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Steel fibre reinforced concrete segmental lining in the Czech Republic

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1 Introduction

The segmental lining from reinforced concrete (RC) concrete is often used for the mechanical tunnelling with tunnelling machines. Currently, more and more tunnels with steel fibre reinforced concrete (SFRC) segmental linings without the traditional steel rebar reinforcement appear. SFRC is a relatively new structural material which can often replace steel rebar reinforced concrete, the tunnel lining from precast segments is one of many examples. Uniformly dispersed steel fibres reinforce the structure of plain concrete and convert the brittle plain concrete to tough steel fibre reinforced concrete. The use of SFRC for segmental linings of tunnels has become a worldwide growing trend.

The main advantages of SFRC segments over widely used steel rebar reinforced concrete (RC) segments are as follows: simple production, higher durability, lower consumption of steel, lower number of defects, etc. A major disadvantage of SFRC segments without steel rebars is their lower bending capacity.

The steel fibres improve the mechanical properties of the concrete. Fibres in concrete enhance its compressive strength, but especially SFRC tensile strength is higher. SFRC has high resistance against the development of microcracks. This feature is related to SFRC's high resistance against dynamic load and resistance against sudden temperature changes.

SFRC is especially suitable for structures loaded in more than one direction, where traditional bar reinforcement is problematic (Fig. 1). This means that SFRC is not appropriate for unidirectionally loaded structures, because the randomly oriented fibres would be largely unloaded. SFRC is therefore suitable for tunnel segments loaded in various directions during their production, installation and permanent function.

SFRC segments can have complicated details, as every part of the segment is uniformly reinforced by fibres in comparison with RC segments (Fig. 1). There is therefore less damage of segments during transportation and installation, which means that there is a lower risk of leakage and fewer repairs are required.

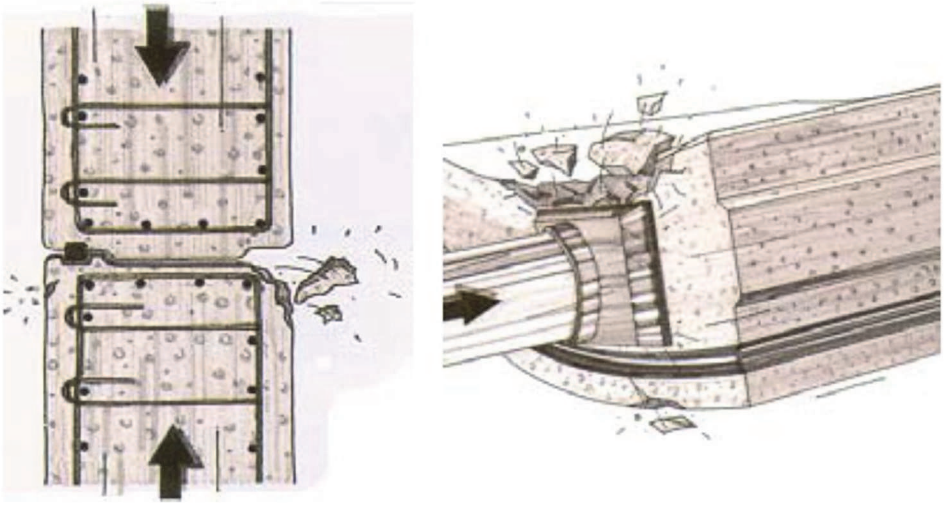

Fig. 1: Spalling of unreinforced edges of traditionally reinforced segments, Rivaz (2008)

2 Testing of SFRC samples

Laboratory tests of SFRC samples are similar to plain concrete tests. Produced samples of SFRC were used for four types of tests. Cube compressive strength and tensile splitting strength were tested on cubes according to EN 12390–3 and according to EN 12390–6 respectively. The beams were tested for flexural strength according to EN 12390–5 in agreement with German guideline DVB – Merkbaltt (four-point bending tests) and residual equivalent flexural strength on beam with notch in the middle (three-point bending test) according to EN 14651. The major objective of realised tests was to verify properties of the different SFRC mixtures, effect of different dosages and different type of fibres in SFRC samples.

In the first stage, the samples were produced with fibres Dramix RC – 80/60 BN and with Czech fibres Tri-treg. The fibre dosage was 70 kg/m^3. Totally there were produced 30 cubes with a side length of 150 mm and 30 beams with dimensions 150/150/700 mm (width/height/length). The samples were tested in three independent laboratories to increase the objectivity of test results.

In the second stage 12 beams and 12 cubes with the same dimensions as in the first stage were produced. The samples were generated only with Dramix RC – 80/60 BN fibres with fibre dosage 50 kg/m^3. The second stage of testing served mainly to compare impact of different dosage of fibres.

2.1 Tests of cubes

The average cube strength with both fibres in same dosage 70 kg/m^3 was about 74 MPa. In the figure 2a you can see the variation of the value among 9 tests with Dramix fibres in same dosage. The difference between the lowest and the highest measured value was about 30%. This was caused by heterogeneity of concrete mix with higher dosage of fibres. The results with 50 kg/m^3 had more consistent values.

The compressive strength class of the SFRC samples, which was derived from the figure 2a according to EN 1990, is FC 50/55 for samples with Dramix fibres and FC 55/60 for samples with Tri-treg fibres. The compressive strength differed in one class, but the difference between characteristic values was only 3%. The overall difference in the strength class of SFRC was because both values were very close to border line of two classes. Otherwise, the results for the two tested series of samples in compression were the same. It has also been confirmed that fibres affect the resulting compressive strength of the concrete only minimally. The same concrete mix without fibres was classified as C 50/60.

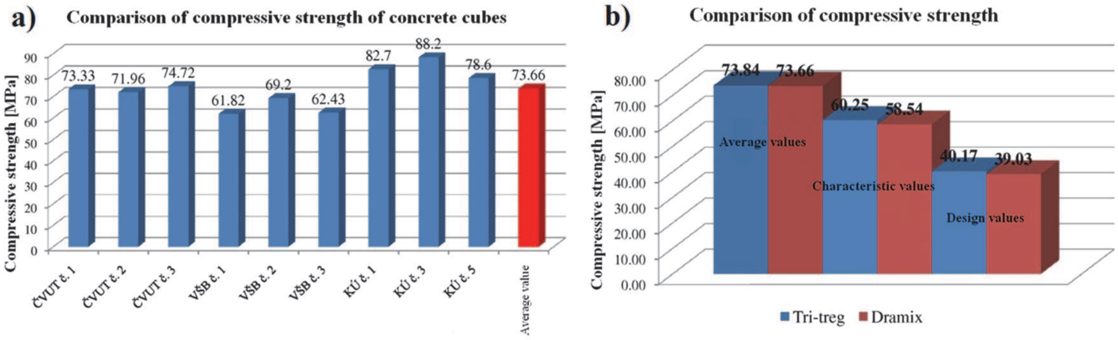

Fig. 2: Compressive strength tested on SFRC cubes a) cubes with Dramix fibres in dosage 70 kg/m^3; b) comparison of compressive strength with different types of fibres in same dosage

It is interesting to note what significant safety is included in the statistical evaluation of tests according to EN 1990 appendix D. Average strength is reduced by about 20% for a characteristic value for both test series. It is then reduced by about 5% when the results are classified into the compressive strength classes. Another significant reduction in strength occurs when the characteristic value is modified on the design value according to EN 1992 by safety factor 1.5. Overall reduction of average strength was about 40% of the average value obtained from the laboratory tests.

2.2 Tests of beams

Four point bending tests of SFRC beams were executed to get tension strength of the material. The tests were realised in Klokner institute in Prague. Results of stress-strain diagrams (FR – δ_t) were determined for agreed deflections δ_{ti} of standard beam for all samples. Graphical output of stress-strain diagrams (FR – δ_t) is presented on Fig. 3.

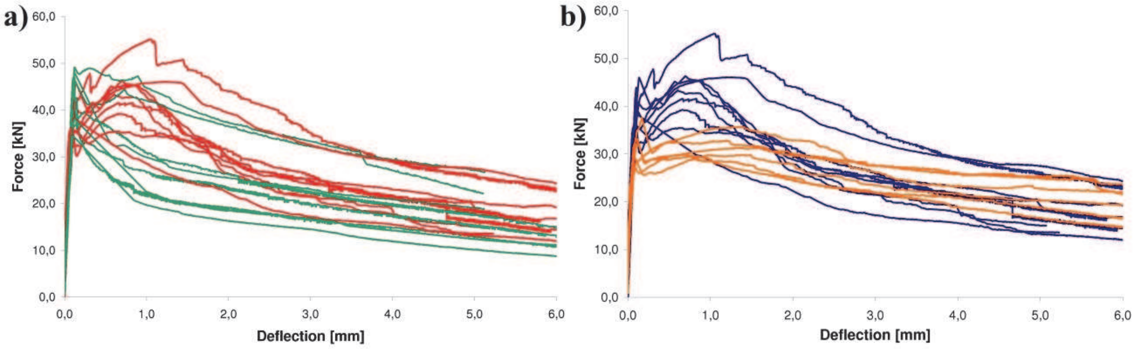

Fig. 3: Comparison of four-point bending tests on beams a) beams with different type of fibres in dosage 70 kg/m^3(red: Dramix, green TriTreg); b) beams with Dramix fibres in different dosage (blue: 70 kg/m^3; orange: 50 kg/m^3)

From the tests with same fibres in different dosage (Fig. 3b) it could be seen that with the higher dosage of fibres there was an increase in flexural strength about 30%, although the residual strength stayed at the same level.

The performed tests could not objectively recommend type of fibres for the production of SFRC segments, more tests with different dosages of different fibres would be required to get higher confidence. Generally SFRC beams with Dramix fibres had slightly better properties (Fig. 3a). They had a higher compressive strength and flexural strength than samples with Tri-treg fibres. They also showed a lower scatter caused by a better distribution of fibres. SFRC beams with Dramix fibres also showed a higher residual strength after cracking.

2.3 Classification of SFRC

Due to added steel fibres, the tensile strength increases usually more than compressive strength. Therefore SFRC cannot be simply classified according to cube compressive strength like plain concrete, as the high tensile strength would not be fully utilized in the design of structures. Therefore laboratory test of SFRC should correspond with this fact.

The following table 1 shows the classification of SFRC based on all performed tests in compression and in bending. Classification in strength classes is done according to the Czech guideline for fibre concrete (Krátký, 2007). The classification is FC (= fibre concrete) cylindrical/cube strength in compression – tensile strength/residual tensile strength (i.e. FC $f_{fc,ck}/f_{fc,cub} - f_{fc,tk}/f_{fc,tk,res1}$).

Tab. 1: Classification of SFRC according the Czech guideline for SFRC

Type and dosage of fibres	Classification of SFRC
Tri-treg 70 kg/m3	FC 55/60 – 4,2/0,6
Dramix 70 kg/m3	FC 50/55 – 4,1/1,0
Dramix 50 kg/m3	FC 55/60 – 3,0/1,2

The results of laboratory test showed that prepared SFRC can be used for segments produced for construction of the Czech transport tunnels. The tests indicated SFRC properties which are important for segments design (especially the compressive strength and flexural strength). Furthermore the tests confirmed a possibility to cast homogeneous SFRC mixture in the precast plant in Senec. Dramix fibres with a dosage 50 kg/m^3 were recommended for production and testing of SFRC segments.

3 Testing of SFRC segments

The pre-cast segments for the loading tests were produced using moulds for the production of segments for mechanised excavation of running tunnels of the Prague metro line A extension. The lining ring had the inner diameter of 5.3 m and outer diameter of 5.8 m and thickness (of segments) of 0.25 m. One lining ring was 1.5 m long (the width of one segment).

In total, one whole ring of RC segments (i.e. 6 segments) and two whole rings of SFRC segments (i.e. 12 segments) were subjected to laboratory tests. All segments were produced in a prefab plant of company Doprastav in Senec, Slovakia. RC segments were reinforced with steel rebar cages with weight of 108 kg/m^3. SFRC segments were reinforced with Dramix fibres in dosage 50 kg/m^3 and later with dosage 40 kg/m^3.

Testing of all RC segments and SFRC segments were realised in Klokner institute in Prague. All executed tests are shown in the figure 4. These tests simulated uniform load of shield rams located on the back part of the tunnelling shield (TBM technology) during its penetration into the ground, leaning on an already assembled ring with compressive force up to 2433 kN for each ram. Segments were loaded by force parallel to the longitudinal tunnel axis and at the centre plane of the segment. The laboratory tests were conducted in a hydraulic machine Amsler 10000 kN with gradually increasing compressive force. The applied force was increased in steps of 600 kN (for one loading point) or 1200 kN (for two loading point). Segments were unloaded to 200 or 400 kN after each step.

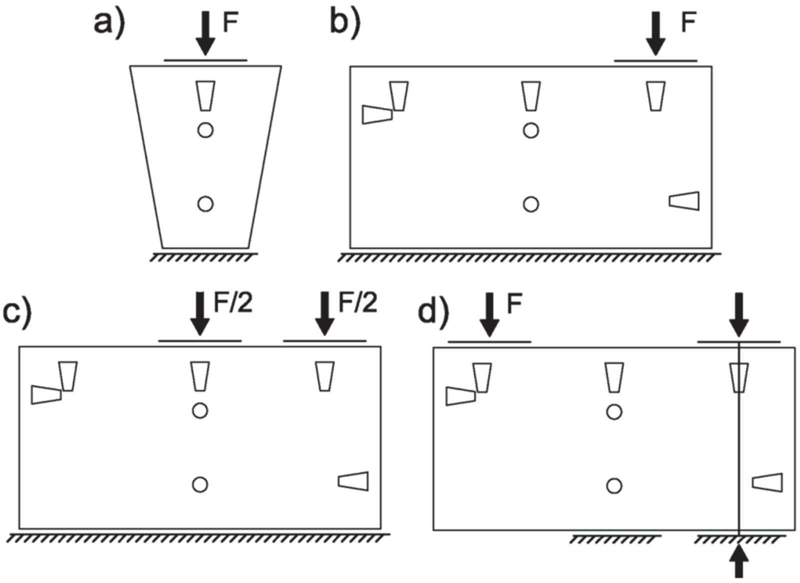

Fig. 4: Tests performed on segments

Test results for SFRC and RC segments are summarized in Table 2. Nine SFRC segments were subjected to compression test. The first crack appeared under the force of about 5400 kN at deformation of 0.25 mm. Subsequently, cracks developed under applied forces, mainly on the external segment surface. A crack running through the whole thickness of the segment appeared mostly under the loads in load step of 6000 kN. The maximum reached force was about 8000 kN. Most of segments failed by splitting in the area under applied force.

The RC segments were loaded by one or two forces (Fig. 2a, 2b, 2c), the same as SFRC segments. When the force was applied on one loading point, the first crack appeared under the loaded point. Whereas in the test set with two applied forces, the first crack appeared between them. Cracks were parallel to tunnel axis. The first crack appeared at an average force of 5100 kN at deformation of 0.2 mm for one load force and at 0.4 mm for the two load forces. The first crack was caused by the lateral tensile under the acting loads. Most cracks were through the whole thickness of the segment and thereby the segment lost the waterproofness. By increasing the load, the original crack developed further, but no other cracks appeared. Upon further increase of loading force, cracks formed around niches for assembling screws. This was due to their statically unsuitable rectangular shape, as the tension concentrates in the corners, and consequently, a local crack appears. The segment usually broke so that the coating thickness detached from the concrete body under the applied force. As a result, the segment did not lose bearing capacity completely, but, due to wide cracks, it no longer satisfied the SLS (the segment lost waterproofness). On average, the segments lost serviceability at the force of 8000 kN.

In general, the results of laboratory tests suggest that the dosage of 40 and of 50 kg/m^3 leads to comparable results. In view of the fact that very small number of tests were carried out, the tests could not be credibly statistically evaluated. It could be stated that the use of higher dosage of fibres leads to problems in the production, due to difficulties with uniformly dispersing fibres in the concrete. This fact was also confirmed by the results of tests. For example test bearing capacity in segment plane; these tests were carried out on four segments. Two segments were with dosage of 40 kg/m^3 and two with dosage of 50 kg/m^3. The highest and the lowest bearing capacity were achieved on segments with a dosage of 50 kg/m^3 (see Tab. 2). Similar bending capacity was achieved for segments with dosage of 40 kg/m^3. This suggests that the concrete with a dosage of fibres 50kg/m^3 is difficult to mix and hence the results of reached bending capacity had a higher variance. It was likely that one segment featured very good placement of fibres while the other featured very uneven placement of fibres. High strength might be due to accumulation of fibres at the bottom surface of the segment, i.e. in the tension zone of element and thus significantly increased the bearing capacity of segment. This might be caused, for example, by intensive vibration of concrete mix during production. This phenomenon is not favourable since it could be assumed that carrying capacity of the segment will be reduced when the stress is in an opposite direction. In the construction site the segments are loaded in both directions.

The test results give a realistic idea about the behaviour of SFRC lining in ULS and in SLS. The greatest advantage of SFRC is greater dispersal of cracks and later creation of a crack through the whole width of the segment than in the case of RC and so smaller risk of lost impermeability of lining. In case of SFRC segments formation a number of small cracks was observed, one crack began to expand, and then bearing capacity of the segment began to decrease. RC segments have been broken differently. One dominant crack appears which began to ramify in achieving high stress. ULS was not reach, but the segment did not comply with the SLS because of large cracks openings.

Total production costs of SFRC segments are slightly lower than of RC segments, although the steel fibres are more expensive than conventional steel rebars reinforcement. The savings arise mainly due to lower costs associated with production, storage and repair of segments. Additional savings results from significant reduction of number of damaged segments during installation and therefore lower number of required repairs (Vanderwalle 2005).

Tab. 2: Results of laboratory tests on segments

Segment	Type of reinfor-cement	Dosage o fibres or rebar reinforcement [kg/m^3]	Appearance of first crack [kN]	Appearance crack through the segment thickness [kN]	Maximum applied force [kN]
Loading uniaxial compression of segment (Fig. 4a)					
K	SFRC	50	4200	4500	7250
K	RC	108	3300	3300	5870
Loading uniaxial compression of segment (Fig. 4b)					
S1-L	SFRC	40	6000	6000	6600
S2-L	SFRC	50	4800	4800	7500
S3-L	SFRC	40	6000	6000	6600
S3-P	SFRC	40	6000	6000	7480
S4-L	SFRC	50	5400	6000	8300
S4-P	SFRC	50	6000	6600	7900
B	RC	108	5400	5400	8450
A1	RC	108	4800	4800	7240
A1	RC	108	5400	6000	7260
Loading uniaxial compression of segment with two forces (Fig. 4c)					
S5	SFRC	40	3600	6000	9000
S6	SFRC	50	3600	6000	9300
C	RC	108	6000	6000	8600
A2	RC	108	4800	5800	---
A3	RC	108	6000	7200	8960
Loading by bending in segment plane (Fig. 4d)					
S11	SFRC	50	200	400	540
S12	SFRC	50	400	650	820
S13	SFRC	40	300	300	660
S14	SFRC	40	300	600	660
S15	RC	108	300	370	660
S16	RC	108	200	350	1070

4 Conclusion

SFRC is increasingly used as a structural material for precast segmental tunnel linings excavated by tunnelling machines. The utilisation of steel fibre reinforced concrete instead of traditional reinforced concrete for some structures can bring many advantages. All advantages are given by properties of SFRC, partly by strength properties, mainly by strain characteristics. The following advantages of SFRC segments can be mentioned:

- possible price reduction (less steel is used, and there is faster production);
- easier production (less manual work, no problems with the shape and the position of cages);
- simpler placing of tunnel equipment (no risk of drilling to steel bars);
- reduced risk of segment damage during transportation and installation (the edges are reinforced by fibres);
- longer durability (no problems with corrosion).

Successful laboratory test results have confirmed the possibility of using SFRC segments in Czech transport tunnels. This finding has been confirmed by their application in the Prague metro as 15 m long test section. As this test section was successful, Metrostav decided to construct whole running through tunnels in Ejpovice with total length of 8 km with SFRC segments.

5 Literature

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