Southeastern Europe Tunnelling Conference (SETC-2025)
1-3 October 2025, Belgrade, Serbia

DOI: 10.5937/SETC25008R

Design and construction of FRC tunnel precast segment with fibre enabled carbon footprint reduction

Benoit de Rivaz[a]*

[a] NV Bekaert, Zwevegem, Belgium; benoit.derivaz@bekaert.com

Abstract: The construction industry is a major producer of CO_2 emissions. The significant impact of the construction industry largely arises from the embodied carbon in the primary construction materials, cement and steel. 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 should pro-mote sustainable design. Fiber reinforcement plays a vital role in reinforcing concrete linings in underground structures and tunnels. This paper will explain how High-performance steel fiber reinforcement over rebar, combined with structural design optimization and the utilization of Supplementary Cementitious Materials (SCM) concrete mixture, the embodied carbon in the segmental lining and permanent spray concrete lining can be reduced by nearly 50%.

Over the past years the use of Fiber Reinforced Concrete (FRC) for finagling has increased dramatically. One aspect allows the boosting the use of FRC was the publication of guideline for FRC design: in 2012, the international Federation for structural concrete (fib) presented Model Code 2010 which include specification section on FRC. the Mode code 2020 just published has led to a successful and now widespread use of FRC in the final lining tunnelling with considerable benefits to owners, designers, and contractors. This paper will describe design principle and detail carbon counting from recent project around the world in Europe, Australia, North America and middle east.

Keywords: carbon counting; fibre-reinforced concrete

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 (Allen, 2021). 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 to develop solutions for low carbon lining.

*Corresponding author: benoit.derivaz@bekaert.com (Benoit de Rivaz).

Mechanical excavated tunnels (tunnels excavated with a TBM – Tunnel Boring Machine) are more and more used in Civil Engineering. In these tunnels, the lining is made by 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 recommendations 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 projects have 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. Sustainability and Structural Requirement

For a sustainable use of structural concrete, environmental and mechanical performance of concrete structures must have the same importance. By means of sufficiently high mechanical performances, the structural safety of a construction is ensured. At the same time, a low environmental impact guarantees sustainable development, which is, in accordance with the definition by the Brundtland Commission of the United Nations, a "development that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland Commission, 1987).

FRC acts on the tensile behaviour of cracked concrete and imparts ductility to fragile material. FRC's excellent properties which overcome cracking as well as its improved durability over reinforced concrete are why we continue to develop that material and explain its economic success. Life Cycle Assessment (LCA) is a methodology for assessing environmental impacts associated with all the stages of the life cycle of a product or process. It quantifies a material impact on the environment over its entire existence, from extraction of the raw materials required for its production up to its end of life. This approach, combined with research into a low-carbon solution, will give new momentum to FRC.

3. Basic FRC Behaviour

A minimum tensile (strength) strength > 2200 MPa is recommended for final lining application considering the performance required and concrete classes.

The hooked ends ensure the desired fiber pull-out. This is the mechanism that generates the renowned concrete ductility and post-crack strength.

The tensile strength of a steel fiber has to increase in parallel with the strength of its anchorage. Only in this way can the fiber resist the forces acting upon it. Otherwise, it would snap, causing the concrete to become brittle. On the other hand, a stronger wire cannot be fully utilized with an ordinary anchor design. Therefore, the tensile strength of a fiber has to be perfectly aligned with its anchorage system and its diameter.

Wire ductility and concrete ductility are two different aspects. Dramix® 4D steel fibers create concrete ductility by the slow deformation of the hook during the pull-out process, and not by the ductility of the wire itself. The network provides by the fibre get a fundamental importance. Recommended diameter is 0.75mm and l/D= 80 to ensure a network > 10km/m^3 with 40kg/m^3. This network will play a key role in cracking control, structural ductility and allow low dispersion in the result.

Table 1. Influence of the l/D ratio on the network effect.

l/D	80/60	65/60	45/50
Length (mm)	60	60	50
Diameter (mm)	0.75	0.90	1.05
Aspect Ratio	80	65	45
Network (m/kg)	276	200	147

4. Design Principle

Model Code 2010 is the most comprehensive code on concrete structures. It covers their complete life cycle from conceptual design, dimensioning, construction, and conservation through to dismantlement. It is edited by fib Model Code 2010 and was produced through the exceptional efforts of participants in 44 countries from five continents. The fib bulletin 83 document aims to support designers, contractors and clients with guidance for the use of steel fibre-reinforced concrete, known as FRC, in precast segmental lining tunnels constructed using tunnel boring machines (TBMs) The document is intended to complement the fib Model Code 2010 (MC2010), which presents a section on the design of FRC, with the Model Code 2010 being considered as the reference basis for the design of FRC segmental lining.

Fig. 1. Design process.

The tensile behavior of the materials was characterized by performing bending tests on a notched beam. The tests were performed according to the EN 14651 European code, which is the reference standard for the CE label of steel and for ISO certification.

The compressive strength of the materials was measured by a testing cube with a side of 150 mm. For every cast made to produce every single segment, three beams were produced. In agreement with EN

14651, nominal strengths corresponding to four different crack mouth opening displacement (CMOD), namely 0.5, 1.5, 2.5 and 3.5 mm, were evaluated.

.

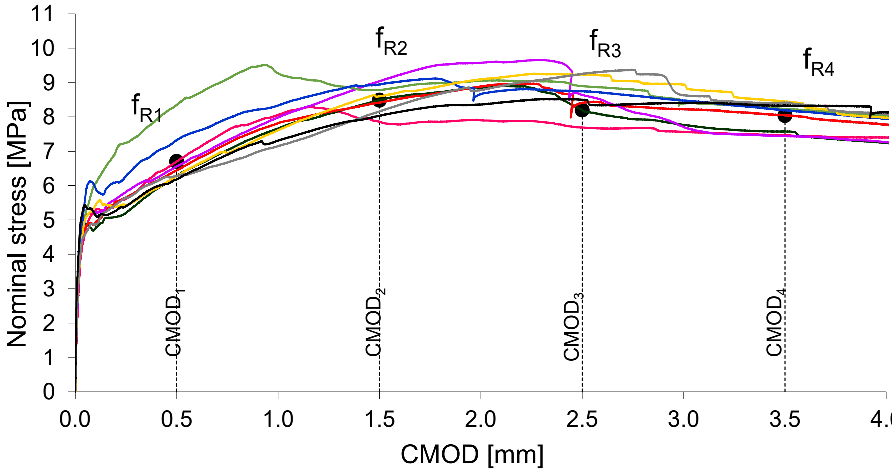

Fig. 2. Curve Load -deflection of the beam bending tests according to EN 14651. (Roma University Report).

Figure 2 and Table 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, fR1 and fR3 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

Table 2. Results of the beam bending tests according to EN 14651 mean and characteristic value (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

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 behavior, fiber reinforcement can be used as substitution (even partially) of conventional reinforcement (at ULS), only if both the following relationships are fulfilled:

- fR1k/ fLk > 0.4
- fR3k / fR1k > 0.5

Where fLk 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 behavior at section level (beam test) is allowed immediately:

- Cracking control at SLS
- Structural ductility (ULS)

The figure 2 how 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,

- Fr1k> 5MPA
- Fr3k/fr1k> 1,3

Indeed, materials with fR1k ranging from 4.0 MPa mini to 6.0 MPa are commonly used for precast tunnel segments without any bar reinforcement, combine with a fR3k / fR1k ratio in the ranges 1.1 < fR3k / fR1k < 1.3 or1.3 < fR3k / fR1k < (class d and e respectively, according to the Model Code 2010 definition).

5. Carbon Counting

Among various construction processes, tunnel construction results in a significant amount of CO_2 emissions because almost all tunnels are lined with rein-forced 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 $C0_2$eq is what we want to minimize from environmental product declaration and by decreasing the total mass of material.

Table 3. CO_2 eq Factors from EPDs For Each Mix Design Component.

Mix Design Components	Portland Cement	Slag (GGBS)	Fly Ash	Silica Fume	Admixture	Aggregate	Rebar	Steel Fiber
CO_{2eq} Factor (kg CO_{2eq})	0.92	0.1466	0.093	0.014	1.67	0.06	1.85	0.7

An 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 ex-ternal auditor. It contains information on the impact 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 environmental impact of Dramix® product (cradle to gate with options) is largely dependent on the energy intensive production of steel (half product) on which the manufacturer has only a limited influence. The carbon impact of steel production (Wire Rods) in the product stage A1 is as high as 85%. The impact of the production line largely depends on the amount of electricity consumed by manufacturing plant (0.34 kWh/kg of product). There are no significant emissions or environmental impacts in the A3 production processes alone (partly gas combustion). The production process itself does not have significant environmental impacts in the life cycle.

6. Low Carbon Precast Segment Case Studies

6.1. Grand Paris

The use of steel to replace all or a part of conventional reinforcement has been demonstrated to lower the embodied CO_2 of the segmental lining. While it is possible to significantly reduce the embodied CO_2 of a concrete mixture for segment production by replacing a portion of its cement content with alternative cementitious materials, there is little or no difference between the cementitious blends and contents required to produce fiber reinforced or conventionally reinforced concrete segments for tunnel linings.

Figure 3 shows an example reduction in CO_2 emissions on a project made possible by modification of the concrete and further reduction by being able to replace the rebar with steel fibers in a dosage that satisfied all the design requirements. On a per pound (kg) basis the embodied CO_2 of conventional rebar and steel fibers is assumed to be the same. This is a generalization assuming the wire rod that the fiber is produced from, and the rebar has similar % recycled material content and similar steel production methods. In a precast segment the reduction in carbon footprint is due to the steel fibers being more efficient in reinforcing the element. In this example the elimination of the right binder and steels fibre could conduct to a reduction of 70%.

Fig. 3. Project jobsite Grand Paris, photo credit by Eiffage Génie Civil.

The recent project for the Grand Paris Linea 16.1 has shown the following:

- From the saving in the ratio of fibers compared with steel reinforcement bars, leading to a significant reduction in CO_2 emissions during transportation. If we compare 85kg/m3 for steel reinforcement bars with the 40kg/m^3 for fibers, we get a saving on materials of more than 50%.
- By the benefit of better optimized loading for the fibers. 22 big bags of 1,100/kg per truck = 24.2 tons per load for the delivery of the fibers in comparison with 60 equivalent segments per truck = 17.85 T for the de-livery of the concrete reinforcement bars.
- From the small diameter of the fibers which helps to further limit toxic emissions from the primary steel industry, due to primary coils which do not exceed 1 mm of wire diameter. The drawing technology is low emission.
- Fewer trucks on the road and optimized waste management in a large city like Paris is an important element to take into account. From an ecological point of view, the carbon balance is therefore very positive. In this respect, Bekaert has recently obtained its EPD (Environmental Product Declaration) Type III ITB certificate number 215/2021.
- The concrete chosen for Line 16 Lot 1 fibre reinforced segments has a low carbon footprint of 170kg CO_2 equivalent/m^3 and reduces the carbon weight of the steel in the segments by 90kg equivalent CO_2/m^3 or nearly 11,000 tons equivalent CO_2 per 10km.

In terms of concrete, there will be a before and after Grand Paris Express. Until now, to design the segments, we used reinforced concrete, that is to say concrete poured around cages of massive metal reinforcements.

The graph hereunder illustrates the main impact gain in terms of carbon emission for typical precast segment ring used for a Metro tunnel.

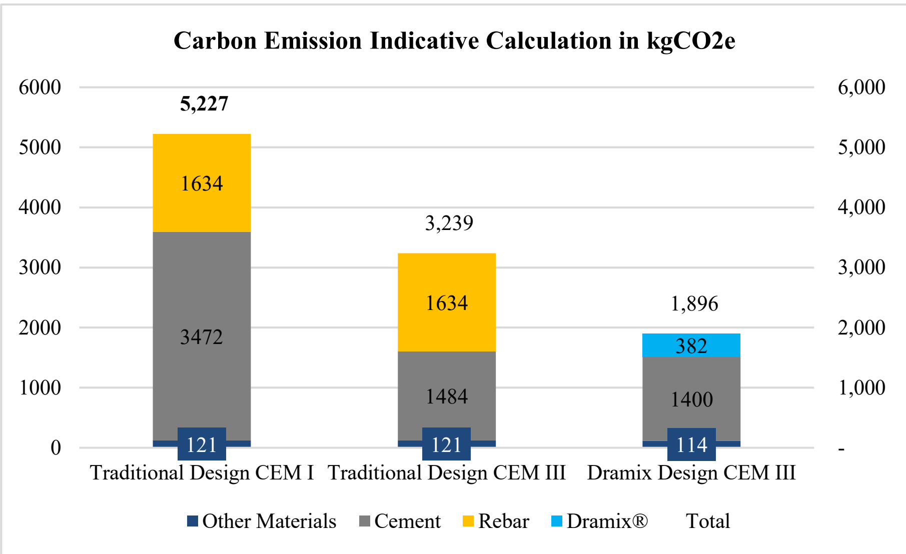

Fig. 4. Typical metro project, precast segment carbon emission counting.

This example, Fig. 4 is based on the following assumption.

- Using CEM III vs CEMI improves the CO_2 score significantly.
- As we use 60% less reinforcement (100kg rebar vs 40 kg Dramix®) and also average rebar EPD is higher than Dramix® EPD, we end up with this difference with reinforcement.
- Using FRC allows thickness reduction by 2cm mini which results in additional savings in concrete.
- Thickness 38 cm.

6.2. Middle East Journey

A paper by consultant COWI Denmark entitled 'Consultant's view of durable and sustainable concrete tunnel constructions in the Middle East" WTC 2018 Dubai provides this example how much CO_2 emission saving was reached by replacing traditional concrete and steel-reinforced with steel fiber reinforcement and adding GBBS/FA to the concrete mix. provides an example of reduction of concrete and further reduction by being able to replace the rebar with steel fibres in a dosage that satisfied all the design requirements.

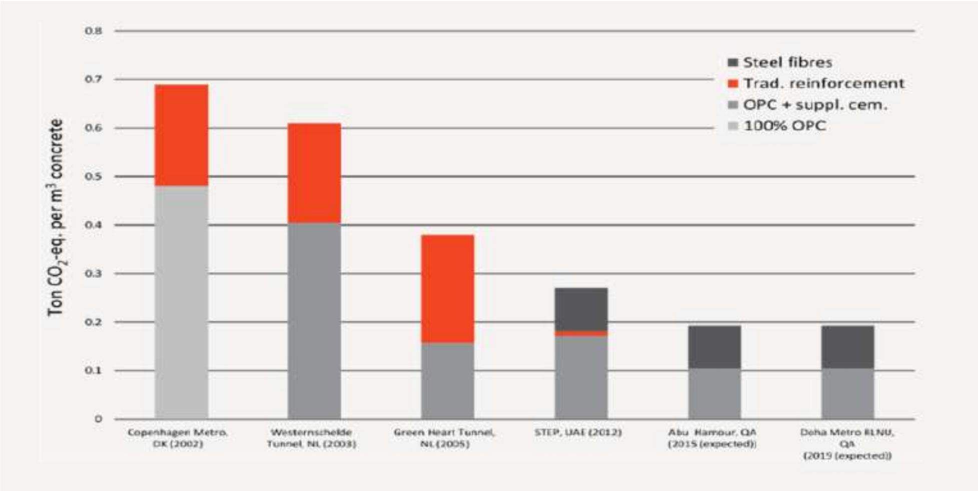

Fig. 5. Evolution of Precast segment lining (Cowi /C.Edvarsen publication WTC 2018).

This project as Doha Metro Green line has been designed with FRC using Dramix® fibre based on MC2010 to meet some specific condition:

- Very high chloride content: 10,000 - 50,000 mg/l
- High sulphate content: 100 – 5,500 mg/l
- High soil temperature: 28 - 32°C

Main advantages

- Increased resistance to chloride-induced corrosion
- Eliminated risk of stray current-induced corrosion
- Easier production/handling
- Simplified segment precasting process

This return of experience in Middle East demonstrates that by using FRC in-creased resistance to chloride-induced corrosion and reduced carbon footprint. Durability and sustainability go hand in hand.

6.3. The Montreal Metro Blue Line Extension Project

The Montreal Metro Blue Line Extension Project consists of construction of 6 kilometers of tunnel, as well as five new underground stations. This represents a good example showing that durability and sustainability goes 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. CO_2 savings in the segments are realized by replacing rebar with steel fibers as the quantity of steel required is 50% less per m3 of concrete with fibers (40 kg/m^3 vs 80 kg/m^3). Additionally, the CO_2 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 the table below summarizing the results of the evaluation showing a reduction in total CO_2 equivalent by nearly 50% using SFRC with an optimized SCM concrete mix design.

Table 4. Embodied carbon in unit volume for the baseline and the optimized final mix designs.

		Baseline Concrete Mixture (OPC) with Rebar			**Optimized SCM Concrete Mixture with Steel Fiber**		
Mix Design Component	**CO_{2eq} Factor**	**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**	

Table 5. Embodied carbon in unit volume for the baseline and the optimized final mix designs.

	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 SCM w/ Fiber	1.8	6000	9.3	8.6	17.7	59046	387.6	3.8	22,886

6.4. The Forrestfield Airport Link

"The Forrestfield airport link is a "design and construct" type of project; it will deliver an 8.5 km extension of the existing PTA urban rail network in Perth, Western Australia, connecting the Midland Line, just past Bayswater Station, to Forrestfield. The twin-bored tunnels will travel underneath the Swan River, Ton-kin Highway and Perth Airport. The project will include three new stations; Recliffe Station (located underground in Redcliffe), Airport Central Station (located underground at Perth Airport to service both domestic and international terminals) and Forrestfield Station. The tunnel excavation diameter is 7,100 mm; the segmental lining has an inside diameter of 6,170 mm, and thickness of segment is 300 mm with an average length of 1,600 mm".

The segmental lining was designed to meet the project's concrete requirements of 120-year service life with a minimum water/binder ratio of 0.35. This article draws its attention to the specific concrete mix design from the design up to the construction phases of the precast segmental linings.

Several trials were performed with cast concrete beams according to standard BS EN 14651 (single trial was made with #9 concrete beams) with 35 kg/. The characteristic values of these results were more than the serviceability state 5.08 MPa at CMOD1 and 5.28 MPa at CMOD3. The results have confirmed the assumptions for the quantity reduction and the mix with 35 kg/m3 of Dramix® 4D 80/60BGP steel fibres content was adopted in project work.

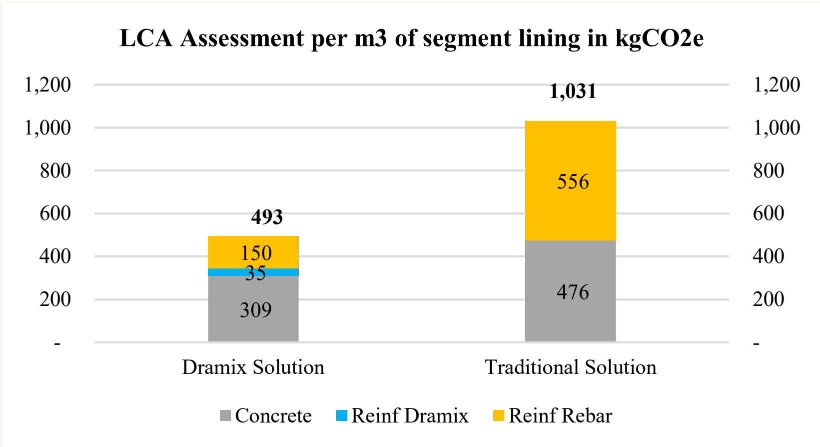

Fig. 6. One Click LCA calculation.

7. Conclusion

There has been a trend in the last years that concrete tunnel linings have increased material consumption, cost, and environmental loads. Nowadays develop and/or improve tunnel construction methodology to choose the optimal tunnel lining, including environmental footprint and cost-effectiveness. Create required knowledge to produce final lining to meet new large infra-structure projects with modern demands to functionality incl. 100-year service life and environmental impact.

The use of steel fibre reinforced concrete will highly participate in meeting low carbon lining by concrete consumption and steel reinforcement saving. If ductility-ty and durability have been the key words in the last 40 years, sustainability will be the key driver for further FRC lining development in the coming years.

Indeed, a new generation of binder combined with FRC allows new achievement:

- Provide excellent long-term durability performance exceeding that of Portland cement-based concrete.
- Excellent long-term durability performance exceeding that of Portland cement-based concretes. Extremely low embodied carbon footprint compared to conventional concretes on Port-land cement.
- Compared to reinforced concrete, fiber-reinforced concrete notably rep-resents savings of around 5,000 tons of steel for 10 kilometers of tunnels (Typical Metro Tunnel).

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

References

Allen, C., 2021. Low Carbon Concrete/rules of the thumb. *T&T Journal*.

Brundtland Commission. 1987. Our Common Future. Report of the World Commission on Environment and Development, 1987. United Nations World Commission on Environment and Development. Published as Annex to General Assembly document A/42/427.

EN 14651. 2005. Test Method for metallic fibre concrete. Measuring the flexural tensile strength.

April 2022. *A leap forward for SFRC segmental linings in France*, Tunnel Tech.

Edvardsen, C., 2010. The consultant's view on service life design, WTC Congress, COWI A/S, Paral-lelvej

FIB. 2010. *Model Code 2010 – First complete Draft*. Bulletin 55-56.

Forrestfield airport link project in Perth, Western Australia -Precast concrete segmental lining. S.C. Scaffidi, Salini Im-pregilo S.p.A., Milano, Italia now e Build Spa &A. Anders, S. Porto & E. Torres SI-NRW JV, Redcliffe, Perth, *Western Australia published in WTC 2019*.

ITB. 2021. *EPD – Environmental Product Declaration Type III ITB No. 215/2021.*

ITA TECH. 2024. *Low Carbon Lining*. Guideline N°35.

October 2017. *Precast tunnel segments in fibre reinforced concrete fib bulletin 83*.

Verya Nasri, Medhi Bakshi, 2023. Design and Construction of FRC Tunnel Segments in North America with Fiber-Enabled Carbon Footprint Reduction. fib ACI 2023.