

DESIGN AND CONSTRUCTION OF FIBER REINFORCED CONCRETE (FRC) TUNNEL PRECAST LINING WITH FIBER ENABLED CARBON FOOTPRINT REDUCTION

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ABSTRACT: The construction industry is a major contributor to CO₂ emissions, largely due to the embodied carbon in materials like cement and steel. In tunnelling projects, 60-70% of embodied carbon is found in concrete linings. Promoting sustainable design is crucial. High-performance steel fiber reinforcement, combined with optimized structural design and Supplementary Cementitious Materials (SCM) in concrete mixtures, can reduce embodied carbon in segmental and spray linings by nearly 50%. The use of Fiber Reinforced Concrete (FRC) in tunnelling has grown significantly, driven by guidelines like the fib Model Code 2010, which included FRC specifications. The recently published Model Code 2020 has further expanded FRC's use in tunnel linings, benefiting owners, designers, and contractors. This paper explores design principles and carbon reduction examples from projects in Europe, Australia, North America, and the Middle East.

1. INTRODUCTION

Underground space plays a vital role in sustainable urban planning as it provides a solution to the limited surface area available. In terms of transportation, underground networks enable efficient and rapid mass transit, helping alleviate congestion and reduce carbon emissions. Moreover, underground space is essential for the infrastructure required to sustain cities, such as dense networks of pipes for delivering fresh water and sewers for wastewater treatment. Additionally, it accommodates the extensive network of cables and service stations necessary for modern communication systems.

By utilizing underground space, cities can optimize their resource management and minimize their environmental impact, contributing to a more sustainable urban future. For a sustainable use of structural concrete, environmental and mechanical performances of concrete structures must have the same importance. By means of sufficiently high mechanical performances, the structural safety of a construction is ensured.

In a tunnelling project, it is generally considered that 60% to 70% of embodied carbon is contained in the concrete linings of the shafts and tunnels. It is paramount, therefore that the tunnelling industry does its utmost to significantly reduce or eliminate its use of cement in all applications – segmental linings, in-situ linings, sprayed concrete, and annulus grouts.

This is the reason why a great challenge for the coming years will be develop solution for low carbon lining. Mechanical excavated tunnels (tunnels excavated with a TBM – Tunnel Boring Machine) are increasingly used in Civil Engineering. In these tunnels, the lining is made assembling precast segments used by the TBM as reacting elements in the excavation process.

The use of Fibre-Reinforced Concrete (FRC) allows to reduce or eliminate the traditional reinforcement in the precast segment production. Over the last twenty years, the use of this technology has increased. The use of Fibre Reinforced Concrete (FRC) allows several advantages, compared with traditional steel mesh or steel bar reinforcement according to fib bulletin 83 and all main recommendation published as:

Cracking control during construction phases

Higher impact resistance

Durability advantages at final stage

Reduction of costs

Sustainability advantages

Boosting of the production process

Recent project has demonstrated that structural ductility, durability, and sustainability are going hand in hand.

This holistic approach will be clearly a new booster for FRC tunnel lining. This paper will provide the start of the art on this issue, the key design principal and detail recent cases studies showing impact in carbon calculation saving in France, Middle East, and Australia.

2. PERFORMANCE REQUIREMENT

Minimum performance required hardening post crack behaviour at section level according to EN 14 651 three point bending test allow immediately cracking control at SLS and structural ductility ULS. A recommended performance class 5d according to MC 2010 could be guaranteed with the use high performance steel fibre with some minimum requirement as diameter max 0.75mn, tensile strength > 2200 MPA and optimized hook.

The tensile strength of a steel fibre has to increase in parallel with the strength of its anchorage. Only in this way can the fibre resist the forces acting upon it.

Figure 1 and 2 shows a typical result of the beam tests considering 40KG fibre type Dramix® 4D 80/60BGP with significant strength values. FL is peak force, f_{R1} and f_{R3} are the stresses related to CMODs equal to 0.5 and 2.5 mm respectively. These values are the reference ones for final lining design performed according to the fib Model Code 2010 prescriptions.

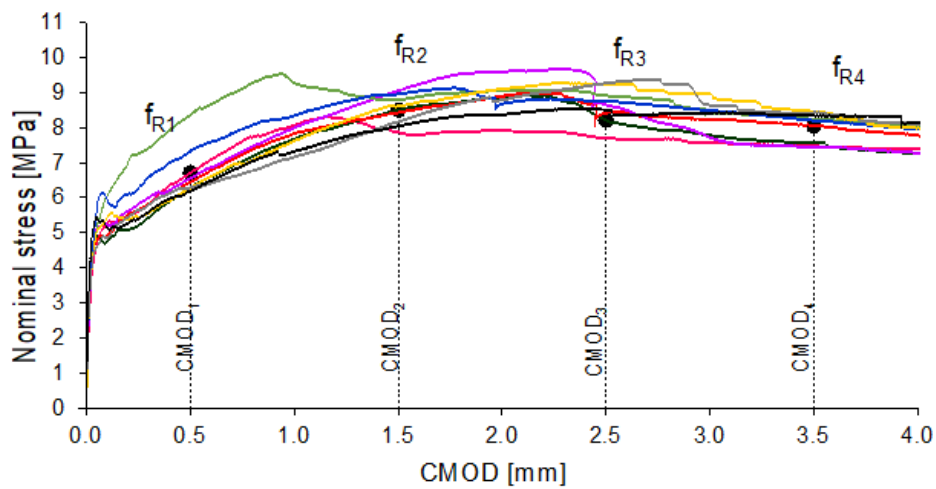


Figure 1: Curve load-deflection of the beam bending tests according to EN 14651 (Roma University Report).

	f _L [Mpa]	f _{R1} [MPa]	f _{R2} [MPa]	f _{R3} [MPa]	f _{R4} [MPa]
Beam_01	4.68	6.70	7.86	7.69	7.47
Beam_02	4.90	6.28	8.49	8.20	7.58
Beam_03	4.78	6.45	8.41	8.42	8.04
Beam_04	5.15	6.56	9.04	8.64	7.44
Beam_05	5.72	7.33	8.95	8.75	8.19
Beam_06	5.03	6.27	8.60	9.23	8.45
Beam_07	5.63	7.75	10.2	8.99	8.54
Beam_08	4.60	6.28	8.16	9.25	8.40
Beam_09	5.43	6.18	8.03	8.50	8.33
Average	5.10	6.64	8.64	8.63	8.05
Characteristic	4.30	5.58	7.26	7.65	7.19

Figure 2: Results of the beam bending tests according to EN 14651 mean and characteristic value (Roma University Report).

To dimension a steel fiber-reinforced concrete segment, a reference test methodology needs to be adopted for the characterization of performance. In addition to the mechanical performance, various properties of the FRC can be specified.

Since brittleness must be avoided in structural behaviour, fiber reinforcement can be used as substitution (even partially) of conventional reinforcement (at ULS), only if both the following relationships are fulfilled:

$$f_{R1k} / f_{Lk} > 0.4$$

$$f_{R3k} / f_{R1k} > 0.5$$

Where f_{Lk} is the characteristic value of the nominal strength, corresponding to the peak load (or the highest load value in the interval 0 – 0.05 mm), determined from the EN 14651 beam test.

It is recommended to realize 12 beams per dosage and concrete mix formula.

If fibres are used as the only reinforcement for final lining, hardening post-crack behaviour at section level (beam test) allow immediately:

Cracking control at SLS

Structural ductility (ULS)

The figure 1 shows the typical expected result considering FRC only as reinforcement. The performance class according to Model Code 2010 in this example is C40/50 5e FRC material, which means,

$$f_{R1k} > 5 \text{ MPa}$$

$$f_{R3k} / f_{R1k} > 1,3$$

Indeed, materials with f_{R1k} ranging from 4.0 MPa mini to 6.0 MPa are commonly used for precast tunnel segments without any bar reinforcement, combine with a f_{R3k} / f_{R1k} ratio in the ranges $1.1 < f_{R3k} / f_{R1k} < 1.3$ or $1.3 < f_{R3k} / f_{R1k} <$ (class d and e respectively, according to the Model Code 2010 definition).

3. CRACKING CONTROL: RETURN OF EXPERIENCE

Recent project has demonstrated that structural ductility, durability, and sustainability are going hand in hand. This holistic approach will be clearly a new booster for FRC tunnel lining.

The new recent breakthrough for major project as Grand Paris (200km) provide a detail return of experience.

The detailed return of experience includes type of Dramix® fiber selected, a robust testing campaign, from beam tests to full-scale segment tests under bending and concentrated loads. A detail crack with description at different load level underlying the FRC benefits.

An efficient and controlled feeding of the fibers into the dosing unit was developed for this purpose. A buffer was therefore set up upstream, allowing a pre-feeding in a single movement of 8 big bags at the beginning of the day (about 9 tons of fibers).

This device was supplemented by a triple weighing system of the quantity of fibers introduced into the mixer (doser, fiber reception belt and mixer feeding belt).



Figure 3: Dosing equipment installation specially design for glued fibre.

As regards durability, the requirement for conventional reinforcement cages was 100 years. However, comparative checks on the segments installed have shown that the fiber reinforced segments have a better crack control behaviour.

The use of fibers is perfectly suited to this type of geometry, especially since the cracking process generates finer cracks than the cracking process of a beam on two supports. In the case of tunnel lining segments, the final coating constitutes a hyperstatic mechanical system. This is a situation in which the fibers work perfectly.

Indeed, as only micro-cracks (≤ 0.2 mm) are observed and the segments work in compression when the ring is formed, they close-up automatically.

When the cracks are very fine, i.e. with crack openings not exceeding 0.5 mm, the fibers are much more efficient than reinforcement bars in acting on this cracking. This is simply because the diameter of the fibers is mechanically better suited to these cracks than the diameter of concrete reinforcement bars. It is a problem of coherence of scale, as Pierre Rossi reminds us (international expert on fiber concretes/Fiber Concretes Martialis Edition).

In effect, most steel fiber concretes are mechanically efficient up to crack openings not exceeding about 2 mm. Crack openings of between 1 and 2 mm, correspond, for the vast majority of cases, to the ultimate behavior of steel fiber concrete structures. Therefore, studying the durability of steel fiber concretes for crack openings around 1 mm can be considered as meaningless and seems unnecessary for the practice. Also noteworthy is the excellent corrosion behaviour of the fiber reinforced segments, linked to the small diameter of the fibers and their distribution.

4. EXAMPLE OF CARBON COUNTING: MONTREAL METRO

Among various construction processes, tunnel construction results in a significant amount of CO₂ emissions because almost all tunnels are lined with reinforced concrete and utilize various high energy consuming equipment for excavation. Embodied carbon and high energy consumption can be minimized through three distinctive ways. Two main complementary approaches can be adopted to mitigate embodied carbon and reduce high energy consumption. The first method includes decreasing the overall quantity of reinforced concrete utilized through design optimization. The second approach is lowering the embodied carbon within each unit volume of the reinforced concrete by reducing the usage of Portland cement and steel rebar. This can be established by substituting Portland cement in the concrete mix low carbon binder and rebars by steel fibre. Indeed, the total mass of CO₂eq is what we want to minimize from environmental product declaration and by decreasing the total mass of material.

Environmental Product Declaration (EPD) is a document that transparently communicates the key environmental performance indicators of a product over its lifetime. A third-party verification ensures that data relating to environmental aspects of Dramix® has been validated by an external organization. This declaration is the Type III Environmental Product Declaration (EPD) based on EN 15804:2012+A1 and verified according to ISO 14025 by an external auditor. It contains the information on the impacts of the declared construction materials on the environment. Their aspects were verified by the independent body according to ISO 14025. Basically, a comparison or evaluation of EPD data is possible only if all the compared data were created according to EN 15804:2012+A1.

The Montreal Metro Blue Line Extension Project consists of construction of 6km of tunnel, as well as five new underground stations. This represents a good example as well showing that durability and sustainability go hand in hand. Indeed, the reduction in segment thickness achieved with fibers can be primarily attributed to the concrete cover requirements of 60-75 mm on both intrados and extrados rebar to ensure the durability against corrosion when designing according to Canadian code CSA A23.1:19 (2019). In contrast, when subjected to chloride exposure, corrosion in steel fiber reinforced concrete is limited to just a few millimeters from the surface, and nonetheless, does not lead to spalling cracks and is not regarded as a durability issue. CO₂ savings in the segments is realized by replacing rebar with steel fibers as the quantity of steel required is 50% less per m³ of concrete with fibers (40 kg/m³ vs 80 kg/m³). Additionally, the CO₂ equivalent factor for rebar is reported to be 1.85 vs 0.88 for

fibers. The fiber reinforced segments can be reduced in thickness due to no requirement for cover like rebar. This quantity of concrete savings also lowers the carbon footprint.

The owners' design engineer, AECOM, as part of a commitment to integrating sustainability best practices, performed a study utilizing the Envision framework to evaluate alternatives to achieve a most sustainable infrastructure project. Based on the results of this study the TBM bored tunnel sections will be lined with steel fiber reinforced precast concrete segments using low-carbon Supplementary Cementitious Materials (SCM) concrete.

In the TBM tunnel sections lined with pre-cast concrete segments, high performance Dramix® steel fiber 4D80/60BGP with a dosage of 40 kg/m³ is designed as standalone reinforcement.

See below table summarizing the results of the evaluation showing a reduction in total CO₂ equivalent by nearly 50% using SFRC with an optimized SCM concrete mix design:

Table 1: Calculation of total embodied carbon footprint of the PLB tunnel segmental lining for the baseline and the optimized final designs.

Mix Design Component	CO _{2eq} Factor	Baseline Concrete Mixture (OPC) with Rebar			Optimized SCM Concrete Mixture with Steel Fiber		
		Mass (kg/m ³)	CO _{2eq} (kg/m ³)	% Replacement by Mass	Mass (kg/m ³)	CO _{2eq} (kg/m ³)	% Replacement by Mass
Portland Cement	0.92	475	437		346.8	319.056	
Slag	0.1466	0	-	0%	104.5	15.3	22%
Fly Ash	0.093	0	-	0%	0	0	0%
Silica Fume	0.014	0	-	0%	23.8	0.3	5%
Admixtures	1.67	4.5	7.5	1%	4.5	7.5	1%
Aggregate	0.006	1430	8.6		1430	8.6	
Steel bar	1.85	80	148		-	-	
Steel Fiber	0.92	-	-		40	36.8	
Total		Total	601.1		Total	387.6	

	Ring width (m)	Tunnel length (m)	D _{ex} (m)	D _{in} (m)	Ring Volume (m ³)	Total concrete volume (m ³)	CO _{2eq} /m ³ (kg)	CO _{2eq} /1 m tunnel (ton)	Total CO _{2eq} (ton)
40 cm Thick Segments	1.8	6000	9.4	8.6	20.4	67858	601.1	6.8	40,79
35 cm Thick Segments	1.8	6000	9.3	8.6	17.7	59046	387.6	3.8	22,886

5. NEW DEVELOPMENT TO MOVE FROM A PIECE OF STEEL TO A PEACE OF MIND FIBER REINFORCED PRECAST SEGMENT

Until now, the quality control of fibre-reinforced concrete (FRC) is performed in terms of the fibre content and post-cracking residual strength of the material. The former usually assessed according to the standard EN 14721:2006 (CEN, 2006), which consists of washing out and weighting the fibres present in a certain volume of fresh concrete.

This procedure takes around 45 minutes per test and requires the use of many litres of water. It may also be performed in hardened samples, thus requiring to completely crush a concrete sample, and afterwards to extract and weight the fibres present in that sample.

Consequently, it is a very expensive, time demanding and environment unfriendly destructive technique. All these disadvantages limit the number of tests that may be performed per day, thus compromising both the statistical representativeness of the results and limiting the effectiveness of the quality control system.

To overcome this disadvantages, the research group by Professor A. Aguado at the Polytechnic University of Catalonia (UPC-BarcelonaTech) developed the non-destructive magnetic induction test – the Inductive

Method – (Juan 2011; Torrents et al. 2012), that allows assessing the fibre content and orientation in FRC specimens using a method with reduced cost and in a matter of less than two minutes. This method is one of the main contributions of the research group to the field of systems to control and characterize FRC and it is based on the ferromagnetic properties of the steel fibres that are able to alter the magnetic field around them.

The inductive method represents a step towards an enhanced methodology for FRC characterisation given that it can be implemented in an easy and user-friendly way, which allows fast, repetitive and reproducible measurements in many concrete samples. This test provides an easier, more reliable and robust characterisation of the fibre content in FRC and is oriented to the optimization of a systematic quality control for FRC in terms of fibre content and orientation of the fibres.

The Dramix® eyeD Inspector is registered brand that encompasses a line of products for the assessment of material properties and structures.



Figure 4: Dramix® eyed Inspector

A huge testing program conduct by Roma University with the Extraction of 7 cores from 2 segments and 4 specimens for each core means 28 samples.

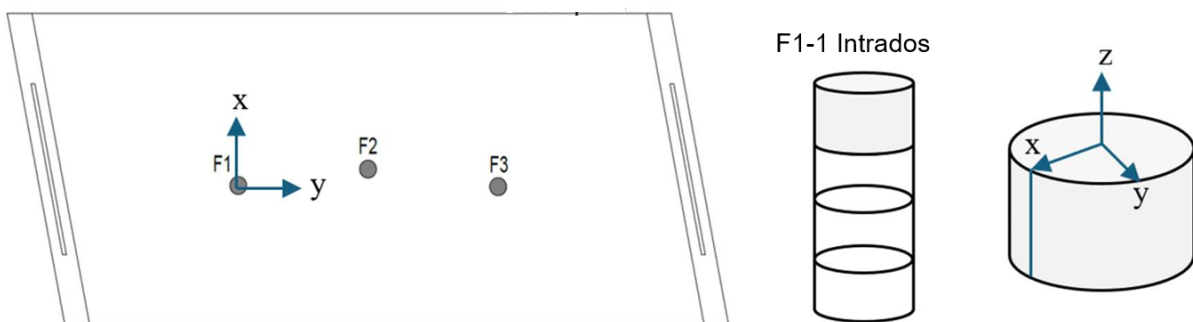


Figure 5: Specimen core from segment.

Dramix® eyeD Inspector device shows good sensitivity and can be considered a valid screening tool, but its accuracy strongly depends on the acceptance threshold adopted.

The Dramix® eye D Inspector device could be used with a lower margin than that indicated in Bulletin 83, and, if necessary, supported by destructive tests on specimens that exceed this threshold, in order to ensure compliance more reliably.

In addition to the technical aspects, the use of the inductive method offers significant economic, time-related advantages. The ability to perform checks without crushing the specimens allows for reduced costs, shorter verification times.

6. CONCLUSION

We all believe that tunnels should use smart and sustainable construction materials. The future of tunnelling is choosing these materials today. High-performance Dramix® steel fibre could play an important role in this final lining sustainable journey.

LITERATURE

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