Consultant’s view of durable and sustainable concrete tunnel constructions in the Middle East)

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ABSTRACT

This paper presents the latest developments in concrete technology achieved on recent tunnel projects in the Middle East region. Strenuous requirements have been defined on recent underground concreting works in terms of strength, durability, workability and associated construction cost. COWI's concrete technology and design teams worked closely with international contractors to implement the requirements given by the Employers in combination with recommendations of different design codes, among others the fib Model Code 2010, ITA guidelines, and Ciria Guideline CS 163. The efforts resulted in a highly durable and high strength concrete mix designs that can be used in various permanent structural lining of tunnels, shafts and underground cavities. Recent experience covers a wide range of applications from metro, drainage (stormwater and groundwater) and sewage tunnels constructed with tunnel boring machines as well as shafts and tunnels realized with conventional excavation.

Steel fibre reinforced concrete (SFRC) is often used for concrete structures subject to severe exposure conditions e.g. bored tunnels exposed to saline ground water containing high levels of sulphates. In lieu of international, harmonised standards, the structural design of SFRC is covered by a number of national and international guidelines which describe considerations required for the SFRC in structural design along with classification of the mechanical properties of SFRC from standard tests. However, the durability design of SFRC is not sufficiently addressed by existing standards/guidelines, and consequently careful and thorough design processes need to be undertaken.

In order to assess the durability of SFRC a number of parameters such as the exposure conditions and concrete quality, have to be considered, in particular with regard to chlorides. This paper details selected deterioration mechanisms which affect the concrete durability design. In addition, specific structural design aspects of SFRC are presented through case studies from recent projects successfully carried out by COWI in collaboration with international contractors in the Middle East.

Key Words: Durability Design, Reinforced Concrete, Steel Fibre Reinforced Concrete, Bored Tunnels, Sustainability.

1. INTRODUCTION

For the past decades, the construction industry has boomed in major part of the Middle East. One of the rising markets within the construction industry has been bored tunnels with segmental lining for various usage, e.g. metro, sewage and stormwater to mention a few examples. The harsh environmental exposure conditions in the Middle East, such as very high content of chlorides and/or sulphates in the soil and groundwater challenge the durability design of the reinforced concrete structures in order to meet the, often seen, extended requirements to design life, 80 – 120 years.
The aim of this paper is to summarize trends in durability design of bored tunnels recently constructed or currently under construction in the Middle East Region. These trends are derived from the authors' own experience working as a consultant on the projects described herein. Furthermore, this paper presents an insight in the considerations made with regard to environmental sustainability while developing innovate durability-related solutions for the aforementioned projects.

2. DESIGNING FOR DURABILITY IN THE MIDDLE EAST

Guidance to the durability design of reinforced concrete structures in the Arabian Peninsula is given in e.g. CIRIA 163, Ref. [1]. Such guidance, in the form of cement types, water to binder (w/b) ratio, requirements to minimum concrete cover thickness etc. do not consider structures with an extended service life, such as major infrastructure projects: “Structures with extended design lives, i.e. greater than 30 years, and structures in extreme exposures require special consideration and may need some form of enhanced protection…” Ref. [1]. Typically, the required service life for major infrastructure projects, such as bored tunnels with segmental linings is in the range 80 – 120 years, calling for special consideration, e.g. modelling, regarding the durability design as called by CIRIA 163: “Modelling is a specialist activity…” Ref. [1]. Moreover, international standards such as Eurocode, are often not appropriate for application in the Middle East, since they are not tailored for the harsh environmental exposure conditions found in e.g. soil and groundwater in the Middle East; high temperatures as well as extremely high contents of chlorides and sulphate. Consequently, other measures than traditional deemed-to-satisfy recommendations given in e.g. Eurocode for durability design of concrete structures are required to achieve the required design service life.

One of the ways to design for extended service life requirements is to use the performance-based approach for durability design modelling the deterioration and exposure conditions over time. An example of a performance-based approach is the full probabilistic design approach for modelling of chloride-induced corrosion of carbon steel reinforcement bars presented in fib Model Code 2010, Ref. [2]. The output of that modelling is requirements to the concrete’s resistance to chloride ingress (in terms of the maximum chloride migration coefficient) and the minimum required concrete cover thickness.

As an alternative to traditional bar reinforcement, steel fibre reinforced concrete (SFRC) has gained significant momentum as construction material for e.g. pre-cast segments for bored tunnel linings, for the past decades.

While the use of SFRC for segmental linings appears to continuously grow, there is a general lack of harmonised international standards, e.g. Eurocode, for design of SFRC structures. Consequently, structural designers have to rely on national and/or other guidelines. In addition, a review of requirements regarding durability of SFRC, as given in international guidelines, has shown that there is a general inconsistency between the durability-related requirements given in those references, see Ref. [9]. In order to study the durability of SFRC, COWI has initiated a PhD project “Corrosion resistance of steel fibre reinforced concrete structures” in collaboration with the Technical University of Denmark (DTU).
3. REFERENCE PROJECTS

The authors of this paper have been the lead durability-designer for a large number of permanent concrete assets for the infrastructure in the Middle East within the past decade. This section provides brief presentations of selected, recent bored tunnel projects in the Middle East, illustrating trends from the region within design for durability and sustainability. Figure 1 shows the location of the projects covered in separate sub-sections below, while Table 1 provide further details about the specific projects.

![Figure 1. Illustration of location and names of bored tunnel projects presented in this paper.](image)

<table>
<thead>
<tr>
<th>Project</th>
<th>Country</th>
<th>Client</th>
<th>Design Service Life</th>
<th>Use</th>
<th>Tunnel Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>Length</strong></td>
</tr>
<tr>
<td>STEP</td>
<td>UAE</td>
<td>Salini-Impregilo</td>
<td>80 years</td>
<td>Sewage</td>
<td>41 km</td>
</tr>
<tr>
<td>Abu Hamour Tunnel</td>
<td>Qatar</td>
<td>Salini-Impregilo</td>
<td>100 years</td>
<td>Storm-water</td>
<td>9.5 km</td>
</tr>
<tr>
<td>Doha Metro (RLNU)</td>
<td>Qatar</td>
<td>Salini-Impregilo, SK Engineering &amp; Construction, Galfar Al Misnad JV</td>
<td>120 years</td>
<td>Metro</td>
<td>11.5 km</td>
</tr>
<tr>
<td>Doha Metro (GLU)</td>
<td>Qatar</td>
<td>Porr. Saudi Bin Laden Group, Hamad Bin Khalid Contracting JV</td>
<td>120 years</td>
<td>Metro</td>
<td>16.5 km</td>
</tr>
<tr>
<td>IDRIS MTS 01</td>
<td>Qatar</td>
<td>Bouygues</td>
<td>100 years</td>
<td>Sewage</td>
<td>16 km</td>
</tr>
<tr>
<td>Jebel Ali Stormwater and Groundwater Tunnel</td>
<td>UAE</td>
<td>Porr-SixCo JV</td>
<td>100 years</td>
<td>Storm-water and groundwater</td>
<td>12 km</td>
</tr>
</tbody>
</table>
As seen from Table 1, COWI has a proven record of accomplishment to successfully collaborate with different, international contractors on tunnels for different use, i.e. metro, sewage, stormwater and groundwater supplying durability and structural design, widening COWI’s experience within this field.

3.1. STEP, Abu Dhabi
The Strategic Tunnel Enhancement Programme (STEP) was constructed to improve the waste water system in Abu Dhabi and it is designed to carry 1.7 million m³ sewage each day. The project was divided into three contracts of which COWI was the designer (structural and durability) for two of the contracts, i.e. STEP 2 and STEP 3 with a combined length of the bored tunnel of 25 km. In addition those two contracts covered other types of structures, e.g. 10 shafts.

From a structural perspective, three options were considered for the design of the segmental lining of the bored tunnel in the initial phase of the project:

- Pre-cast concrete segments with traditional (carbon steel) reinforcement cages
- Pre-cast concrete segments with stainless steel reinforcement cage, and
- Pre-cast segments with steel fibre reinforced concrete (SFRC)

The bored, segmental lining is located in an area with very high chloride (10-12%) and sulphate content (up to 5,000 mg/l) in the soil/groundwater. Moreover, as the tunnel is designed for carrying sewage, special attention was given to the risk of microbiological concrete corrosion at the internal surface of the tunnel. Considering the very high content of chlorides in the soil/groundwater the first option for the segmental lining, i.e. pre-cast segments solely reinforced with traditional carbon steel reinforcement cages, was ruled out. The reason for that was that this option would require a very high concrete cover thickness (≥ 80 mm) when using a normal “European” concrete as preferred in the first instance by the contractor in order to achieve the required 80 year design service life. Such high concrete cover thickness is impractical as there is a significant risk that the (un-reinforced) concrete cover of the segments would crack during installation due to splitting stresses caused by the push rams of the TBM. The second option, i.e. pre-cast segments solely reinforced with stainless steel reinforcement was effectively ruled out due to the price. Moreover, the initial structural design revealed that the third option (pre-cast segments solely reinforced with steel fibres, SFRC) was feasible. Hence that option was initially considered for the segmental lining. At a later stage of the design it was noticed that additional reinforcement, i.e. steel bars, was required to cope with splitting forces at the radial joints. At time of realizing this, the development of the concrete mix design for the pre-cast segments (SFRC) was well progressed, and it took one year to tune and optimize the concrete mix design and quality to achieve durability-related requirements arising from the use of carbon steel reinforcement in combination with 65 mm concrete cover. Hence, for the initially installed segments, the additional reinforcement constituted of stainless steel reinforcement, and once the acceptable concrete quality in terms of resistance to chloride ingress was achieved, traditional (carbon steel) reinforcement bars were used as additional reinforcement, together with the steel fibres.

It is generally accepted that steel fibres embedded in un-cracked concrete has a high intrinsic resistance to chloride-induced corrosion, i.e. a high chloride threshold value, several times higher than that of traditional (carbon steel) bar reinforcement, even when manufactured from the same virgin material, see e.g. Dauberschmidt, Ref. [3]. This is, among other factors, due to their limited size, the casting
condition which ensures a dense steel/matrix interface protecting the fibres, and the manufacturing process (cold-drawing) which evens out defects at the surface of the steel fibres prone to initiation of corrosion. Hence, the use of un-cracked SFRC for the pre-cast segments is an obvious choice to ensure the durability of the tunnel. By design, the segments are designed un-cracked (SLS). Acknowledging that cracks may occur during installation, e.g. due to accidental load-cases such as over-loading, a programme for injection of leaking cracks was established. The concrete mix design for the pre-cast segments contained a triple blend binder; 50% ordinary Portland Cement (OPC), 20% fly ash (FA), and 30% ground granulated blast-furnace slag (GGBS), all by weight of total binder content. The w/b ratio of the concrete for the pre-cast segments was ~0.33, to ensure a sufficiently dense concrete. In order to protect the additional traditional carbon steel reinforcement bars against chloride-induced corrosion, strict requirements were established for the concrete’s resistance to chloride ingress. The requirements to the concrete cover thickness and the chloride migration coefficient were established using the full-probabilistic approach for chloride-induced corrosion presented in fib Model Code 2010, Ref. [2], yielding 65 mm concrete cover and a maximum chloride migration coefficient of 2.4 x 10^-12 m²/s when tested in accordance with NT Build 492, Ref. [5]. While the selected concrete mix design, as advantageous with regard to resistance to chloride ingress, the selected binder combination is also sufficient to mitigate the risk of sulphate attack of the concrete.

Finally, to mitigate the risk of microbiological attack of the concrete caused by gaseous sulphuric acid formed above the sewage transported in the tunnel, the Employer’s requirements specified the use of a so-called corrosion protection lining (CPL) at the intrados of the segmental lining. The cross section of the bored tunnel including the CPL is presented in Figure 2.

**Figure 2.** Cross section of bored tunnel incl. CPL, STEP.

As seen from Figure 2, the CPL at the intrados of the segmental lining consists of a concrete lining, 225 mm thick, lined with an high density polyethylene (HDPE) membrane (2.5 mm thick) at the upper 330° of the cross section. The thicknesses of the concrete lining and the HDPE membrane were pre-defined by the Employer. After installation of the segmental lining, the cast-in place concrete lining at the intrados was cast against the HDPE membrane which was placed in the formwork. Installation of the HDPE membrane in one part of the tunnel is shown in Figure 3.

**Figure 3.** Installation of HDPE lining, STEP.
The design of SFRC for the pre-cast segments was carried out in accordance with the German Guideline for SFRC, Ref. [4]. The SFRC was manufactured with hooked-end steel fibres (length = 47 mm and diameter = 0.8 mm), 40 kg/m³, yielding fibre class F1.4/0.6 in accordance with the aforementioned reference. Prior to production of the pre-cast segments, a strict testing regime was set up in order to ensure that the expected mechanical and durability-related properties of the concrete mix design were achieved. The distribution of steel fibres in the fresh concrete was examined by simple wash-out testing, while the distribution of steel fibres throughout the pre-cast segments was examined from saw-cut segments, see Figure 4. To confirm, that the specified chloride migration coefficient was achieved, a segment was cast from the concrete mix design (without steel fibres) and subsequently cores were taken for round robin testing at three independent laboratories in Abu Dhabi and Denmark, see Figure 5.

![Figure 4. Fibre count in](image)

![Figure 5. Illustration of segment cored for round robin NT Build 492 testing hardened concrete](image)

The introduction of pre-cast segments reinforced with steel fibres was, according to the authors’ knowledge, the first time this innovative construction material was used for this purpose in the Middle East. Furthermore, testing of the concrete’s chloride-migration coefficient in accordance with NT Build 492, Ref. [5] as introduced by COWI for this project was applied for the first time in the Middle East for tunnels. Since then, the approach has been adopted by a number of other Owners in the Middle East, as a measure during running production for the concrete’s durability-performance.

### 3.2. Abu Hamour Tunnel, Qatar

The Abu Hamour Tunnel in Qatar is constructed for transport of storm and groundwater in Doha, Qatar. As for all underground projects in Qatar, the structures of the Abu Hamour Tunnel project are in contact with soil/groundwater with very high levels of chlorides as well as sulphates. According to the Employer’s geotechnical investigations the content of chloride and sulphate in the soil/groundwater is up to 30,000 mg/l and 5,000 mg/l, respectively at the location of the Abu Hamour Tunnel. The tunnel is designed for the same aggressive conditions on the outside as well as the inside.

For this project, the Employer’s Requirements, i.e. the contractual requirements, had stipulated tight durability-related requirements to the permanent concrete structures in order to meet the design service life (100 years). The durability design for the
segmental lining of the bored tunnel conforming to the Employer’s Requirements is presented to the left of Figure 6, referred to as the “Original solution”.

![Original solution](image)

**Figure 6.** Schematic illustration of original solution (left) and new solution (right) for the segmental lining

As seen from Figure 6, two types of segmental linings are used; one with “Typical segments”, reinforced with steel fibres (comprising the vast majority of the segments for the bored tunnel) and “Special segments”, reinforced with steel fibres and rebars (used in selected locations where additional structural capacity is required, e.g. close to adits/shafts). While the durability design of the segmental lining, as illustrated in the left sketches of Figure 6, addresses the exposure conditions, the required service life, and the Employer’s Requirements, COWI together with the Contractor decided to value-engineer the durability design of the segmental lining. The motivation for this exercise was to optimize the durability design without compromising the overall project requirements to durability and service life, as a number of the requirements given by the Employer were considered superfluous for a tunnel designed for stormwater. The outcome of the value-engineering is schematically illustrated in the right of Figure 6 showing the “New Solution”.

As seen from a comparison of the two solutions presented in Figure 6, the HDPE membrane at the internal surface and the epoxy coating at the external surface were removed while the carbon steel reinforcement of the special segments was replaced by stainless steel reinforcement.

The very high sulphate content of the soil/groundwater corresponds to exposure class S3 in accordance with Ciria 163. Ref. [1]. To mitigate the risk of sulphate attack of the segments, the concrete mix design for the pre-cast segments contained 30% OPC, 65% GGBS, and 5% micro silica (MS) all by weight of total binder content. Furthermore, as proposed by COWI, the concrete mix design for the pre-cast segments was tested after a recently developed short-term test of the sulphate-resistance, i.e. the German SVA method. That test method allows for a significantly faster evaluation of the concrete’s resistance to sulphate attack; the duration of the test method is approximately 3 months, compared to the traditional test method, e.g. ASTM C1012, Ref. [6], which is usually taking 6 – 18 months. The testing was carried out at the Technical University of Munich and was witnessed by COWI. As an illustration, Figures 7 and 8 present a failed and a passed test specimen, respectively, after testing in accordance with the SVA test method.
The concrete mix design passed the SVA tests and the time gained by using the SVA test method, meant that the contractor at a much earlier stage than usually, felt comfortable that their concrete mix design fulfilled the Owner’s requirements, reducing his risk and potential, associated delays in the construction phase. In following projects in the Middle East COWI has convinced Owners to allow this test method instead of more traditional methods (and with longer duration) to the benefit of Contractors as well as Owners.

The “New Solution”, which was approved by the Employer’s engineer, resulted in substantial savings (cost and materials) for the Employer and the Contractor without compromising the overall requirement to 100 year service life.

The SFRC segments for the segmental lining were designed in accordance with fib Model Code 2010, Ref. [2], and the post-cracking classification of the SFRC in accordance with the criteria established in that reference was 4c achieved by using 40 kg/m³ hooked-end steel fibres.

In addition to the segmental lining presented above, the project contained 21 circular shafts, up to 30 m in depth and 6-11 m in internal diameter. It was the Contractor’s aim to reduce the use of traditional bar reinforcement for the shafts and therefore the structural designer (COWI) was requested to consider alternative solutions for the permanent works of the shafts. The final design for the circular shafts was largely based on the use of SFRC, and only using traditional reinforcement bars in a limited number of locations, e.g. around openings and at the lower part of the shafts. The structural design of the circular shafts using SFRC was made in accordance with fib Model Code 2010, Ref. [2], defining the post-cracking classification of the SFRC as 3c. High strength, cold-drawn and hooked-end steel fibres at a dose of 35 kg/m³ were used to achieve the required post-cracking classification. Figure 9 and Figure 10 show the SFRC shaft and the shaft with areas where steel fibres in combination with bar reinforcement was used, respectively.

Figure 7. SVA test – failed specimen. Courtesy of VDZ.  
Figure 8. SVA test – passed specimen. Courtesy of VDZ  

Figure 9. Shaft cast entirely from SFRC  
Figure 10. Shaft with SFRC + traditional reinforcement bars around openings and at cantilevers
3.3. Doha Metro, Qatar

Phase 1 of the Doha Metro, Qatar, contains three lines; Red Line, Green Line, and Golden Line, with a combined length of the alignment around 190 km and around 80 stations. The design service life of the permanent concrete structures is 120 years. The authors of this paper were initially responsible for the durability design of the permanent concrete structures including the bored tunnels (segmental lining) for the Red Line North Underground (RLNU) containing ~11.6 km bored tunnel having an internal diameter around 6.2 m. As previously explained in this paper, the exposure conditions in the soil/groundwater zone in Doha are rather extreme; The Owner’s Requirements GIR stipulate contents of chloride and sulphate in the soil/groundwater up to 55,000 mg/l and 5,500 mg/l, respectively, and a groundwater temperature around 30°C. Furthermore, the Owner (QRail) had very strict requirements to the watertightness of the bored tunnel; Waterproofing Class 1, corresponding to “Acceptable amount of water in the tunnel structure: no water”. These requirements by the Owner set very demanding requirement to the design, structural and durability, of the segmental lining, in particular considering the onerous exposure conditions and a high ground water table.

The pre-cast segments for the bored tunnels are manufactured from SFRC (at a limited number of locations additional stainless steel reinforcement required for structural capacity was provided). The SFRC for the pre-cast segments was designed in accordance with fib Model Code 2010, Ref. [2], post-cracking classification 4c, using approximately 40 kg/m³ concrete, hooked end steel fibres.

An epoxy coating at the extrados, in accordance with the Owner’s Requirements, covered the initial segments installed for the segmental lining of the RLNU project. After value-engineering by the Consultant, showing the epoxy coating to be superfluous, as the durability and watertightness was ensured by other means, the Owner accepted to omit the requirement for epoxy coating of the following pre-cast segments.

The metro traction power is driven by direct current (DC), and it is generally accepted that DC stray-current shall be considered carefully for traditional bar reinforced concrete structures. A pre-requisite for the initiation of stray-current induced corrosion is the circulation of current by the steel reinforcement (bars or fibres). For SFRC, experimental studies carried out by one of the authors of this paper have shown that steel fibres are much less prone to picking up and transferring direct current compared to traditional bar reinforcement, see e.g. Ref. [7]. This is, as explained in the reference, due to the limited length of the fibres making it difficult to form an anode and a cathode on the same fibre (required for transfer of current by the fibre). Hence, as the fibres likely do not transfer stray-current there is in practice no risk of stray-current induced fibre corrosion.

The durability design with regard to chloride-induced fibre corrosion is similar as for the STEP project, see Section 3.1. In short, the resistance of steel fibres to chloride-induced corrosion is much higher than for traditional carbon steel reinforcement bars, and is consequently not regarded as a problem as long as the structural design properly address the utilization of the steel fibres.

Upon completion of the detailed durability design for permanent concrete structures for the RLNU project, QRail encouraged the JV’s of the other lines to assign COWI
as their concrete durability design consultant. Consequently, the JV's for the following parts of the Doha Metro Project assigned the authors of this paper as their concrete durability design consultants:

- Green Line Underground (GLU),
- Green Line Elevated & at-grade (GLE)
- Red Line South Elevated & At-grade (RLSE)
- Track Slab System for all three lines

The GLU project contains ~16.6 km bored tunnel constructed with segmental lining. Also for this project, pre-cast segments with SFRC (classification 4c) were used, i.e. the same durability design approach as for the RLNU project. Results from production testing of the concrete mix design for the segmental lining are presented in Figure 11 and Figure 12, showing durability-related test results and results from mechanical testing (3 point bending), respectively.

![Figure 11. Durability test: Requirements and test results, GLU](image)

![Figure 12. 3 Point bending: Test results and characteristic values, GLU](image)

As seen from Figures 11 and 12, the developed concrete mix design conforms to the durability-related requirements stipulated by the Owner while at the same time achieving the classification 4c required by the structural design, both by a solid margin.
3.4. IDRIS MTS 01, Qatar

The IDRIS MTS 01 project in Doha, Qatar is designed for transport of sewage from urban areas to sewage treatment facilities and is currently (2018) under construction. The main trunk sewer (MTS) is constructed as a bored tunnel with segmental lining, with a design service life of 100 years. The length of the bored tunnels for MTS 01 is approximately 16 km with an inner diameter varying in the range 3-4 m.

Considering the use of the tunnel, i.e. transport of sewage, with the risk of microbiological attack of the concrete, the Employer required a double-protective design to mitigate such attack of the segmental lining, i.e. a sacrificial concrete layer (not to be considered as part of the permanent structure) and an internal HDPE membrane. The sacrificial concrete layer and the structural part of the segments were cast using the same concrete mix design, i.e. an SFRC concrete mix design with high content of supplementary cementitious materials (GGBS) and a low w/c ratio (< 0.40). The HDPE membrane was attached to the internal surface of the segments during casting.

The durability of SFRC against chloride-induced corrosion as well as the resistance of the concrete mix design towards sulphate attack considering the prevailing exposure conditions in Doha are already discussed in Section 3.3 of this paper.

3.5. Jebel Ali Stormwater and Groundwater Tunnel, Dubai

The Jebel Ali Stormwater and Groundwater Tunnel, is located in Dubai, and is currently under design. The main tunnel, having a length of approximately 10.4 km is designed as a bored tunnel with segmental lining and shall, according to the Employer’s Requirements, have a design life of 100 years. The main tunnel is the biggest stormwater tunnel ever constructed in the Middle East. The main tunnel is at close proximity to the Arabian Gulf, and the chloride and sulphate content in the soil/groundwater is very high, chlorides up to 55,000 mg/l and sulphates up to 6,800 mg/l according to the Employer’s GIR. Hence, from a durability perspective, the use of steel fibres instead of traditional reinforcement cages would be favoured to mitigate the risk of chloride-induced corrosion. However, as the required internal diameter of the tunnel is 10.0 m, the structural designers are under pressure to find a design solution for the segmental lining without traditional reinforcement bars/cages; according to Ref. [8] there is less than a handful of segmental linings worldwide with an internal diameter of 10.0 m or greater, constructed solely from SFRC. In case traditional reinforcement bars are required for the pre-cast segments, due to structural capacity, this shall be epoxy-coated as specified in the Employer’s Requirements.

4. INNOVATIONS – DURABILITY DESIGN & SUSTAINABILITY

From the descriptions of the reference projects listed above, it is noted that advances with regard to durability are carried on from either previous projects from the region. Moreover, as will be presented in the following, the advances in terms of durability are associated with a gain in terms of sustainability, but it is stressed that the advances in terms of sustainability, e.g. reduction of CO₂ emission, have been made without sacrificing the durability of the concrete structures. The key to the innovations and the corresponding gains with regard to durability and sustainability lies in a thorough understanding of the exposure incl. use of the structure, the
construction materials and the overarching design. Some examples presenting selected trends with regard to concrete durability design of bored, segmental linings in the Middle East are presented along with the benefits from a sustainability perspective are given in the list below.

- Steel fibre reinforced concrete
  - Less maintenance
  - Increased durability
  - Reduced steel content and CO₂ emission

- Use of supplementary cementitious materials, i.e. GGBS, FA, and/or MS
  - Required to achieve denser concrete (reduced diffusion)
  - Reduced CO₂ emission

- Omission of epoxy coatings on segment surface
  - Reduced cost
  - Reduced CO₂ emission

To illustrate the sustainability-advances made in recent years by using supplementary cementitious materials such as GGBS and FA as partial replacement for OPC, as well as using steel fibres instead of traditional bar reinforcement, Figure 13, presents schematically the calculated CO₂-eq. emission from production per m³ concrete from some of the projects presented herein, along with other, similar European reference projects.

![Figure 13](image)

**Figure 13.** Calculated CO₂-eq. emission from production per m³ concrete from selected projects

As seen from Figure 13 the use of supplementary cementitious materials as partly replacement of OPC leads to a remarkable reduction in emission of CO₂-eq.; Comparing Doha Metro RLNU Project with Copenhagen Metro, the calculated emission of CO₂-eq. from the binder combination is reduced by more than 75%. Furthermore, the use of steel fibres instead of traditional bar reinforcement also has a significant impact on the emission of CO₂-eq.; Again comparing Doha
Metro RLNU Project with Copenhagen Metro the reduction in CO₂-eq. by using steel fibres is more than 50%. These numbers clearly demonstrate that there are potential savings in terms of sustainability by careful selection of the right materials for the structure.

For the Abu Hamour Tunnel Project, further CO₂ reductions were achieved using the “New Solution”, among others:

- **Epoxy coating**
  - The CO₂ emission from the production of the epoxy coating applied at the external surface of the segments in the “Original Solution” constitutes approximately 10% of the total CO₂ emission from the production of materials for the segmental lining, i.e. SFRC, HDPE and epoxy.

- **HDPE membrane**
  - The CO₂ emission from the production of the HDPE membrane applied at the internal surface of the segments in the “Original Solution” constitutes approximately 6% of the total CO₂ emission from the production of materials for the segmental lining, i.e. SFRC, HDPE and epoxy.

The numbers above only cover the “Typical segments”, as they constitute the vast majority of the produced segments (~98% of all segments are “Typical segments”).

5. CONCLUSION
This paper concerns trends in concrete durability design of segmental linings for bored tunnels in the Middle East, illustrated with the authors’ experience from selected, recent projects in the region. Special focus is set on the use of SFRC for segmental linings for bored tunnels in this paper.

SFRC is increasingly used for pre-cast segments. However, as to there is a general lack of harmonised international standards, e.g. Eurocode, for design of SFRC structures structural designers have to rely on national and/or other guidelines. Furthermore, a review of requirements regarding durability of SFRC, as given in international guidelines, has shown that there is a general inconsistency between the durability-related requirements given in those references. To study the durability of SFRC, COWI has initiated the PhD project “Corrosion resistance of steel fibre reinforced concrete structures”.

Apart from the use of SFRC for segmental linings and shafts presented herein, the paper also covers other topics such as sulphate resistance, requirements to resistance to chloride ingress for concrete reinforced with traditional carbon steel reinforcement bars, etc. Finally, in addition to the presented trends with regard to concrete durability design, this paper also presents examples of gains in terms of sustainability. As presented herein, the use of SFRC for segmental lining along with the use of supplementary cementitious materials as partial replacement of OPC has significant beneficial effects with regard to CO₂ emission. While experience from previous projects is brought into new projects, it shall be emphasized that each project requires careful consideration regarding e.g. the exposure conditions, the use etc. in order to prepare the durability design; this is an expert task.
6. REFERENCES


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