Application of Precast SFRC Tunnel Segment Lining in HK and its Benefit

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ABSTRACT

Precast concrete tunnel segment lining reinforced with conventional steel rebar have been generally used with the Tunnel Boring Machine (TBM) since 1950s. As ample concrete cover needs to be provided to protect the steel reinforcement tunnel lining against corrosion and fire, concrete cover would be easily damaged during the segment handling, erection and TBM thrusting. This will induce different degrees of damaging to the precast tunnel segment lining which affects the long-term durability performance of the permanent lining and involves substantial maintenance to the tunnel structure. To tackle the subjected problems, steel fibres are adopted to replace the conventional steel reinforcement in precast concrete segment. The adoption of precast steel fibres reinforced concrete (SFRC) tunnel segment lining increased significantly in tunnel industry since 2000 with the increase on the understanding of SFRC behavior and enhancement on the quality assurance on production.

Until now there is no precedent case project using precast SFRC segments as the permanent tunnel lining in Hong Kong, but Dragages Hong Kong (DHK) has stepped forward as a pioneer contractor to promote the adoption of precast SFRC segment as the temporary tunnel lining for pilot tunnel in two highway tunnel projects which can provide the foundation on expanding the usage of precast SFRC segment to the permanent tunnel lining in the near future.

This paper is to present the general mechanical behavior and design principles on SFRC and discuss in detail for the appropriateness and benefit on the adoption of SFRC for the permanent precast concrete tunnel segment lining in Hong Kong. This paper also shares the local experience on using precast SFRC segments in HK.

1 INTRODUCTION

In the construction industry, people are understanding plain concrete has inherent deficiencies such as low tensile strength, low post cracking capacity, and brittleness. The weakness in tension can be overcome by the use of conventional steel reinforcement and to some extent by the inclusion of a sufficient dosage of certain fibres. The concept of using fibres in order to reinforce the concrete matrices weak in tension is more than 4500

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years old. Steel fibres mixed into the concrete can provide an alternative to the provision of conventional steel bars or welded fabric in some applications. The concept has been in existence for many years (the first patent was applied for in 1874) and it has been used in a limited range of applications: among the first major uses was the patching of bomb craters in runways during World War II. However, it was during the 1970s that commercial use of this material began to gather momentum, particularly in Europe, Japan and the USA. Today, major applications for fibre-reinforced concrete include ground-supported and pile-supported floors, external paved areas, sprayed concrete, composite slabs on steel decking and precast elements, industrial floor slabs, shotcrete and prefabricated concrete products and full replacement of the conventional reinforcing cages for precast tunnel segments.

Depending upon the use and the strength requirement to achieve, steel fibres have different shape and size as shown in Plate 1.

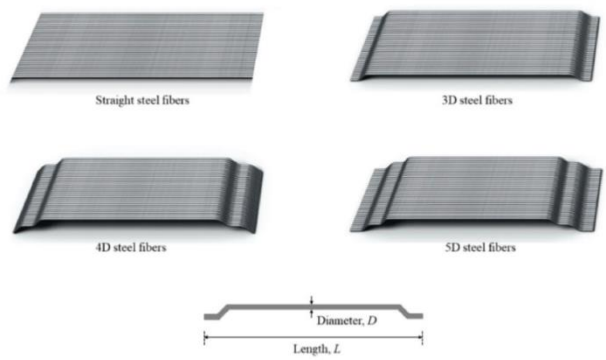


Fig. 1—Steel fibers with different end hooks.

Plate 1: Steel fibres with different end hooks and straight end (courtesy of Kwan et al. (2024))

End hooks of steel fibres provide a stronger bridging force across the concrete matrix in SFRC. Previous research findings including Kwan et al. (2024) confirmed that the improvement of the concrete flexural behavior (toughness and flexural strength) exhibited by hooked end steel fibres was better than that of straight steel fibres because the end hooks of steel fibres provide a better anchorage at the fibre ends and hence stronger bridging force across the concrete matrix in SFRC. A properly designed concrete mix is essential for avoiding fiber balling. To prevent the potential of fiber balling formed before mixing with concrete which will affect the fibre distribution in concrete, so glued fibres technology has been developed by blinding the fibres into bundles with the glue. Then the glue will be dissolved in water during concrete mixing, so the fibre can spread evenly throughout the concrete matrix. With this arrangement, balling of fibres can effectively be avoided and a homogenously mix of high performing steel fiber reinforced concrete can be achieved.

Table 1 below shows the essential characteristics and properties of a commonly-used glued hooked-end steel fibres:

Type	Hard-drawn wire and ungalvanized	BS EN 14889-1: 2006
Length	60 mm +/- 10%	BS EN 14889-1: 2006

Diameter	0.75 mm +/- 10%	BS EN 14889-1: 2006
Aspect ratio (length/dia.)	80 +/- 15%	BS EN 14889-1: 2006
Nominal Tensile strength	2,200 MPa +/- 15%	BS EN 14889-1: 2006
Bending	Withstand 3.2 mm diameter pin to an angle of 90° at temperatures not less than 16°C without breaking	ASTM A820

Table 1: Essential characteristics and properties of a commonly-used glued hooked-end steel fibres

2 GENERAL MECHANICAL BEHAVIOUR OF STEEL FIBRES IN CONCRETE

SFRC is a composite material that incorporates steel fibres well distributing into the concrete matrix (see Plate 2) to enhance its mechanical properties such as the flexural tensile strength and toughness of concrete (see Plate 3) thus creating the necessitate flexural bending capacity and also minimizing the potential damage to the concrete covers. Moreover, the inclusion of steel fibres could help reducing early-age thermal cracking, dry shrinkage cracking and the risk of spalling when exposing to fire incident.

Plate 2 - Steel fibres in wet concrete

Plate 3 - Steel fibres exposed in a cut concrete section

The general mechanical behavior of SFRC is influenced by the type, shape, size, dosage and distribution of steel fibres within the concrete matrix. The key aspects of its mechanical behavior include the following enhanced characteristics: tensile strength, flexural tensile strength, crack resistance, ductility and post-crack tensile strength. Even after the initial cracking, SFRC maintains its load-carrying capacity due to the bridging action of the steel fibres (see Plate 4). This post-crack behavior is characterized by a gradual reduction in load rather than a sudden failure, providing a safer and more predictable performance.

Plate 4:Post-crack behaviour of SFRC

3 ADVANTAGES OF USING SFRC

3.1 General advantages of using SFRC

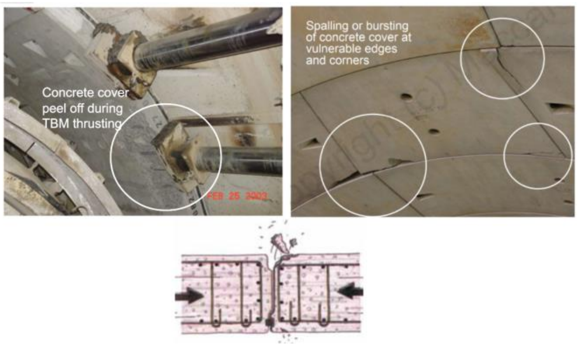
The general advantages of using SFRC are summarized in Table 2 below:

Homogeneous distribution	Steel fibres spread close to the surface, ensure excellent reinforcement at the joints of segments
Multidirectional reinforcement	Steel fibres provide resistance to stress in all directions
Increased load bearing capacity	Steel fibres provide substantial increase in load capacity to the first crack and ultimate load at the joints
High impact resistance	The absorbed energy by the steel fibre reinforced concrete during impact is many times greater than the energy absorption of plain concrete
Excellent control of shrinkage cracks	Large number of steel fibres in the concrete ensure good control of shrinkage cracks
Best durability solution available	Several research investigations have shown that the durability of SFRC under chloride exposure is superior to RC

Table 2: Advantages of using SFRC (BEKAERT)

3.2 Advantages of using SFRC on precast segmental tunnel linings

During the installation of precast segmental tunnel lining through TBM tunnelling advancement, the TBM thrusting rams in the tail shield exert a longitudinal force on the circumferential joint of precast segments to ensure them be stayed in contact with the previous ring to ensure the water gasket still in compression before the annulus grouting is applied to the gap between the ground and segment. Since the hydraulic rams impose loads concentrated over small bearing surfaces, these loads in turn redistributed within the segment body. This concentrated load redistribution leads to transverse tensile stress, also known as bursting or splitting stress at the segment joint. Furthermore, spalling tensile stresses are generated between the adjacent jack pads along the circumferential joint. As ample concrete cover needs to protect the steel reinforcement of conventional reinforced concrete tunnel lining against corrosion and fire, concrete cover would be easily damaged during the TBM tunnel construction (Plate 5) and be deteriorate in long-term durability. The thrust loads acting in the cross section of the tunnel induce spalling and bursting stresses in the circumferential joints of the tunnel segments (see Plate 6).



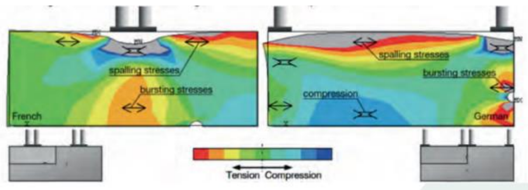


Plate 5: Damage of concrete caused by jacking

Plate 6: Bursting stresses due to jacking (ITA)

Compared to conventional reinforced concrete tunnel segments, no concrete cover is required for SFRC tunnel segments. The use of steel fibres instead of 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. This bursting stress due to thrusting force on segment is resisted by the tensile strength of SFRC which can help to prevent damages to the concrete and minimize the cracks due to bursting or splitting stresses.

Even though steel fibres can be exposed on the surface of tunnel linings (see Plate 7), concrete spalling is not anticipated to occur since the fibres are small in diameter and discrete, and so the expansion force due to corrosion causing concrete spalling is negligible. In addition, the steel fibres are surrounded by the concrete matrix which is alkaline basis, so the steel fibres are not easy to be corroded and spread to other fibres. On the other hand, concrete spalling due to corrosion of steel reinforcement was commonly observed on the surface of conventional precast R.C. tunnel segments (see Plate 8).

Plate 7:Steel fibres exposed on surface of tunnel linings

Plate 8:Concrete spalling caused by corrosion

When spalling occurs, a conventional R.C. tunnel segment has to be repaired or even replaced for obvious reasons of durability. This however delays the tunnel construction progress and leads to a high long term maintenance cost.

In addition, steel fiber reinforcement is present in the cover zone where having the tensile resistance in resisting the impact loads during segment handling and erection. This will significantly reduce the potential on the tunnel segment damage when comparing with the conventional reinforced segment.

The permanent loading situation under normal circumstances (including self-weight, surcharge, vertical and horizontal ground pressure and water pressure, see Figure 1) of circular, segmental tunnel linings is typically characterized by the dominance of hoop forces combined with relatively small bending moments due to the confined pressure from the ground, surcharge and water around the tunnel.

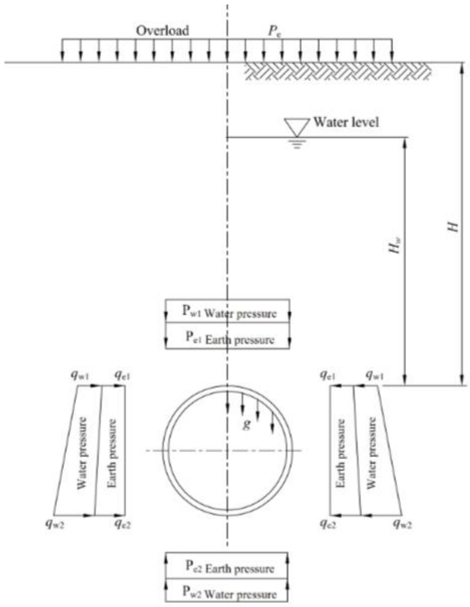


Figure 1: Permanent loadings of designing tunnels

If high bending moment is generated by high accidental loadings (e.g. earthquake) or insufficient hoop force due to lacking of confinement pressure under shallow ground condition, the use of steel fibres alone may not be sufficient and a hybrid of conventional steel reinforcement and SFRC is required. However, the seismic hazard in Hong Kong is much lower than places like Japan, Taiwan and the western USA where lie close or within the Earth's more seismically active zones along crustal plate boundaries, and the seismicity of Hong Kong is low to moderate. Therefore, in Hong Kong, the bending moment acting on tunnel linings induced by earthquake loading is not high and so SFRC to replace steel reinforcement cage (Plate 9) may represent a cost-effective alternative to the precast concrete tunnel segments.

Plate 9: Steel reinforcement cage of tunnel segment

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4 DESIGN PRINCIPLE OF SFRC FOR PRECAST CONCRETE TUNNEL LININGS

The fundamental design principle of SFRC structural elements is based on its residual flexural tensile strength after cracking (see Figure 2). The steel fibres control the crack by transmitting stress through the bond at the deformed anchors at both fibre ends to the concrete matrix, thereby providing resistance to the crack widening and fracturing process. Once the maximum bond strength with the concrete is reached, the pull-out action takes full effect.

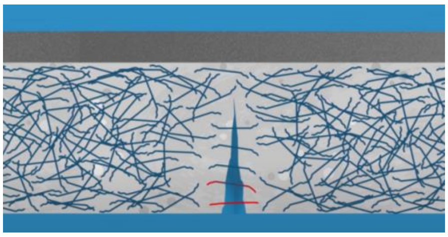

Figure 2: Steel fibres can prevent crack widening

RILEM TC162-TDF "Test and Design Method for SFRC" published by the International Union of Laboratories and Experts in Construction Materials, Systems and Structures **(RILEM)** has been widely used for the design of tunnel linings. AECOM and Dragages had experience in the design and construction of SFRC tunnel lining in number of oversea projects based on RILEM which provides comprehensive guidelines for testing and designing SFRC to ensure its effective use in construction. RILEM recommends determining the flexural tensile strength of SFRC section through three-point beam (550 mm x 150 mm x 150 mm) bending test in accordance with BS EN 14651 (see Plate 10). The flexural tensile behaviour of SFRC is evaluated in terms of residual flexural tensile strength values, determined from the load-crack mouth opening displacement (CMOD) curve (see Figure 2), obtained by applying a centre-point load on a simply supported notched beam. Typical result of three-point beam bending test is shown in Figure 3.

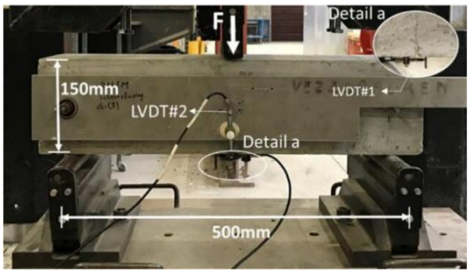

Plate 10: Set-up of three-point beam bending test

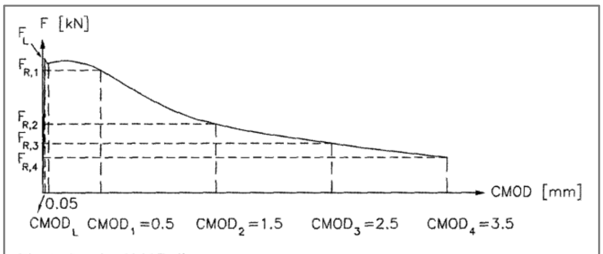

Fig. 1 - Load – CMOD diagram.

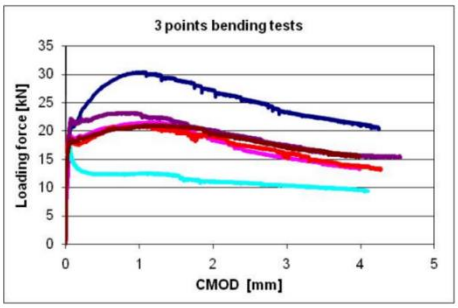

Figure 2: Load-CMOD diagram (RILEM)

Figure 3: Typical results of beam bending test

The forces F_L, $F_{R,1}$ and $F_{R,4}$ are recorded respectively at defined Limit of Proportionality (LOP) and CMOD values of 0.5 mm and 3.5 mm. Based on the obtained force values, the residual flexural tensile strengths, $f_{R,1}$ and $f_{R,4,}$ are calculated based on the following equation of RILEM (Figure 4).

$$f_{R,i} = \frac{3\, F_{R,i}\, L}{2\, b\, h_{sp}^2} \quad (N/mm^2) \qquad (7)$$

where:
b = width of the specimen (mm)
h_{sp} = distance between tip of the notch and top of cross section (mm)
L = span of the specimen (mm)

Figure 4: Calculation for residual flexural tensile strength (RILEM)

Hardened SFRC is classified by using two parameters that are determined by the residual flexural strengths $f_{R,1}$ and $f_{R,4}$. The first parameter $FL_{0.5}$ is given by the value of $f_{R,1}$ reduced to the nearest multiple of 0.5 MPa, and can vary between 1 and 6 MPa. The second parameter $FL_{3.5}$ is given by the value of $f_{R,4}$ reduced to the nearest multiple of 0.5 MPa, and can vary between 0 and 4 MPa. These two parameters denote the minimum guaranteed characteristic residual strengths at CMOD values of 0.5 and 3.5 mm, respectively. Subsequent to the tensile stress block developed in the stress distribution along the section, stress parameters σ_1, σ_2, and σ_3 can be derived as per RILEM (Figure 5).

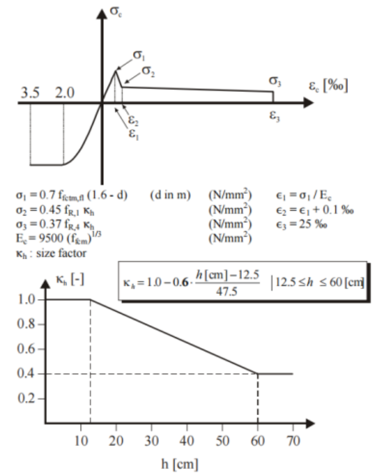

Figure 5: Stress-strain diagram (*RILEM)*

The compression and tension resistance of SFRC following the moment thrust interaction (M-N) diagram for SFRC (see Figure 6) can be derived in accordance with the simplified rectangular stress-strain curve and the HK Concrete Code. The calculation of moment capacity in SFRC uses the same principles as conventional reinforced concrete. The partial material factor, γc, adopted in SFRC is 1.5 for both flexural and tensile failures. The simplified rectangular stress-strain curve is shown in Figure 7 below:

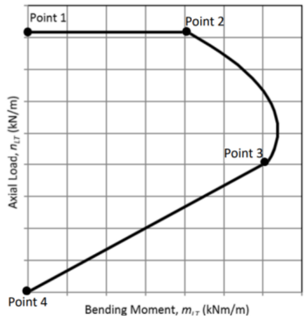

Figure 6: M-N curve for SFRC design

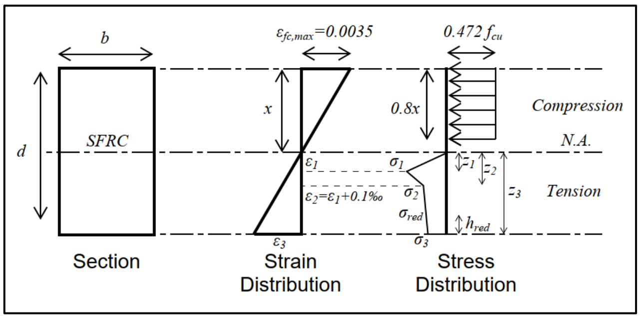

Figure 7: Simplified stress block for SFRC design

Comparison of the stress-strain behaviour (i.e. stress block) between conventional reinforced concrete and SFRC sections is given in Figure 8 below:

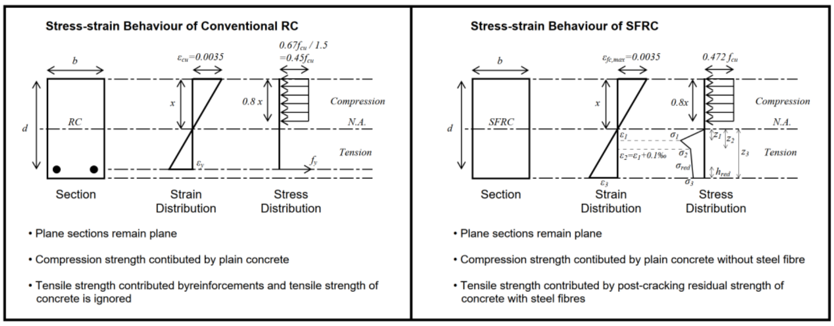

Figure 8: Comparison of stress block between RC and SFRC

For SFRC, the tensile stress block is developed using data obtained from a 3-point bending test for the tensile performance, while the tensile stress block of conventional reinforced concrete is solely based on the tensile strength of the main reinforcing bars.

5 OVERSEAS PROJECTS USING PRECAST SFRC SEGMENTAL TUNNEL LINING

Traditionally, tunnel segments for shield excavated tunnels have utilized conventional steel reinforcement. Since early 2000s, there has been a growing tendency to consider steel fibres to replace steel reinforcement in precast concrete tunnel linings. 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 conventional steel reinforcement cage were constructed by means of full-face TBM.

The latest completed SFRC tunnel was the Grand Paris Express subway in France that supporting the capital hosting the 2024 Summer Olympic Games (https://www.tunnel-online.info). In that tunnel project, Olympic Village and the Press Village were set up. Saint Denis, both have an underground railway station for metro Line

16.1 of the Grand Paris Express, including segments made of SFRC over a length of 12 km. 6000 tunnel rings with a diameters of 8700/9500mm were installed. The achievements in using SFRC for the project included the following:

- Firstly, comparing the 40 kg/m^3 steel fibres against the 85 kg/m^3 of steel reinforcement yielded a potential material saving of more than 50% (ITATech Report No. 7 recommends a steel fibre dosage of 30 to 50 kg/m^3, a range commonly used in SFRC tunnel projects worldwide).
- Secondly, the reduction of steel quantity required also provided a corresponding reduction in transport-related CO_2 emissions. One truckload delivery of fibres to the manufacturing plant allows the production of nearly 185 precast concrete tunnel segments, compared with 60 equivalent segments per truckload of conventional steel bar reinforcement; &
- Furthermore, SFRC reduced the quantities of concrete by 2 cm to 3 cm in segment thickness

Past research found that, in a typical metro tunnel of 10 km length, SFRC tunnel segments can save up to 5000 tonnes of steel reinforcement and 10,000 tonnes of CO_2 can be reduced.

6 SHARING OF LOCAL EXPERIENCE IN SFRC TUNNEL LININGS

SFRC precast tunnel linings were installed by Dragages in Liantang/Heung Yuen Wai Boundary Control Point Site Formation and Infrastructure Works Contract 2 and Central Kowloon Route projects of Highways Department in Hong Kong. These were installed in medium to large diameter pilot bored tunnels section for approx. 1 km in total through faulted, mixed and rock conditions. In both projects, SFRC was adopted as temporary lining as part of an early initiative to evaluate its suitability under Hong Kong's underground construction environment. These pilot applications aimed to address common issues observed in conventional RC segments, particularly spalling and cracking under handling and TBM thrust jacking.

Detailed information of the 2 SFRC temporary tunnels is summarized in Table 2 below.

	Liantang Project	***Central Kowloon Route Project***
Tunnel length with SFRC segment	*Approx. 314 m*	*Approx. 710 m*
Tunnel Internal Diameter	*12600 mm*	*6170 mm*
Lining Thickness	*500 mm*	*330 mm*
Nominal Ring Width	*1600 mm*	*1500 mm*
Concrete Grade	*Grade 50*	*Grade 50*
Steel Fibre Content	*35 kg/m3*	*45 kg/m3*
Characteristic Residual Flexural Strength, f_{R4}	*2.5 MPa*	*3.4 MPa*
Characteristic Tensile Splitting Strength	*3.8 MPa*	*4.8 MPa*
Encountered Ground Conditions	*Rock and mixed ground with fault zone*	*Rock with fault zone*

Table 2: Summary table of SFRC tunnel lining constructed in Liantang and Central Kowloon Route projects

Geological profile of the 2 tunnels is shown in Plates 11 and 12 below.

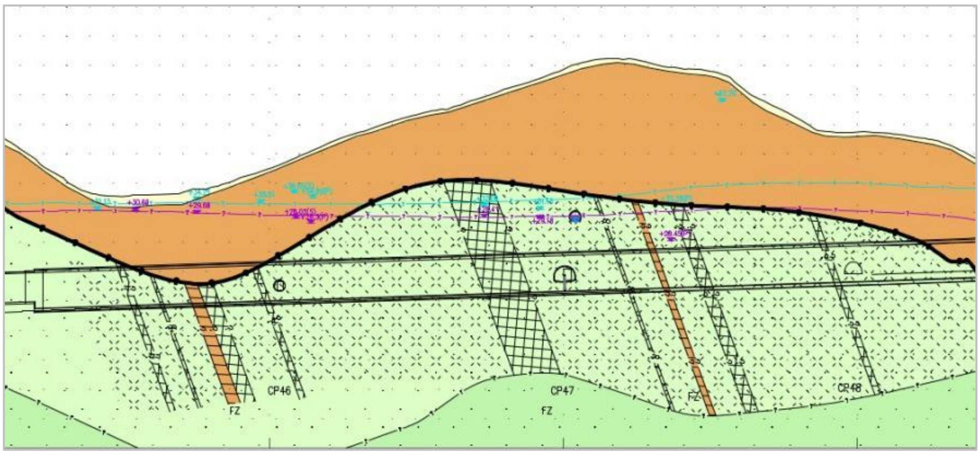

Plate 11: Geological profile of SFRC tunnel lining section in Liantang Project

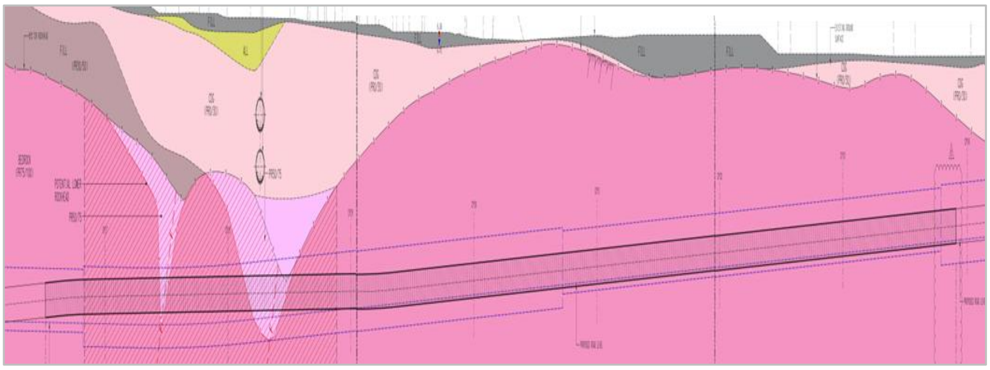

Plate 12: Geological profile of SFRC tunnel lining section in Central Kowloon Route Project

Segment performance was benchmarked against RC segments. key findings included reduced cracking, improved handling resilience and no spalling observed under TBM thrusting force (X. Monin. et al.). The adoption of steel fibre reinforcement in replacing steel rebar reinforcement accelerated segment production, and reduced labour intensity and optimized steel consumption. This full-scale application served as a technical validation step to assess SFRC performance under real TBM tunnelling conditions in Hong Kong. The experience and performance data collected from these two tunnelling projects provided confidence in the use of SFRC for tunnel linings and established a robust local reference to support further investigation into its permanent application.

While these pilots demonstrated technical feasibility, several challenges must be addressed for broader adoption in permanent tunnel linings:

- Code Compliance: Local construction standards do not yet fully address SFRC design based on residual flexural tensile strength and associated test methods.

- Industry familiarity: Wider understanding of SFRC's characteristics, performance behaviour, and quality assurance requirements are required across approval authorities, clients, designer and precast subcontractors.
- Fire and long-term performance: Further validation is required to confirm SFRC behaviour under fire exposure, and to assess long-term durability under local groundwater, load and environmental conditions.

7 CONCLUSION

In this paper, the benefits of adopting SFRC for precast tunnel segments are discussed. The experience gained in using SFRC for overseas tunnel projects and two pilot local tunnels of short sections with temporary SFRC tunnel linings were shared.

SFRC offers significant potential for tunnel construction in Hong Kong. Its enhanced tensile strength, crack resistance, and ductility are particularly beneficial make it ideal for the city's geotechnically challenging conditions. SFRC minimizes maintenance needs, reduce carbon emission, increases structural resilience, and effectively accommodates dynamic loads, ensuring safer, long-lasting tunnel infrastructure. Additionally, SFRC can effectively withstand dynamic loads and seismic activities, ensuring long-lasting and safer tunnel structures. Also, the use of SFRC can significantly reduce the material and labour cost of producing precast tunnel segments, and speed up the casting process. By incorporating SFRC, Hong Kong can achieve more efficient and sustainable tunnel construction, meeting the city's growing transportation and infrastructure demands.

AECOM and Dragages are collaborating together to implement the adoption of SFRC permanent precast segments for the first time in a tunnelling project of Hong Kong and hopefully that project will be completed successfully and have a review on the performance which we can share the experience gained later.

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