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Variable density

Herrenknecht's switchable machine

MOVING TO LOW-CARBON LININGS

Benoit de Rivaz of Bekaert claims the inclusion of steel fibres into precast tunnel segments can lead to significant reductions in the CO_2 emissions of tunnel linings

Scientists have shown that human-generated emissions of greenhouse gases (primarily CO_2) from fossil-fuelled power supplied to industrial processes and fossil-fuelled vehicles, are the primary contributors to the dramatic rise observed in the Earth's temperature since the 1950s.

Although the consequences of climate change are difficult to predict, it is clear that the rapid increase in the Earth's temperature will bring about detrimental impacts to future generations. It is increasingly evident that we must act to reduce manmade levels of CO_2 emissions into our atmosphere. To be considered a sustainable project today, design engineers are required to make conscious efforts to reduce carbon footprints, as well as provide for a minimum service life of the structures they are designing.

Concrete is recognised as the second most widely consumed commodity on the planet after water. It also contributes around 8% of global carbon emissions; the main source of these emissions is the manufacture of Ordinary Portland Cement (CEM I).

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

This is why a great challenge for the coming years will be to develop solutions for low-carbon linings. Recent projects have demonstrated that structural flexibility, durability and sustainability go hand in hand, and this combined approach will clearly constitute a new boost for FRC tunnel linings.

HISTORY

Steel fibre-reinforced concrete (SFRC) was introduced to the European market in the mid-1970s. No standards or recommendations were available at that time and this was a major obstacle for the acceptance of the new technology. Since then, SFRC has been applied to many different construction applications, such as tunnel linings, mining, floors on grade, floors on piles and prefabricated elements – to name but a few.

In the beginning, steel fibres were used to substitute as secondary reinforcement, or for crack control in less critical construction components. Nowadays, steel fibres are widely used as the main and unique reinforcement for industrial floor slabs and prefabricated concrete products. Steel fibres are also considered for structural purposes, helping to guarantee performance and durability in:

- Foundation pile reinforcement
- Reinforcement of slabs on piles
- Full replacement of standard reinforcing cages for tunnel segments
- Reinforcement of concrete cellars and slab foundations
- Steel fibres as shear reinforcement in pre-stressed construction elements.

This evolution to structural applications was mainly the result of progress in SFRC technology, as well as the research undertaken at universities and technical institutes in order to understand and quantify the material properties. In the early 1990s, design recommendations for steel fibre-reinforced concrete started to be developed.

Since October 2003, recommendations for Rilem TC 162-TDF have been available for steel fibre-reinforced concrete design[1] .

Over recent years, the use of this technology has increased dramatically. One aspect boosting the use of Fibre Reinforced Concrete (FRC) was the publication of guidelines for FRC design: in 2013, the International Federation for Structural Concrete (fib) presented Model Code 2010[2] which included a specific section on FRC.

The use of FRC offers several advantages, compared to traditional steel mesh or steel bar reinforcement:

- It can facilitate remote working from the face to enhance workforce safety and may remove the need for traditional reinforcement.
- Provides crack control and a small enhancement of concrete's tensile properties
- Is less prone to carbonation and chloride attack
- Brings cost reductions and time savings
- Uses less material (by minimising the amount of steel and concrete cover required).

SUSTAINABILITY AND STRUCTURAL REQUIREMENT

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

Fibre reinforcement acts on the tensile behaviour of cracked concrete and imparts ductility to a fragile material. FRC's excellent properties overcome cracking, and its improved durability over conventionally-reinforced concrete are why we continue to develop the material and highlight its economic success.

Lifecycle assessment (LCA) comprises a set of standardised data which quantify a material's environmental impact over its entire existence, from extraction of raw materials up to the end of its life. This approach, combined with research into a low-carbon solution, will give new momentum to FRC.

Bekaert's global sustainable development strategy is based on four major pillars: our responsibility in the workplace; in the market; to the environment; and to the society in which we operate. For example, Bekaert is providing its expertise and support to the innovative Cargo Sous Terrain (CST) underground cargo logistics initiative in Switzerland. In reality, CST is just reinforcing and systematising the aspects of sustainability which are already inherent in the system. Apart from the fact that CST provides a zero-emissions delivery route which is climate neutral, a work group is also already making preparations for construction in accordance with recognised sustainability standards.

BASIC FRC BEHAVIOUR

A minimum tensile strength greater than 1,800MPa is recommended for final lining applications, considering the performance required and the concrete class.

The hooked ends of fibres ensure the desired fibre pull-out. This is the mechanism that generates concrete's renowned ductility and post-crack strength. Bekaert's Dramix 4D steel fibres use the same principle, and this translates into an improved anchorage and ductile behaviour.

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. Otherwise it would snap, causing the concrete to become brittle. On the other hand, a stronger wire cannot be fully used with an ordinary anchor design. Therefore the tensile strength of a fibre has to be perfectly aligned with its anchorage system and its diameter. Dramix 4D is designed to capitalise on the wire strength to the maximum degree.

Wire ductility and concrete ductility are really two different aspects. Dramix 3D and 4D steel fibres create concrete ductility by the slow deformation of the hook during the pull-out process, and not by the ductility of the wire itself.

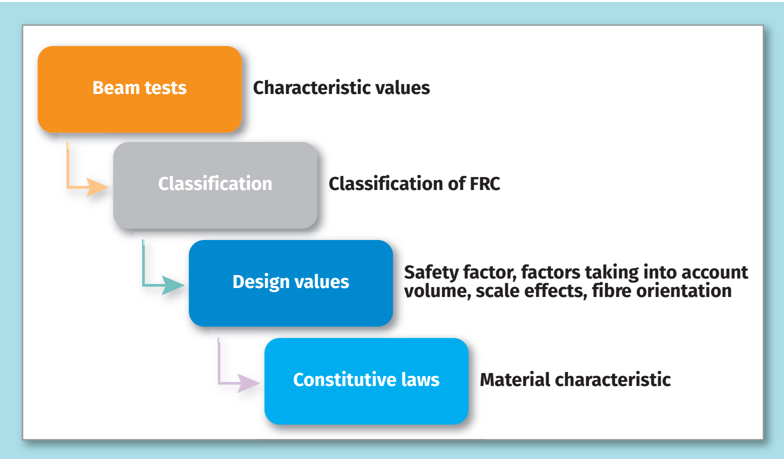
EPD CERTIFICATE

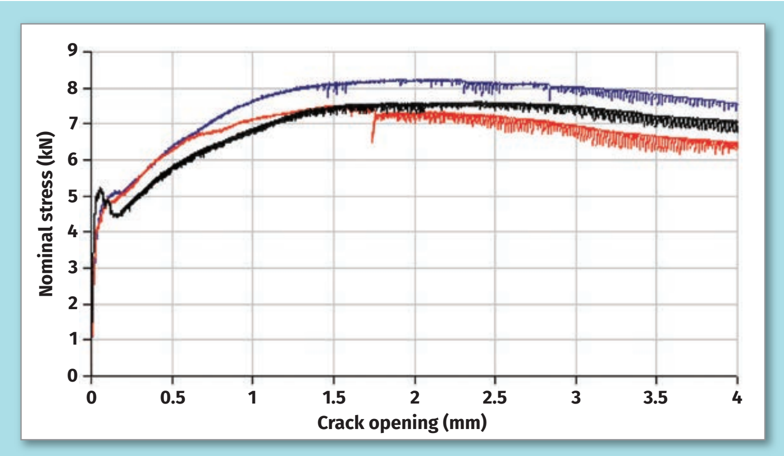
An Environmental Product Declaration (EPD) is a document that transparently communicates the key environmental performance indicators of a product over its lifetime. A third-party verification ensures that data relating to environmental aspects of Dramix have been validated by an external organisation

This declaration is the Type III 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[3] .

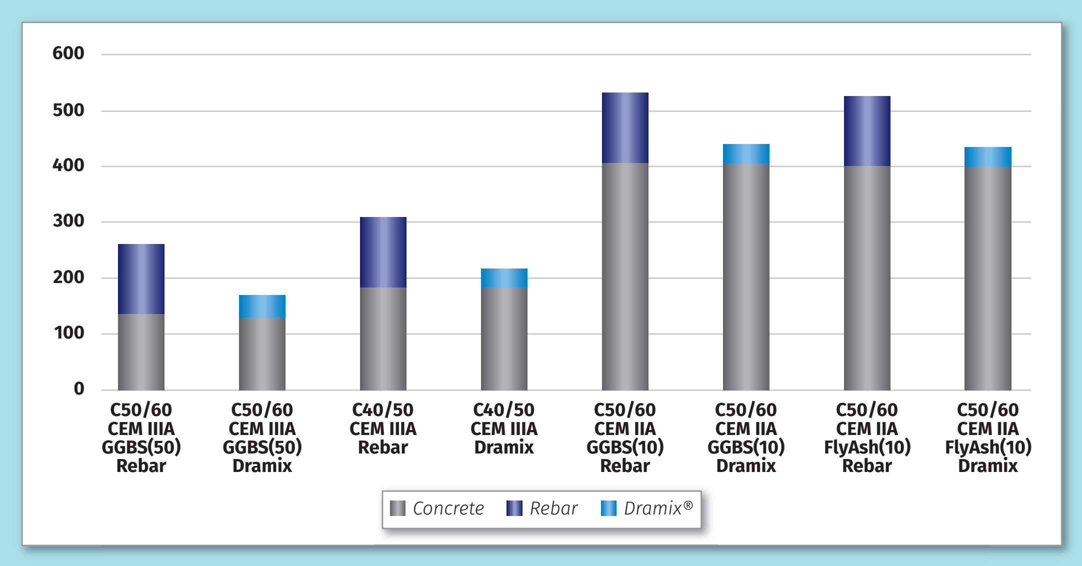
The environmental impact of Dramix product (cradle-to-gate with options) is largely dependent on the energy intensive production of steel (half product) on which the manufacturer has only a limited influence. The carbon impact of steel production (wire rods) at the product stage A1 is as high as 85%. The impact of the production line largely depends on the amount of electricity

Below, figure 1: Design process





Above, figure 2: Typical results of beam tests of FRC according to EN14651 using 40kg/m³ Dramix 4D80/60BG



Right, figure 3: CO_2 emission comparison

consumed by the manufacturing plant (0.34kWh/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 on the life cycle.

Interrogation of the life cycle assessment (LCA) results show that the cradle-to-gate carbon (Global Warming Potential) impact of 1kg of fibre production is 0.88kg CO_2 equivalence. For comparison, a ton of steel produced worldwide in 2019 emitted on average 1.85tons of CO_2.

The LCA results show that the cradle-to-gate primary energy demand of fossil fuel is equal to 9.4MJ. This is equivalent to the nuclear energy produced by the Czech Republic. The transport of raw materials across considerable distances is optimised and not significant (0.007kg CO_2/kg).

Above, figure 4: Grand Paris project jobsite PHOTO: EIFFAGE GÉNIE CIVIL

DESIGN PRINCIPLE

Model Code 2010 is the most comprehensive code on concrete structures. It covers their complete lifecycle, from conceptual design, dimensioning, construction and conservation, through to dismantlement. It is edited by fib (Fédération Internationale du Béton (International federation for structural concrete)). fib Model Code 2010 was produced through the exceptional efforts of participants in 44 countries across five continents.

Figure 1 below illustrates the design process involved, from beam tests, classification, design values, and constitutive laws.

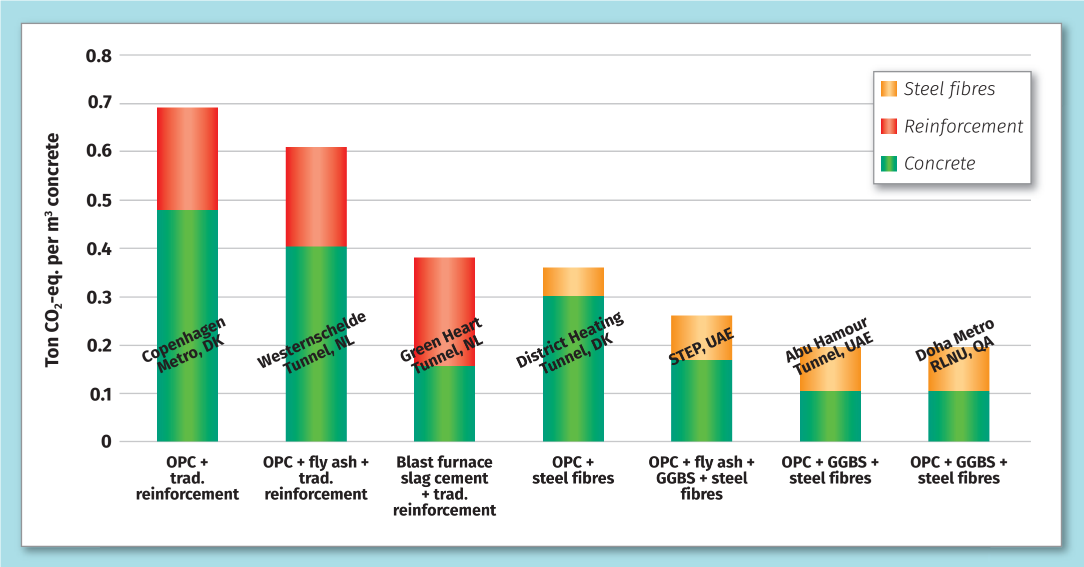
The tensile behaviour of the materials was characterised by performing bending tests on a notched beam. The tests were performed according to the EN 14651 European code, which is the reference standard for the CE label of steel and for ISO certification.

The compressive strength of materials was measured by a test cube with 150mm sides. For every cast made for the production of every single segment, three beams were produced. In agreement with EN14651[4] , nominal strengths corresponding to four different crack-mouth opening displacements (CMOD), namely 0.5mm, 1.5mm, 2.5mm and 3.5mm, were evaluated.

Figure 2 shows a typical beam test result with significant strength values. FL is peak force, fR1 and fR3 are the stresses related to CMODs equal to 0.5mm and 2.5mm respectively. These values are the reference ones for final lining design performed according to the fib Model Code 2010 prescriptions.

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

Since brittleness in structural behaviour must be avoided, fibre reinforcement can be used as a substitute (even partially) for conventional reinforcement (at ULS),



Left, figure 5: Comparison of embodied CO_2 for different types of binder and steel reinforcement used for major infrastructure projects (Edvardsen et al)

only if both the following relationships are fulfilled:

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

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

In the above, f_{Lk} is the characteristic value of the nominal strength, corresponding to the peak load (or the highest load value in the interval 0 – 0.05mm), determined from the EN14651 beam test. It is recommended to achieve 12 beams per dosage and concrete-mix formula.

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

- Cracking control at SLS
- Structural ductility (ULS).

PRECAST SEGMENTS

The use of steel to replace all or part of conventional reinforcement has been demonstrated to lower the embodied CO_2 of a segmental lining. While it is possible to significantly reduce the embodied CO_2 of a concrete mix 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 the contents required for the production of fibre-reinforced or conventionally-reinforced concrete segments for tunnel linings.

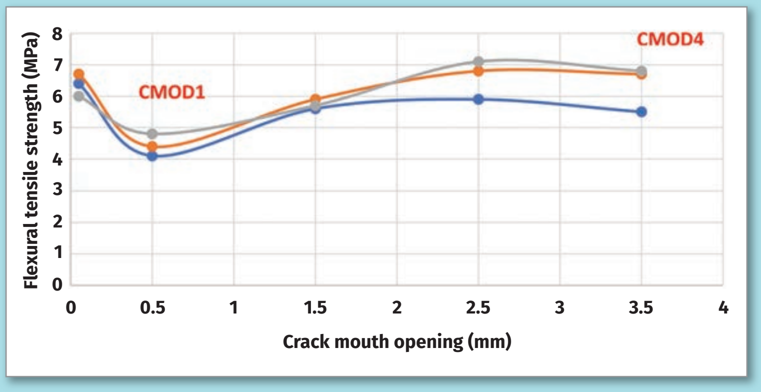
Figure 3 shows example reductions in CO_2 emissions on a project with modified concrete, with further reductions achieved by replacing rebar with steel fibres in dosages that satisfied the design requirements.

On a per pound (kg) basis, the embodied CO_2 of the conventional rebar and steel fibres is assumed to be the same. This is a generalisation, assuming the wire rod that the fibre is produced from and the rebar have similar percentage recycled material content and similar steel production methods. In a precast segment, the reduced carbon footprint is due to steel fibres being more efficient in reinforcing the element. In this example, the elimination, the combination of the right binder and the steel fibres could lead to a reduction of 70% .

The recent project for the Grand Paris Line 16.1 has demonstrated the following:

- Savings in the ratio of fibre compared to 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/m³ for fibre, we get a saving on materials of more than 50%.
- Benefits from better optimised loading of fibres. A total of 22 big bags of 1,100/kg per truck equals 24.2t per load for the delivery of fibres, compared to 60 equivalent segments per truck = 17.85t for the delivery of concrete rebar.
- Benefits arise from the small diameter of fibres which helps to further limit toxic emissions from the primary steel industry, due to primary coils which do not exceed 1mm of wire diameter. The drawing technology is itself low emission.
- Fewer trucks on the road and optimised waste management in a large city like Paris are important considerations. Ecologically, the carbon balance is therefore very positive. In this respect, Bekaert has recently obtained its Environmental Product Declaration (EPD) Type III ITB certificate number 215/2021.

In terms of concrete, there will be a 'before' and 'after' Grand Paris Express. Until now, we used reinforced concrete to design segments, that is to say, concrete poured around cages of massive metal reinforcement. Since 2020, on line 16.1, around 4km of tunnel have been designed in FRC, and a much larger deployment is now planned given the latest contracts awarded. This scale of deployment is rare in the transport infrastructure sector in France.



Above, figure 6: EFC Geopolymer Concrete beam test at 145 days of age
(CHARLES ALLEN)

BENEFITS AT ALL LEVELS

FRC consumes less steel and saves resources. As its name suggests, reinforced concrete is reinforced by a steel frame which necessitates large quantities of steel, "around 100kg of steel for 1m³ of concrete", declares Alex Moubé, head of the low-carbon mission at the Greater Paris Society. The FRC option consumes twice less steel for the same performance. It takes 40kg of steel fibre for 1m³ of concrete for Line 16.1 thanks to Dramix 3D 80/60BGP. Steel consumption is half and 5,000t of steel are saved over a 10km stretch of tunnel – achieving substantial cost savings in the process. In terms of resources, the reduced quantity of fibre-reinforced concrete can reduce segment thicknesses by between 20mm-30mm.

In addition to the quantities of steel and concrete saved, FRC also makes it possible to reduce CO_2 expenditure, both in cement plants and in steelworks: 10,000t of CO_2 are saved on average for 10km of tunnels compared to conventional reinforced concrete.

That is not all. Fibre-reinforced concrete also improves the technical performance of structures. Fibres give segments better crack performance. Not only are the cracks less important than for reinforced concrete, but they also close over time. Similarly, the segments are more resistant to corrosion. It is well known that steel, in contact with air and water, corrodes. Fibres are dispersed within the cementitious matrix, so if a fibre is corroded, it will not spread its corrosion to the other fibres. This means that a much more durable material will result.

A paper by Carola Edvardsen of Cowi Denmark entitled 'The consultant's view on service life design'[5] provides an example reduction of concrete and a further reduction by replacing rebar with steel fibres in a dosage that satisfied all the design requirements.

In a recent paper, Charles Allen (OTB Consulting) refers to the case for using Earth Friendly Concrete (EFC) geopolymer concrete in segmental tunnel linings[6].

"The incorporation of EFC geopolymer concrete is considered to be an action that could be undertaken in the manufacture of reinforced concrete tunnel lining segments. EFC is able to provide significant reductions in the embodied carbon footprint of tunnel linings, estimated to be of the order 210kg/m³ of concrete – approximately 1.8 tonnes of embodied CO_2 per linear metre of a typical rail tunnel. Additionally, when casting EFC in segment moulds on a carousel system, the curing chamber temperature is able to be reduced to around 30°C, thereby reducing energy consumption and associated carbon emissions. The final costings and environmental benefits of the use of EFC in tunnel linings could be quantified by conducting full-scale production trials with the segment manufacturer."

CONCLUSION

Recent years have seen concrete tunnel linings consume more material, incur increased costs and apply more loads on to the environment. Today, improved tunnel construction methodology allows the creation of optimal tunnel linings, with better environmental footprints and cost effectiveness. The know-how exists to enable production of final linings that meet the demands and functionality of modern, large infrastructure projects with a 100-year service life and improved environmental impact.

The use of steel fibre-reinforced concrete will contribute to meeting low-carbon requirements by reducing the quantities of concrete and steel reinforcement used. If ductility and durability have been the key words these past 40 years, sustainability will be the key driver for the further development of FRC linings over the coming years.

The new generation of binders combined with FRC provides:

- Excellent long-term durability, exceeding that of Portland cement-based concretes
- Extremely low embodied-carbon footprint compared to conventional concrete or Portland cement
- For a 10km length of typical metro tunnel in reinforced concrete, fibre-reinforced concrete can represent savings of around 5,000t of steel.

REFERENCES

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- 2 FIB 'Model Code 2010 – First complete Draft', 2010, Bulletin 55-56.
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- 4 EN 14651 'Test Method for metallic fibre concrete. Measuring the flexural tensile strength'. 2005
- 5 Edvardsen, C. 'Consultant's view on service life design', WTC Congress, COWI A/S, Denmark. WTC Congress.
- 6Allen, C. 'Low Carbon Concrete', Tunnels and Tunnelling International, Nov 2021, pp28-33.