**Study of Sustainable Tunnel Construction by Evaluating Usage of Fibre Reinforced Concrete for Enhanced Efficiency and Safety under Various Geological Conditions.**

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**Abstract.** In tunnel construction, linings such as segments and permanent linings are crucial for withstanding forces during both construction and service stages. Traditionally, reinforced concrete has been the norm, but there's a global shift towards Fibre Reinforced Concrete, which offers numerous advantages. These include enhanced worker safety, cracking control, improved tensile properties, and reduced susceptibility to environmental degradation. Specifically, SFRC segments are noted for their sustainability, significantly lowering carbon footprints by reducing reinforcement usage and enhances production techniques compared to Conventional Reinforced Concrete. In India's underground metro projects, tunnel segments adhere to specific standards regarding diameter and thickness to manage various loads like ground pressure and water during service. These segments endure axial force, bending moment, and bursting forces, compounded by additional operational loads from TBM thrust and segment handling. This study investigates the feasibility of using SFRC segments in India's metro tunnels, considering constant structural parameters and different rock and soil types considering overburden loads, earth pressure coefficients, and ground elasticity for different geological and geotechnical conditions, aiming to optimize segment design and performance across diverse terrains. The goal is to enhance construction efficiency and safety by recommending SFRC or reinforced concrete types suited to specific geological contexts. This study's findings aim to inform metro infrastructure design, ensuring robustness and longevity amidst varied geological challenges. By leveraging SFRC's benefits, metro projects can achieve both environmental sustainability and structural integrity, crucial for urban infrastructure resilience in growing cities like those in India.

**Keywords:** Fibre Reinforce Concrete • Sustainability • Segments • Metro Tunnel

# Introduction

Human-generated greenhouse gas emissions, primarily CO₂ from fossil-fuel-driven industry and transport, are recognized as major drivers of rising global temperatures. While the full impacts of climate change are uncertain, the rapid temperature increase threatens future generations, making immediate CO₂ reduction imperative. In sustainable development, design engineers must minimize the carbon footprint of structures while ensuring durability. Reinforced cement concrete (RCC), heavily used in tunnelling, is one of the most consumed materials worldwide and modifications in design procedures and materials may provide a sustainable solution towards reductions of CO2 emissions.

Typically, tunnel segments are reinforced with conventional rebars embedded in reinforced concrete (RC) elements to resist tensile stresses at both Serviceability (SLS) and Ultimate Limit States (ULS). Over the last two decades, Fibre Reinforced Concrete (FRC) has been increasingly adopted worldwide for use in precast tunnel segments, either in combination with or as an alternative to conventional rebars. FRCs are composite materials consisting of a cementitious matrix and discontinuous fibres made from metal, glass, synthetic, or natural material. Fiber Reinforced Concrete (FRC) offers post-cracking tensile strength, making it a viable alternative to Reinforced Cement Concrete (RCC) segments in several applications. This substitution can significantly reduce steel consumption, thereby lowering the carbon footprint in terms of material use. Additional benefits of FRC include easier transportability, which reduces fuel consumption, and environmentally favourable production processes. This study investigates the potential for FRC segmental linings, adopting geometries common in India but under varied geological conditions, to replace RCC segments. The aim is to identify areas where FRC can provide a more sustainable and structurally resilient solution. A parametric study has been conducted by varying tunnel depths and geotechnical parameters to reflect the diverse geological profiles encountered across India. The results summarize where FRC can be effectively utilized and identify appropriate FRC grades. Furthermore, this study offers insights into production considerations and quality management practices for FRC segments.

## Benefits of FRC concrete

1. Improved Post-Cracking Behaviour: Fibres significantly enhance the post-cracking performance of concrete, commonly referred to as toughness.
2. Enhanced Crack Control and Durability: Fibre reinforcement, particularly when combined with traditional reinforcing bars, enables superior crack control. This results in smaller crack openings at the Serviceability Limit State (SLS), thus considerably improving the durability of the structure.
3. Increased Impact Resistance: Fibres provide higher resistance to impact loading, making the structure more robust against dynamic forces.
4. Efficiency in Industrial Production: Fibre reinforcement offers the potential for a partial or complete substitution of conventional rebars. This leads to reduced time in handling and placing curved rebars and minimizes or eliminates the need for large storage areas for traditional reinforcement.
5. Uniform Reinforcement Distribution: Fibre reinforcement is uniformly distributed throughout the segment, including the concrete cover. In reinforced concrete (RC) segments, the cover is often required to be significantly thick to meet fire protection and durability standards.
6. Improved Durability: Durability is commonly associated with concrete permeability but also relates to the presence of microcracks or cracks due to internal and external strains. Fibre reinforcement can significantly reduce cracking and control the permeability of concrete under stress.
7. Sustainability: Fibre reinforcement contributes to the sustainable use of structural concrete by lowering the environmental impact while enhancing the mechanical performance of structures.

# Design Principles and Assumptions of FRC concrete.

In fibre-reinforced concrete (FRC), fibres must resist concrete’s alkalinity without degrading and should not impair properties like workability, strength, or durability (e.g., carbonation, frost, and water resistance). Fibers should also meet temperature, fire resistance, and safety standards. Effective bonding is achieved through optimized fibre anchorage (e.g., hooks, embossing). Uniform fibre distribution requires precise dosing and thorough mixing.

Assessing FRC suitability for a project involves evaluating its mechanical performance compared to conventional bar reinforcement. Key factors include the concrete matrix's strength, durability, fibre type and quantity, and fibre-matrix interface properties, such as post-crack residual strength. Fibres may be used alone or in combination with steel reinforcement, offering modest enhancements in flexural capacity, which can be beneficial for handling, installation, or controlling crack widths under bending.

Fibre reinforcement differs from traditional reinforcement in that fibres are distributed throughout the cross-section rather than concentrated in specific areas. This results in distinct differences in weight, spacing, and placement. Mechanically, fibres provide resistance through pull-out mechanisms at the crack interface, promoting crack bridging and improving the material's post-cracking behaviour. Importantly, fibres control cracking without affecting the performance of uncracked concrete. The effectiveness of fibre anchorage depends on its shape, fibre-concrete friction, matrix density, and fibre tensile strength.

## Design Principle for Fibre Reinforced concrete.

The primary purpose of adding fibres to a cementitious matrix is to enhance tensile performance after cracking by increasing residual tensile strength and ductility. Fibre-reinforced concrete (FRC) is a composite material, not just a simple addition of fibres to concrete.

Post-cracking residual properties are influenced by fibre characteristics such as material, shape, aspect ratio, quantity, orientation, and the properties of the cementitious matrix. However, fibres do not affect the elastic modulus, Poisson's ratio, or compressive strength, meaning the pre-cracking behaviour of concrete remains unchanged.

To assess FRC's post-cracking behaviour under tension, various test methods are available. Uniaxial tensile tests provide direct insights into the post-cracking tensile performance (whether softening or hardening), though they are challenging to perform. Design recommendations typically rely on bending tests, which assess the flexural response of cementitious composites after cracking. Once an initial crack forms, the material exhibits either flexural softening or hardening depending on the type and amount of fibre reinforcement and the matrix properties.

EN-14651 provides beam testing standard determined by 3 point bending teat on a notched beam that has been used by Modal Code 2010 for various correlations pertaining to FRC concrete.

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**Fig. 1.** Typical details of 3-point test as per EN 14651 and Force v/s Deformation Plot as Obtained from test expressed as CMOD (Crack Mouth Opening Displacement (Source: Model Code 2010)

The residual post-cracking strength serves as a key performance indicator for designers and must meet specific requirements. For precast FRC tunnel segments, this parameter should be consistently monitored through conformity testing during production. To evaluate the post-cracking strength of FRC, the characteristic residual strength relevant to both serviceability (fR1k) which is defined in termed of values of 1.0 to 8.0 MPa corresponding to crack mouth width as per allowable standards with respect to different projects and ultimate conditions (fR3k) which is defined in terms of class (“a” to “e”) for a range of ratio of fR3k/ fR1k is used, focusing particularly on two main parameters.

The above-mentioned values are used to determine the design tensile strength of FRC concrete fFts and fFtu by constitutive laws of Rigid-plastic post-cracking model given by Eqn. (1) and Linear Post Cracking Behaviour given by Eqn. (2) and (3).

(1)

(2)

(3)

Here wu corresponds to the allowable crack width and CMOD3 is generally considered as 2.5mm. The values obtained for design tensile strength shall be obtained by reducing the strength by corresponding Factor of safety.

# Parametric study of forces and application of FRC segmental lining for different geological conditions.

The use of Fiber Reinforced Concrete (FRC) in tunnel segment linings has gained significant interest due to its potential advantages over traditional Reinforced Cement Concrete (RCC), particularly in challenging geological conditions. The objective of this study is to assess the applicability of FRC segments over RCC segments for urban metro tunnels under various geological conditions commonly encountered in India. A parametric study is conducted, considering variations in geological properties, tunnel dimensions, overburden, surcharge, and groundwater levels. Additionally, the impact of seismic forces is evaluated for tunnels located in seismic Zone IV, as per IS 1893:2016. The analysis aims to provide insights into the structural performance and capacity of FRC segments under these complex loading scenarios.

## Tunnel Geometry

Urban metro tunnels in India typically follow specific geometric standards that have evolved over time. This study uses a standard tunnel diameter and corresponding segment thickness, reflecting configurations adopted across multiple metro projects in the country. The segment thickness is designed to ensure structural integrity while optimizing material use and construction efficiency.

**Table 1.** Details of Tunnel Geometry.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Grade of concrete | I- Jointed Segment  (m4/m) | E  (MPa) | A (m2/m) | Thickness (mm) | External Diameter (m) |
| M50 | 0.00111 | 35355 | 0.275 | 275 | 6.35 |

## Geological Properties

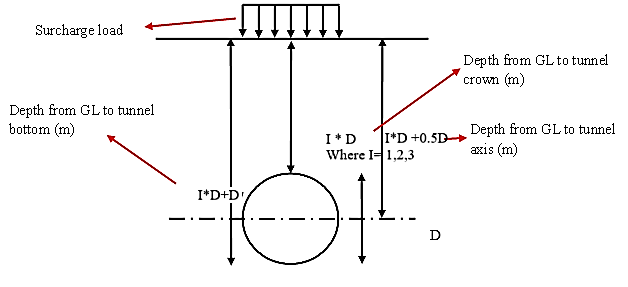
For this study, the surrounding geology is assumed to be a homogeneous isotropic medium. This assumption simplifies the analysis while providing a reasonable approximation of many real-world conditions. The geological medium is characterized by its elastic properties, and the study evaluates how FRC segments respond to variations in these properties under different loading conditions.

**Table 2.** Details of Geology considered for parametric study.

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| --- | --- | --- | --- | --- | --- | --- |
| Geology | Soil Type 1  (Weak Soil) | Soil Type 2  (Moderate Soil) | Soil Type 3  (Stiff Soil) | Rock (Gr V) | Rock (Gr IV) | Rock Grade (III/II) |
| γʹ (kN/m3) | 20 | 20 | 20 | 25 | 25 | 25 |
| φ ʹ (˚) | 30 | 30 | 30 | 50 | 50 | 50 |
| E (kN/m2) | 25000 | 50000 | 75000 | 250000 | 500000 | 750000 |
| νur | 0.3 | 0.3 | 0.3 | 0.25 | 0.25 | 0.25 |
| K0 | 0.50 | 0.50 | 0.50 | 0.33 | 0.33 | 0.33 |

## Overburden and Surcharge conditions.

The effect of varying overburden depths is considered by modelling overburden as integer multiples of the tunnel diameter (D, 2D, 3D, etc.). Surcharge conditions, such as those caused by traffic, buildings, or other surface loads, are also included to simulate realistic urban environments. The general surcharge is considered as 60 kPa as per Model RDSO DBR. The interaction between the tunnel lining and the surrounding soil is analysed under these variable loading scenarios.



**Fig. 2.** Typical details arrangement of Tunnel, overburden and surcharge

## Loading conditions on segmental rings

* Demoulding of Tunnel Segments
* Storage and Transportation
* TBM thrust forces
* Service Loading conditions due to

1. Ground loads
2. Existing building surcharge
3. Hydrostatic forces
4. Earthquake loads
5. Live load

## Ground loads

The influence of static ground loads on the tunnel lining is analysed using analytical solutions derived from the work of Curtis Muir Wood, specifically for homogeneous isotropic media. These solutions provide a framework for estimating the stress distribution around the tunnel and the resulting forces acting on the segmental linings. The analysis accounts for both the vertical overburden pressure and the horizontal stresses exerted by the surrounding geology.

## Seismic loads

Given the location of most Indian metro projects in seismically active zones, the effect of earthquakes is an important consideration. For this study, the seismic effects are evaluated for Zone IV with Peak Ground Acceleration for Operating Design Earthquake (ODE) being 0.18g and for Maximum Design Earthquake (MDE) as 0.36g, with vulnerability factor of 1.5 as classified by IS 1893:2016. The Maximum Moment Magnitude is considered as 7.0 with source to site distance as 50-100 km. The forces resulting from seismic activity are calculated using analytical methods developed by Hashash[2], which consider both horizontal and vertical ground accelerations. These forces are superimposed on the static loads to determine the combined effects on the FRC tunnel segments.

## Load combination and Design standards

The analysis incorporates multiple load combinations, including static ground loads, surcharge, groundwater pressure, and seismic forces. These loads are combined according to the principles outlined in IS 456 to ensure that the design remains within the acceptable limits of safety and serviceability. The capacity of FRC segments is evaluated based on these combined loading conditions. The structural design of tunnel segments is done by fIB Model code 2010[6] and fIB bulletin 83[7] which are the globally standard codes for FRC design.

# Results and Discussion of analysis

As outlined in the previous section, a typical tunnel configuration used in Indian metro systems has been adopted for this study. The analysis has been conducted for varying overburden conditions, specifically 1D, 2D, and 3D, where D represents the diameter of the tunnel. These overburden variations simulate the range of geological depths that metro tunnels commonly encounter. The study also takes into account a variety of geological conditions, including both soil and rock, to comprehensively evaluate the potential of replacing traditional RCC segments with Fiber Reinforced Concrete (FRC) segments.

In assessing the performance of FRC segments, the minimum fibre class used for design has been defined as "5d," in accordance with the "Guidelines for the Use of SFRC Segments" issued by the Delhi Metro Rail Corporation (DMRC). The fibre class designation is critical for understanding the ductile behaviour of FRC under load. According to the Model Code 2010, class "d" refers to the ratio of post-crack flexural strengths, with 1.1 ≤ fR3k / fR1k ≤ 1.3. For this design analysis, the upper bound value of 1.3 has been adopted to ensure a conservative assessment of segment performance under demanding conditions.

To further investigate the application of FRC under various geological conditions, the characteristic flexural strength fR1k, which represents the first crack flexural strength has been varied parametrically. The chosen values for fR1k are 5 MPa, 6 MPa, and 7 MPa. This parametric variation allows for a detailed understanding of how different FRC grades perform across diverse geological scenarios, such as in softer soils versus harder rock formations. By analysing this range of fR1k values, the study aims to determine the optimal grade of FRC that can completely replace RCC segments while maintaining safety and performance standards under varying loads and geological stresses.

The characteristic values of different design parameters and Factor of safety for design and analysis of FRC segments has been presented in the table below.

**Table 3.** Characteristic Values of design parameters as per different grades of SFRC.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Classification | 5d | 6d | 7d |  |
| Characteristic compressive strength (cube), fck | 50 | 50 | 50 | MPa |
| Characteristic compressive strength (Cylinder), fcyl | 40 | 40 | 40 | MPa |
| Constitutive Model followed for Fiber Reinforcement | Linear post-cracking | | | |
| Characteristic residual flexural strength (CMOD=0.5mm), f R1k | 5 | 6 | 7 | MPa |
| (fR3k/fR1k) | 1.3 | 1.3 | 1.3 |  |
| Characteristic residual flexural strength (CMOD=2.5mm), fR3k | 6.5 | 7.8 | 9.1 | MPa |
| Long term effect on the compressive strength coefficient, αcc | 0.85 | 0.85 | 0.85 |  |
| Characteristic residual tensile strength, fFtuk | 2.25 | 2.7 | 3.15 | MPa |
| Partial safety factor for concrete and FRC in compression, γc | 1.5 | 1.5 | 1.5 |  |
| Partial safety factor for FRC in tension, γf | 1.5 | 1.5 | 1.5 |  |
| Design compressive strength, fcd | 22.67 | 22.67 | 22.67 | MPa |
| Design tensile strength, fFtud | 1.5 | 1.8 | 2.1 | MPa |

## Design for FRC in Soil

The analysis of Fiber Reinforced Concrete (FRC) segments classified as "7d" was conducted for various overburden depths, specifically focusing on soils with stiffness values of 25 MPa and 50 MPa. These stiffness values represent weak to moderately stiff soils, which are often encountered in metro tunnelling projects. The results of this analysis indicate that the forces generated within the tunnel lining under these conditions significantly exceed the design capacity of the FRC segments.

The elevated forces observed can be attributed to the relatively low stiffness of the surrounding soil, which offers limited support to the tunnel lining. As a result, the lining is subjected to higher bending moments and axial forces, surpassing the capacity of FRC segments designed under the "7d" classification. Despite the enhanced tensile strength and crack control properties of FRC, the combination of weak soil and high overburden imposes loading conditions that these segments cannot adequately withstand.

Given that soils with stiffness values of 25 MPa and 50 MPa are typical of weak to moderate conditions, it can be inferred that FRC segments, even those with high performance like class "7d", may not be suitable in such scenarios. RCC segments are better equipped to handle the elevated forces encountered in weak to moderately stiff soils due to their enhanced compressive and flexural strengths. Therefore, in cases where the surrounding soil exhibits lower stiffness and generates higher forces on the tunnel lining, RCC segments emerge as a more dependable and robust option for ensuring structural integrity and long-term performance of the tunnel.

The structural behaviour of Fiber Reinforced Concrete (FRC) segments significantly improves as the surrounding soil becomes stiffer, particularly when the modulus of elasticity (E) of the soil exceeds 75 MPa. In such cases, the stiffer soil provides better confinement and support to the tunnel lining, reducing the overall forces and bending moments acting on the segments. The analysis of FRC grades 5d, 6d, and 7d under these conditions reveals that all three grades can withstand the forces imposed by the combination of overburden and soil interaction.

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**Fig. 3.** Interaction Diagram for soil with E value of 25 MPa and 50 MPa

For FRC segments in stiff soils, grade 5d, is structurally sufficient to bear the applied loads, the design margin is comparatively lower than for higher grades like 6d and 7d. This indicates that grade 5d segments operate closer to their capacity limits when subjected to the typical ground forces encountered in soils with a modulus of elasticity around 75 MPa or higher. While this is acceptable from a design standpoint, the lower margin of safety suggests that 5d segments should be employed with caution in regions where additional forces, such as seismic loads, might further stress the structure.

In areas where seismic activity is a critical factor, particularly in higher seismic zones (Zone IV or Zone V as per IS 1893), the overall design moment will be significantly influenced by earthquake forces. Under such circumstances, FRC grades with a higher capacity, such as 6d or 7d, may offer more reliable performance due to their superior flexural strength and crack control. However, in regions with lower seismic activity, such as Zone III or below, the contribution of seismic forces to the total design moment is substantially reduced. This allows for the use of grade 5d FRC segments, which, despite having a lower design margin, remain structurally viable in these less earthquake-prone areas.

In summary, as the soil stiffness increases to the order of 75 Mpa and above, it provides greater support to the tunnel lining, even the lower grade FRC segments (e.g., 5d) become feasible for use, provided that the design is adequately conservative in regions with low seismic risk. In higher seismic zones, however, higher FRC grades (such as 6d or 7d) should be preferred to ensure the safety and durability of the tunnel lining under combined ground and seismic forces. It is recommended to provide conventional RCC segments in areas having soil with lesser stiffness for sustaining the forces

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**Fig. 4.** Interaction Diagram for soil with E value of 75 MPa

## Design for FRC in Rock

In the case of rock formations, the structural performance of Fiber Reinforced Concrete (FRC) segments improves due to the significantly higher modulus of elasticity (E) of rock compared to soil. Rock provides much better confinement to tunnel linings, which results in reduced deformation and improved load distribution. For instance, completely weathered rock typically has an E value ranging from 250 MPa to 300 MPa, whereas moderately weathered rock, classified as Grade III, exhibits a higher E value in the range of 500 MPa to 750 MPa. This substantial increase in stiffness enhances the support provided by the surrounding ground, which in turn reduces the forces acting on the tunnel lining.

The analysis shows that in completely weathered rock, the performance of FRC grade “5d” is marginal, meaning it is close to reaching its design limits under certain loading conditions. For such cases, FRC grade “6d” offers a sufficient safety margin across all depths, demonstrating better suitability for more demanding conditions where forces are greater due to the surrounding geology. Although FRC grade 5d segments may fall slightly short in completely weathered rock, they provide adequate structural performance when higher grades of rock, such as highly weathered or moderately weathered (Grade IV or less), are present.

In cases involving rocks of higher quality, such as moderately weathered or better, the confinement provided by the rock significantly reduces the overall stresses on the tunnel lining. This allows even the lower FRC grade “5d” to perform adequately across various depths, without nearing its design limits. The improved confinement of the rock acts to distribute the forces more evenly, reducing the bending moments and axial loads acting on the FRC segments.

As a result, for regions classified as seismic Zone III or lower, where the seismic forces are relatively minor, FRC grade "5d" emerges as an economical option for tunnels excavated through completely weathered rock. Additionally, in the case of rocks classified as Grade III or lower (i.e., moderately weathered or more intact rocks), FRC grade "5d" can be used safely, regardless of the depth and seismic zone. This is because the higher confinement provided by the rock ensures that the tunnel lining is subjected to reduced stress, allowing for the use of a lower FRC grade without compromising structural safety or performance.

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**Fig. 5.** Interaction Diagrams for rock with different grades with E values of 250 MPa, 500 MPa and 750 MPa

To summarize, the combination of higher modulus of elasticity in rock and the improved confinement compared to soil makes FRC grade "5d" a feasible and cost-effective choice in completely weathered rocks under moderate seismic conditions. For more demanding conditions higher seismic activity, upgrading to FRC grade “6d” ensures adequate safety margins without excessive material overuse. Furthermore, for rock formations that are highly weathered or better (e.g., Grade IV or stronger), FRC grade "5d" is sufficient, providing an optimal balance between performance and cost.

## Design for FRC For other Transient conditions and Quality control.

In addition to ground and surcharge loads, tunnel segments are subjected to various transient forces during different stages of handling and installation, such as demoulding, stacking, and the application of thrust loads from the tunnel boring machine (TBM). These transient forces are critical, as they often occur when the concrete is in a more vulnerable state. During stacking and demoulding, for instance, the concrete may not have reached its full strength, which increases the risk of damage or cracking. Similarly, TBM jacking forces impose highly localized, concentrated short-term loads on specific areas of the segment. Therefore, the fibre-reinforced concrete (FRC) used in the segments must have sufficient capacity to endure these conditions, ensuring structural integrity throughout these critical stages.

**Demoulding and Stacking:** A minimum compressive strength (fck) should generally be ensured during demoulding to evaluate the required bearing capacity of segments and prevent collapse, ensuring worker safety. Verification at the ultimate limit state (ULS) is typically necessary. To evaluate concrete fracture parameters, it is recommended to test specimens with the same curing process, or, as an approximation, assume the fracture properties at demoulding are proportional to the compressive strength, though no specific early-age relationships exist.

For stacking, similar concerns apply regarding early-age concrete strength, and avoiding cracking is crucial. Misaligned supports during stacking can introduce eccentricities and high bending moments, especially in fibre-reinforced segments.

Key design steps include:

* Evaluating concrete compressive strength at demoulding or storage.
* Assessing or estimating fracture parameters of FRC for stacking and demoulding.
* Determining ULS forces from demoulding and stacking configurations.
* Deciding on curing time and strength gain for transient conditions.
* Establishing a stacking process to prevent cracking and collapse.

**TBM jack Thrust Force:** During TBM operation, the circumferential face of tunnel segments is subjected to significant concentrated forces generated by the thrust pads of the TBM jacks. The magnitude of these forces can vary across different projects, depending on factors such as the TBM’s turning radius, local geology, and the overburden pressure. These concentrated forces induce a splitting tendency in the segments, which must be carefully evaluated based on the grade of fibre-reinforced concrete (FRC) and its capacity to resist the tensile forces generated.

It is essential to consider these factors when determining the feasibility of fully replacing reinforced concrete (RCC) segments with FRC segments or adopting a hybrid approach that includes additional splitting reinforcement at the segment ends. The same principle applies to the splitting tensile forces in the radial direction caused by axial loads from earth and surcharge pressures. Both scenarios require careful evaluation to ensure the structural integrity of the segments.

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**Fig. 6.** Typical representation of SFRC and Hybrid Segments (Source: ITA: 20 years of FRC tunnel segment practice)

A typical configuration of hybrid segments as shown in Fig. 6, incorporating splitting reinforcement at critical locations, is depicted below to illustrate how these forces are managed effectively.

**Quality control:** For effective quality assurance in Fibre-Reinforced Concrete (FRC), special attention is required to prevent cracking, ensure proper alignment during stacking, maintain adequate curing, and manage segment handling to avoid eccentric forces. As suggested by fIB bulletin 83[7] Quality control procedures should be established during the design phase and typically involve two key steps: initial material qualification (trial testing) and ongoing production testing.

* Initial Testing:

Before segment production, compressive and flexural (bending) tests must be conducted following EN 14651 standards to verify that the material meets the specified design requirements. Compressive strength testing should follow standard procedures used for conventional concrete, while tensile properties must be assessed using EN 14651 beam tests. For accurate results, at least 12 beams should be tested at 28 days of curing for each fibre dosage and concrete mix to determine the values of fR1k and fR3k and accordingly fix the grade of FRC.

* Fibre Content Verification:

Fibre content can be measured in both fresh and hardened concrete states using EN 14721 standards. In hardened concrete, core samples are drilled from segments to verify the uniform distribution of fibres across different sections. If necessary, cores can be further examined in layers to check for fibre segregation. A deviation of less than 20% from the nominal fibre content is generally acceptable.

* Production Testing:

During production, regular testing is essential to ensure material quality. Flexural and compressive strength tests should be conducted routinely, with at least 3 beam tests performed for each control set, similar to compressive strength tests on cubes or cylinders. The testing process must be tailored to the expected production rate and potential variations over time, as determined by the designer. Conformity control should follow the guidelines of EN 206, as applied for compressive concrete testing.

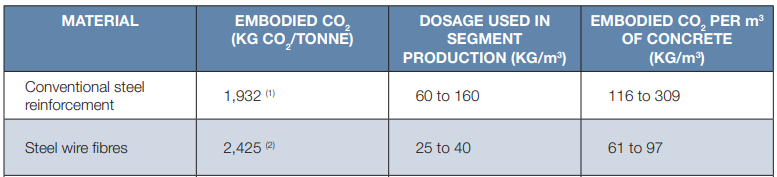
# Sustainability of FRC segments

The replacement of all or part of conventional steel reinforcement with steel fibres in precast tunnel segments has been shown to significantly reduce the embodied CO₂ of the segmental lining. On a per kilogram basis, the embodied CO₂ of both conventional rebar and steel fibres is generally assumed to be comparable. This assumption is based on the premise that both the wire rod used for steel fibres and rebar have similar recycled material content and are produced using similar steel production methods. However, in precast segments, the reduction in carbon footprint is primarily due to the increased efficiency of steel fibres in reinforcing the element. By eliminating traditional rebar and using the appropriate combination of binder and steel fibres, a reduction of up to 70% in embodied CO₂ can be achieved.

The carbon savings primarily arise from the following factors:

* **Reduced fibre-to-rebar ratio**: Steel fibres, when used in place of conventional rebar, lead to a significant reduction in CO₂ emissions. For instance, conventional reinforcement typically requires 90 kg/m³ of rebar in RCC segments in rock and stiff soils, while only 45 kg/m³ of steel fibres is required, representing a material savings of more than 50%.
* **Optimized transportation**: The transportation of steel fibres is much more efficient compared to rebar. Reinforcing bars require more sophisticated transportation facilities due to their bulk, and additional time and energy are needed for cutting, binding, and placing the bars during construction. In contrast, steel fibres are easier to handle, which reduces emissions related to transport.
* **Reduced emissions from primary steel production**: Steel fibres, typically produced from wire rods with diameters not exceeding 1 mm, further limit toxic emissions from the steel industry. The production of these small-diameter fibres uses advanced drawing technologies that are characterized by lower emissions compared to conventional rebar production.

Considering data from the International Tunnelling Association (ITA) shows significant differences in the embodied CO₂ content of conventional reinforcement, steel wire fibres, and synthetic fibres. These variations depend on factors such as the dosage rates of the materials (which differ by project), the power sources used during manufacturing (e.g., coal, gas, oil, nuclear power), and the type of furnace used for steel production (basic oxygen or electric arc).



**Fig. 7.** CO2 emission for different types of reinforcement (Source: ITA: Guidelines for SFRC segmental lining)

Overall, the use of fibre reinforcement as an alternative to conventional reinforcement cages in the design and manufacturing of precast concrete tunnel segments can dramatically lower their embodied CO₂. This reduction stems from lower steel production emissions, improved transportation efficiency, and simplified segment casting processes.

# Conclusion

The significant rise in global temperatures has been largely attributed to human-generated greenhouse gas emissions, particularly CO₂ from fossil fuel-powered industrial processes. In the pursuit of sustainable development, engineers are increasingly focused on reducing the carbon footprint of their designs, while ensuring adequate service life. Reinforced cement concrete (RCC) remains one of the most widely used materials globally, but Fiber Reinforced Concrete (FRC) is emerging as a viable alternative, particularly for precast tunnel segments. Over the past two decades, FRC has gained popularity due to its numerous advantages over RCC, such as improved post-cracking behaviour, enhanced crack control, increased impact resistance, and superior durability.

While FRC does not affect the elastic modulus, Poisson's ratio, or compressive strength, its post-cracking properties are heavily influenced by the characteristics of the fibres, including their material, shape, aspect ratio, quantity, orientation, and the properties of the cementitious matrix. This allows FRC to offer uniform reinforcement distribution and efficiency in industrial production, contributing to more sustainable construction practices.

In this study, a parametric analysis was conducted to evaluate the feasibility of using FRC in place of conventional RCC segments under various geological conditions, tunnel dimensions, overburden pressures, and surcharge loads. The results suggest that for tunnels in stiffer soils with Modulus of Elasticity >75 MPa or Completely to Weathered rock formations with Modulus of elasticity values ranging from 250-500 MPa, lower-grade FRC segments (e.g., 5d) can be successfully employed across all depths, provided they are designed conservatively and located in regions with moderate seismic risk. In higher seismic zones, higher FRC grades (such as 6d or 7d) are recommended to ensure safety and durability.

In areas where the geology consists of Highly weathered rock or better, FRC grade "5d" proves to be a cost-effective and feasible solution for tunnel lining across all depths, while offering the added benefits of sustainability and reduced embodied CO₂.

The adoption of FRC for transient conditions, such as segment stacking and demoulding, requires careful consideration of curing times, strength gain, and the prevention of cracking during handling. For the splitting forces generated by TBM thrust forces in both circumferential and radial directions, it is essential to evaluate the FRC's tensile strength and determine whether a hybrid segment design, with additional splitting reinforcement, is necessary.

In India, the production chain for FRC segments is still underdeveloped, and the following considerations are critical:

* FRC is most suitable for stiffer soils or areas with moderate to good-quality rock formations.
* Rigorous geotechnical investigations are necessary to anticipate any unexpected geological changes.
* Fiber dosage should be determined in accordance with fIB 83 and other relevant standards, supported by adequate testing procedures to determine tensile strength of FRC grade.
* Quality control during production is crucial, with consistent testing of tensile strength parameters, fibre dosage, and fibre distribution in each batch in accordance with fIB 83 and other relevant codes.
* Special care must be taken to avoid cracking during handling, ensuring proper alignment during stacking, adequate curing, and careful management of segment handling to prevent eccentric forces.

In conclusion, the use of FRC as a sustainable alternative to conventional RCC segments offers significant potential to reduce the embodied CO₂ of tunnel segment production. The amount of conventional rebars that are being used in design of tunnel segment is generally around 90 kg/m3 while a strength of “5d” to “6d” can be achieved in FRC segments by usage of Fiber dosage of 45 kg/m3 which leads to reduction in steel usage by 50 %. Moreover, sustainability is also driven by the lower emissions associated with steel production, more efficient transportation, and streamlined segment manufacturing processes leading to lesser resource management. While the use of FRC segments holds promise, its application must be carefully tailored to the specific geological and structural requirements of each project, ensuring both safety and environmental sustainability.

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