Durability and Sustainability aspects of steel fibre reinforced concrete (SFRC) under severe exposure conditions

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ABSTRACT

Recent industrial trends require service lives of 80 – 120 years for infrastructure projects such as tunnel and bridges. At the same time low environmental impact in production of the composite materials is of vital interest, i.e. carbon foot print. A concurrent trend is the increase of exposure conditions as for instance prevailing in the gulf with high chloride content in ground waters.

The design solution proposed by COWI for bored tunnels with segmental lining is the use of steel fibre reinforced concrete (SFRC). While SFRC has its limitation in the load bearing capacity compared to conventional reinforced concrete it is a viable solution for segmental lining which is mainly under compression and subject to limited bending moments. In case of segmental lining steel fibres may be used as sole reinforcement.

There are several advantages of using SFRC.

These are

- the omission of bending reinforcement including the cost savings on installation cost
- the reduced amount of steel in kg / m3 and hence reduced CO_2 footprint
- the reduced effects of corroded fibres as opposed to corroded steel reinforcement
- workability requirements for fibre reinforced concrete in line with durability requirements for concrete – i.e. both requirements support each other

Keywords:

- Durability,
- Sustainability,
- Service Life Design,
- Steel fibre reinforced concrete,
- Chloride migration.

Introduction

Since the 1990 an increase in the use of steel fibre reinforced concrete can be observed. This includes precast elements for segmental tunnel lining subject to severe exposure conditions such as saline ground water. The SFRC is an alternative construction material to traditionally reinforced concrete for structures mainly subject to compression and limited bending moments (as the post cracking load bearing capacity of SFRC is limited though higher than unreinforced concrete). Depending on the structural requirements steel fibers added during the concrete mixing process maybe the sole reinforcement or alternatively combined with traditional reinforcement. Steel fibers might further more positively influence the ductility of the concrete, reduce and control crack width and even distribution and by that alone improve the durability of the concrete structure. Steel fibers improve the impact and abrasion resistance and the freeze thaw resistance and by the influence on the concrete paste impact general durability requirements such as chloride migration coefficients. Steel fibers simplify construction processes by substituting complex and/or curved reinforcement fabric with narrow tolerances, high cover requirements and reduced wall thicknesses, which often is difficult to install. Steel fiber reinforced concrete is easy to place and to consolidate.

The structural design of SFRC is covered by a number of national and international guidelines, e.g. fib Model Code 2010 (fib 2012), which describes how to consider SFRC in structural design, and how to classify the mechanical properties of SFRC from standard tests.

The model code does not consider the durability design which is critical for achieving service live under severe exposure conditions.

Other guidelines on structural design of SFRC exist, e.g. Meson et al, 2016, but do not consider durability of SFRC in consistent manner, in particular the corrosion of fibers.

Durability of SFRC has been subject to research programs. These programs have focused on:

- Corrosion resistance (chloride threshold) of steel fibers e.g. Dauberschmidt 2006
- Impact of cracks on the susceptibility of fiber corrosion under various exposure conditions an overview is presented in Meson et al, 2006
- Risk of stray current induced fiber corrosion described by Solgaard et al, 2013

Till date the large amount of literature regarding durability of SFRC has had only limited echo in the existing standards for design of SFRC.

In the course of this paper a presentation on durability of SFRC is given with regards to the wide range of deterioration mechanisms. It is described how these design considerations were applied on recent projects such as the

- STEP project in Abu Dhabi (Sewer tunnel)
- Abu Hamour project in Qatar (Sewer tunnel)
- Red line north Underground project in Qatar (Metro tunnel)
- Green line Underground project in Qatar (Metro tunnel)
- District heating tunnel in Copenhagen (far-heating tunnel)

1. Sustainability and Durability of steel fibre reinforced concrete (SFRC)

In order to assess the durability of SFRC a number of parameters such as the exposure conditions, concrete quality, etc. have to be considered. In the following, selected deterioration mechanisms are discussed.

Note:

Only deterioration mechanisms concerning fibre-corrosion of carbon steel are presented, as deterioration of concrete due to e.g. sulphate attack is outside the scope of the paper.

1.1 *Durability of SFRC – General overview*

Steel fibres may corrode due to one or a combination of the following exposure conditions:

- Chloride-exposure,
- Carbonation,
- Stray current,
- Exposure prior to installation.

Cracks in the concrete matrix embedding the steel fibres will promote the ingress of e.g. chlorides and therefore need to be considered when assessing the durability of SFRC.

1.1.1 Chloride exposure

Reinforcement steel embedded in concrete structures is susceptible to corrosion when permeation of chloride increases the chloride content at the surface of the steel hence exceeding a chloride threshold level (CTL).

The CTL is an important influence on the service life of concrete structures exposed to chloride environments.

CTL is best presented in this paper as total chloride by weight of cement in %.
Another measure is the ratio of [Cl^-]:[H^+] in that these include the aggressiveness of chlorides (i.e. free and bound chlorides) and inhibitive nature of cement matrix.
The key factor on CTL was found to be a physical condition of the steel–concrete interface, in terms of entrapped air void content, which is more dominant in CTL rather than chloride binding, buffering capacity of cement matrix or binders, see e.g. (Buenefeld, et al. 2004).

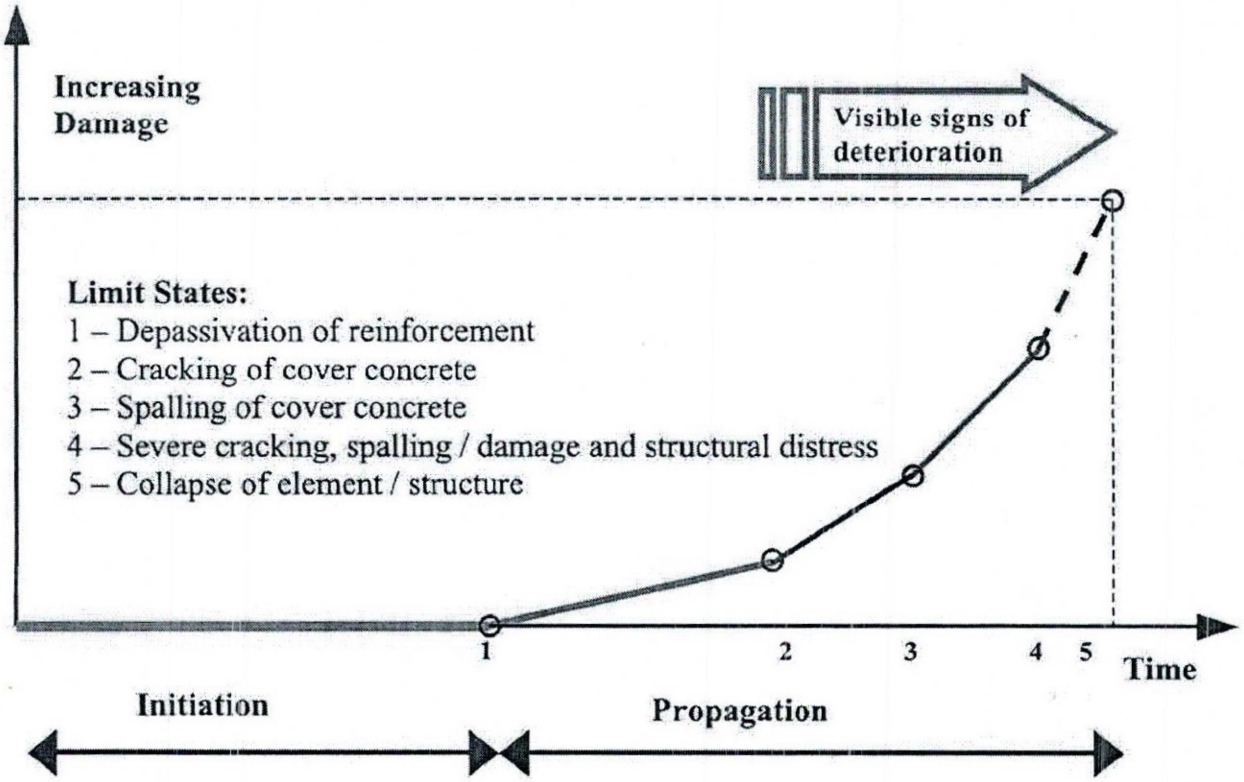

Fig. 1. Corrosion process in reinforced concrete (fib 2006) (Dauberschmidt, 2006)

When SFRC is cast, fibers are mixed-in and floating in the concrete matrix. This leads to the formation of an adhesive concrete - steel interface. Opposed to that is the fixed reinforcement where voids and/or bleeding channels may occur during casting and compaction.
(Dauberschmidt, 2006) records that the formation of other, denser hydration products at the concrete - steel interface is favored under the casting conditions of SFRC.
All these effects improve the protection of the embedded steel fibers hence resulting in an increased chloride threshold.
Another reason for the improved corrosion resistance of SFRC is the difference in the dimensions to reinforcement steel, i.e. the length. In order to form a distinct anode and cathode area on the surface of reinforcement steel a difference in electrochemical potential between the two areas is required.
The required potential difference for building up anode and cathode areas is therefore significantly lower for steel fibers as compared to the much longer reinforcement bars.

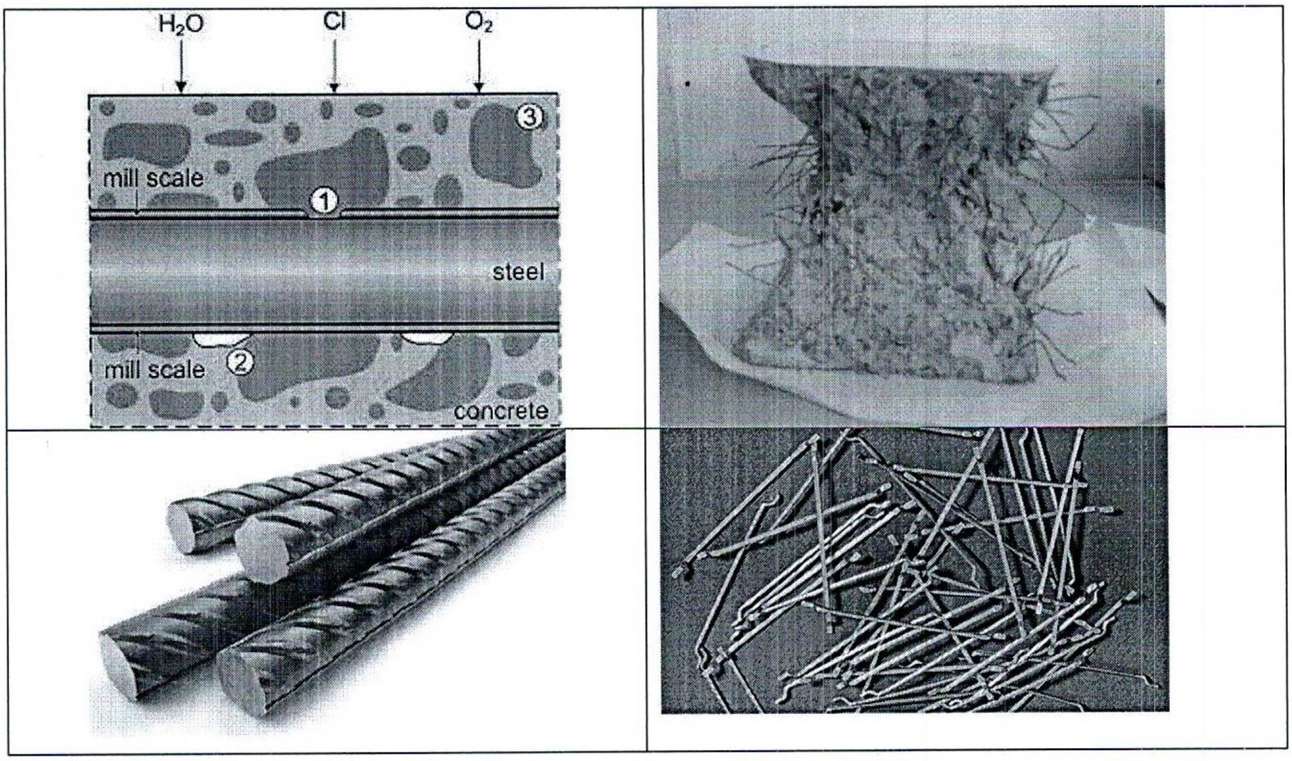

Fig. 2. Comparison concrete matrix steel reinforced concrete and SFRC (Dauberschmidt, 2006) / STEP Project

Un-cracked concrete

The resistance of steel fibres embedded in un-cracked SFRC to chloride-induced corrosion is greater than that of traditional reinforcement bars/cages. This is generally attributed to the following conditions:

- The chloride threshold of steel fibres,
- The casting conditions of SFRC
- The dimensions of the steel fibres,

The chloride threshold of steel fibres embedded in un-cracked concrete is reported to be significantly higher than that of traditional reinforcement bars, up to 5-10 times higher see e.g. (Dauberschmidt, 2006). Dauberschmidt presents results from an experimental program where the main factors influencing the chloride threshold are systematically investigated. Results from those investigations are presented in Figure 3:

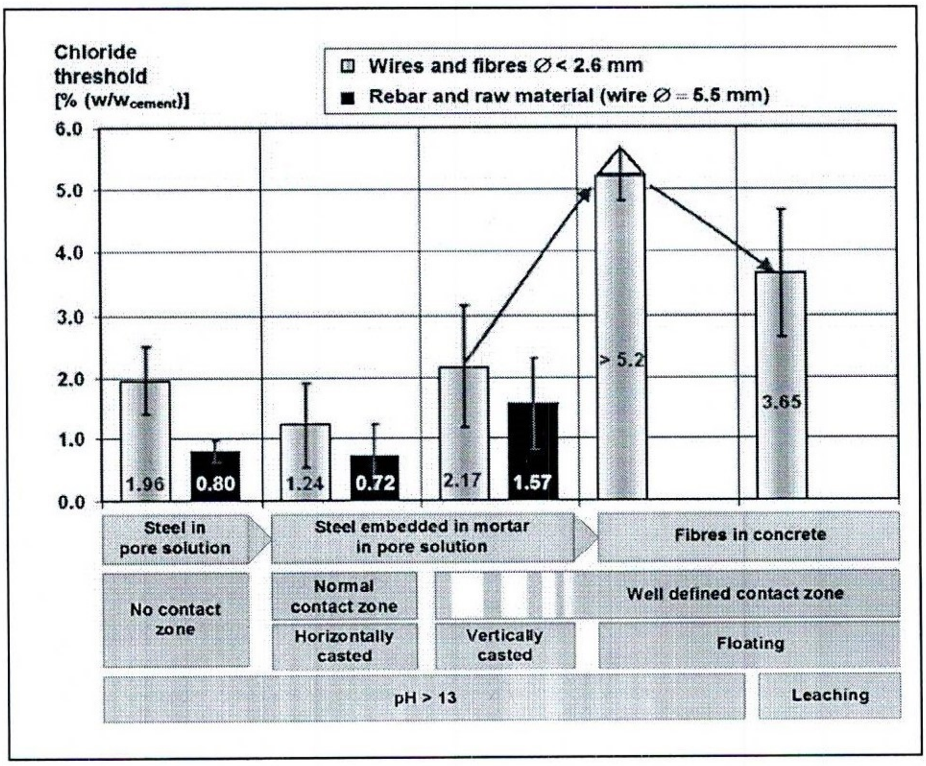

Fig. 3. Results from experimental investigations of the chloride threshold of steel fibres, reinforcement bars (rebar) and steel wires under various conditions (Dauberschmidt, 2006)

As seen from Figure 3, the measured chloride threshold of steel fibres in concrete is greater than 5.2 %/wt. of cement. In comparison, the chloride threshold of carbon steel reinforcement bars is significantly less; *fib* Model Code for Service Life Design (*fib*, 2006) specifies a mean value for the chloride threshold of reinforcement bars of 0.6 %/wt. of cement.

Cracked concrete

In traditional reinforced concrete cracks promote the ingress of harmful substances such as chlorides.
Various design guidelines set limits for the crack width, depending on the exposure conditions.
A number of studies exist for the effect of cracks on SFRC.
For an overview of the available literature see e.g. (Meson et al., 2016).
The mechanisms controlling fibre-corrosion are not yet fully understood.
The issue of cracks is therefore treated differently in various international guidelines for SFRC.
Results in the literature concern experimental investigations on e.g. the exposure conditions, fibre type, crack width, etc.
The crack width limitations proposed in the literature vary significantly.
However, general consensus is that for crack widths less than 0.2 mm, the long term durability of the fibres is not affected.
Considering the fact that the limiting crack width for SFRC is still subject to discussion, cracks in SFRC during the permanent loading condition, are often not allowed.

1.1.2 Carbonation

Carbonation-induced corrosion of steel fibres in un-cracked concrete is typically limited to the outer regions of the SFRC, where the availability of oxygen for the corrosion process is high. The thickness of this outer region where fibres corrode due to carbonation is controlled by various parameters such as the concrete quality, the type of cementitious materials used, the exposure conditions and time, etc.
For dense low permeability SFRC concrete e.g. w/c < 0.40, which is usually used for permanent structures with high requirements to the service life, the thickness of this region is a couple of millimetres.
Corrosion of fibres exposed at the concrete surface show as rust stains on the concrete surface.

According to (DAfStB, 2001) cracking and/or spalling of the concrete cover due to fibre-corrosion has not been observed so far.

1.1.3 Stray-current

The term "stray-current" concerns the phenomenon where current from e.g. metro tracking systems, cathodic protection system etc. finds an alternative path to the intended. This is illustrated in Figure 2:

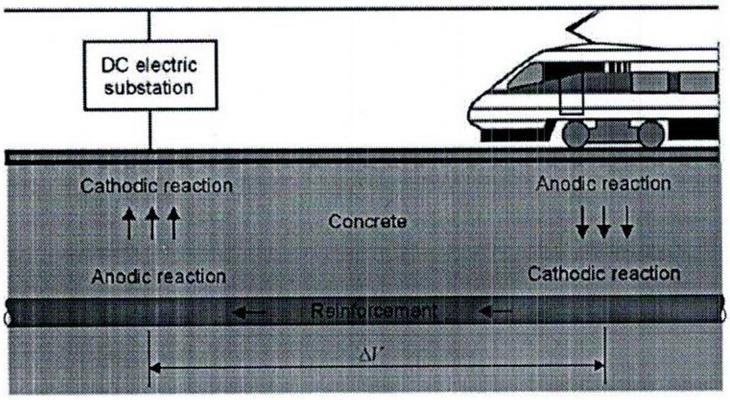

Fig. 4. Current, originating from electrified (DC) railway line, picked up by traditional reinforcement embedded in concrete (Bertolini et al., 2007)

As seen from Figure 4, a cathode is formed where the stray current enters the reinforcement and an anode is formed where the stray current leaves the reinforcement.
Stray current is only a problem if it is transferred by the reinforcement and as described in (Bertolini et al., 2007), direct current (DC) is much more problematic to the reinforcement than alternating current (AC).
Results from experimental investigations on the susceptibility of stray-current induced fibre corrosion are presented in (Solgaard et al., 2013).
The studies investigated the tendencies of embedded fibres and reinforcement picking up stray current.
It showed that traditional reinforcement bars are more likely to pick up current than smaller steel fibres under the same conditions.
This so-called 'length-effect' has been confirmed by The American Concrete Institute, (ACI, 2002), where it is stated:

> ... *"Since the fibers are short, discontinuous, and rarely touch each other, there is no continuous conductive path for stray or induced currents or currents from electromotive potential between different areas of the concrete."*

Based on the results presented in (Solgaard et al., 2012) it is concluded that the risk of stray current induced corrosion of steel fibres is generally low and significantly lower than for traditional reinforced concrete.

1.2 Experience with SFRC worldwide

The application of SFRC for bored tunnels has increased for the past decades; Figure 3 presents an overview of selected projects worldwide where steel fibres have been used as the sole reinforcement or in combination with traditional reinforcement for bored tunnels.

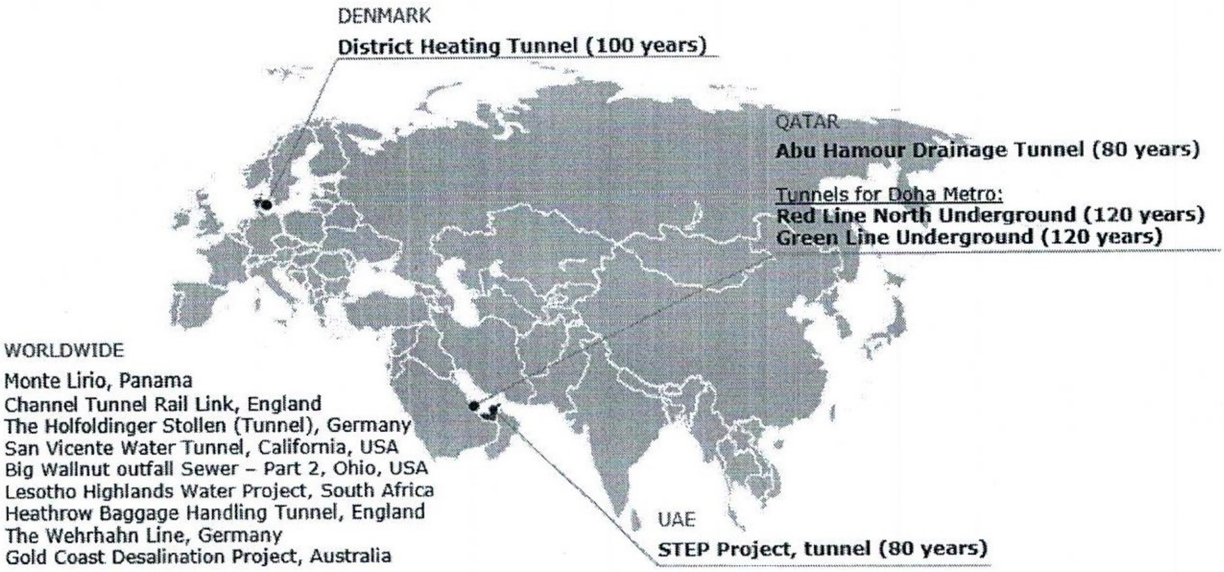

Fig. 5. Selected projects where steel fibres have been used either as the sole reinforcement or in combination with traditional reinforcement

The majority of the projects where the authors were involved are located in the Middle East with severe exposure conditions, e.g. high temperature and significant chloride content in soil/groundwater.
The design service life, if available, is given in parenthesis next to each project.
A practical example of service life design of a tunnel constructed from pre-cast SFRC segments is presented in the following.

2. Service life design case study – the STEP project in Abu Dhabi

The STEP Project in Abu Dhabi is a major sewer tunnel system covering an approx. length of 41 km of bored tunnel designed to carry approx. 1.7 million m³ of sewage every day. The tunnel is considered to be of the longest descending waste tunnels in the world. The project is divided into 6 contracts for the civil engineering works; 3 tunnels, 2 micro tunnels, and 1 pump station. See figure 6.

The flows will be channeled by gravity via the deep tunnel sewer to the main pumping station, and then lifted to centralized wastewater treatment facilities. The treated sewage effluent (TSE) will return to the metropolitan area for irrigation purposes.

The Client is Abu Dhabi Sewerage Service Company. The authors of this paper have worked as the designer for the Italian contractor Impregilo on 2 of the tunnel-contracts, i.e. STEP 2 and STEP 3 with a combined length of 25 km.

The project also covers other types of structures e.g. 10 shafts. However, in the following, focus is set on the durability design of the bored tunnel with pre-cast SFRC segments.

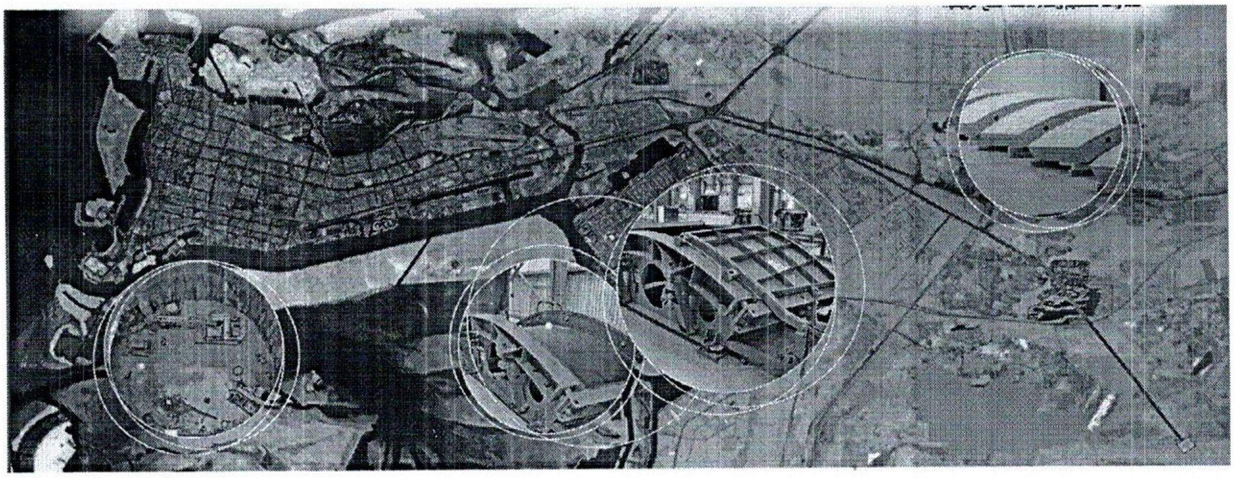

Fig. 6. Location of the STEP Project in Abu Dhabi by ADSSC

According to the contract specifications, all concrete structures had to be designed for an 80 year service life.

The extremely severe exposure conditions included:

- ground and groundwater with very high contents of chlorides and sulphate,
- sewage which introduces the risk of microbiologically concrete corrosion,
- Average temperatures around 30°C.

Special attention on the durability design of the concrete structures was required to achieve the required 80 years of service life.

The applied segment design is described below together with the durability design with regard to selected (governing) deterioration mechanisms.

2.1 Segment design

With the severe chloride exposure conditions and the high temperature which further aggravates the chloride ingress in concrete, three different design solutions for the pre-cast segments of the bored tunnel were considered in the initial design phase:

- Pre-cast concrete segments reinforced with traditional reinforcement cages,
- Pre-cast concrete segments with stainless steel reinforcement, and
- Pre-cast SFRC segments

All of these solutions were feasible from a structural point of view.

The solution with traditional reinforcement cages would require very high concrete covers considering the prevailing exposure (chloride) conditions. Such high concrete covers would present problems since the risk of forming cracks in the (unreinforced) cover, during e.g. installation of the segments would be high and the thickness of the segments would need to be increased.

The design solution with pre-cast concrete segments reinforced with stainless steel was feasible from a structural and durability point of view but was rejected due to its high cost.

The design solution with SFRC segments was feasible with significant economic benefits. Since the tunnel will be mainly subject to compressive load during operation, the bending load is limited.

Consequently SFRC was chosen for the segments together with a limited amount of traditional reinforcement at the joints. These reinforcement cases were necessary in order to cope with splitting forces at the radial joints caused by the high water pressure at depth of up to 80m below ground.

A schematic of the reinforcement layout is shown in Figure 7.

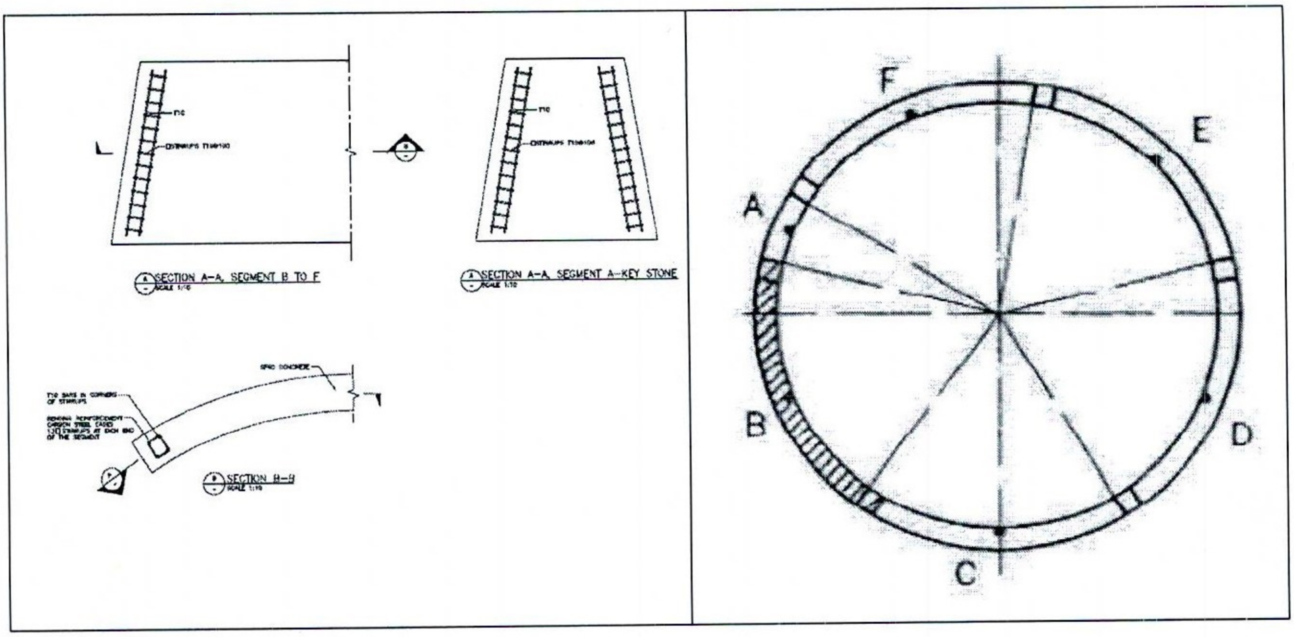

Fig. 7. Schematic of segment layout

The durability design of the segments with regard to selected deterioration mechanism is described in the following section.

2.2 *Durability design*

Selected details of the concrete mix design used for the segments are given in Table 2.

Table 1. Selected properties of the concrete mix design used for segments

Property	Value
Cement, CEM I [kg/m^3]	220
Fly ash [kg/m^3]	90
Ground granulated blast furnace slag [kg/m^3]	130
Water [kg/m^3]	145
Steel fibre content [kg/m^3]	40
w/cm [-]	0.33
Fibre class (in accordance DafStB, 2001)	F1.4/0.6
Compressive strength (cylinder/cube) [MPa]	50/60

As part of the durability design various deterioration mechanisms were identified, and mitigation measures were chosen to cope with these mechanisms. In the following, selected deterioration mechanisms with regard to the steel fibres and the concrete and the selected mitigation measures are discussed. The structural design as well as the durability design is completed by ensuring that the requirements to the SFRC are achieved.

This includes various tests prior to and during construction and an overview of selected tests is presented at the end of this section.

2.2.1 *Sulphate attack*

The soil and groundwater at the location of the tunnel contains very high amounts of sulphate with up to 5000 mg/l.

These exposure conditions correspond to sulphate class S3 in accordance with (CS163, 2008), are extreme and not observed in natural European soils.

Therefore the concrete needs to be designed as sulphate-resistant.

The available options are e.g. using sulphate-resistant cement (SRC) or supplementary cementitious materials such as fly ash (FA) and/or ground granulated blast furnace slag (GGBS) for the binder composition in combination with a low w/c ratio.

For the STEP project, the chosen binder was combined of OPC, FA and GGBS, which were separately dosed during the mixing process. In addition a low w/c ratio provided sufficient resistance to sulphate attack.

2.2.2 *Microbiological concrete corrosion*

The domestic sewage transported by the tunnel is not aggressive to the concrete in itself.

However, due to aerobic bacterial activity leading to the production of sulphuric acid the concrete needs protection against acid attack.

The exposure to of sulphuric acid, and the risk of acid attack, is only relevant for the upper parts of the tunnel which are exposed to the sewerage gases.

No risk of acid attack exists for the tunnel invert which is constantly submerged by sewage.

In order to protect the upper part of the tunnel a high-density polyethylene (HDPE) membrane was installed on the upper 330-350° of the intrados of the tunnel section.

The HDPE membrane was placed in the formwork prior to casting of a secondary lining.

This unreinforced secondary lining formed part of the corrosion protection system providing a sacrificial layer of concrete.

The intrados of the bored tunnel is shown in Figure 8, where the blue colour is the HDPE membrane.

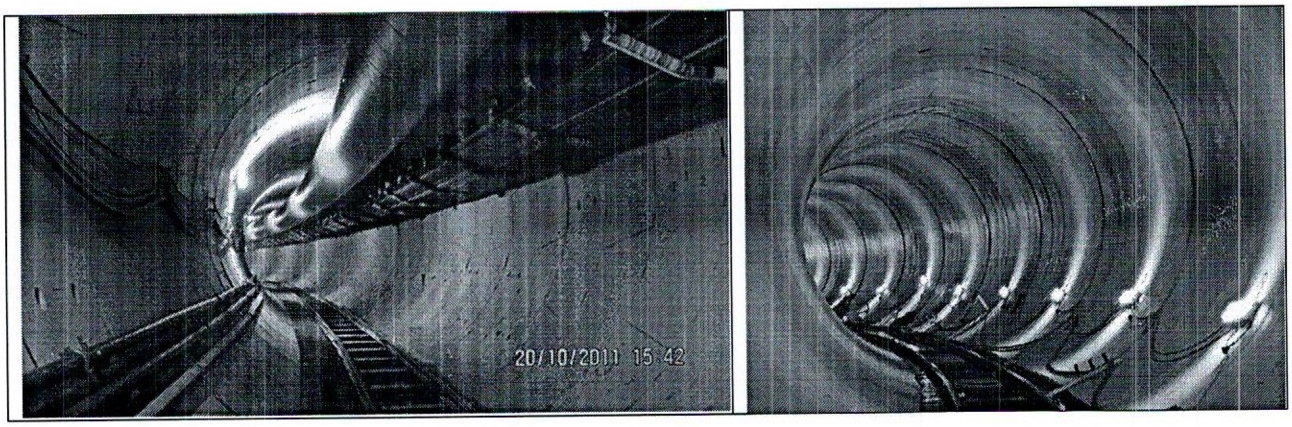

Fig. 8. Intrados of bored tunnel – Photographs by PMO

2.2.3 *Fibre-corrosion*

The durability of SFRC with regard to chloride-induced fibre corrosion is explained in Section 1.1.1 above.

Because of the high intrinsic resistance of the fibres against chloride-induced corrosion durability of un-cracked SFRC under chloride-exposure is considered not a problem.

Additionally the SFRC segments are protected by the HDPE membrane and the secondary lining on the intrados protecting the segments against wetting/drying cycles with chloride-saturated sewage.

The durability of cracked SFRC with regard to chloride-induced corrosion is still being debated in the literature.

As there are no international guidelines regarding the maximum crack width for SFRC in order to achieve the required service life, the tunnel has been designed, structurally, to be in overall compression when in service.

On the rare occasion where segments had cracks they were rejected prior to installation.

Cracks observed during installation were injected.

Hence the SFRC segments can be considered to be un-cracked with regards to the requirements of the durability design.

2.2.4 *Conventional Reinforcement (splitting)*

The chloride induced corrosion of the conventional reinforcement was considered using a service life design approach in accordance with *fib* Bulletin 34, (fib 2006) and (Edvardsen, 2010).

In addition a full probabilistic model, the Duracrete model (Duracrete, 2000) has been used.

This approach allowed the specification of the cover to the conventional splitting reinforcement and the chloride migration coefficient for the concrete in order to achieve the 80 year service life.

2.2.5 SFRC tests

The Contract specified that requirements to the structural performance and the durability arising from the design (structural and durability) shall be ensured by testing prior to construction, i.e. trial casting, as well as during construction.

As seen from Table 2, the requirement to the mechanical performance of the SFRC is a compressive strength of 50 MPa (cylinder) and the fibre class of F1.4/0.6, according to (DafStB, 2001).

The fibre class refers to an equivalent flexural strength of 1.4 MPa and a residual flexural strength of 0.6 MPa, and was e tested on 150 x 150 x 700 mm beams in 4-point bending in accordance with (DafStB, 2001).

In addition the fibre distribution and fibre content was tested on a regular basis.

The durability-related tests include tests of the w/c ratio and the resistance to chloride penetration, in terms of the chloride migration coefficient.

Table 2 presents a summary required mechanical and durability tests, the testing frequency and the acceptance criterion during production.

Table 2. Required tests, acceptance criteria and testing frequencies

Property	Acceptance criterion	Frequency
Compressive strength	50 MPa (cylinder)	3 specimens/day
w/c ratio	0.33	2 times/day
4-point bending	F1.4/0.6	3 specimens/month
Fibre amount and distribution, hardened concrete (petrographic analysis)	40 kg/m^3	1 specimen/month
Fibre amount, fresh concrete (wash-out test)	40 kg/m^3	1 specimen/week
Chloride migration coefficient (cast cubes and cores from segments)	2.4 x 10^{-12} m^2/s @ 56 days	Cubes: 1 specimen/week first 3 months. If no deviation, 1 specimen/month
		Cores: 1 specimen/week first month. If no deviation, 1 specimen/month

The chloride migration coefficient was tested in accordance with NT Build 492 in order to determine the chloride-transport properties of the concrete matrix. The test was carried out on specimens without steel fibres, since these would alter the results based on electrical conductivity.

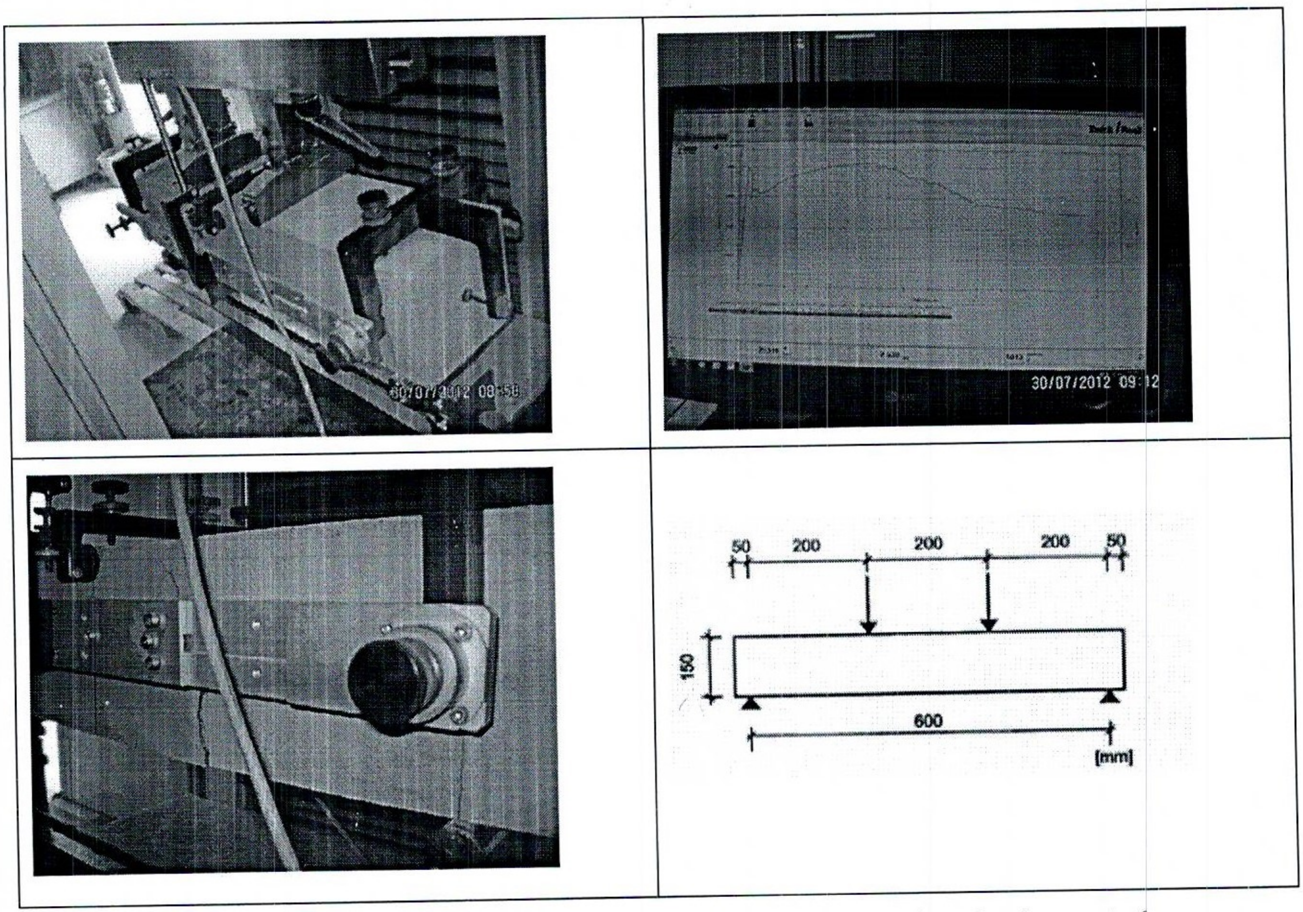

Fig. 9. Four point bending according to DAfStb test under local production control

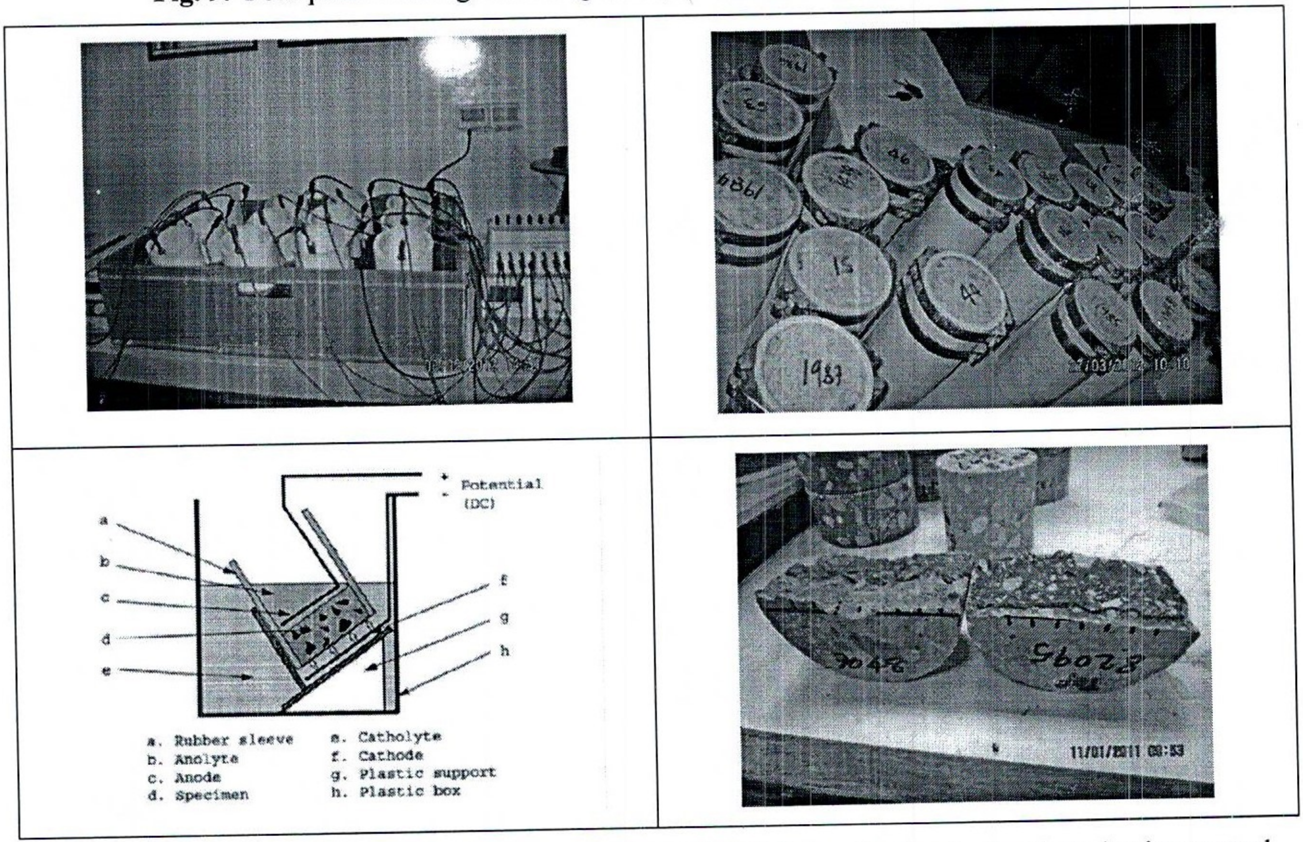

Fig. 10. Chloride migration coefficients acc. to NT build 492 determined under local production control

3. Service life and sustainability

Material selection and construction methods for civil structures are based on technical performance criteria such as durability and service life. However, sustainability has become important and should be considered in the design already.

When constructing a structure the production of concrete is usually the main source of embodied CO_2. Another key source of embodied CO_2 is the production of steel reinforcement. The embodied CO_2 can be influenced significantly by the selection of the materials used, with for instance the replacement of a proportion of the cement with fly ash and/or ground granulated blast furnace slag (GGBS) and by the use steel fibres instead of conventional steel reinforcement.

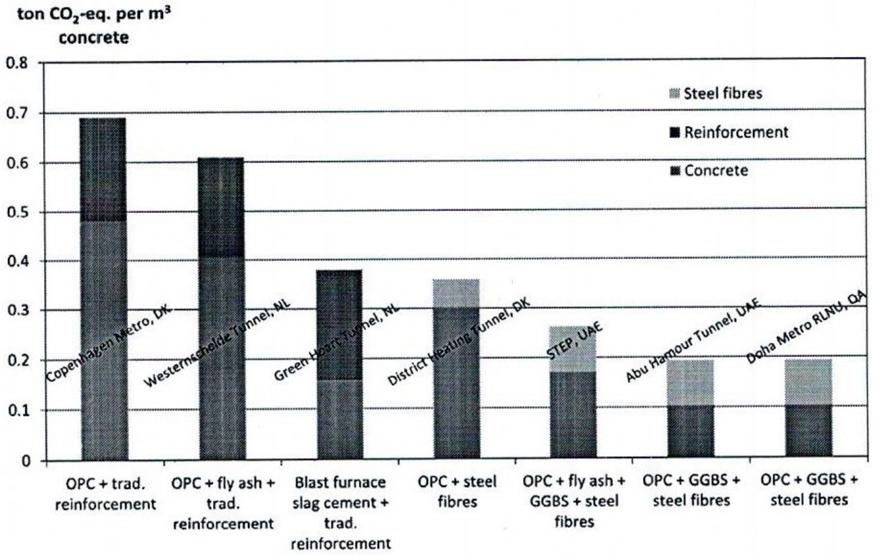

Fig. 11. Comparison of embodied CO_2 for different types of binder and steel reinforcement used for various recent and major infrastructure projects

Figure 11 shows how the embodied CO_2 from the production of concrete and reinforcement can be reduced by careful selection of binder materials and reinforcement type.

The CO_2 emission from the STEP project compared to other segmental tunnels utilizing traditional reinforcement and higher contents of OPC is significantly lower, up to 60% reduction. While this effect results mainly from the replacement of OPC with supplementary cementitious materials, the use of steel fibres in lieu of traditional reinforcement also had a significant impact on the reduction of the embodied CO_2.

It is expected that requirements to reduction of embodied CO_2 will be an integral part of future infrastructure projects worldwide. As an example, a large project is underway in Denmark, the Cityring, where the client has set out strict environmental requirements.

Among these requirements to the contractor is a minimum 30% reduction of embodied CO_2 compared to the existing Metro line.

4. Conclusion

The use of SFRC for segmental (bored) tunnels has gained momentum worldwide particularly under severe exposure conditions.

Examples of selected projects worldwide with SFRC tunnels are provided including such constructed under severe exposure conditions as high temperatures, high concentrations of sulphate and chloride as prevalent. in the Middle East and North Africa. These severe exposure conditions require due considerations with regard to the durability design taking into account service life requirements up to 120 years.

The paper presents an overview over selected deterioration mechanisms for SFRC and discussions on the possible mitigation measures in order to avoid these.

The suitability of SFRC under severe exposure conditions is illustrated by the recent STEP project in Abu Dhabi, a segmental tunnel for sewage. This tunnel is carried out under severe exposure conditions and the case study presents the durability design with regard to selected (governing) deterioration mechanisms to achieve the required 80-year service life.

Finally, a brief introduction is given to the benefits with regard to environmental sustainability given by the use of SFRC with high contents of supplementary cementitious materials instead of concrete with mainly OPC as cement.

5. Acknowledgements

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