Utilisation of Fibre Reinforced Sprayed Concrete for Primary Lining of the Považský Chlmec Tunnel

M Baláž[1], M Uhrin[2], P Růžička[3] and M Hilar[4]

[1]FCE CTU in Prague and HOCHTIEF CZ a. s.

[2]SUDOP PRAHA a.s.

[3]HOCHTIEF CZ a. s.

[4]FCE CTU in Prague and 3G Consulting Engineers s.r.o.

E-mail:

martin.balaz@hochtief.cz

michal.uhrin@sudop.cz

pavel.ruzicka@hochtief.cz

hilar@3-g.cz

Abstract. The aim of this paper is evaluation of the possibility to utilise fibre reinforced sprayed concrete for the primary lining of the Považský Chlmec Tunnel and comparison of such alternative design with the realised standard solution. The paper also includes a short description of the encountered geotechnical conditions and performed numerical modelling, which was necessary for determination of internal forces in the designed underground structure. The evaluation of fibre reinforced tunnel lining capacity is based on international standards. The paper also contains additional information about tunnel linings from fibre reinforced sprayed concrete such as standards and guidelines in the Czech Republic and abroad, project experience from the Czech Republic and abroad, details about design and construction or relevant laboratory testing.

1. Introduction

Internationally, it has become common practice to utilize fibre reinforced sprayed concrete for the lining of tunnels if the geotechnical and other project conditions allow so. The structural fibre reinforcement is ideally meant to replace a conventional reinforcement comprising lattice girders, mesh or re-bar, and thus achieve simpler, faster and overall more efficient construction. [9]

However, in the Czech Republic and Slovakia there have so far been very few attempts in this area. An indirect consequence of such development is that local legislation, technical standards, standards of large client organizations and common practice of design, construction and supervision are „unprepared" for this this construction system.

Hochtief CZ considered use of fibre reinforced sprayed concrete for the Považský Chlmec Tunnel project during the construction preparation stage based on two key factors: First, very favourable

ground conditions. And second being the fact that the project delivery was contracted under “yellow fidic” contract conditions that allowed design and specification changes by the contractor to some extent. Overall, the motivation was construction, cost and programme efficiency.
In the end the tunnel was constructed using the conventional reinforcement system mostly due to lack of time to fully prepare the alternative fibre reinforcement system including all required formal approvals. However, considerable effort was spent on preparation of the competitive alternative system and the solution was developed to a high level of detail. This paper details the lessons learned during this exercise and presents key issues encountered on the way.

2. Basic information about the Považský Chlmec Tunnel

The Považský Chlmec Tunnel is situated on the D3 motorway section on the northern side of town Žilina in Slovakia. The alignment with the aggregated length of 4250 m first overcomes the Hričov dam reservoir on a dual carriageway viaduct. The route then smoothly passes to the western portal of the Považský Chlmec Tunnel. It emerges from it after another 2 kilometres and passes to the dual carriageway bridge over the Kysuca River.
The excavation of the twin-tube tunnel started in January 2015 and was finished in August 2016. The tunnel was excavated according to the NATM principles with horizontal excavation and lining sequence (top heading, bench and invert). Cut-and-cover sections were situated not only in the areas of the eastern and western portal but also at the mid-point construction pit. Special feature of the Považský Chlmec Tunnel is the fact that the tight construction schedule required work at up to six headings. Taking into consideration the tunnel length, this fact is undoubtedly a rarity. HOCHTIEF CZ was the contractor for the excavation of the tunnel from the mid-point construction pit. TuCon was its sub-contractor for driving the tunnel from the western and later eastern portal (Figure 1).

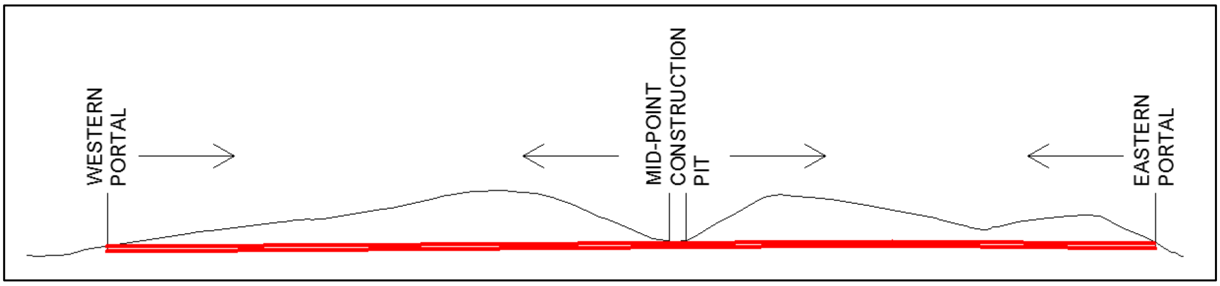

Figure 1. Construction sequence schematic shown in longitudinal section

3. Encountered geological conditions

The tunnel was mostly excavated in relatively strong ground with high overburden (in some parts almost 120 m). A thin sprayed concrete layer of primary lining in these geotechnical conditions performs especially a safety function.
The area along the tunnel route is formed by flysch series of claystones, sandstones and layers of conglomerate. The rock mass was affected by folding and tectonics. Several typical excavation conditions were defined along the tunnel route for design purposes (strength of rock mass, properties of discontinuities, permeability etc.). For further analysis of mined sections the rock mass was divided within the framework of the engineering geological survey into four quasi-homogeneous blocks (M1, M2, M3 and the worst M4).

4. Calculation of internal forces

Numerical analyses were carried out to assess the feasibility of the considered structural systems for the primary lining. Internal forces in the primary lining were calculated by FEM software Plaxis 2D. The predicted internal forces depended mostly on the geotechnical conditions (height of overburden, properties of rock mass) and stiffness of the primary lining (thickness, modulus of elasticity and rockbolts).

4.1. Examined cross sections

For excavation there were designed 8 support classes (ESC 4.1, 4.2, 5.1, 5.2, 6.1, 6.2, 6.3 and MP1). The differences between the classes are thickness of the primary lining, number of wire mesh layers, number and length of rockbolts, length of advance, maximum distance between workplaces (top heading, bench and invert) and reinforcement type of invert.

The assessment of fibre reinforced concrete lining was examined for three excavation support classes in three cross sections of the tunnel. Maximum values of internal forces were calculated for support classes 4.2, 5.1 and 6.2 with different thickness of primary lining (150 mm, 200 mm and 250 mm). For each examined cross section there was created one calculation model with different input parameters (Figure 2).

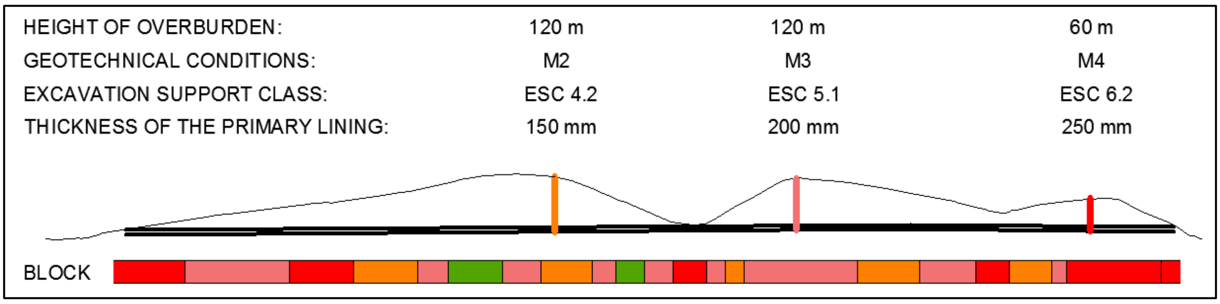

Figure 2. Locations and basic parameters of analysed FRSC sections

4.2. Load cases

Calculation load cases represent the main steps of the construction process (Figure 3). In the performed calculations there was taken into account also the relaxation effect of the ground. The relaxation of ground represents the three-dimensional effect of rock mass behaviour (the value of relaxation depends on length of advance, size of excavation profile, geotechnical conditions and other factors).

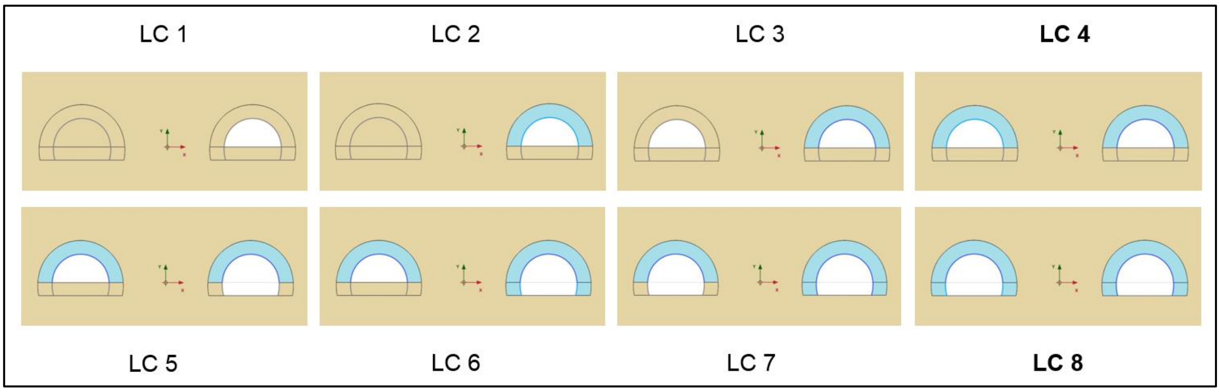

Figure 3. Load case schematics for the excavation support class 5.1

4.3. Calculated internal forces in the primary lining
Values of normal forces and bending moments in the primary lining were used as basic parameters for further assessment of the lining performance. The results with maximum lining stress values from the three FEM models for examined load cases are shown in Figure 4.

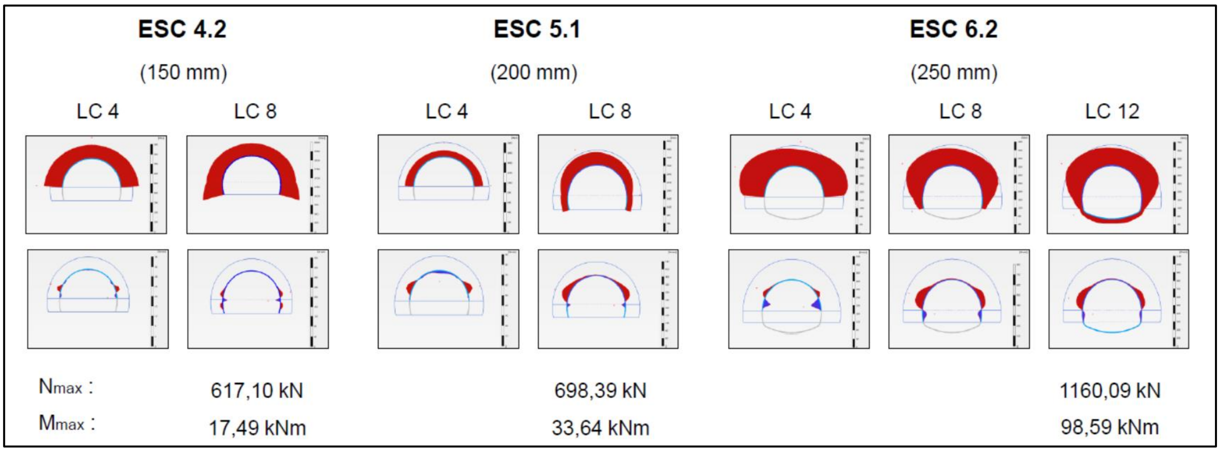

Figure 4. Calculated internal forces in the primary lining for the particular load cases (LC)

The whole primary lining in the examined excavation support classes is loaded in compression. Most parts of the lining are also loaded in bending but with relatively low values (especially in classes 4.2 and 5.1). These results are not surprising for tunnel construction in similar geological conditions (hard rock with high overburden). The calculated combinations of internal forces are appropriate for the design of fibre reinforced sprayed concrete lining which has a limited load bearing capacity compared to standard solution with wire mesh.

5. Assessment of load bearing capacity of fibre reinforced primary lining

Recent civil contracts typically require design according to the currently valid standards. The basic guidelines for the design of structures in the Czech Republic and Slovakia are Eurocodes. Unfortunately, Eurocode 2 (the standard for design of concrete structures) gives no guidance for dimensioning of fibre reinforced concrete.
For a comparison the following steps were carried out: First, calculation of load bearing capacity of standard reinforced primary lining with wire mesh (Figure 6a). Secondly, load bearing capacity of plain concrete without positive effect of fibres was determined (Figure 6b) and in the last step was considered effect of fibres according to foreign guidelines (Figure 6c). In the exercise the load bearing capacity of FRSC primary lining was assessed first according to the international standard Model Code 2010 (results being presented in this paper) and, as additional independent check, according to Austrian guidelines (Richtlinie Spritzbeton and Richtlinie Faserbeton). The main difference between these two standards is in the approach to determine the residual tensile strength of the fibre reinforced concrete.

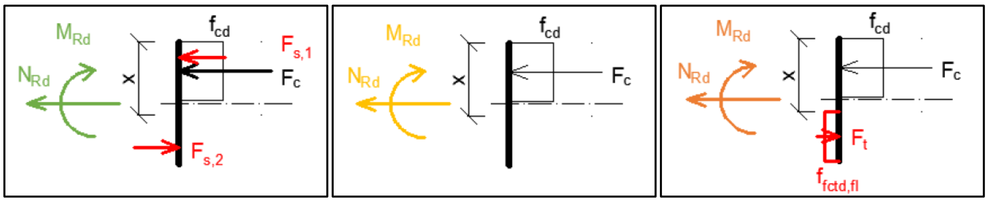

Figure 6. Principle for calculation of load-bearing capacity (wire mesh, plain concrete and fibre reinforced concrete)

5.1. Load bearing capacity without positive effect of fibres

The objective of the second calculation was determination of baseline for assessment of the impact of fibres on the overall flexure strength. The calculation of the load bearing capacity without positive effect of fibres is similar to standard case of reinforced concrete, but only without compressive and tensile forces in reinforcement (Figure 6a and 6b). The compressive strength was determined according to the strength class of the specified concrete (fibres have no significant impact on compressive strength).

The proposed FRSC lining satisfied the condition of load bearing capacity without the effect of fibres for the excavation support classes 4.2 and 5.1. In the case of support class 6.2 the load exceeded the capacity of unreinforced case interaction chart (Figure 7).

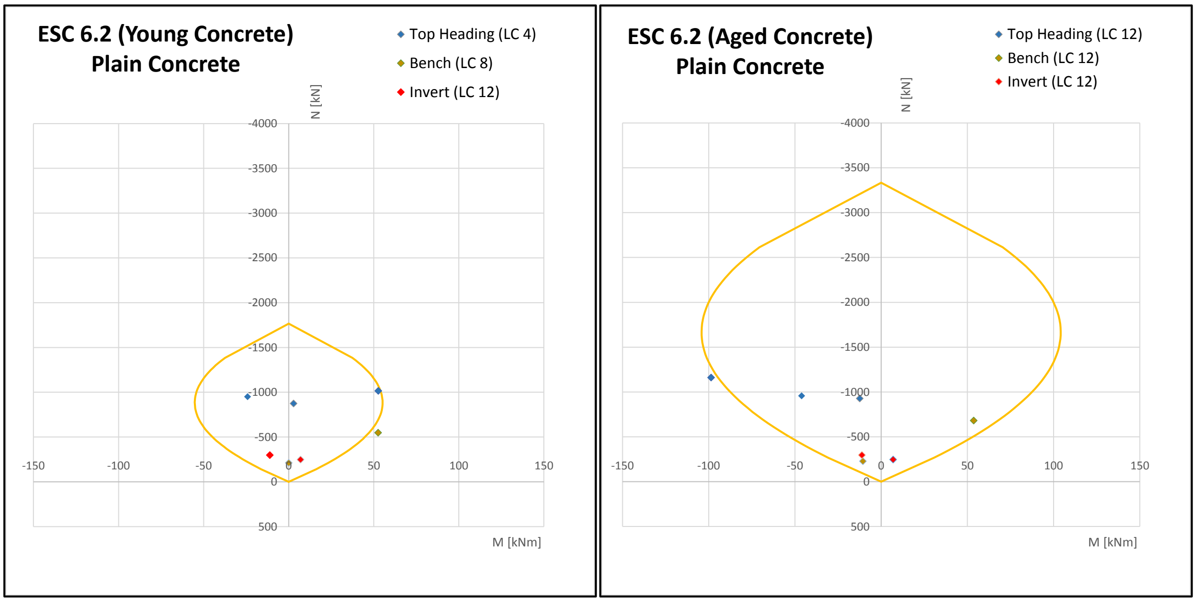

Figure 7. Assessment of load bearing capacity **without** positive effect of fibres (ESC 6.2)

5.2. Load bearing capacity with positive effect of fibres

Assessment of load bearing capacity with positive effect of fibres was performed according to the principles of Eurocodes with additional application rules adopted from international guidelines. Load bearing capacity was calculated according to Model Code 2010 and Austrian guidelines. In both cases the performed calculations led to the similar results.

Addition of fibres in the concrete mix influences mechanical properties of the final product. FRSC is a composite material with residual tensile strength (the value of it depends on the type of fibres, dosage, cohesion of a cement matrix and discrete fibres etc.). The specified fibre reinforced primary lining with residual flexural tensile strength 1.5 MPa satisfied the condition of load bearing capacity (Figure 8).

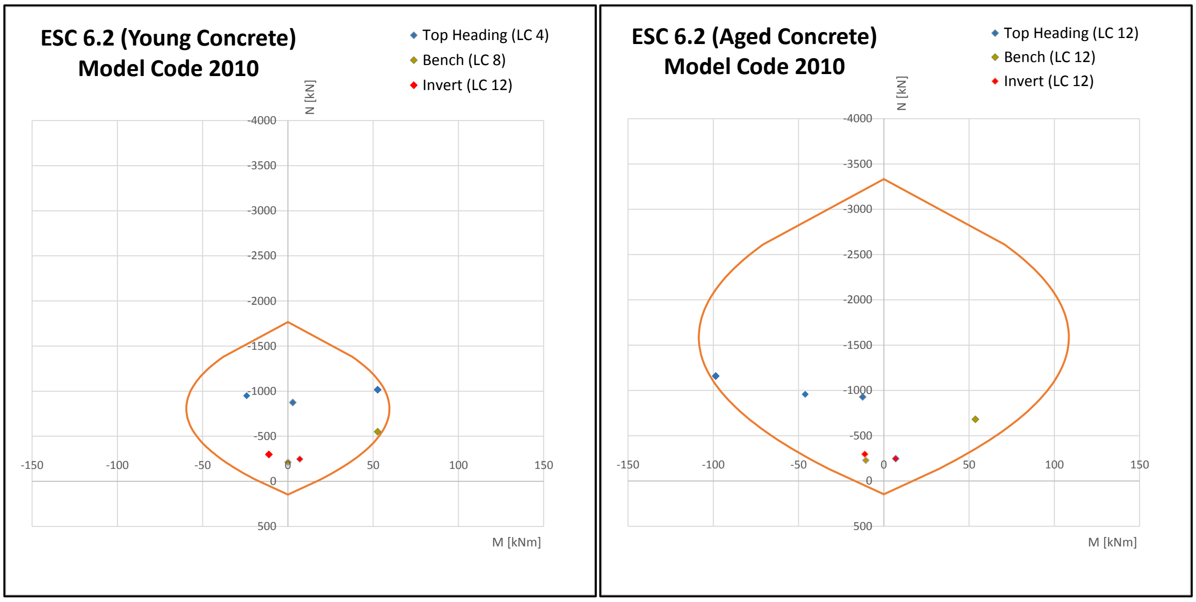

Figure 8. Assessment of load bearing capacity **with** positive effect of fibres (ESC 6.2)

6. Flexural tensile strength and toughness of fibre reinforced shotcrete samples

Mechanical properties of fibre reinforced sprayed concrete can be determined by loading tests. Besides common concrete tests the fibre reinforced sprayed concrete samples can be also tested for determination of energy absorption (on panels) and flexural tensile strength (on beams).
The first group of tests on panels practically simulate the area of primary lining between rockbolts which is loaded by unstable rock block. The second group of tests on beams is typical for European guidelines like RILEM or Model Code 2010 (three-point load test) and Austrian Richtlinie (four-point load test).
Figure 5 shows the results of three point load tests according to EN 14651 from a foreign tunnel project. In underground constructions the common dosage is 25 – 45 kg/m^3 of steel fibres or 4 – 6 kg/m^3 of structural plastic macro fibres.

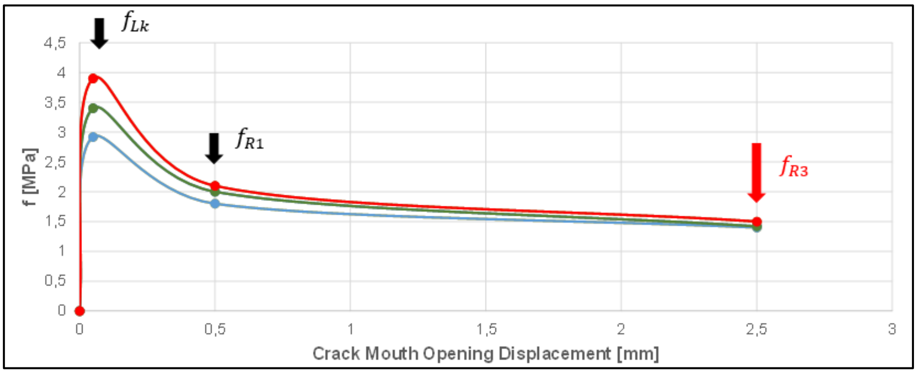

Figure 5. Results of three point load test (flexural tensile strength vs crack mouth opening)

On the basis of known results from foreign tunnel projects for the purpose of initial evaluation on the Považský Chlmec Tunnel there was specified a sprayed fibre reinforced concrete with residual flexural tensile strength of 1.5 MPa (sprayed concrete class **C20/25 D1S2.0 D3S1.5** according to EN 14487-1). This value was used in chapter 5.2 for determination of load bearing capacity of the fibre reinforced primary lining.

Besides assessment of the load-bearing capacity, it was also necessary to assess the toughness of the fibre reinforced structure (Table 1). The toughness check was assumed to represent equivalent of code minimum reinforcement check for RC structures. The assessment of toughness was carried out also according to Model Code 2010 (equations (1) and (2)).

$$\frac{f_{R1}}{f_{Lk}} > 0{,}4 \quad (1)$$

$$\frac{f_{R3}}{f_{R1}} > 0{,}5 \quad (2)$$

Table 1. Assessment of toughness of FRSC samples

Test no.	Measured Flexural Tensile Strength [MPa]			Assessment of Toughness according to Model Code 2010			
	f_{LK}	f_{R1}	f_{R3}	f_{R1}/f_{LK}	f_{R3}/f_{R1}	$f_{R1}/f_{LK} > 0{,}4$	$f_{R3}/f_{R1} > 0{,}5$
1	2.9	1.8	1.4	0.6	0.8	OK	OK
2	3.4	2.0	1.4	0.6	0.7		
3	3.9	2.1	**1.5**	0.5	0.7		

7. Time savings

The performed calculations proved that it was possible to design the primary lining of FRSC with the same thickness as the standard solution in all excavation support classes (150 mm, 200 mm and 250 mm). On the basis of these results we can compare both solutions in terms of time savings of NATM operations. On the Figures 9 and 10 are shown average times of NATM operations. In the calculations was considered the same time for spraying conventionally reinforced and fibre reinforced concrete.

ESC 5.1 - Top heading (average advance speed 3,54 m/day)			Standard solution (wire mesh and lattice girders)
Average time of NATM operations	[min]	[%]	Time [%]
Drilling	97	14,0	
Charging and blasting	77	11,1	
Ventilation	28	4,0	
Loading and hauling, scaling and geological mapping	156	22,5	
Construcion of wire mesh and lattice girders	78	11,3	
Shotcrete	125	18,1	
Rock bolts	45	6,5	
Machinery failures	20	2,9	
Downtime	37	5,3	
Other	29	4,2	
Σ	**692**	100	

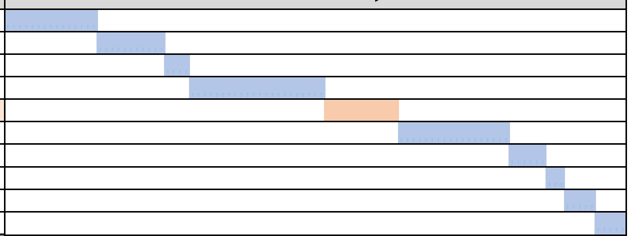

Figure 9. Average time of NATM operations and advance speed of tunnelling in the case of **standard solution** (wire mesh and lattice girders)

ESC 5.1 - Top heading (average advance speed 3,99 m/day)		
Average time of NATM operations	[min]	[%]
Drilling	97	15,8
Charging and blasting	77	12,5
Ventilation	28	4,6
Loading and hauling, scaling and geological mapping	156	25,4
Construcion of wire mesh and lattice girders	0	0,0
Fibre reinforced shotcrete	125	20,4
Rock bolts	45	7,3
Machinery failures	20	3,3
Downtime	37	6,0
Other	29	4,7
Σ	**614**	100

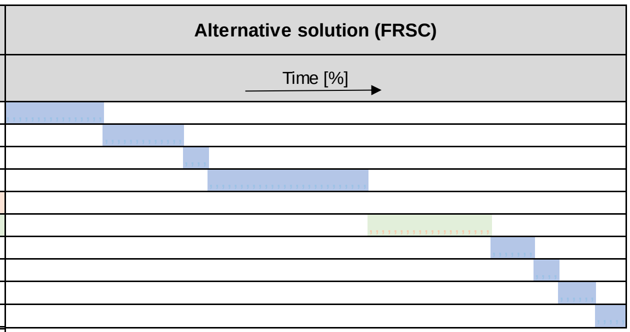

Figure 10. Average time of NATM operations and advance speed of tunnelling in the case of **alternative solution** (fibre reinforced sprayed concrete)

8. Conclusion and comparison of alternative design with realised standard solution

Time and economic advantages of the utilisation of FRSC in underground construction were studied. According to performed calculations it was found that the alternative was more efficient in this specific case. The main advantages of FRSC were considerable time savings (approx. 16 %) and lower production cost (over 6 %).

On the other hand, in some cases the primary lining without wire mesh and lattice girders may not be appropriate. Especially in adverse geological conditions the addition of fibres in the concrete cannot fully substitute the effect of wire mesh (the influence of added fibres in concrete on load bearing capacity of primary lining was calculated approx. 5 % in this case). It is always necessary to make a study for a specific project. Equally important is the availability of material, experience of technicians and workers with new technologies, attitude of project owner towards innovative solutions etc. The main advantages and disadvantages are summarized in Table 2.

Table 2. Summary of advantages and disadvantages of the alternative solution

Fibre Reinforced Sprayed Concrete for Primary Lining of the Považský Chlmec Tunnel	
Advantages	Disadvantages
Time savings (milestones, competitive offer, possible production cost savings)	Higher material costs
Construction safety (workers do not have to work under unsupported ground to install wire mesh and lattice girders)	In adverse geological conditions cannot fully substitute standard primary lining with steel bar reinforcement
Advantageous for complicated shapes (cross passages and tunnel crossings)	In case that construction of secondary lining is planned it necessitates a higher profiling accuracy
Higher quality of sprayed concrete layer (shadowing behind bar reinforcement)	In case of steel fibres it is necessary to provide a thin cover layer under waterproofing
Construction material savings (environmental considerations)	Additional requirements of loading tests (panels or beams)

9. Acknowledgements

Financial support by the research grants SGS17/057/OHK1/1T/11 and TACR TE01020168 is gratefully acknowledged.

References

[1] Baláž, M.: *Utilisation of SFRC for Primary Lining of the Považský Chlmec Tunnel*, Thesis, FCE CTU, 2017

[2] *EN 14487-1: Sprayed concrete, Part 1: Definitions, specifications and conformity*, CEN, 2005

[3] *EN 14651: Test method for metallic fibered concrete – Measuring the flexural tensile strength (limit of proportionality (LOP), residual)*, CEN, 2005

[4] Mařík, L.: *Považský Chlmec Tunnel on Žilina (Strážov) – Žilina (Brodno) Section of the D3 Motorway – from Design to Realisation*, Tunel 3/2015

[5] Matúška, T.: *Tunnel Excavation and Steel Fibre Reinforced Shotcrete*, Thesis, TUKE FBERG, 2016

[6] *Model Code 2010 – Volume 1*, CEB FIP, 2010

[7] *Model Code 2010 – Volume 2*, CEB FIP, 2010

[8] RILEM TC: *Test and design methods for steel fibre reinforced concrete*, Materials and Structures, Vol. 36, 2003

[9] Růžička, P.; Uhrin, M.; Píšová, B.: *Design and Application of Fibre Reinforced Sprayed Shotcrete in Convetional Tunnelling, 43th Conference Foundations*, Brno 2015