Experience with use of the tunnel linings from precast SFRC segments

M. Hilar
3G Consulting Engineers s.r.o. and FCE CTU in Prague, Prague, Czech Republic

J. Beňo
Metrostav a.s. and FCE CTU in Prague, Prague, Czech Republic

ABSTRACT: Steel fibre reinforced concrete (SFRC) has started to more frequently replace standard reinforced concrete (RC) with steel rebars. Uniformly dispersed wires (steel fibres) reinforce the structure of plain concrete and convert the brittle concrete to tough SFRC. It is possible by means of the proper selection of wires, their incorporation into fresh plain concrete during its production, optimal composition of fresh concrete and optimal production procedure to produce precast SFRC lining segments, which can replace standard steel bar reinforced concrete segments. The following benefits of SFRC segments can be mentioned:

- The possibility of reducing the cost of the tunnel lining structure
- Simpler and quicker production (the production and placement of reinforcement cages is left out)
- Lower requirements for space during production (no storage of steel cages)
- Saving of steel (saving of energy and reduced production of CO_2)
- Simpler installation of tunnel equipment (without the risk of hitting steel bars by drilling)
- Reduced risk of breaking off of corners and edges of segments during handling (lower requirements for repairs)
- Lower requirements for maintenance during the service life
- Longer service life is expected (no risk of corrosion of reinforcement)

Therefore SFRC was used for segmental linings on a range of tunnelling projects. They mostly related to tunnels with smaller profiles (water, gas or heat supply tunnels) and, in some cases, to metro sections (London, Barcelona, Napoli). The most extensive application of SFRC segments was experienced at tunnels for the high-speed rail link between Paris and London (the Channel Tunnel Rail Link - CTRL), where 2 x 24 km of single-track tunnels with the lining consisting of precast SFRC segments without using common steel rebars were constructed by tunnelling machines. This paper is focused on the use of SFRC for segmental tunnel linings, some major applications are mentioned.

1 LININGS FROM PRECAST SEGMENTS

The development of modern tunnelling methods and materials significantly increased the effectiveness and attraction of the construction of underground structures and, at last but not least, accelerated the construction process. The number of completed structures year by year grows. Nowadays, the preferred tunnelling methods are either the conventional excavation method (usually the NATM) or mechanised driving by means of full-face tunnelling machines (TBM technology), depending on geological conditions, the height of overburden, the level of water table, the tunnel diameter and its length.

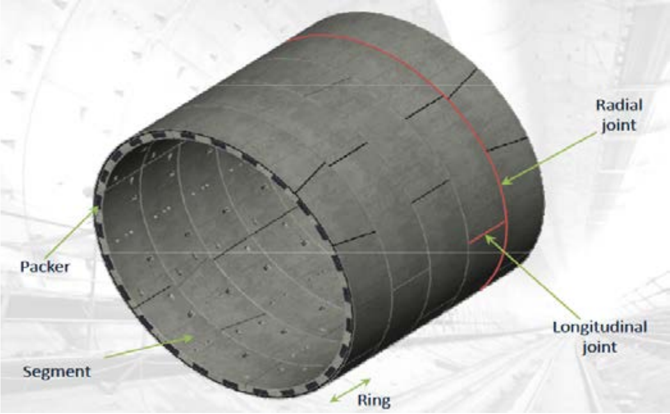

Figure 1. Tunnel lining generated from precast concrete segments

Mechanised tunnel excavation by means of shields is closely associated with the construction of the final lining. The lining is installed immediately during the excavation, behind the tunnelling machine. This circular lining is formed by rings, which usually consist of precast steel bar reinforced concrete segments. Individual segments are installed to required positions by means of an erector (a hydraulic arm at the back end of the machine). One ring is usually made up of several segments identical in the shape; the shape of the closing segment (the key) is usually different. During the construction, individual segments are usually connected with bolts and the space between the lining and ground mass is usually backfilled with grouting mix.

Pre-cast concrete segments can be installed after the required strength is reached. The lining of tunnels driven by full-face tunnelling machines is circular. This geometry is advantageous in terms of the prevention of the development of higher bending moments. In common geotechnical conditions the segments are therefore subjected first of all to compression (normal) forces.

However, this does not apply during the construction process. The segments have to resist stressing by bending moments when they are being removed from moulds (see Fig. 2), during the storage (see Fig. 3) and transport. They have to further resist temperature stresses; first of all they have to resist the high stresses induced just after they are incorporated into the tunnel lining by hydraulic cylinders shifting the shield ahead. The last of the above-mentioned stresses is usually the deciding factor for the segment design.


Figure 2. Segments handling during production


Figure 3. Storage of pre-cast steel bar reinforced concrete segments

2 SEGMENTS FROM SFRC

Steel fibre reinforced concrete (SFRC) is concrete with an admixture of short steel fibres (wires) – (see Fig. 4). Even though SFRC has been known for a longer time, its use for the lining of tunnels is relatively new. Uniformly dispersed short wires reinforce a plain concrete structure, thus converting brittle plain concrete into tough SFRC. It is possible by properly selecting the wires, incorporating them into fresh plain concrete during its production and ensuring optimum composition of fresh concrete and optimum production procedure to produce precast SFRC lining segments, which can replace standard steel bar reinforced concrete segments.

Figure 4. Fresh SFRC (the length of fibres is 60 mm)

The length of wires should correspond approximately to three times the maximum size of aggregate grains. The reason is the requirement for the bridging of the cracks which are formed just on the borders of individual grains and for the prevention of pulling of a wire from concrete when these cracks originate. The ends of the wires are usually bent, widened etc. The most widely spread is the type with bent ends. During the process of the pulling of the wire from concrete the bent end has to deform until it is absolutely straight. Owing to this property the resistance to the pull-out is significantly increased. Wires glued together by water-soluble glue are sometimes used because the dozing process is simpler. The bunches of wires are dissolved during mixing and are uniformly distributed in the concrete mix.

Polypropylene fibres cannot be used for the reinforcement of load-bearing concrete structures because their modulus of elasticity is low (lower than concrete) and they significantly deform even under small loads. In addition, they lose mechanical properties at 50°C and melt at 165°C. Nevertheless, polypropylene fibres can be added to steel fibre reinforced concrete or steel bar reinforced concrete to increase fire resistance.

SFRC segments are usually produced using concrete grade C40-C60. It is very important to ensure uniform distribution of steel fibres, good bond between the fibres and concrete and sufficient workability of the mix. The dosing of fibres is determined by means of McKee theory; the minimum dosage, measured in kg/m^3 of concrete, depends on their length and thickness (the aspect ratio). The spacing between fibres determines the density of fibres, thus also the quality of reinforcement; it should not be lower than 0.45 of the fibre length.

3 CONFRONTATION OF SFRC SEGMENTS AND RC SEGMENTS

The cost of production of SFRC segments is slightly lower than that of steel bar reinforced concrete segments despite the fact that the material (steel fibres) is more expensive than classical steel bars. Savings originate first of all owing to lower demands for work, handling and storing. The number of segments damaged during the installation is lower. As a result, steel itself is saved, which has a positive influence on the reduction of emissions originating during its production.

When the concrete tensile strength is reached, the deformation of steel fibre reinforced concrete does not grow stepwise; instead, the deformation grows slowly owing to the uniformly distributed steel fibres. The cause of this is that the fibres are activated continuously and are step-by-step pulled out of concrete (see Fig. 5). The size of cracks remains relatively small. But the tensile strength (flexural) is significantly lower than it is in the case of steel bar reinforced concrete.

Figure 5. Steel fibres pulled out of concrete at total failure

The behaviour of steel bar reinforced concrete is different. When the tensile concrete strength is reached, the deformation starts to grow until the reinforcement is fully activated. This is why the cracks which develop are wider than they are in the case of steel fibre reinforced concrete. Nonetheless, deformations then get settled and grow approximately linearly until the yield strength of steel is reached. It is significantly higher than the tensile strength of SFRC. For that reason a SFRC lining is suitable first of all to low bending stress conditions, where circular linings consisting of pre-cast segments generally belongs. If there is a threat of the origination of higher bending stress in the segments, it is necessary to provide the steel fibre reinforced concrete segments even with classical steel bar reinforcement.

Lining segments are stressed by large loads induced by hydraulic cylinders on tunnelling machines. Careless handling may result in delivering blows to the segments. Steel bar reinforced concrete segments are completely unreinforced on the surfaces, at edges and corners so that the minimum concrete cover is ensured. However, stresses in the segments are the most critical in these places. If a blow or excessive loading occurs, parts of the steel bar reinforced segments crumble and are broken off. Damaged segments have to be repaired or replaced so that the design life length of the structure is guaranteed. This work is very unpleasant in terms of time, finances and technology.

The use of steel fibres instead of classical steel bar reinforcement can be an advantageous alternative. Steel fibres are uniformly dispersed through the segment and the minimum concrete cover required to prevent corrosion is irrelevant. The orientation of steel fibres in the space is chaotic, which means that the transfer of tensile stresses is possible in all directions. As a result the resistance of segments to breaking off, crumbling and blows is significantly increased (see Fig. 6).

Figure 6. Edges of steel bar reinforced concrete segments breaking off when loaded by shield jacks (Herka & Schepers 2012)

It is dangerous for SFRC segments if the tensile strength of the steel fibre reinforced concrete is exceeded. In such a case the SFRC segments also suffer from breaking off. From this point of view, it is first of all necessary to prevent the origination of geometrical inaccuracies both during the production and, first of all, during the lining installation, so that the bending moments acting on the lining are as small as possible.

Figure 7. Steel reinforcement cages placed to moulds dutiny production of steel bar reinforced concrete segments

Reinforcing bars are usually placed into steel bar reinforced concrete segments in the form of a reinforcement cage (see Fig. 7). It consists of steel mesh mats on the inner and outer surfaces of the segment, which are separated by stirrups welded to them. The main function of steel mesh is to withstand the stresses which originate during the production, storage, transport and installation. The shape of the reinforcement cage must be circular; it must fit into the casting mould without problems and must respect the minimum concrete cover. The ratio of reinforcement of steel bar reinforced concrete segments reaches values usually ranging from 65 to 120 kg/m^3. By contrast, a SFRC segment is reinforced only by homogeneously distributed and omni-directionally oriented steel fibres. This provides trouble-free transfer of tensile forces in all directions. There is therefore no labour consumption associated with the preparation and placement of the reinforcement cage required. The production is simpler. The dosage equipment mixes the fibres into concrete and the mixture is cast into the mould. The consumption of steel mostly reaches 30 – 50 kg/m^3, which is significantly less than in the case of steel bar reinforced concrete segments.

Quality of concrete (low porosity and permeability) is fundamental for good protection against corrosion. It can be achieved by low water/cement ratio, placticisers or by using cinder. The higher quality of concrete the better resistance of concrete to carbonation and chloride ion and sulphate aggression. The advantage of steel fibre reinforced concrete over steel bar reinforced concrete is the impossibility of the origination of corrosion. Steel fibres are dispersed in the mixture uniformly; they usually do not touch one another and are completely surrounded and protected by alkali environment formed by concrete. The spreading of corrosion is therefore prevented. In addition, this system minimises the risk of defects caused by the volume of steel increasing during the process of corrosion. Steel fibres are subjected to corrosion on the structure surface and may cause unappealing tinting of the concrete surface. However, from the structural point of view, this plays no role at all. If it is required for aesthetic reasons to exclude the corrosion even on the structure surface, it is possible to use galvanised fibres.

Homogeneously and omni-directionally distributed steel fibres are capable of transmitting stresses in all directions. The steel fibres effectively prevent the opening of plastic cracks, e.g. caused by shrinking, which fact has a positive influence on the service life of the structure (the width of cracks is reduced by adding steel fibres).

4 PROJECTS WITH SFRC SEGMENTS

Initial attempts to use steel fibre reinforced concrete as a structural material in construction of tunnels took place in the first half of the 1970s, when several trial applications of SFRC were conducted. More significant increase in the use of SFRC for pre-cast segmental linings began in 1982. Several water supply tunnels where this system of lining was used were built in southern Italy and on Sicily (about 20 km in total). This technology proved itself well; SFRC was used for the construction of a transport tunnel for the first time in 1992 on the extension of Neapol metro, Italy.

Figure 8. SFRC segments generated and tested in the Czechoslovakia in 1984 - 1988

The research into SFRC segments conducted in Czechoslovakia (Krátký et al. 1999) is also worth mentioning. Series of tests on the circular pre-cast lining of a main sewer tunnel with the diameter of 3.6 m were carried out in 1984 - 1988. The ring consisted of six 200 mm thick segments with tongued and grooved joints. The batches of steel fibres were relatively great (98 kg/m^3); the fibres were smooth and straight. The tests were conducted both on the individual segments and on complete rings. It was verified by the tests that the required load-bearing capacity was exceeded several times and was comparable with steel bar reinforced concrete segments. Several times higher reliability as far as mechanical damaging is concerned was proved by the tests in the area of joints between individual segments. The same increase was proved even in the area of segment edges. These facts unambiguously confirmed that the necessity for repairs was significantly reduced.

Since the initial tests and applications, SFRC segments have been successfully installed on several tens of projects (Vandewalle 2005, Froněk 2011), first of all within the framework of the European Union, but also in other places of the world (Australia, the USA, Brazil etc.). In the majority of cases smaller-diameter tunnels are still in question (water, gas or heat supply tunnels); in some cases even metro sections (London, Barcelona – Fig.9, Napoli, Sao Paulo, Madrid, Genova) or railway tunnels (Channel Tunnel Rail Link – Fig.10, Oenzberg, etc.) have these segments. Nevertheless, first applications of SFRC segments to road tunnels have begun to appear - Brisbane Airport Link with the inner diameter of 11.34 m (Harding & Chappell 2012), Yokohama Circular Route Northern Section with the inner diameter of 11.5 m. An overview of some projects with basic data is presented in Table 1 (Froněk 2011).


Figure 9. Line 9 of Barcelona metro with SFRC segments


Figure 10. Tunnel CTRL with SFRC segments

5 CONCLUSION

Steel fibre reinforced concrete as a material has some advantageous properties regarding prefabricated production of lining segments for tunnels driven by full-face tunnelling shields, from which the possible benefits of SFRC segments compared with steel bar reinforced concrete segments.

Therefore SFRC was used for segmental linings on a range of tunnelling projects. They mostly related to tunnels with smaller profiles (water, gas or heat supply tunnels) and, in some cases, to metro sections (London, Barcelona, Napoli). The most extensive application of SFRC segments was experienced at tunnels for the high-speed rail link between Paris and London (the Channel Tunnel Rail Link - CTRL), where 2 x 24 km of single-track tunnels with the lining consisting of pre-cast SFRC segments without using common steel bar reinforcement were constructed by means of full-face tunnelling machines.

At the moment, the Faculty of Civil Engineering of the Czech Technical University in Prague is conducting, in collaboration with Metrostav a.s., research into SFRC segments for tunnel linings. Loading tests of SFRC segments are being conducted in the Klokner Institute within the framework of the research. Results of some tests are being compared with the tests on steel bar reinforced concrete segments used during the construction of the extension of 5th section of the Line A of Prague metro.

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Tab.1 Overview of some tunnelling projects lined with SFRC segments.

	Project	State	Purpose	Year	Total lenght [km]	ID [m]	Lining thickness [mm]	Amount of fibres [kg/m³]	Bar rein-force-ment
1	Abatemarco	Italy	Water supply		18.0	3,5		40	no
2	Fanaco	Italy	Water supply		4.8	3	200		
3	Neapol metro	Italy	Metro	1995	5.2	5,8	300	40	no
4	Janov metro	Italy	Metro			6,2		25	yes
5	Barcelona - line 9	Spain	Metro	2014	43.0	12	350	30 & 25	yes
6	Madrid metro	Spain	Metro			10		25	yes
7	Heathrow - baggage	UK	Baggage	1995	1.4	4,5	150	30	no
8	Jubilee Line Exten-sion	UK	Metro	1999	2.4	4,45	200	30	no
9	Channel Tunnel Rail Link	UK	Railway	2007	48.0	7,15	350	30	no
10	Heathrow - HexEx	UK	Railway	2008	3.2	5,675	220	30	no
11	Heathrow - PiccEx	UK	Metro	2008	3.2	4,5	150	30	no
12	Heathrow - SWOT	UK	Water supply	2006	4.0	2,9	200	30	no
13	DLR Extension	UK	Railway	2009	3.6	5,3	250		
14	Portmouth	UK	Water supply		8.0	2,9			
15	Sorenberg	Switzerland	Gas supply	2002	5.2	3,8	250	40	no
16	Oenzberg - TBM	Switzerland	Railway	2004	0.1	11,4	300	30	yes
17	Oenzberg - shield	Switzerland	Railway	2004	1.0	11,4	300	60	no
18	Hachinger Stollen	Germany	Water supply	1998	7.0	2,2	180		
19	Hofoldinger Stollen	Germany	Water supply	2007	17.5	2,9	180	40	no
20	Wehrhahnlinie Düs-seldorf	Germany	Metro	2014		8,3		30	no
21	Heat supply, Copen-hagen	Denmark	Heat supply	2009	3.9	4,2	300	35	no
22	Big Walnut sewer	USA	Sewer	2008	4.8	3,7		35	yes
23	San Vicente	USA	Water supply	2006	13.2	2,6	177	30	no
25	Brightwater East	USA	Sewer	2010	4.2	5		35	no
26	Brightwater Central	USA	Sewer	2010	9.7	4,7	325	40	no
27	Brightwater West	USA	Sewer	2010	6.4	3,7	325	35	no
28	La Esperanza	Equador	Water supply	2002	15.5	4	200	30	no
29	Sao Paulo metro	Brazil	Metro		1.5	8,43	350	35	
30	Gold Coast	Australia	Industrial / Water supply	2008	4.2	2,8	200	35	no
31	Hobson Bay	New Zeeland	Sewer	2009	3.0	3,7	250	40	no
32	Lesotho Highlands	South Africa	Water supply	1995	0.1			50	no
33	STEP Abu Dhabi	United Arab Emirates	Sewer	2014	15.6	5,5		30	yes
34	MRT Line adits	Singapore	Technology		1.4	5,8		30	no
35	Railway tunnels Singapur	Singapore	Railway			5,8		35	no
36	Brisbane Airport Link	Australia	Road		4	11,34	400		