Use of Fibre-reinforced Shotcrete for Primary Lining in the Dekani Tunnel

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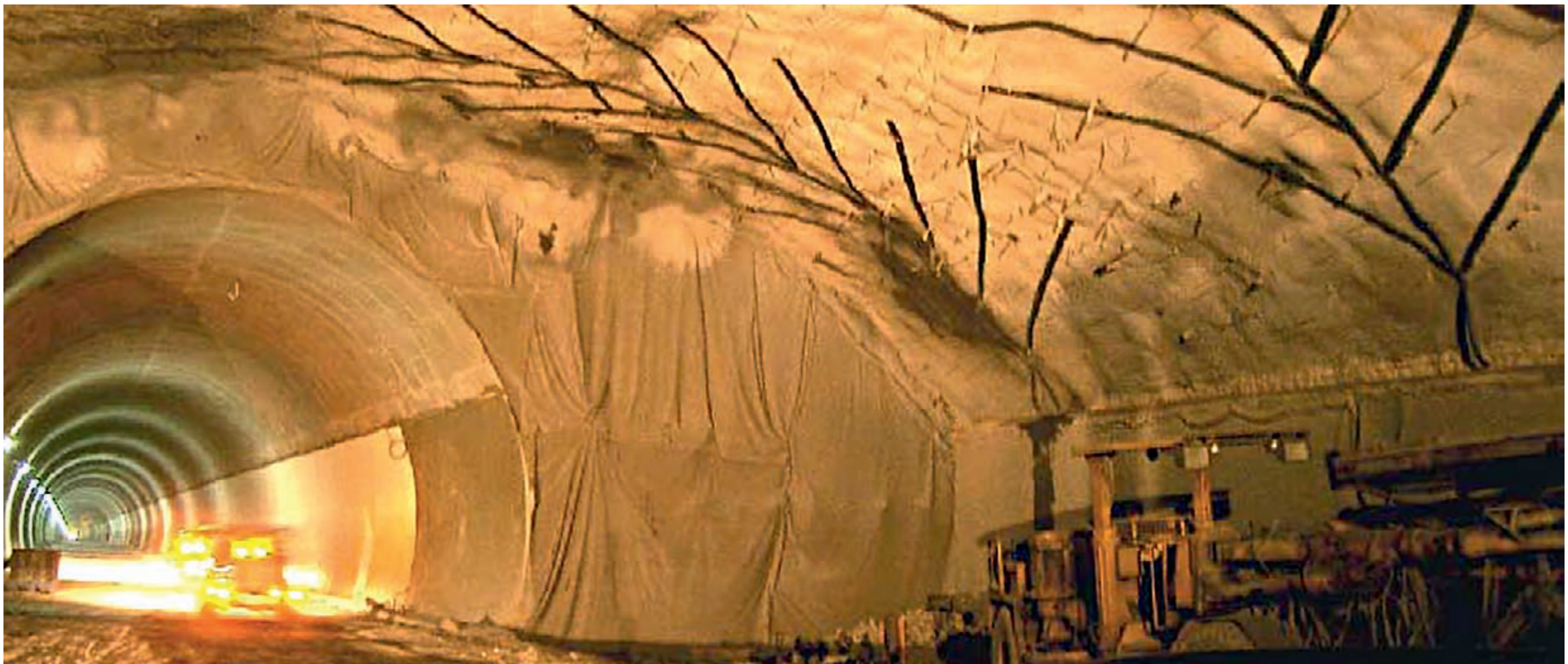
Abstract:

A 10 m-diameter motorway tunnel at Dekani was constructed using the principles of the NATM method. The tunnel was located in the flysch geological sequence, which is classified as weak rock. The aim of the research presented in this paper was to examine whether fibre-reinforced shotcrete (FRS) can be successfully used as the only material for the primary tunnel lining in these geological conditions. In-depth interpretation of the interaction between the FRS lining and the surrounding rock, which was based on monitoring in a 60 m-long test field, is presented in the paper. The success of the test field led to the use of FRS for the primary lining in a 410 m-long section of the tunnel.

1. Introduction

Steel fibre-reinforced shotcrete (SFRS) has a relatively long history of application in tunnelling. Steel fibres were introduced as a component of shotcrete in the 1970s to impart ductility in an otherwise brittle material. Ductility is of particular importance for the distribution of load between the tunnel lining and the surrounding ground. During interaction between the two, the lining is prompted to carry a significant load only once the ground is deforming. The large deformations that occur in the ground can easily overload brittle material such as plain shotcrete and lead to failure.

It is demonstrated in this paper that the combination of fibres and shotcrete makes a composite material of sufficient ductility to accommodate large ground deformations several hours after the application.



These deformations are accommodated from their very onset, when they develop most rapidly, without damage to the composition of the FRS, so that the lining does not lose any of its initial capacity. The subsequent gain in strength of the lining with time is enhanced by the lessening of ground deformation. From this point of view, FRS is an ideal material for tunnel lining.

2. The test field

The geological structure in the area of the Dekani tunnel is dominated by flysch, which is a turbidite material deposited off the continental shelves during the Cretaceous period. At the time of formation, collapses in the underwater depository slopes were common – the macrostructure of flysch is dominated by their failed shapes. The Dekani flysch is characterised by intermittent layers of marl and sandstone, the latter varying in thickness from a few centimetres to one to two metres. An important feature of the Dekani flysch is that the original sequence was tectonically alternated and is now heavily folded, featuring a chaotic distribution of layers and joints, as shown in Figure 1.

The interaction of the rock mass and the tunnel lining was closely observed during construction of the tunnel using real scale measurements. These were carried out to measure the convergence of the cavity and the degree of mobilisation of the tunnel support elements. For this purpose, measuring profiles were installed systematically at characteristic sections along the tunnel. As part of the active design approach, back analyses were performed to determine the relevant mechanical characteristics of the rock mass and to refine the support measures.

The 60 m testing field, in which the FRS lining was used alone, was particularly well covered by instruments. Sets of geodetic targets around the perimeter of the excavation of the tunnel were used to measure radial and longitudinal convergence. Sets of extensometers installed at depths of 3, 6, and 9 m were used to measure movements within the body of the surrounding rock mass and sets of radial measuring anchors were used to measure the mobilised anchor forces.

The purpose of the test field was to examine whether a 20 cm-thick FRS lining of class C20/25 can be equally efficient as a standard lining, when used in similar geological conditions. The standard NATM lining in this case comprised steel meshes ϕ6 mm/15 cm, TH21 steel arches at 1.5 m spaces, and 20 cm-thick shotcrete of class C20/25.

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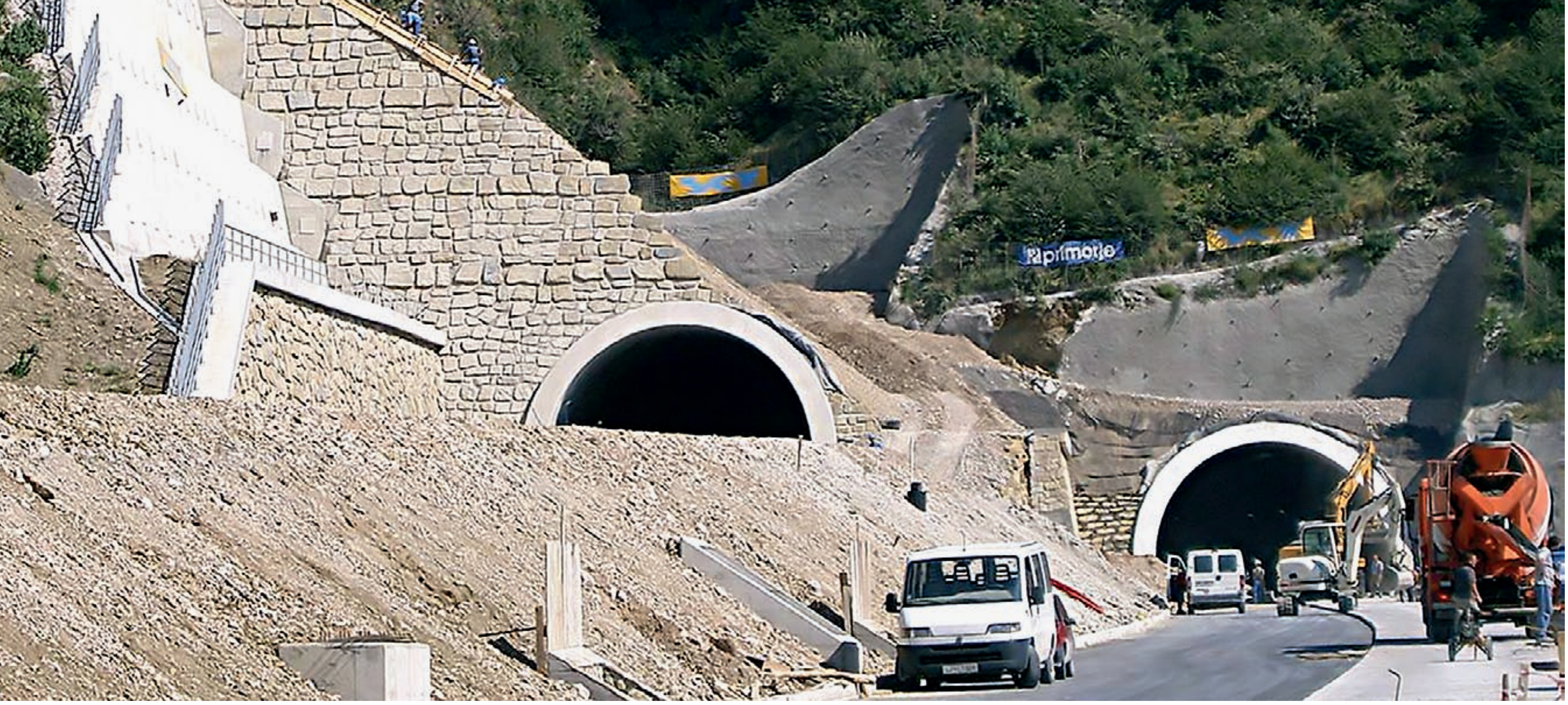
3. Description of the performance of the new FRS

A combination of steel and polypropylene fibre was used to prepare the mix for the FRS. Based on previous experience, the following ingredients were used for the preparation of the FRS:

- cement (CEM II);
- high-range super-plasticiser;
- accelerator;
- steel fibres with length of 16 mm and with diameter of 0.40 mm – 0.4% of total volume;
- polypropylene fibres with length of 10 mm – 0.05% of total volume;
- crushed limestone aggregate – fractions: 0–1, 0–4 and 4–8 mm.

The FRS was mixed wet. All the processes of preparation, transportation and spreading were performed as for plain shotcrete according to the technical specification. Fresh FRS was mixed in the ready-mixed concrete plant, with steel and polypropylene fibres added, and was then delivered to the

Figure 1: Typical texture of the Dekani flysch sequence exposed during excavation of the tunnel (marl sequence is coloured grey and sandstone sequence is coloured brown)



site by a truck mixer. The accelerator was added into a truck mixer during controlled mixing. By careful choice of the length and the amount of fibres added, there were no difficulties with the placeability of the FRS during the spreading.

The following properties of the FRS were tested: compressive strength, modulus of elasticity, ultimate flexural strength, and properties obtained with a wedge splitting test. The latter test, developed by Tschegg and Linsbauer (1986), is schematically shown in Figure 2 from Linsbauer and Šajna (1996). The wedge splitting test was designed to minimise some of the problems of the third-point bending test on a notched prism in evaluating the ductility of concrete.

Wedge splitting tests were used to measure the ultimate strength, the strength at the first crack and the

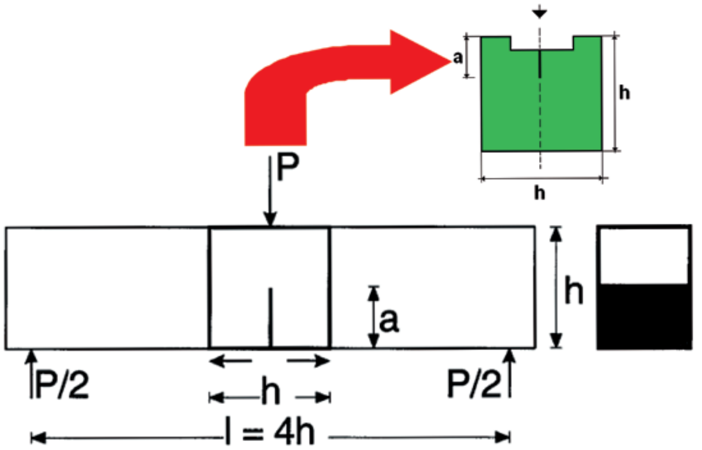


Figure 2: Wedge splitting test (WST) method (after Linsbauer and Šajna (1996)).

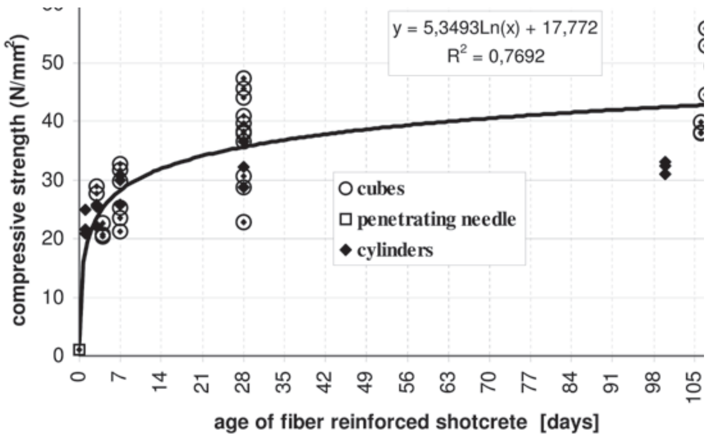


Figure 3: The rise of compressive strengths of FRS with time.

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IRMA – the Institute for Research in Materials and Application

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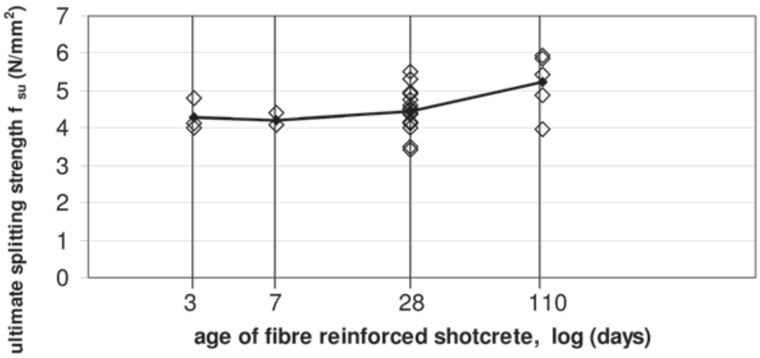


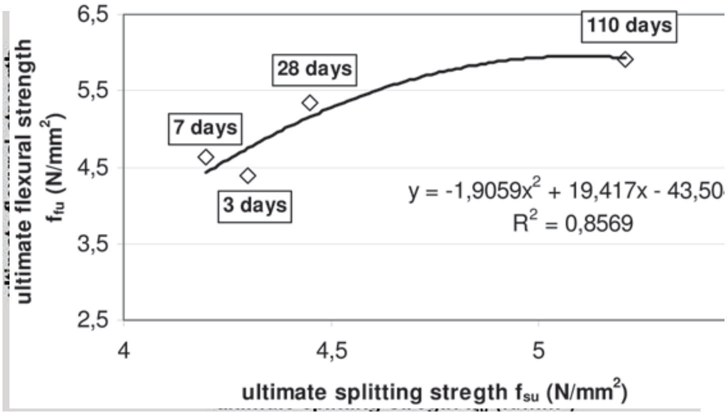
Figure 4: Influence of age of FRS on ultimate splitting strength.

equivalent strengths up to selected crack widths of 0.1, 0.2, 0.3 and 0.4 mm.

The critical parameter for the efficiency of a sprayed concrete lining is early compression strength. On average, a compressive strength of 1.0 N/mm² was obtained at 1 h and 40 min after the placing of the FRS. Further progress of measured compressive strength with regard to the age of the FRS is shown in Figure 3. As can be seen, the average compressive strength of about one-day-old FRS exceeds 20 N/mm². This was already approximately 50% of the average compressive strength achieved for 110-day-old FRS.

The influence of age of the FRS on ultimate splitting strength is shown in Figure 4. It can be seen that the ultimate splitting strength fsu increases with the ageing of FRS, at a similar rate as compressive strength.

Figure 5: Correlation between average results of ultimate splitting strength f_{su} and ultimate flexural strength f_{fu}.



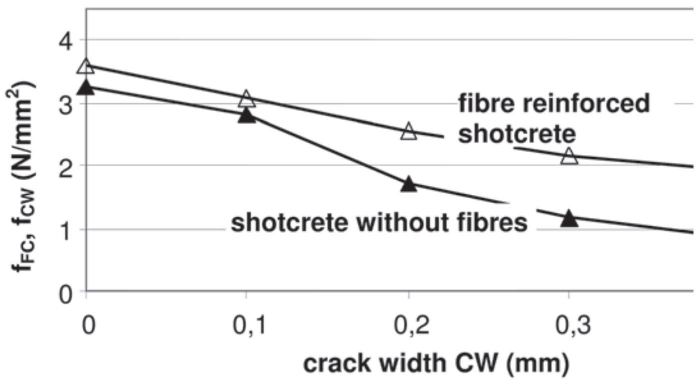


Figure 6: Influence of fibres on the increase of the crack opening resistance of shotcrete at the age of 28 days.

Linsbauer and Šajna (1996) argue that the wedge splitting test method can be considered as a variant of the third-point bending test method on a notched prism (Figure 2). Following this assumption, a correlation between ultimate splitting strength f_{su} and ultimate flexural strength f_{fu} was plotted, as shown in Figure 5. It can be seen that these two strengths correlate strongly, despite different notch depths (the cubes had a notch depth of 5 cm and the prisms had a notch depth of 3.3 cm).

An attempt was also made to compare directly the performance of the plain shotcrete and the FRS. The higher strength of the FRS is the result of higher ductility and higher crack-opening resistance. This can be evaluated by measuring equivalent strengths up to the selected crack widths (Šušteršič et al., 2001). 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 taking into account the values of the absorption energy capacity derived from the load-deformation curves.

The increase of crack-opening resistance of the shotcrete by addition of fibres relative to shotcrete without fibres is shown in Figure 6. The average equivalent strengths f_{CW} and the strength at the first crack f_{FC} (crack width = 0.0 mm is a notation for the range of micro-cracks) of the samples of the FRS and the plain shotcrete are plotted for the same crack width at the age of 28 days. It can be seen that the presence of fibres increases the crack-opening resistance of shotcrete within the range of 10% at 0.0mm cracks, up to 100% for cracks of 0.4mm.

4. Results of observation in the test field and subsequent back analyses

The results of the observation of the interaction between rock-mass and tunnel lining are compared for a test field and for a regular measuring profile. Two profiles were compared: 20cm-thick FRS lining and the equivalent conventional NATM lining (steel meshes ϕ6 mm/15 cm, steel arches T21 at 1.5 m spaces, and 20 cm-thick shotcrete). Both linings were supported by a set of identical SN radial anchors ϕ=28 mm, l=6.0 m at approximately 2.0m distance along the perimeter and 1.5 m longitudinally. The profiles were chosen within similar geological conditions and the same level of overburden. The measurements of convergence displacement of the two linings showed no significant difference.

Back analyses of the interaction of the rock-mass and the FRS lining in the test field were carried out using the 3D finite element program PLAXIS. The model, shown in Figure 7, featured a finite element mesh of about 14,000 elements. All stages of the excavation, and support of the top, bench and the invert were separately modelled, as indicated in the figure. A hardening soil model (Schanz et al., 1999) was used to model the behaviour of the rock mass using the parameters presented in Table 1.

The purpose of the back analyses was twofold: a) to examine the efficiency of the interaction between the tunnel lining and the rock mass and b) to evaluate the parameters for the rock mass model relevant for tunnel construction as performed in the test field. The back analyses were performed by simulating in detail the steps of tunnel construction while attempting to match the observed behaviour in the test field by changing the material parameters of the modelled material. The material parameters were iterated until good agreement between the observed and the calculated behaviour was achieved. The back-calculated parameters were then used to refine the design in the remaining section of the tunnel.

The final comparison of the calculated and measured convergence movements is shown in Figure 8. The difference in convergence of the FRS tunnel lining and the conventional NATM lining is also shown in the figure.

Bending moments in the lining were not measured

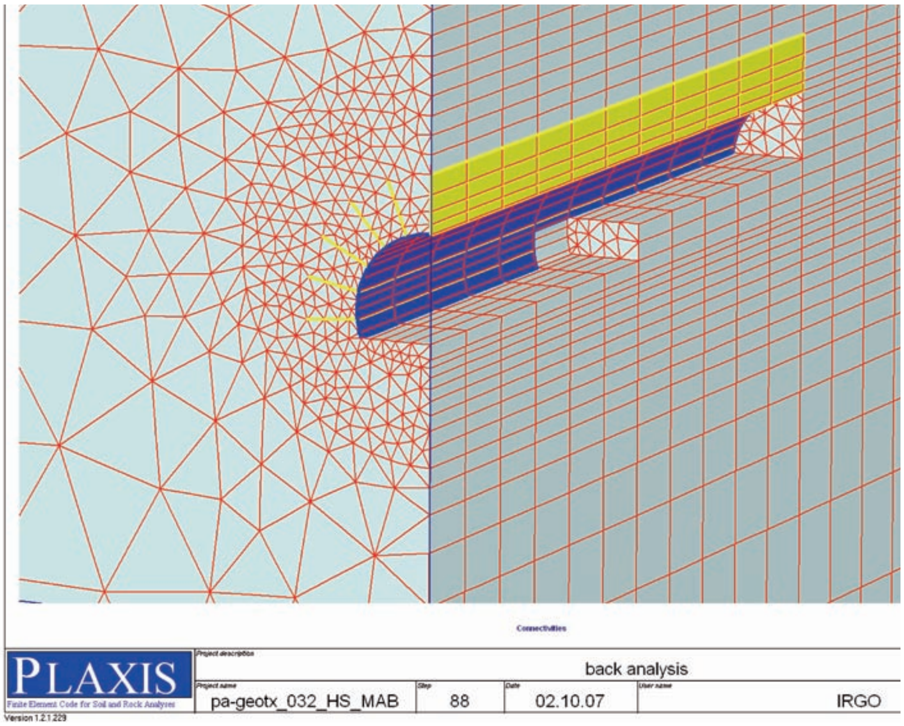


Figure 7: Finite element model of the construction of the Dekani tunnel

	Unit weight γ [kN/m^3]	Cohesion c [kN/m^2]	Friction angle φ [°]	Young's modulus E_{50} [GPa]	Young's modulus E_{ur} [GPa]	Poisson's ratio ν
initial	26	239	38	0.50	2,.0	0.20
final	26	295	41	0.75	3.00	0.20

Table 1: Initial and final material parameters of the flysch for the back analyses

in the field. Given the fair agreement between the other indicative parameters, it is plausible to expect that the bending moments obtained in the back analysis would be close to the actual field values. The back analyses indicate that for the given FRS lining, the actual field bending moments would be at the upper mark of 20 kNM/m.

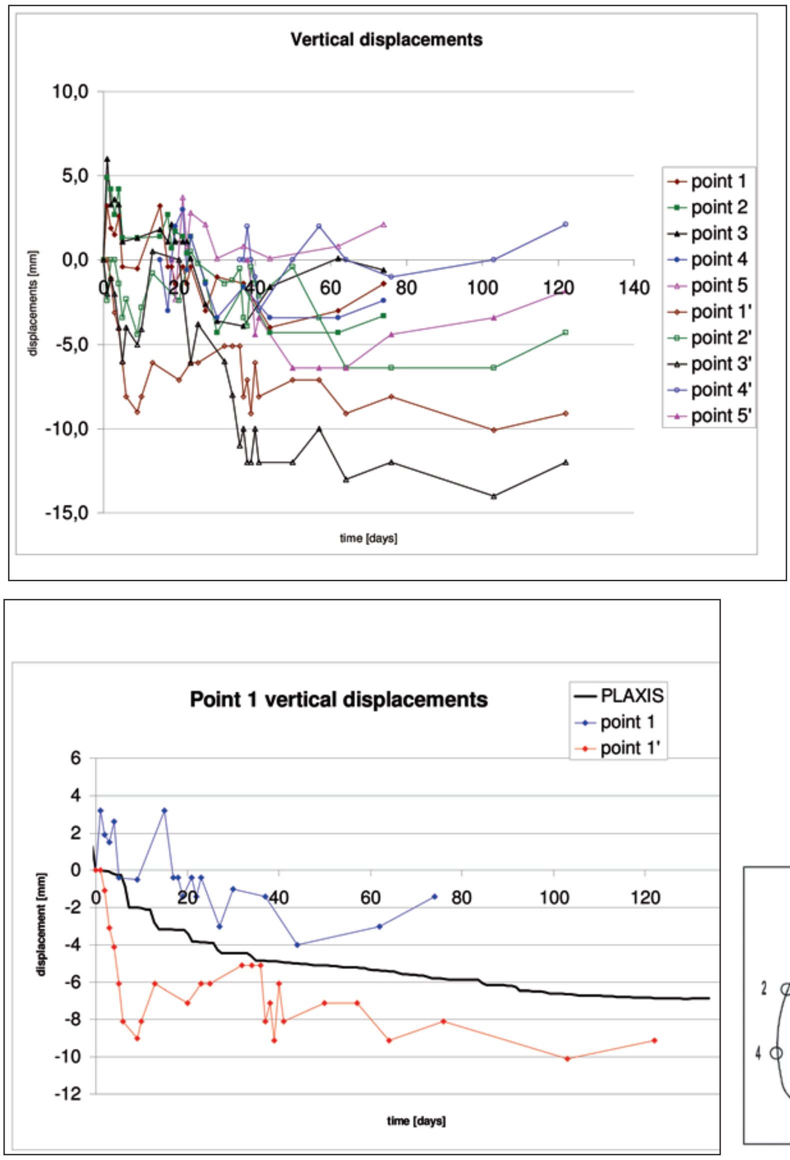
5. Discussion and conclusion

The purpose of the use of the steel arches, an integral part of the conventional NATM lining, is mainly to provide short-term support to the tunnel excavation, before the sprayed concrete sets in and integrates with the steel reinforcement meshes. But after several hours, their role becomes mainly obsolete, despite the considerable efforts to put them in place.

The installation of the reinforcement meshes is demanding and requires exposure of working force to the open faces of the excavation. Initially, the meshes have low efficiency, as the integration of the meshes and the sprayed concrete is done after the main convergence deformations in the tunnel have already taken place. This is the usual explanation for the often-seen brittle failure of the sprayed concrete lining that occurs in the first few days after the excavation.The fibres in FRS have an almost immediate effect and, due to improved ductility and a high post-crack strength, the FRS remains load-bearing during the main convergence deformations in the tunnel.

This paper has shown that FRS can be a highly appropriate material for tunnel linings constructed in weak rock, such as flysch. Using real-scale measurements in the testing field and numerical back analyses, it was shown that FRS can achieve a comparable strength capacity to the mesh-reinforced sprayed concrete of a conventional NATM lining.

The use of the FRS in the testing field proved successful and a further 410 m of tunnel was constructed using this method. Savings were made in the use of working force and materials. The contractor achieved advancements in given ground conditions of about 7 m per day, as opposed to 5 m per day as planned. This resulted in the conclusion of the works some four months ahead of schedule. This was achieved without any compromise in the required quality of the works or health and safety procedures.



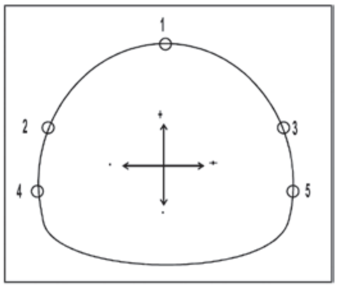


Figure 8: Comparison of the calculated and measured vertical convergence movements (points 1–5 are movements measured for the FRS lining, whereas points 1'–5' are movements measured for the conventional NATM lining)

Acknowledgements

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