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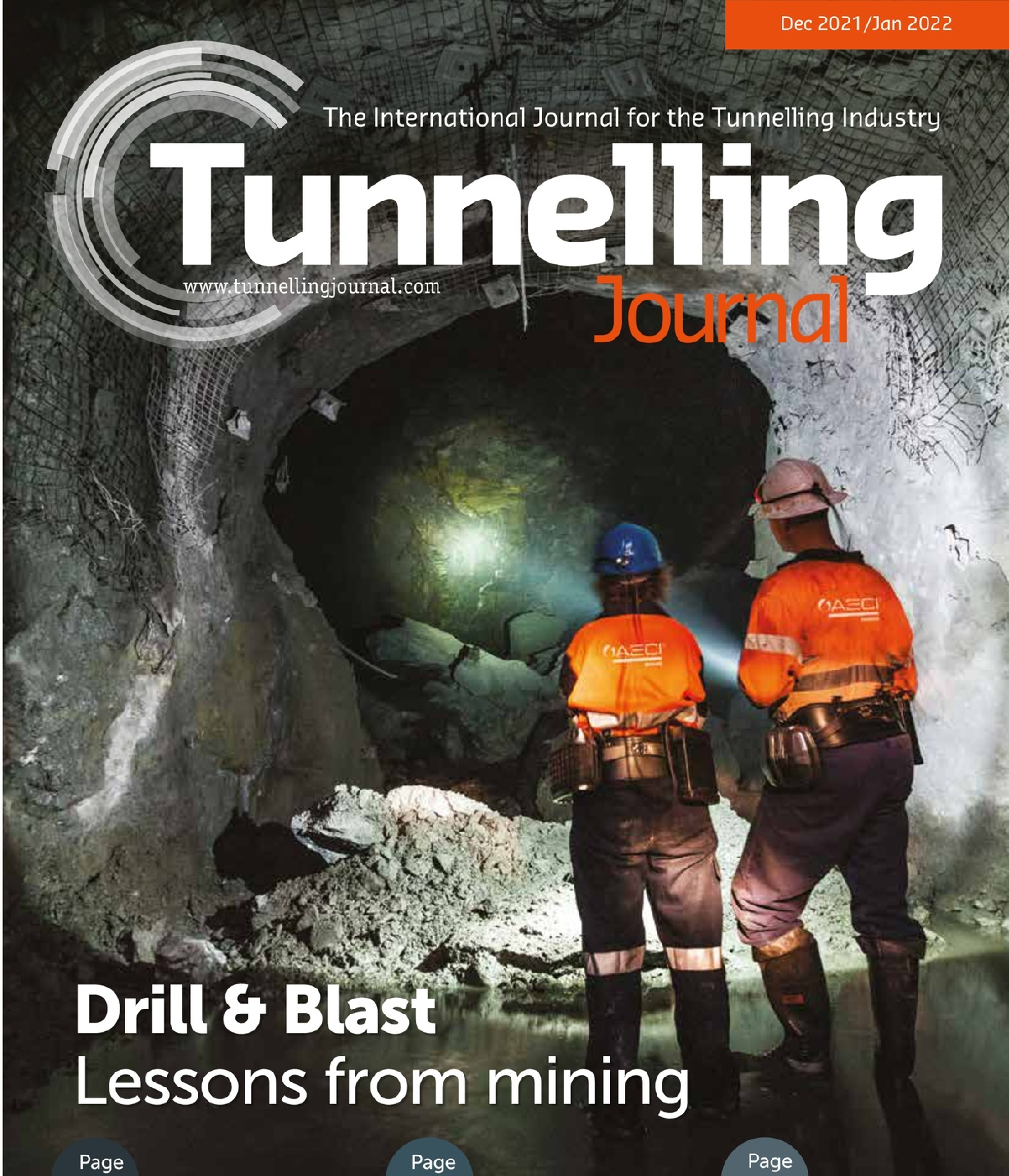

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Drill & Blast
Lessons from mining

Changing Perceptions on Grand Paris' Line 16-1

How to validate the use of steel fibres in the reinforcement of the tunnel lining segments of 13km of the new 19.6km long Line 16-lot 1 of the Grand Paris Express (GPE), when the technical specifications asked for a traditional solution (steel cages) and when experience in France was limited to a few examples of sacrificial segments or small-scale confidential tests? AFTES recommendations dating from 2013 and the 2017 FIB 83 reference document (Precast tunnel segments in fibre reinforced concrete) exist but have yet to be applied in France. Here, Jean Luc Bischoff, EIFFAGE, and Bernard Bergé and Benoit de Rivaz, both of Bekaert explain how the use of SFRC segments was successfully achieved on this section of France's mega-project.

At the start of construction of the Grand Paris Express (GPE) Line 16-1 in early 2020, Steel Fibre Reinforced Concrete (SFRC) tunnel lining segments in France were almost exclusively used in temporary (sacrificial) phases of construction or for experimental purposes (in storage areas for example). In Europe, with the exception of Spain (which uses hybrid segments) and the United Kingdom (mainly in small diameter tunnels and numerous segments per ring, 9+1 generally to distribute the loads as in the CTRL), there is no history of the use of 100% fibre reinforced tunnel lining segments in large diameter subway lines.

Globally, and since the publication of the Model Code 2010, English-speaking countries have been the forerunners of the use of SFRC.

Project Description

The GPE Line 16-1 is a significant undertaking, consisting of the construction of 19.6km of tunnels using six TBMs of three different diameters; five stations, SDP (Saint Denis Playel), SDF (Stade de France, LCO (La Courneuve), LBG (Le Bourget) and LBM (Le Blanc Mesnil): 21 ancilliary structures, including four tunnel junctions; the removal of 6 Million tonnes of spoil; and the placement of 800,000m^3 of structural concrete with 200,000m^3 of concrete for segments - all within a tight 69 month deadline.

The technical specifications for Line 16-1 originally stipulated the use of conventional reinforcement (steel cages without fibres) for the tunnel's segmental lining, but some six months after the award of the major construction contract to the Eiffage Génie Civil Group (EIFFAGE), the Client, Société du Grand Paris, having considered the economically beneficial variations presented by EIFFAGE, asked the contractor if it would carry out a feasibility study, at the contractor's expense, for the production of segments reinforced exclusively with steel fibres.

The following article will document the experience from the Client's request up to the start of the manufacture of SFRC lining segments for Line 16-1 in Bonna Sabla's plant in Conflans Sainte

TBMS ready to drive on GPE Line 16-1

Honorine in December 2019.

With the first segments installed in-tunnel by EIFFAGE in July 2020, this 7+0 segment/ring, placed via four TBMs represents an important reference and technical challenge for the 13km of 8.7m i.d., 9.5m o.d., tunnel that are 100% SFRC.

Steps to Success

Very early on, in 2017, Bekaert ran an information campaign aimed at promoting a "fibre" solution to be specified by the Client, the General Contractors, and prefabrication stakeholders.

As soon as the contract for Line 16-1 was awarded, EIFFAGE negotiated the subcontracting of the segment manufacture with Bonna Sabla. A structural fibre concrete testing campaign then began in summer 2018. Although fibre characteristics and prices were requested from the solicited suppliers, only technical criteria prevailed in the selection process. Bekaert was finally considered a favored potential partner by the stakeholders involved, after consideration of the quality of their fibres.

The objective was clearly defined by the Société du Grand Paris and EIFFAGE: to demonstrate that fibres work as well as traditional solutions.

In terms of results - according to the Model Code 2010 - a 4D SFRC is required, with the understanding that the minimum characteristic values to be achieved were:

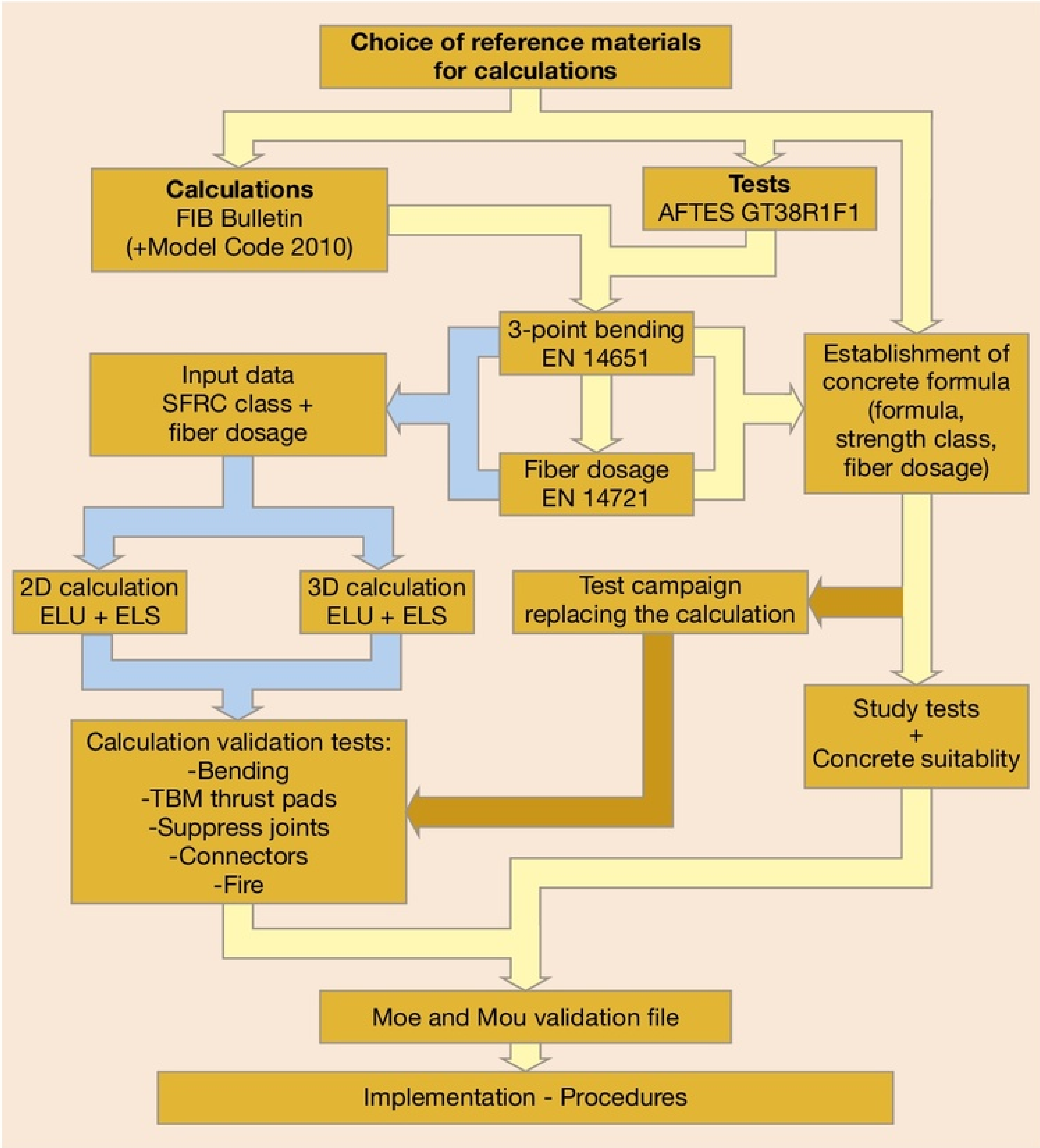
- Fr1k = 4.4Mpa
- Fr3k= 5.7Mpa

The FIB 83 bulletin based on the 2010 Model Code was used to determine and classify the characteristic values of the residual strengths (fLk, fR1k and fR3k) of SFRC.

Of the three segment diameters to be produced on Line 16-1 (i.ds: 6.7m, 7.75m and 8.7m) only the largest diameter will be considered by this study (8.7m).

For preliminary calculations and dimensioning, many documents have been published:

- RILEM (Technical Committee TC 162) Test and design methods for SSFRC
- FIB Model Code 2010 and Bulletin 83
- Guide for the Design and Construction of the SFRC structures ITA-report 16 WG2 (Italy)
- ACI 544 7R (USA)
- AFTES GT38R1F1 (France)



The FIB Bulletin 83 (2017) VP 1.4.1 which complements the FIB Bulletin known as the Model Code 2010 (2010) sets out the general rules for loads that may occur during the life of a segment. For the sake of completeness, there are 10 of these load cases. The FIB 83 Bulletin takes into account four load cases which represent different stages in the life of a segment during its manufacture, transport and installation in the tunnel:

- Demolding
- Storage
- Handling
- Transport

As well as two load cases related to the life stages of the segments in the tunnel:

- Cylinder thrust
- Geology

A Robust Test Campaign

Characterization tests: To verify the suitability of Bekaert's fibres for the concrete matrix, the fibres were tested by EIFFAGE, in Dramix 3D and Dramix 4D versions, along with three other competing fibres.

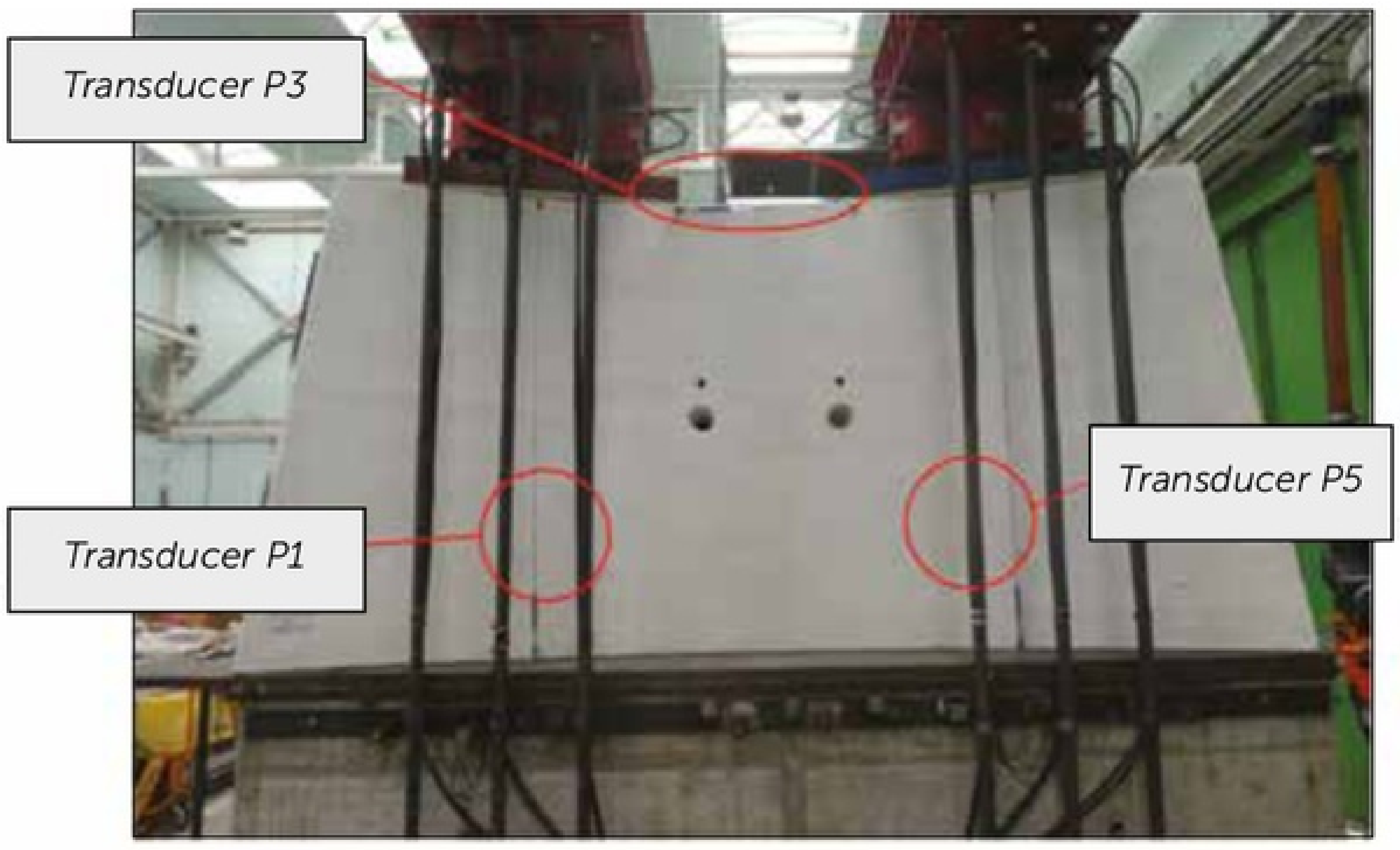
The implementation of the formula and its validation takes time and adjustments are necessary: Grading curve, sand, G/S ratio, cement quality, water/cement ratio (Eeff/C) are some of the important parameters, given that a minimum of fines is essential for properly incorporating the fibres and distributing them in the concrete matrix.

To begin with, five fibres and three different base formulations were used to ensure a successful

solution would be found.
These three formulations can themselves be broken down into different secondary formulas with variations in the dosage of materials and tested with the five types of fibres.

EIFFAGE' commitment was therefore for 18 months, in a colossal test phase at the start of the operation. The number of total beam tests = 1000 u, gives a total cost for the campaign of €1.2M.

At the end of this initial characterisation and consultation phase, Bekaert fibres were declared to be the top performers for the presented formulations. Since then, under the eye of EIFFAGE, a work schedule was set up between EIFFAGE, Bekaert and Bonna Sabla. The key words were rigor, tenacity and commitment for the successful implementation of a fibre-based solution.



Bending test to check the resistance to bending

On completion of this phase, the full-scale tests were still to be carried out, along with the fire tests and the design and suitability tests.

Design tests: The design tests allow the characterisation studies to be formally validated, according to a process that includes the terms of a conventional concrete study test, which has been completed in terms specific to the SFRC, taken from the Fib 83 Bulletin and the AFTES Recommendations of 2013, in consultation with the EIFFAGE Project Management and validated by it.

Full-Scale Tests: The University of Tor Vergata, Rome, and Professor Alberto Meda were appointed as EIFFAGE' consultant and laboratory for the full-scale tests. The role and expertise of Professor Meda and the quality of the university's facilities are key to the success of the project.

The number of segments tested at full-scale = 40. For these full-scale tests, at least two segments per series are necessary, one to check the resistance to the thrust of the hydraulic cylinders and the other to check the rupture resistance of the segments

Segment field tests check the resistance to the thrust of the hydraulic cylinders. EIFFAGE worked with Herrenknecht TBMs with a maximum thrust of 5,200kN.

A dosage of 40kg of steel fibres was to be validated to pass the test with one of the two Bekaert fibres. This fibre has a specific geometry that provides an important network effect that we will discuss in more detail in the next section.

Fire tests

The fire tests are conducted at CERIB in Epernon (28). Although it is generally accepted that synthetic microfibres, usually made from polypropylene (PP), provide passive fire resistance, the steel fibre + polypropylene segments had to be proven and pass the test to attain the load-bearing capacity (R), fire resistance (E) and thermal insulation (I) of the segment subjected to a fire according to the normalised temperature-time curve of the NF EN 1363-1 standard for a duration of 120 minutes, under load. Three segments were tested to temperatures from 0 to 1,000 degrees Celsius, for a 2-hour exposure, with 20 mins to reach the standard exposure temperature of 800°C. Lastly, a dosage of 0.9kg of micro synthetic fibres was validated to pass the test.

Suitability Tests

The purpose of the suitability tests is to validate the concrete manufacturing process to validate the formula in the SFRC. For this validation, EIFFAGE included the fire tests, the full-scale 1 tests (bending, cylinder thrust), as previously presented, as well as connector pull-out tests, and PAC system pull-out tests (catenaries, supporting structures). A test to determine the fibre orientation coefficient, K, had also been requested and carried out, but given the circumstances unique to France for this test, which has no equivalent in the world in a control process, and the difficulties of interpretation of the test, it was eventually removed from the validation process.

In total, the campaign, comprising the characterisation tests, study tests and suitability tests, including the full-scale tests and fire tests, lasted 18 months with completion in December 2019.

Strict Quality Control

The Petrovice plant in the Czech Republic was awarded the manufacturing contract for the steel fibres for the project. Following the tests, the final choice was to use a Dramix 3D 80/60 BGP fibre.

First of all, the emphasis is on the tensile strength of the fibre. Dramix 3D fibres generally have values between 1,100 and 1,300N/mm^2. To improve the Fr3 values of the performance levels to be achieved, a higher strength of 1,800N/mm^2 was decided upon. The tensile strength of a steel fibre should increase in line with the strength of its anchorage (hook shape, concrete matrix). Only in this way can the fibre resist the forces exerted on it.

A high L/D (Length vs. Diameter) ratio, in this case 80, was also a determining factor in the choice made. The fibres are long, 60mm, which allows the aggregates to be perfectly integrated (maximum diameter 20mm) and they are relatively fine (diameter 0.75mm), creating a net of 11.6km of fibres/m^3 of concrete.

With 4,584 fibre units/kg, the concrete is guaranteed to have fibres throughout the matrix and especially in the traditionally weak points of the segment such as the corners and edges.

Finally, the fact that the fibres are glued was also an important element of choice to avoid the formation of balls in the industrial production phase. These balls represent a risk of creating nests of pebbles and segregations, as well as differences in fibre ratios in the segment, which are detrimental to the homogeneity of the matrix and therefore to the intrinsic strength of the whole.

Even though the technical data sheet for this product meets the requirements of the specifications, emphasis is placed on quality control throughout the manufacturing process.

Between December 2019 and December 2020, 5,300 tons of fibres were manufactured and a Quality Plan was quickly put in place following a joint visit to the plant.

A first requirement was the source of the wire rod used to make the fibres. A leading European manufacturer was required to guarantee the consistency of the quality of the raw material. Checks on receipt of the wire rod were established according to the factory's ISO controls.

A second check is required on the semi-finished product to verify the tensile strength values obtained.

Finally, a random sample of fibres is taken from the big bags delivered to the prefabrication plant. A double control of compliance with the geometry and tensile strength tolerances of the fibres is carried out in the Bonna Sabla factory and in the Bekaert laboratories in Belgium.

Monthly reports are sent to the customer for quality control purposes.

In terms of logistics, despite the plant's production capacity (80,000 tons of fibres per year), two borders must be crossed (the Czech Republic and Germany) on the 3,500km journey from the plant and the Conflans Sainte Honorine site. This assumes that during peak periods, full truckloads of fibres (24 tons) are delivered every working day from the plant.

The Buffer set-up (left) and the Dosing equipment

The Bonna Sabla Plant equipment

The Conflans Sainte Honorine plant already had molds for the manufacture of tunnel lining segments for the Line 14 extension on behalf of the RATP. Nevertheless, these segments were reinforced with steel cages except for a number of sacrificial segments which were reinforced with steel fibres.

Industrial experience with fibre-reinforced segments was limited at this very early stage in the factory. EIFFAGE stressed the importance of the introduction, the distribution, as well as a guarantee of the dosage of the fibres in the concrete matrix with solutions implemented.

An efficient and controlled feed of the fibres 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 eight big bags at the beginning of the day (about nine tons of fibres).

This device was supplemented by a triple weighing system of the quantity of fibres introduced into the mixer (dosing equipment, fibre reception belt and mixer feeding belt).

A press was acquired to perform tensile strength tests by bending (limit of proportionality - LOP) according to the EN 14 651 standard required for on-site quality control of SFRC 4D.

The acquisition of a new concrete batching plant, molds with the right diameter for line 16-1, the fibre batching machine, the press and the buffer required an investment of about €2M and a real commitment to quality control by Bonna Sabla.

A Significant Ecological Impact

- The saving in the ratio of fibres compared to steel reinforcement bars, lead to a significant reduction in CO2 emissions during transportation. If we compare 85kg/m^3 for steel reinforcement bars with the 40kg/m^3 for fibres, we see a saving on materials of more than 50%.

- By the benefit of better optimised loading of the fibres Twenty-two big bags of 1,100/kg per truck = 24.2 tonnes per load for the delivery of the fibres, i.e. 173 equivalent segments compared to 60 equivalent segments per truck = 17.85 T for the delivery of concrete reinforcement bars.

- From the small diameter of the 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.

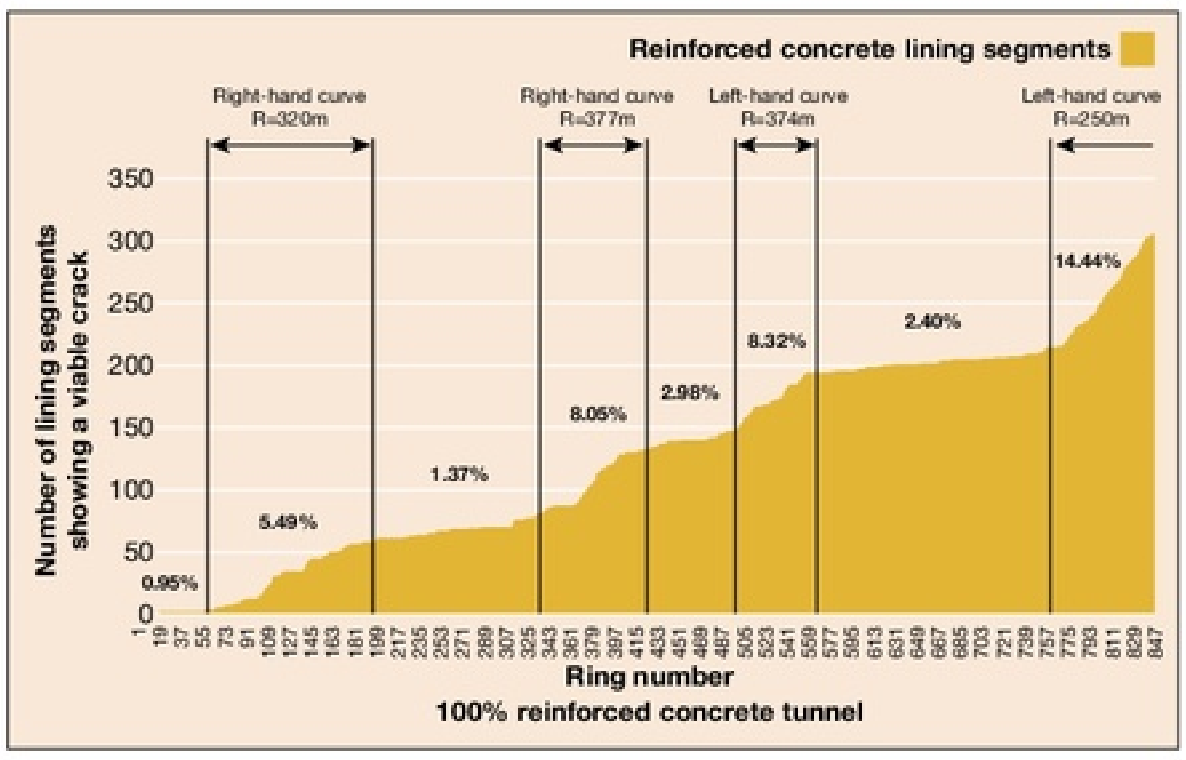
- The drawing technology is low-emission.

- Fewer trucks on the road and optimised 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.

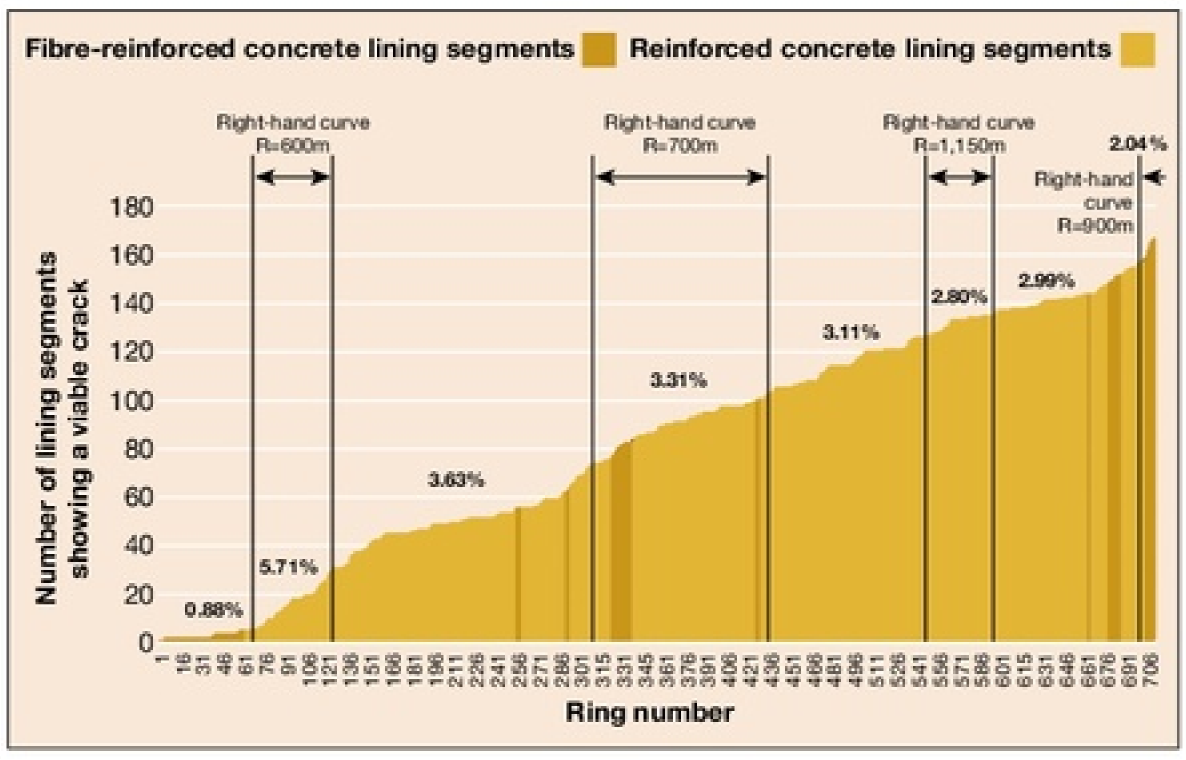
A Beneficial Economic Aspect

In economic terms, the savings can be estimated as being at least the difference in the ratio between conventional reinforced concrete (85kg/m^3) and fibre reinforced concrete (40kg/m^3), adjusted for the relative difference between the price of the fibres and the price of the characterisation, study, suitability and production control campaigns.

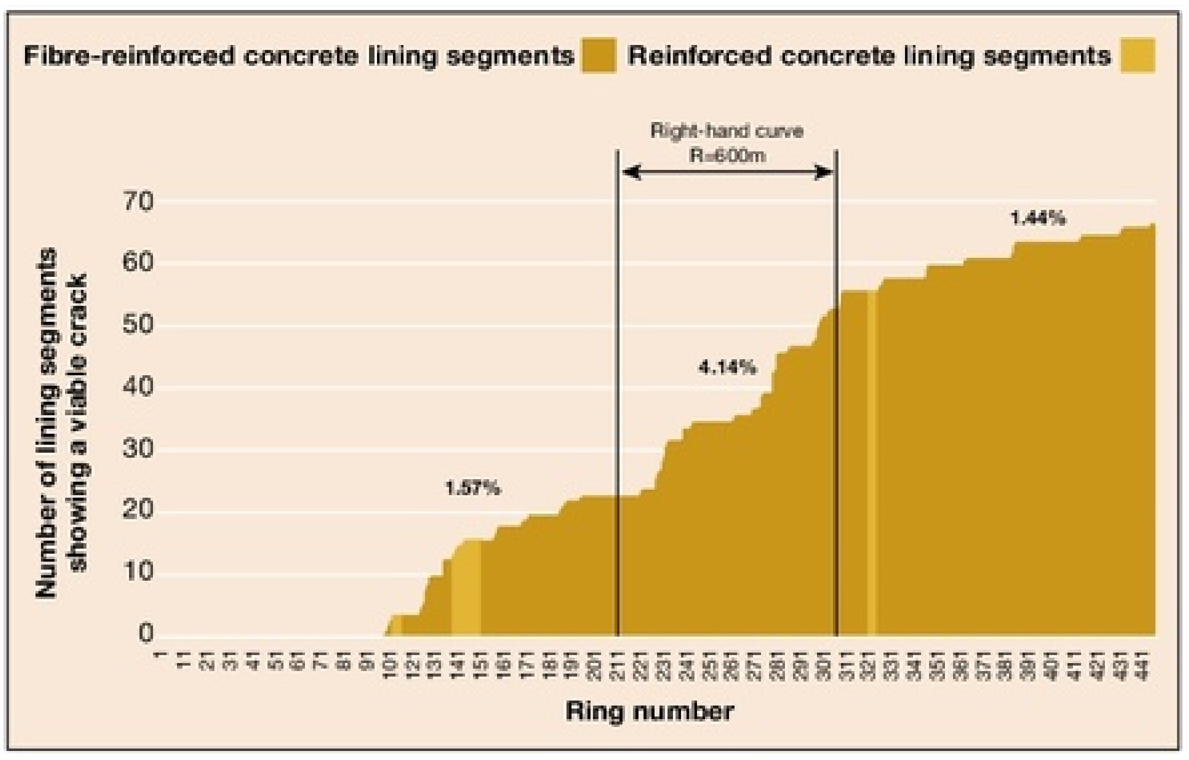
TBM 1 – Total number of cracked lining segments versus progression



TBM2A - Total number of cracked lining segments versus progression



TBM3 - Total number of cracked lining segments versus progression



Given the highly optimised technology for the production of reinforcement cages, particularly in France, and the fact that contracts for reinforcement cages include assembly as a subcontract, the reduction in personnel is clear to see. The saving in space for assembly is unfortunately offset by the need for enclosed and covered fibre storage areas.

However, the production of SFRC segments provides a benefit in terms of productivity compared to structures using conventional reinforced concrete, which is difficult to assess other than qualitatively. The time saved in setting the reinforcement cage in the mould and placing the inserts afterwards is then corrected by the longer time for floating the SFRC than for conventional reinforced concrete.

The production of 100% SFRC segments, if the processes of dosing, introduction of the fibres into the mixer, and quality control on the steel fibre during the different phases of the fibre's life are mastered, provide an attractive alternative to the restrictive quality processes for the assembly of reinforcement cages with very high quality welds for conventional reinforced concrete segments.

Better Crack Control

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

The use of fibres is perfectly suited to this type of geometry, especially as the cracking process generates finer cracks than the cracking process of a beam on two supports.

Indeed, as only micro-cracks (<=0.2mm) are observed and the segments work in compression when the ring is formed, they

Handling a freshly demolded segment

close up automatically.

Also noteworthy is the excellent corrosion behavior of the fibre reinforced segments, linked to the small diameter of the fibres and their distribution.

The L16-1 construction site provided feedback on the cracking of the reinforced concrete and SFRC segments during installation and on the constitution of the rings.

The objective is to compare the cracking rate between BA and SFRC rings.

In summary, a SFRC segment does not crack more than a reinforced concrete segment, with a corresponding smaller crack size, the cracks close more easily as well, providing a much better risk/benefit balance in terms of corrosion.

A SFRC segment ensures greater durability than a reinforced concrete segment.

Conclusion

The production of structural segments as a final 100% fibre-reinforced concrete lining on L16-1 for a passenger railway structure is a first in France, if not in Western Europe.

There were three main objectives: performance, sustainability and ecology.

The reasons for the performance of this operation have been extensively discussed in this article, with emphasis

	Number of rings inspected			Number of lining segments inspected			Number of lining segments showing cracking			Proportion of cracked lining segments		
	FRC	Reinforced concrete	Total	FRC	Reinforced concrete	Total	FRC	Reinforced concrete	Total	FRC	Reinforced concrete	Total
TBM-1	0	855	855	0	5,985	5,985	0	304	304		5.08%	5.08%
TBM-2A	618	88	706	4,326	616	4,942	134	15	149	3.10%	2.44%	3.01%
TBM-3	390	104	494	2,730	728	3,458	43	2	45	1.58%	0.27%	1.30%
TBM-5	607	261	868	4,249	1,827	6076	125	64	189	2.94%	3.50%	3.11%
TBM-6	238	761	999	1,666	5,327	6,993	47	257	304	2.82%	4.82%	4.35%

Expected Benefits

- Reduction in risk of spalling
- Better control of shrink cracking
- Micro-cracking FRC vs expansion cracking RC
- Better coating
- Less prone to corrosion
- Multi-directional strength
- Ductility of FRC > reinforced concrete
- Environmental savings

Expected Limitations

- Localised cracking (areas with fewer fibres)
- Susceptibility to localised stresses
- Susceptibility to jacks stresses
- Control of homogeneity

Learning Points

Conclusive experience : 90% of 12km of tunnel with 100% pre-fabricated FRC, 70% installed

Easy transition from reinforced concrete to FRC

All productivity benefits of reinforced concrete lining segment maintained in terms of:
- Number of lining segments/ring
- Length of lining segment
- Power of machines (Jack/stresses)

Better level of cracking as a percentage as for reinforced concrete:
- Lower crack size
- Cracks close up

The result is improved corrosion resistance/ X reinforcement) and therefore greater durability of filter-reinforced lining

Environmental benefits (reduced consumption of raw materials, manufacture of fibres creates less pollution than rebar, saving on transport of fibres = 300% v. rebar)

on a reassuring test campaign and the choice of a suitable fibre, i.e., one with a large network and glued.

The use of steel fibres for this type of structure is therefore becoming technically and economically self-evident. The Line 16 Lot 1 project is one of the references for large-diameter, 100% fibre-reinforced rings as the final lining for a metro line.