε) diagram, or post-peak softening response.

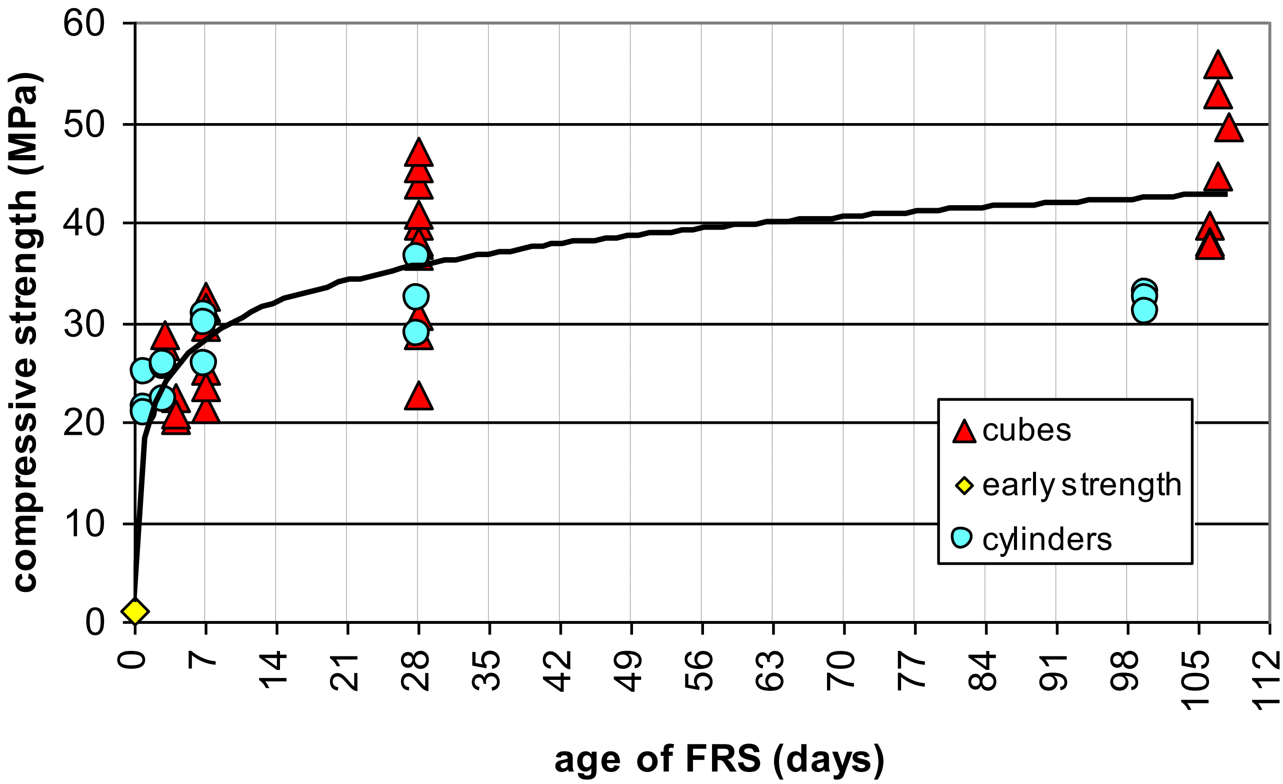

Figure 1. Influence of age of FRS on compressive strengths.

What kind of influence have fibres on behaviour of young FRS, is the second question of our interest. Therefore, we began with the research project with the intention of search for the answers to those questions.

The tests of young FRS and shotcrete without fibres (SC) have been carried out on the samples only few hours after their preparation at very law levels of compressive strength. Thus, the fresh FRC and SC were prepared in a laboratory mixer with a vertical shaft and after that they were cast in moulds and compacted on a vibrating table. In the paper, some initial and typical findings of the current project are shown.

2 COMPRESSIVE STRENGTH AND SOFTENING TESTED ON THE HALVES OF THE BEAMS

At the beginning of the research project, following ingredients were used for preparation of FRS in the laboratory: cement (CEM II), high-effective accelerator, steel fibers with length of 16 mm and with diameter of 0.50 mm – 0.75 vol.%, polypropylene fibers with length of 10 mm – 0.10 vol.% and crushed dolomite aggregate – fractions: 0-4 an 4-8 mm. Fresh FRS was cast in beams with dimensions of 10 cm × 10 cm × 40 cm.

Compressive strength and softening tests were carried out on the halves of the beams, as it is schematically shown in upper part of Figure 2, at the ages of FRS of 3, 7 and 12 hours. Deformations in axial direction were measured by extensometer fixed on the upper part of the testing machine so that displacement of upper platen can be measured. So, load – deformation diagrams were obtained, as they are presented in Fig. 2. Those diagrams show rapid increase of compressive strength with time and ductility behaviour, as well.

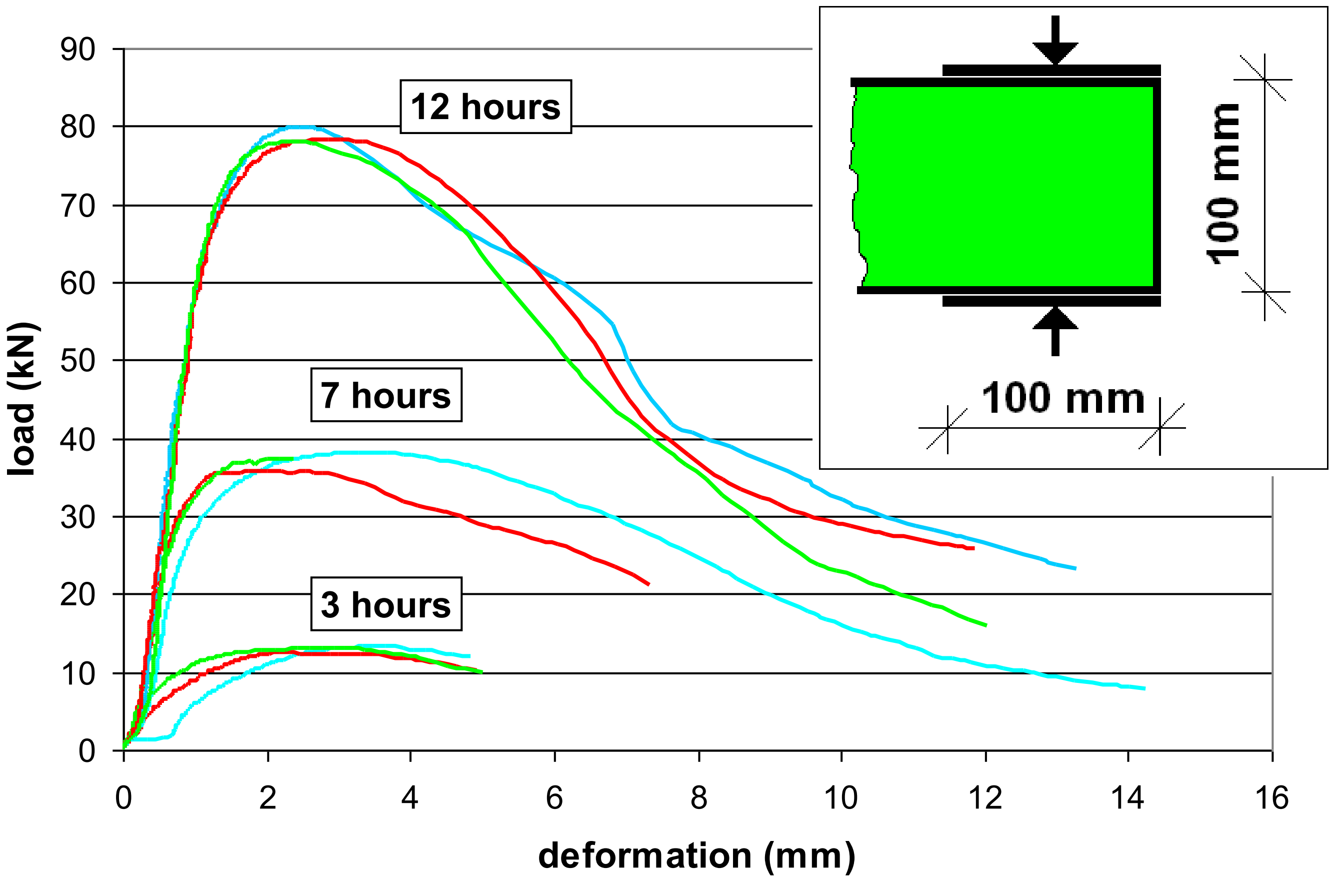

Figure 2. Compressive load – deformation diagrams of FRS at the ages of 3, 7 and 12 hours.

Uniaxial compressive stress, which is nonlinear, can be presented by Equation 1 [Desayi & Krishnan, 1964]:

$$\sigma_c = \frac{E_{ci} \cdot \varepsilon_c}{1 + \left(\frac{\varepsilon_c}{\varepsilon_{c,1}} \right)^2} \tag{1}$$

where: σ_c is the compressive stress, ε_c is the compressive strain, $\varepsilon_{c,1}$ is the compressive strain at the peak stress, E_{ci} is the tangent Young's modulus expressed by Equation 2:

$$E_{ci} = \frac{2 \cdot f_{cm}}{\varepsilon_{c,1}} \tag{2}$$

where f_{cm} is the peak stress.

Experimentally obtained stress – strain diagrams show higher ductility when they are compared with stress – strain diagrams derived from the Equation 1. Experimental and calculating stress – strain diagrams of 7-hour-old FRS is shown in the Fig. 3, as an example.

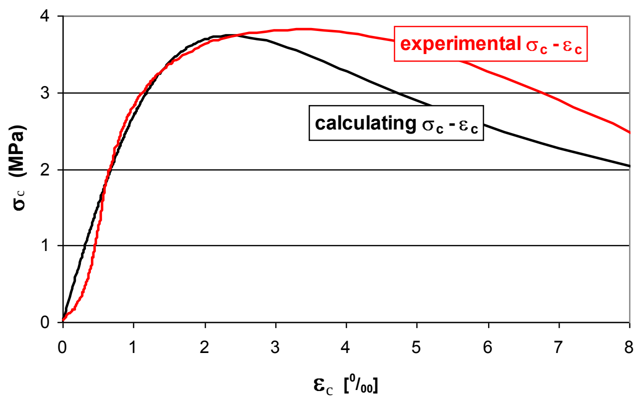

Figure 3. Experimental and calculating stress – strain diagrams of 7-hour-old FRS.

Because of, the peak stress and the post-peak softening diagram are highly dependent on specimen geometry and boundary conditions during the test, the obtained results have been expected. Increasing the boundary restraint between loading platen and concrete specimen leads to more ductile behaviour [Kotsovos, 1983]. On the other hand, increasing the slenderness leads to more brittle post-peak behaviour [Van Mier, 1984]. Therefore, test method for compressive strength and softening, recommended by RILEM Technical Committee TC 148 – SSC [RILEM TC SSC, 2000], has been used after that and it is still using during the implementation of the research project.

3 INVESTIGATION INTO THE BEHAVIOUR OF SC AND FRS UNDER UNIAXIAL COMPRESSION TAKEN INTO ACCOUNT THE TEST METHOD RECOMMENDED BY RILEM TC 148-SSC

3.1 Disposition of investigation program

Very young SC and FRS are investigated with the test method recommended by RILEM TC 148-SSC [RILEM TC SSC, 2000] at the ages between 2 and 8 hours. Strain softening behaviour of concrete under uniaxial compressive loading is tested by that method. Strain softening is defined as the loss of load-carrying capacity of concrete after it has sustained a maximum load [RILEM TC SSC, 2000]. The method is used to evaluate the behaviour of concrete which can be ductile or brittle.

Test configuration is shown in Fig. 4. Specimen – prism of 100 × 100 × 200 mm^3 is placed between the loading platens. Friction-reducing pads are placed between the specimen and loading platens (upper and lower) for the purpose of decreasing the boundary restraint. The friction-reducing pad consists in a sandwich made of two sheets of polytetrafluorethylene foil and a layer of bearing grease, which is added in between those layers. Deformations in axial direction are measured by two extensometers mounted between the loading platens, along two mutual perpendicular planes of the prism. The test is controlled automatically by a computer program which gives obtained results in the form of load – deformation diagram. Loading is increased at a rate of 0,05 mm/s.

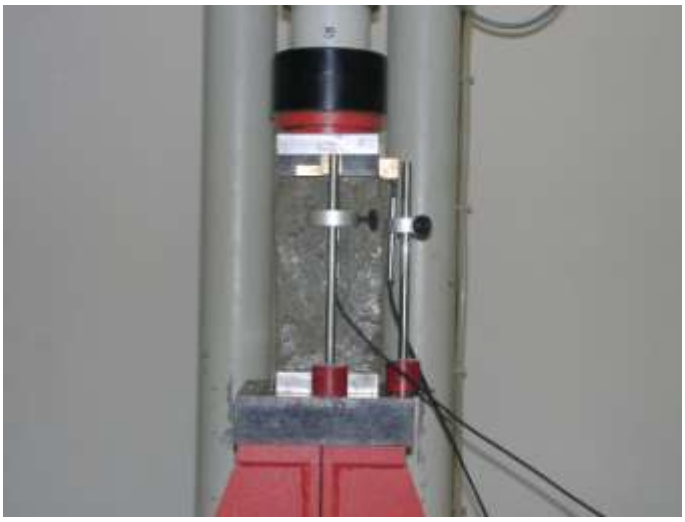

Figure 4. Test configuration for prism of 100 × 100 × 200 mm^3.

3.2 Results and discussions

Mix proportions of SC and FRS are very similar, they distinguish mainly from addition of steel fibres. Following materials were used: cement (CEM II), superplasticizer, accelerator in the small content, limestone flour with D_{max} of 100 μm, crushed river sand with D_{max} of 4 mm, natural river aggregate fraction 4 – 8 mm and hooked steel fibres with length of 16 mm and diameter of 0,5 mm used only in FRS with volume of 0,50 vol.%. Characteristic load – deformation diagrams of SC and FRS at ages of 2, 3 and 8 hours are shown in Fig. 5.

If those diagrams are converted in stress – strain (σ_c – ε_c) diagrams and compared them with calculating σ_c – ε_c diagrams in accordance with the Equation 1, better conformity is achieved (Fig. 6) then in the case of experimental diagrams obtained with tests carried out on the halves of beams (Fig. 3).

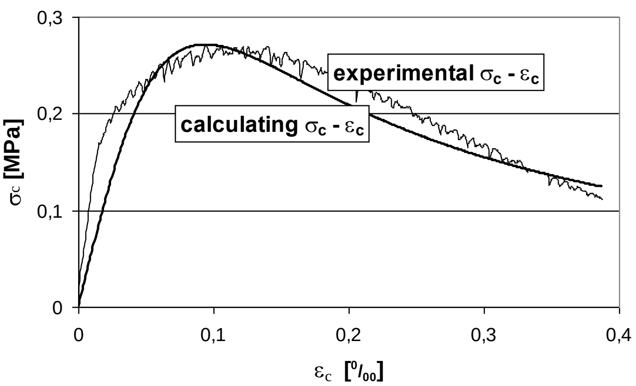

Figure 6. Experimental and calculating stress – strain diagrams of 8-hour-old FRS.

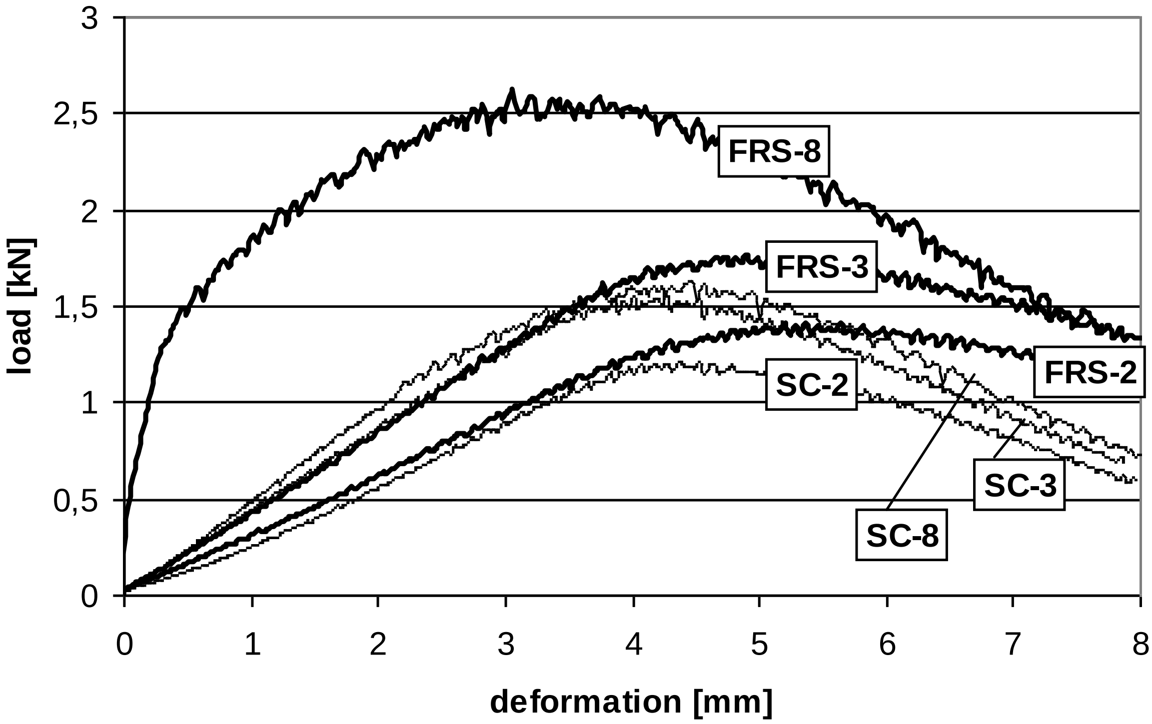

Figure 5. Characteristic load – deformation diagrams of SC and FRS at ages of 2 hours (SC-2, FRS-2), 3 hours (SC-3, FRS-3) and 8 hours (SC-8 and FRS-8).

Those correlations show that problems of specimen geometry and boundary conditions during the compressive test can be solved to a large extent by using test method recommended by RILEM TC 148-SSC.

Diagrams given in Fig. 5 show a great influence of fibres over the behaviour of FRS at all its ages, at the age of 8 hours even more when the difference in behaviour of SC and FRS becomes significant. SC and FRS differ as well in regard to peak stress f_{cm}. FRS reaches higher f_{cm} than SC (Fig. 7).

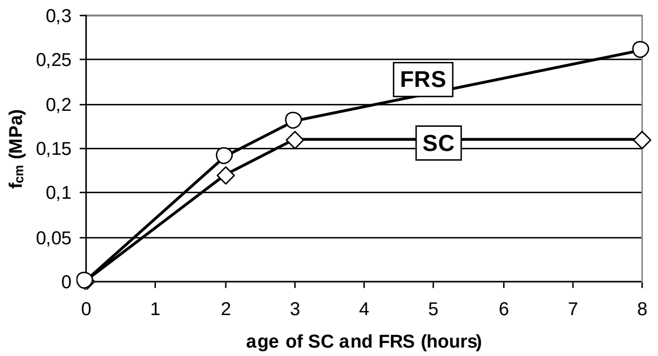

Figure 7: Average values of peak stress f_{cm} of SC and FRS at ages of 2, 3 and 8 hours.

Obtained values of f_{cm} of SC and FRS (Fig. 7) are very small at all ages in comparison with those of FRC which has been used for construction of the tunnel lining on the research field in Dekani Tunnel (Fig. 1) where average f_{cm} of 1,0 MPa has been obtained 1 hours and 40 minutes, already after placing. The main goal of the project, represented in this paper is to investigate behaviour of FRS right after construction when its strength is steel very low. Therefore, smaller content of accelerator was used during preparation of laboratory mixtures of SC and FRS to make the investigations of their behaviour feasible at low strength levels.

Behaviour of SC and FRS is evaluated in regard to amount of absorptive energy up to the limit stress $\sigma_{c,lim}$ with selected value of $0,5 \times f_{cm}$. Different sorts of absorptive energies are calculated from single diagrams shown in Fig. 5. Average values of absorptive energy $W_{c,lim}$ up to the selected point $\sigma_{c,lim}$ on the $\sigma_c - \varepsilon_c$ diagram are given in Fig. 8. Schematic view of $W_{c,lim}$ is shown in Fig. 8 – below.

Fibres effect, significantly on increase of ductility of FRS right after placing, in spite of poor bond between fibres and hardening cement paste in young FRS.

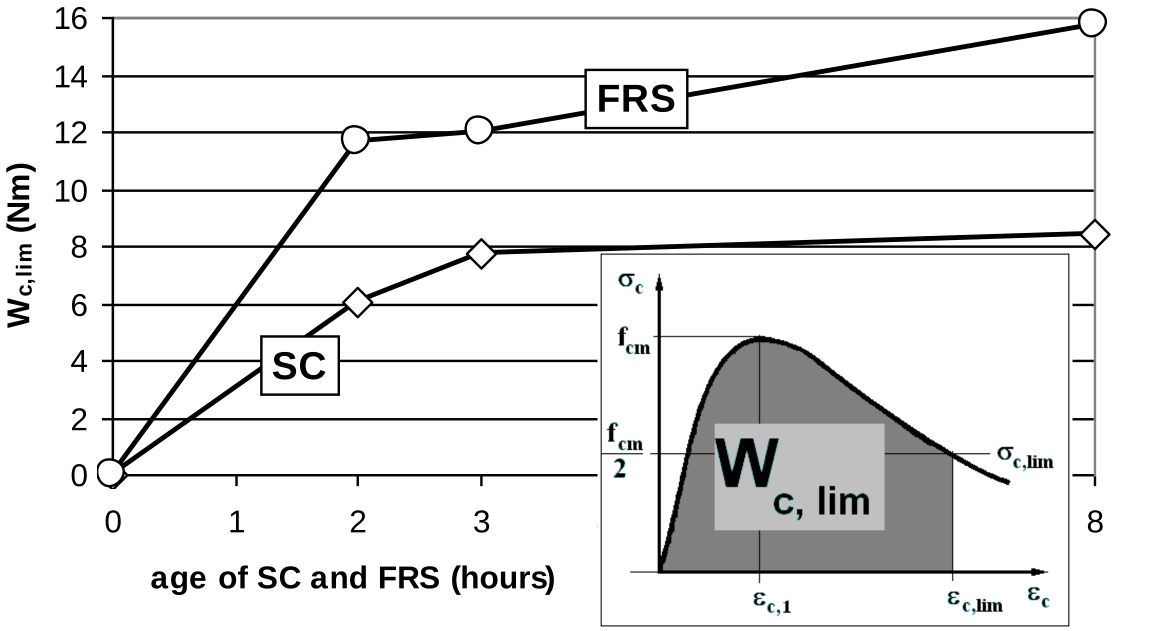

Figure 8. Average results of absorptive energy $W_{c,lim}$ of SC and FRS at ages of 2, 3 and 8 hours.

The same efficiency of fibres is obtained when behaviour of FRS is evaluated by absorptive energy $W_{c,1}$ up to the peak stress f_{cm} and by absorptive energy of descending part of diagram $\sigma_c - \varepsilon_c$ or area of strain softening, respectively W_s between f_{cm} and $\sigma_{c,lim}$. Average results of both absorptive energies are given together in Fig. 9, with the intention of simple comparison of differences between $W_{c,1}$ and W_s of SC and FRS at ages up to 8 hours.

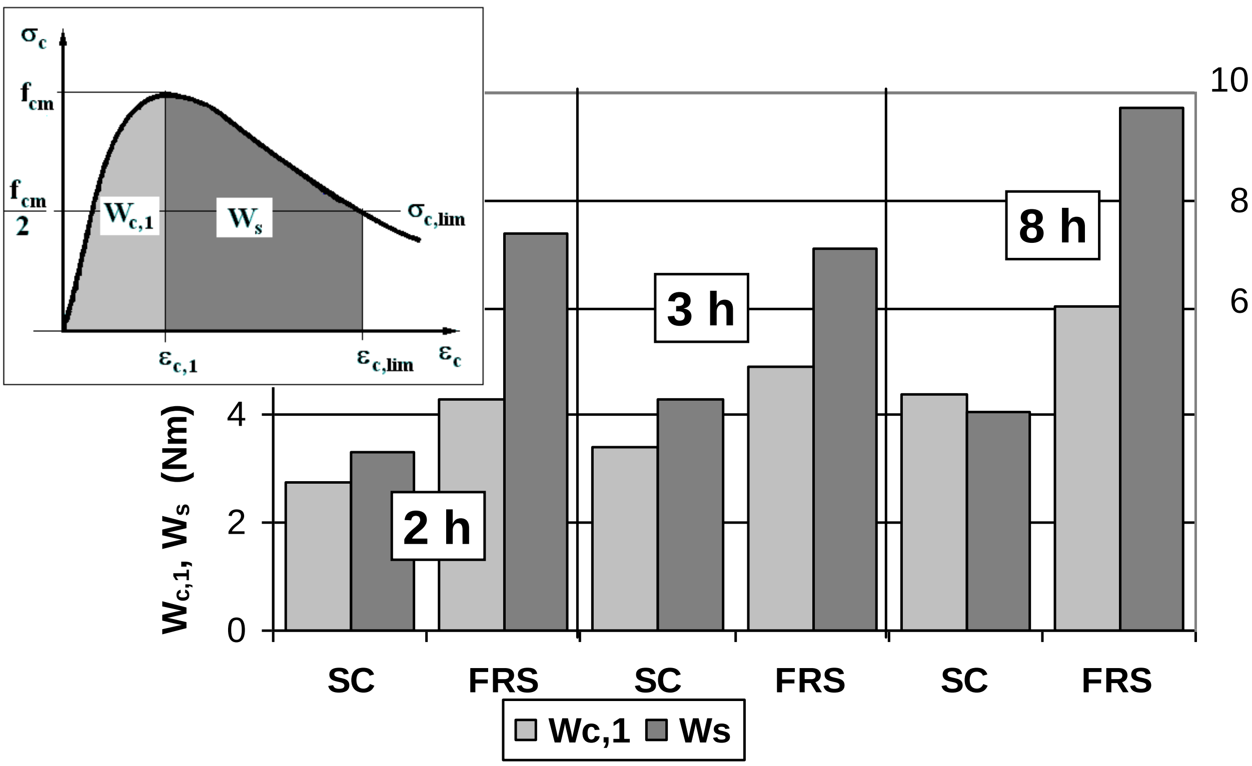

Figure 9. Average values of absorptive energies $W_{c,1}$ and W_s of SC and FRS at ages 2,3 and 8 hours.

FRS reached much higher W_s than $W_{c,1}$ at all ages. Their differences are much higher than differences between W_s and $W_{c,1}$ of SC, moreover W_s is even smaller then $W_{c,1}$ at the age of 8 hours. Those results prove much higher ductility of FRS in comparison with SC.

Strength as well as absorptive energy of FRS increase with increasing of its age as it can be seen from Fig. 10 where characteristic $\sigma_c - \varepsilon_c$ diagram are shown.

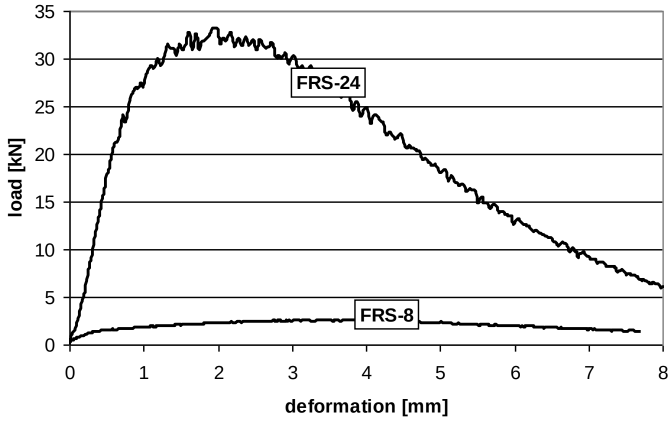

Figure 10. Characteristic load – deformation diagrams of FRS at age of 8 hours (FRS-8)and at age of 24 hours (FRS-24).

Average value of the peak stress of FRS increases from 0,26 MPa (obtained on 8-hour-old FRS) up to 3,32 MPa (obtained on 24-hour-old FRS). Huge increases of all measured absorptive energies $W_{c,lim}$,W_s and $W_{c,1}$ are obtained at the age of FRS of 24 hours (Fig. 11).

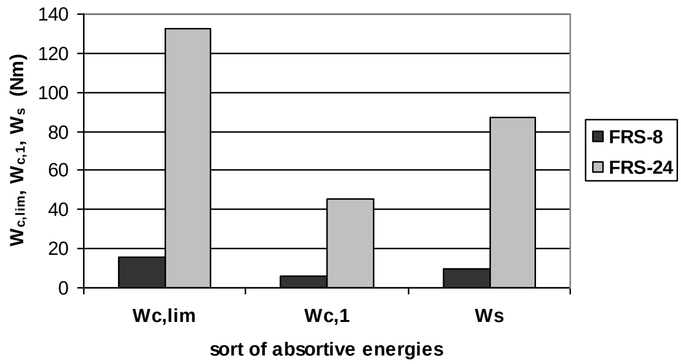

Figure 11. Average values of absorptive energies $W_{c,lim}$,W_s and $W_{c,1}$ of 8 and 24-hours-old FRS.

4 CONCLUSION

High influence of added steel fibres was obtained at the beginning of the research project where early age behaviour of FRS is investigated. Results obtained by uniaxial compressive test method recommended by RILEM TC 148-SSC show that fibres improve ductile behaviour as well as increase peak stress of young FRS up to age of 8 hours. Improvements in those properties of young FRS increase bearing capacity of FRS tunnel lining right after the placement. Results of further investigations which will be carried out within the framework of the project should make an answer to many questions arisen out from first results and findings. We expect that those responses and new statements should give proper data for development of model of young FRS behaviour in tunnel lining.

REFERENCES

Šušteršič, J., Jovičić, V., Zajc, A., Ercegovič, R. Evaluation of improvement in the bearing capacity of fibre reinforced shotcrete tunnel lining. Eds: Di Prisco, M., Felicetti. R., Plizzari, G.A. *Fibre-Reinforced Concrete. BEFIB 2004. Proceedings of Sixth International RILEM Symposium*, 20-22 September, 2004, Varenna, Italy. RILEM Publications S.A.R.L., Vol. 2, pp. 985-994.

Desayi P., Krishnan S. Equation for the Stress-Strain Curve of Concrete. *Journal of the American Concrete Institute*, Vol. 61, No. 22, 1964.

Kotsovos M.D. Effect of testing techniques on the post-ultimate behaviour of concrete in compression. *Materials and Structures*, Vol.16 (1983). str 3 – 12.

Van Mier J.G.M. Strain Softening of Concrete under Multiaxial Loading Conditions. *PhD thesis*. Eindhoven University of technology (1984).

RILEM TC 148-SSC: Strain softening of concrete – Test methods for compressive softening. Test method for measurement of the strain-softening behaviour of concrete under uniaxial cpmpression. Recommendations. *Materials and Structures*, Vol. 33 (2000). str. 347 – 351.