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ABSTRACT

The application and the use of steel fiber reinforced concrete (SFRC) in precast tunnel lining design is a growing trend due to its advantages in performance, durability and ease of manufacturing compared to traditionally reinforced concrete. This project of 16.6 km twin bored tunnels was completed in time using precast segments reinforced with steel fiber only, for all the sections.

The joint venture partner “Porr/Saudi Binladen, HBK” has realized the project, a design and build contract (D&B) for the client Qatar Railway Company.

The precast tunnel lining represented 20,650 rings done by the JV’s own segment plant. Each of the TBM’s for the Doha Metro measures 7.05 m inner diameter and 120 m in length with a max thrust pressure of 54,254 kN. Tunnel outer diameter is 6.77 m; tunnel inner diameter is 6.17 m.

This paper will explain all the SFRC specifications, testing and performance specifically required for this successful and challenging project.

The Model Code 2010 performance class and design approach will be described, as well as the importance of the durability.

1 INTRODUCTION OF THE PROJECT

The Doha Metro is a planned rapid transit system in Qatar's capital city scheduled to become operational by the end of 2019. It will have four lines with an approximate overall length of 300 km and 100 stations. It will be an integral component of the larger Qatar Rail network, which will include a long-distance rail for passengers and freight, linking Qatar to the Gulf Cooperation Council (GCC), and Lusail's city local light rail transit (LRT).

The Green Line - with both underground, elevated and at-grade sections - extends from Msheireb in the East to Doha West. The project's D&B contract of the Green line underground project is given to a JV led by PORR Bau, Saudi Bin Laden Group and Hamad Bin Khalid Contracting.

Herrenknecht manufactured and supplied six EPBMs to the Porr/Saudi Binladen/HBK JV contractor for excavation of the Green Line. The first phase of the project runs underground for 16 km between Education City Station and the Al Rayyan International soccer stadium in the west of the city, and Msheireb in downtown Doha. Contract scope also includes supply of 20 sets of segment molds.

The typical bored tunnel will have a 6.17 meters internal diameter. The lining will be made of concrete precast segments to form rings. According to the design performed at tender stage, the precast segments will be made with steel fiber reinforced concrete (SFRC). The design-build team selected the Dramix® 4D 65/50BG steel fibers (high strength steel wire with an improved hooked end), at a dosage rate of 40 kg/m³.
TUNNEL OVERVIEW

Given a TBM excavation method of a tunnel, a fabricated lining behind the machine is usually the most cost effective option.

The segmental lining of the Green Line comprises universal rings with seven trapezoidal shape segments. The main features of segmental lining are set out here below:

- Internal diameter: 6.17 m
- Lining thickness: 300 mm
- Ring to ring contact width: 200 mm
- Segment to segment contact width: 200 mm
- Universal ring with 50 mm tapering composed of 7 segments
- Main ring length: 1.60 m

The Tunnel Boring Machine – EPB

- Advance rate (open mode): 80 mm/min
- Advance rate (closed mode): 60 mm/min
- Ring building mode: 20 min
- Installed electricity main drive power: 1450 kW
- Max thrust pressure: 54,254 KN
- Total weight TBM + Backup: 890 tons

Steel fibers are the only reinforcement used in the precast segments on this project.

The design service lifetime of the structure is 120 years. The SFRC is to be designed and specified to satisfy this durability requirement.

For durability purposes, the concrete will be compact. The end strength of the concrete will be higher than the design strength. It is expected that the real resistance will be in the range of 70 MPa.

The steel fibers shall comply with the European Standard EN 14889-1, fibres with CE marking, system 1 (fibers for structural use). Steel fibers out of drawn wire with a tensile strength of the steel wire of 1500 MPa minimum.

The dimensional tolerances of the steel fibers shall comply with the European Standard EN 14889-1 and ISO 13 270

The steel fiber reinforced concrete shall be minimum type 4.0 c according to the Model Code classification.

3. STEEL FIBER REINFORCED CONCRETE FOR SEGMENTAL LINING – A VIABLE ALTERNATIVE

Fiber Reinforced Concrete (FRC) is a composite material made of basic concrete in which a homogeneously distributed fiber reinforcement is incorporated.

Fiber addition in concrete controls plastic and hydraulic shrinkage cracking and considerably improves the concrete post-cracking behavior, while the compression strength is the same as the plain concrete.

Steel fiber reinforced concrete (SFRC) behavior depends on:

- Fiber characteristics (geometry, aspect ratio, hooked end shape, tensile strength, etc.)
- Concrete matrix properties (compressive strength at early age and long-term)
- Fiber dosage rate (kg per concrete cubic meter)

3.1 Performance classes based on Model Code 2010

In accordance with fib CEB-FIP Model Code 2010, the structural design of SFRC elements is based on the post-cracking residual tensile strength provided by the steel fibers.

Nominal values of the material properties can be determined by performing a flexural bending test: one of the most common refers to the EN 14651, which is based on a 3-point bending test on a notched beam. (figure 1)
The results can be expressed in terms of force (F) vs. Crack Mouth Opening Displacement (CMOD).

A typical F-CMOD curve for FRC shown in the below picture:

![Figure 2. Typical F-CMOD curve for FRC](image)

Parameters $f_{R,j}$ representing the residual flexural tensile strengths are evaluated from the F-CMOD relationship according to the below equation, (simplified linear elastic behavior is assumed):

$$ f_{R,j} = \frac{3F_{R,j}}{2bh_{sp}} $$

Where:
- $f_{R,j}$ is the residual flexural tensile strength corresponding to CMOD = $CMOD_j$
- $F_{R,j}$ is the load measured during the test [kN]
- $l$ = the span length (distance between support) = 500 mm
- $b$ = the width of the beam = 150 mm
- $h_{sp}$ = the distance between the tip of the notch and the top of the beam = 125 mm

From the above residual flexural tensile strengths, the characteristic values evaluate as follows:

$$ f_{R,jk} = f_{R,jm} - k\Omega $$

Where:
- $k$ is a factor dependent on the number of the specimens
- $\Omega$ is the standard deviation of the test results

For the classification of the post-cracking strength of FRC, a linear elastic behavior can be assumed, by considering the characteristic residual flexural strength values that are significant for serviceability ($f_{R,1k}$) and ultimate ($f_{R,3k}$) conditions.

In particular, two parameters, namely $f_{R,1k}$ (representing the strength interval) and a letter a, b, c, d or e (representing the $f_{R,3k} / f_{R,1k}$ ratio).

Two subsequent numbers in the series define the strength interval:
1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, ... [MPa]

While the letters a, b, c, d and e correspond to the residual strength ratios:
- a if $0.5 \leq f_{R,3k} / f_{R,1k} < 0.7$
- b if $0.7 \leq f_{R,3k} / f_{R,1k} < 0.9$
- c if $0.9 \leq f_{R,3k} / f_{R,1k} < 1.1$
- d if $1.1 \leq f_{R,3k} / f_{R,1k} < 1.3$
- e if $1.3 \leq f_{R,3k} / f_{R,1k}$

The designer has to specify the strength interval $f_{R,1k}$ (number) and the residual strength ratio $f_{R,3k} / f_{R,1k}$ (letter) as well as the material of the fibre.

Fiber reinforcement can substitute (also partially) conventional reinforcement at ultimate limit state, if the following relationships are fulfilled:
- $f_{R,1k} / f_L > 0.4$
- $f_{R,3k} / f_{R,1k} > 0.5$
4 DESIGN OF FIBER-ONLY REINFORCED CONCRETE SEGMENTS

Segmental linings are designed for transient and permanent loading conditions. The most challenging situations are demolding and handling, storage, installation (erection and TBM thrust applied loads during the tunnel excavation) and permanent ground pressure in service.

Several design guidelines are available for the design at serviceability and ultimate limit state, in accordance with the relevant international concrete structures standards:

- ACI 544 Technical Committee published the Emerging Technology Report (ETR), ACI 544.7R-16 - Design and Construction of Fiber-Reinforced Precast Concrete Tunnel Segments.
- ITA WG2: Twenty years of FRC tunnel segments practice: lessons learned and design proposal

5 SFRC MINIMUM DUCTILITY REQUIREMENTS

A bending hardening behavior in a flexural beam test (EN 14651 or ASTM C1609) is suitable for demolding, handling and stacking of precast segments, when the segment is subjected to its self-weight, in an isostatic configuration and can better control the crack formation. In addition, it can guarantee a hardening response in a full-scale test on a segment, because of its higher degree of hyperstaticity (Model Code 2010, 5.6.1 Introduction):

Figure 3. Different response of structures made of FRC having softening or hardening behaviour under uniaxial tension or bending loads

Figure 4 is a beam test diagram for Steel Fiber Reinforced Concrete, C40/50, Dramix® 4D 80/60BG (improved hooked-end high strength steel wire fibers), dosed at 40 kg/m³ realized at the University of Rome:

Table 1. Results of the beam bending tests

<table>
<thead>
<tr>
<th>Beam</th>
<th>fL</th>
<th>fR1</th>
<th>fR2</th>
<th>fR3</th>
<th>fR4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam_01</td>
<td>4.68</td>
<td>6.70</td>
<td>7.86</td>
<td>7.69</td>
<td>7.47</td>
</tr>
<tr>
<td>Beam_02</td>
<td>4.90</td>
<td>6.28</td>
<td>8.49</td>
<td>8.20</td>
<td>7.58</td>
</tr>
<tr>
<td>Beam_03</td>
<td>4.78</td>
<td>6.45</td>
<td>8.41</td>
<td>8.42</td>
<td>8.04</td>
</tr>
<tr>
<td>Beam_04</td>
<td>5.15</td>
<td>6.56</td>
<td>9.04</td>
<td>8.64</td>
<td>7.44</td>
</tr>
<tr>
<td>Beam_05</td>
<td>5.72</td>
<td>7.33</td>
<td>8.95</td>
<td>8.75</td>
<td>8.19</td>
</tr>
<tr>
<td>Beam_06</td>
<td>5.03</td>
<td>6.27</td>
<td>8.60</td>
<td>9.23</td>
<td>8.45</td>
</tr>
<tr>
<td>Beam_07</td>
<td>5.63</td>
<td>7.75</td>
<td>10.2</td>
<td>8.99</td>
<td>8.54</td>
</tr>
<tr>
<td>Beam_08</td>
<td>4.60</td>
<td>6.28</td>
<td>8.16</td>
<td>9.25</td>
<td>8.40</td>
</tr>
<tr>
<td>Beam_09</td>
<td>5.43</td>
<td>6.18</td>
<td>8.03</td>
<td>8.50</td>
<td>8.33</td>
</tr>
<tr>
<td>Average</td>
<td>5.10</td>
<td>6.64</td>
<td>8.64</td>
<td>8.63</td>
<td>8.05</td>
</tr>
<tr>
<td>Characteristic</td>
<td>4.30</td>
<td>5.58</td>
<td>7.26</td>
<td>7.65</td>
<td>7.19</td>
</tr>
</tbody>
</table>

These test results correspond to a 5e material ($f_{R,1k} \geq 5$ MPa; $f_{R,3k} / f_{R,1k} \geq 1.3$) that can be achieved using high strength fibers (1800 MPa min), high dosage rates (40 kg/m³) and an adequate concrete strength with an optimized mix design.

Table 2. Concrete mix design

<table>
<thead>
<tr>
<th>Component</th>
<th>Kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement 42.5 R</td>
<td>480</td>
</tr>
<tr>
<td>Natural sand (0-4 mm)</td>
<td>422</td>
</tr>
<tr>
<td>Crushed sand (0-4 mm)</td>
<td>423</td>
</tr>
<tr>
<td>Crushed aggregate (4-16 mm)</td>
<td>519</td>
</tr>
<tr>
<td>Crushed aggregate (16-25 mm)</td>
<td>350</td>
</tr>
<tr>
<td>Plasticizer</td>
<td>4.8</td>
</tr>
<tr>
<td>Water</td>
<td>170</td>
</tr>
<tr>
<td>Steel Fiber</td>
<td>40</td>
</tr>
</tbody>
</table>
6 DURABILITY OF THE PRECAST CONCRETE TUNNEL – A KEY ISSUE

The Doha Metro is located in a hot and humid environment with high concentrations of chlorides and sulphates, which are present in the ground and groundwater, as well as in the storm water and the dewatering that will flow through the tunnel.

Chloride induced corrosion and sulphate attacks are considered the principal deterioration mechanisms that may influence the long-term durability of concrete structures. Both chloride penetration and sulphate accumulation are accelerated by the cyclic wetting and drying of the structural concrete.

The durability of the concrete is dependent upon the transport of gases, water and dissolved agents through the capillary pores and cracks, so the continuity and occurrence of them are very important. The deterioration of concrete structures is due to the combined effect of the transport mechanisms, the accumulation of aggressive substance (e.g. sulphates) on the concrete, or the increase in chloride levels to threshold values at the reinforcement in case of traditionally carbon steel reinforced concrete.

Concrete resistance to chloride ingress is highly dependent upon the used cement type.

The selected fiber, Dramix® (glued, tensile strength > 1500MPa) in a dosage rate of 40 kg/m³, had to fulfill the SFRC grade, indicated as concrete strength $f_{ck} = C45/55$ and 4c class, where 4 is the strength interval $f_{R,1k} \geq 4$ MPa and c is the residual strength ratio $0.9 \leq f_{R,3k} / f_{R,1k} < 1.1$ (Model Code 2010 classification).

For a given concrete structure and for the same service loading when the cracks have opening lower or equal than 500 microns, a concrete structure with steel fibers, having a bending hardening behavior, contain cracks much thinner and less spaced than the traditional reinforced structure; this is due to the smaller dimensions of the steel fibers compared to the steel rebars.

In addition, the cracks related to the SFRC structures are more tortuous and discontinuous than the cracks of the RC structures. The consequence of this different structural behavior is that liquids and gases penetrate more easily in a RC structure than in a SFRC one.

In a chlorinated environment, in case of corrosion, the superiority of the fiber reinforced concrete is based on the two following points:

- The volume of corrosion products generated by corrosion of rebars can cause the splitting of the concrete cover, which is not the case when the fibers corrode;
- In the case of SFRC, the thinner cracks generate two positive phenomena: clogging of the cracks by corrosion products of the steel fibres and self-healing of them by the hydration process, which is not possible for the larger cracks in the RC structures.

7 CONCLUSIONS

In this paper, a successful experience of a segmental lining tunnel reinforced with only steel fibers for DOHA Metro is presented.

A basic introduction of the new model code 2010 is discussed and some experimental test trial results are shown.

Dramix® 4D 80 /60BG steel fibres, at a dosage rate of 40 kg/m³ to achieve a 4c class, compose the selected SFRC segment lining.

This project confirms that Dramix® fibers are perfectly validated and appropriated for precast segments. Glued fibers can be easily cast and mixed for a homogeneous distribution, high tensile strength (>1500Mpa) and optimized mechanical anchorage (hook end) are required. Performance criteria according to Model Code type C40/50 5c can be easily achieved.

Nevertheless, in order to obtain the desired results, it is worth noting the necessity to develop an accurate study of the material, i.e. the fiber typology suitable to a peculiar matrix at early stage of the project.

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