EVALUATION OF IMPROVEMENT IN THE BEARING CAPACITY OF FIBRE REINFORCED SHOTCRETE TUNNEL LINING

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Abstract
Hybrid fibre reinforced shotcrete (FRS) with steel and polypropylene fibres was investigated during the performance of research field of the tunnel lining. Beside compressive strength at different ages of FRS, modulus of elasticity, flexural strength and above all post-crack behaviour were measured on the samples sawn from the test panels. Toughness obtained with different test methods can be used to determine equivalent strength. Bearing capacity of FRS tunnel lining will improve, if FRC has higher crack opening resistance, which can be measured with equivalent strength at the selected crack width. Wedge splitting test (WST) method was used to obtain load – CMOD curves and determine equivalent strength at the selected crack width. This strength of FRS is high enough to improve bearing capacity of FRS tunnel lining at early age, already.

1. Introduction
Use of fiber reinforced shotcrete (FRS) is an economical and effective method of protection in the excavations of tunnels, where reinforcing meshes are not used. Cost of material is higher, but the method is economical because of:
- decrease of working costs (there is no fixing of reinforcing meshes),
- lower consumption of FRS (FRS lining can follow the exact contours of the rock, whereas reinforcing mesh often requires 5 cm of cover as well as filling of all the voids behind the mesh with shotcrete),
- higher safety of working conditions (fixing of mesh gives lower safety level),
- saving of time (more rapid protection of excavation increases its continuation and shortens time of performance).
Similar conclusions were obtained when the research field was brought to the finish. The research field has been introduced during the excavation of 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. The research project is funded by Slovenian Ministry for Science, Education and Sport, and the Slovenian contractor SCT is co-funding it.

The aim of the research project was to answer to the question of possible wider use of FRS in more demanding geotechnical conditions. Until now, the FRS was used in rock of good quality, i.e. as classified by ÖNORM B 2203 as category A2 or B1. The aim was to lower the boundary of the use of FRS to category B2, which is classified by ÖNORM B 2203 as heavily friable rock mass characterised by large areas of non-elastic zones extending far into the surrounding rock mass.

During the advancing excavation of the tunnel works in the research field there was a change of geological conditions and the rock quality has improved from category B2 to B1. In that sense the field only partly achieved the aim of using the FRS for the category B2, although the technological process was not changed for the category B1.

The use of FRS practically eliminated the use of reinforcement mesh and the steel 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. The technology developed in the research field has been successfully used for the next 350 m of tunnel excavation. As a result of the gains made, the excavation of the tunnel has finished 3 months before the planned time.

Significant development has been made on FRS in the last decades. It is evident from several applications [1 - 5], where steel fibers was used in many these applications. Nevertheless, results of the investigations on the lining showed that the polypropylene fibers added in the shotcrete had significant effect on improvement in the bearing capacity of the lining [3]. Our own experiences grow out of FRS applications, particularly in Velenje Mine, where FRS is placed in lining mine roadways by the dry-mix process. Dry shotcrete mixtures for the mine and for external sites are produced in the plant [6]. But in the case of the research field in Dekani Tunnel, FRS was placed in the tunnel lining by the wet-mix process. Hybrid fibre reinforced shotcrete with steel and polypropylene fibres was applied.

Toughness of fiber reinforced concrete or shotcrete, respectively is much higher than a toughness of concrete (shotcrete) without fibers. Area under load - deformation curve is the measure of the absorbed energy, which is needed to reach appointed deflection and lead to the concept of toughness of fiber reinforced concrete. This toughness can be used to determine equivalent flexural strength $\sigma_{eq}$, which is needed for calculation of the bearing capacity of fiber reinforced shotcrete tunnel lining [7]. Calculation of equivalent
flexural strength \( \sigma_{\text{f}} \) in accordance with Japanese standard JCI-SF4 is carried out on the base of values of absorption energy up to deflection of \( L/150 \) obtained from load – deflection curves.

However, evaluation of improvement in the bearing capacity of FRS tunnel lining of the research field in Dekani Tunnel was provided by taking into account results of wedge splitting test (WST) and by calculation equivalent strengths up to the crack widths of 0.1, 0.2, 0.3 and 0.4 mm. These equivalent strengths represent the measure of crack opening resistance of FRC or FRS [8]. Concrete will have a higher resistance to crack propagation, if the equivalent strength at the selected crack width is higher. Furthermore, concrete element will have higher bearing capacity, if concrete has higher crack opening resistance. Based on this supposition, research field of FRS lining has been performed and FRS has been investigated. Some results of these investigations are shown and discussed in this paper.

2. Preparation of FRS and its transportation

Hybrid fibre reinforced shotcrete with steel and polypropylene fibres was placed in the tunnel lining by the wet-mix process. All processes of preparation, transportation and placing of FRS were performed in a similar way as in the case of construction of the tunnel lining with shotcrete without fibres. Fresh FRS was mixed in the ready-mixed concrete plant and than it was delivered with a truck mixer to the tunnel entrance which is 3 km far from the plant, approximately. Fresh FRS was prepared in the plant without the accelerator, which was added into a truck mixer at the tunnel entrance. After that, FRS was mixed for the fixed time and than delivered to the shotcrete equipment at the place of lining construction in the tunnel. Both fibers (steel and polypropylene) were added in the concrete plant mixer, already.

Following ingredients were used for preparation of FRS:
- 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.

Workability was measured on the concrete plant after mixing in accordance width slump test method. Obtained results ranged between 150 and 190 mm.

3. Program of investigations

During construction of the FRS lining of the research field, FRS was sprayed in the wooden moulds with dimensions of 60 cm × 60 cm × 12 cm. Cubes with edge of 10 cm
and prisms with dimensions of 10 cm × 10 cm × 40 cm were sawn from these test panels for laboratory investigations into the following properties of FRS: compressive strength, modulus of elasticity, ultimate flexural strength, and properties obtained with 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). Specimens were cured in a climate control chamber, at a temperature of 20 ± 4°C and relative humidity of 95%, up to one day before the tests. 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 was obtained, also on cylinders with diameter of 10 cm bored from the test panels.

Compressive strength tests were carried out on cubes, mostly with edge length of 10 cm, and on cylinders with diameter of 10 cm and height of 10 cm. A static third-point bending configuration was used for ultimate flexural strength measurements in accordance with ASTM C 1018 on prisms with dimensions of 10 cm × 10 cm × 40 cm width notch depth of one third of the height (3.3 cm, approximately). Tests in accordance with the wedge splitting test (WST) method were carried out on cubes with an edge length of 10 cm and with initial notch depth of 5 cm. WST method proposed by Linsbauer and Tschegg [9] was used.

4. Results and their discussion

Moderate increase into the compressive strength at early age was reached with addition of the accelerator in mixture of FRS. So, compressive strength of 1.0 N/mm² 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 Figure 1. Compressive strengths, obtained on cubes with edge of 10 cm and on cylinders with diameter of 10 cm are calculated on the compressive strengths of cubes width edge of 20 cm. Average compressive strength of 1-day-old FRS is over 20 N/mm² what is already 50%, approximately of average compressive strength of 110-day-old FRS.

Good correlation between average results of compressive strength and modulus of elasticity, obtained at the same ages of FRS was found (Fig. 2).
Fig. 1: Influence of age of FRS on compressive strengths.

Fig. 2: Correlation between compressive strength and modulus of elasticity of FRS.
Ultimate splitting strength $f_{su}$ obtained by WST method increase with ageing of FRS, similar as compressive strength (Fig. 3).

Fig. 3: Influence of age of FRS on ultimate splitting strength.

One of the fundamental purpose for development of new fracture mechanic test method (wedge splitting test method) by Tschegg and Linsbauer [9] was to minimize some of defectiveness of third-point bending test on the notched prism. Therefore, WST method can be considered as a third-point bending test method on the notched prism, so as it is schematically shown in Figure 4 [10].

Fig. 4: Wedge splitting test method as a third-point bending test method on the notched prism [10].
On the base of that supposition, correlation between ultimate splitting strength $f_{su}$ and ultimate flexural strength $f_{fu}$ is accomplished (Fig. 5).

![Graph showing correlation between $f_{su}$ and $f_{fu}$](image)

This figure shows that those two strengths correlate, although the notch depths of both specimens were not the same (cubes had notch depth of 5 cm and prisms had notch depth of 3.3 cm). Therefore, further evaluation of FRS post-crack behavior is carried out only on the results obtained with WST method.

As it was already stated in the Introduction, FRS tunnel lining will have higher bearing capacity, if FRS has higher crack opening resistance, which can be measured with equivalent strengths up to the selected crack widths [8]. Equivalent strengths which represent toughness indices up to the selected crack widths of 0.1, 0.2, 0.3 and 0.4 mm are calculated by taken into account values of absorption energy capacity derived from load – CMOD curves obtained with WST method. In Figure 6, average equivalent strengths $f_{CW}$ and strength at the first crack $f_{FC}$ (CW = 0.0 mm) of FRS are shown in regard to crack width (CW) and the age of FRS.

Strength at the first crack $f_{FC}$ is higher in comparison width $f_{CW}$ at all ages of FRS. When the crack width increases, $f_{CW}$ of FRS decrease. Those results show that, strain – softening response of FRS was obtained at all ages. The highest values of all strengths were obtained at the age of 110 days. But, the strengths obtained at the age of 28 days are equal, approximately to the strengths obtained at the age of 3 days. The lowest values have the strengths obtained at the age of 7 days. This phenomenon becomes more visible, if separate equivalent strength at the selected crack width dependent on age of
FRS is drawn as it is done in Figure 7 where equivalent strengths at the crack widths of 0.1 and 0.4 mm ($f_{0.1}$ and $f_{0.4}$) are shown in regard to age of FRS. Both strengths, either $f_{0.1}$ or $f_{0.4}$ have higher average values at the age of 3 days in comparison with their average values at the age of 7 days. After that, both strengths increase. But, average value of $f_{0.4}$ obtained at the age 3 days is still higher, in moderate than the average value obtained at the age of 28 days.

Fig. 6: Interdependence of average results of first crack strengths $f_{FC}$ and equivalent strengths $f_{CW}$ of FRS, obtained at different ages and crack width (CW).

Fig. 7: Influence of age of FRS on equivalent strengths at crack widths of 0.1 and 0.4 mm ($f_{0.1}$ and $f_{0.4}$).
Very similar post-crack behavior of SFRC was obtained [11]. Results of toughness indices in accordance with ASTM C 1018 and equivalent strength in accordance with JCI-SF4 were taken into account as the parameters for evaluation post-crack behaviour. The values of these parameters decreased up to the age of 28 days, and after that age they increased. In this case of FRS, equivalent strengths decrease up to the age of 7 days, and after that age they increase, already. Acceleration of FRS hardening would be a possible reason for earlier increase of equivalent strengths. Bond between fibres and cement past improves earlier, so that fibres become more efficient and equivalent strength becomes to increase after 7 days, already although ultimate strengths increase too.

It is evident as well, that FRS is capable to absorb large amount of energy at early age (3 days), already. This characteristic is helpful to improve bearing capacity of FRS tunnel lining shortly after placement.

5. Conclusions

Research field only partly achieved the aim of using the FRS for the heavily friable rock mass, because of change of geological conditions and the rock quality has improved during the advancing excavation of the tunnel works in the field. However, 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. Further investigations of FRS properties and in situ measurements of FRS tunnel lining in the heavily friable rock mass needs to be done to establish by evidence that bearing capacity of the FRS lining improves with improving into the FRS equivalent strengths at the selected crack widths.

References

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