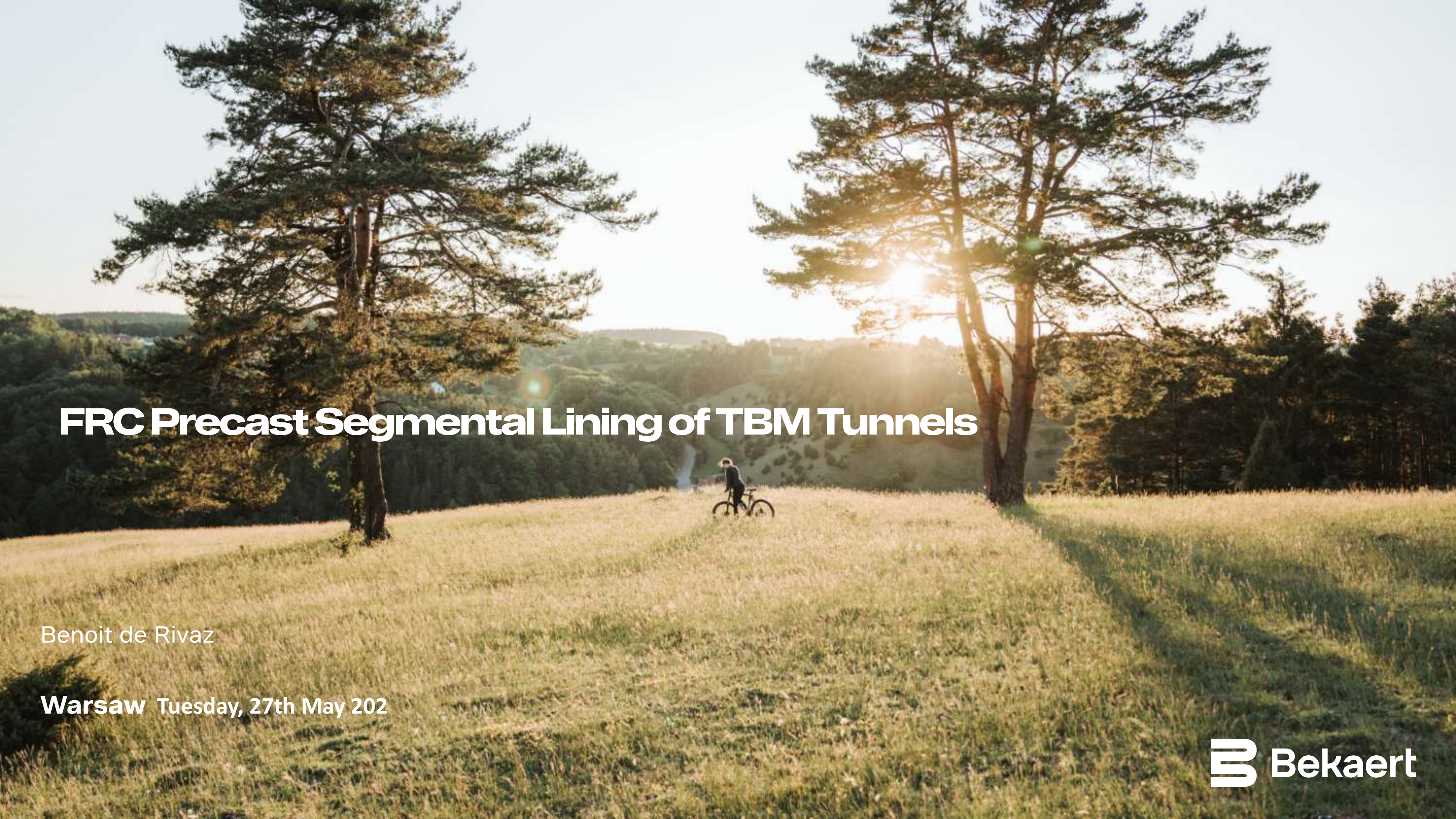


FRC Precast Segmental Lining of TBM Tunnels

Benoit de Rivaz

Warsaw Tuesday, 27th May 202

Bekaert

In this presentation

Iintroduction

Bekaert-Dramix Introduction

Our core competencies

Bekaert is a global market and technology leader in material science of steel wire transformation and coating technologies, and beyond

Steel Wire Transformation

From wire rod 6.5mm...

to drawing, bunching, cabling, profiling, welding, knitting, weaving...

to metal fibers 1 μm

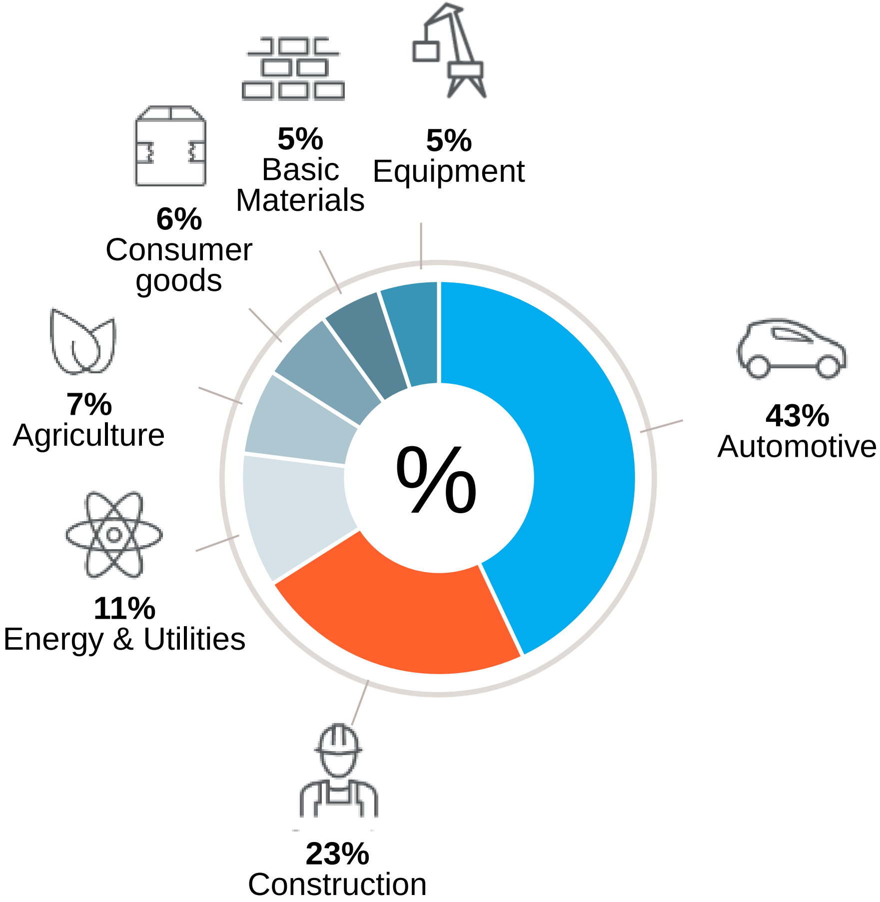
Coating Technologies

from traditional coatings...

to adhesion, corrosion resistance, wear resistance anti-fouling...

to advanced coatings

Bekaert has a strong presence in diverse industry sectors



Bekaert in a nutshell

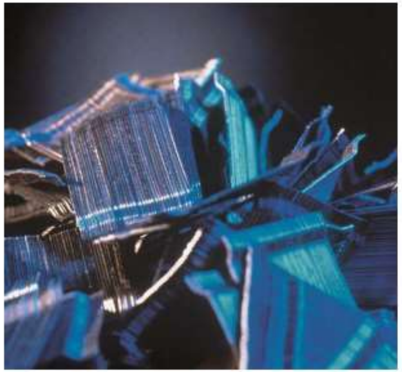
Bekaert is a world market and technology leader in steel wire transformation & coating technologies

We pursue to be the preferred supplier for our steel wire products and solutions by continuously delivering superior value to our customers worldwide. Bekaert (Euronext Brussels: BEKB) is a global company with more than 27 000 employees worldwide, headquarters in Belgium and € 5.9 billion in combined revenue.

Bekaert in your day-to-day life

30% of all tires around the world are reinforced with Bekaert tire cord

Every year, 10 million m³ of concrete is being reinforced with Dramix® steel fibers



Bekaert's customers use 3.5 million kilometer of bookbinding wire per year

Over 1 billion bottles are uncorked annually by removing the *muselet* made of Bekaert steel wire

FIBRE REINFORCED CONCRETE …

- **…provide a**
  - discontinuous
  - evenly distributed
  - 3-dimensional
- reinforcement network to concrete.

- **…are engineered to**
  - replace
  - reduce
  - improve
- traditional concrete reinforcement.

- **It’s a proven technology for more than 40 years.**

– Different types of steel fibres

- Steel fibres for concrete appear in all colours, shapes, sizes and materials.
- The performance of steel fibres in concrete is influenced by different factors:

  - Fibre shape
  - Wire strength
  - Wire ductility
  - Fibre dosage & distribution in concrete
  - Concrete composition

BEKAERT
better together

What makes up Dramix®?

- Engineered fibres
- High aspect ratio
- Bundled fibres
- Certified products and production
- Design software
- Research & Development
- Decades of experience

Dramix® steel fibres are engineered to fully utilize the wire properties while achieving maximum performance in concrete.

- Wire tensile strength aligned with anchorage system
- Anchorage system aligned with wire ductility
- **3D fibres:**
  normal tensile strength, regular hook, controlled pull-out
- **4D fibres:**
  high tensile strength, optimized hook, controlled pull-out
- **5D fibres:**
  ultra high tensile strength, engineered hook, defined wire elongation

BEKAERT
better together

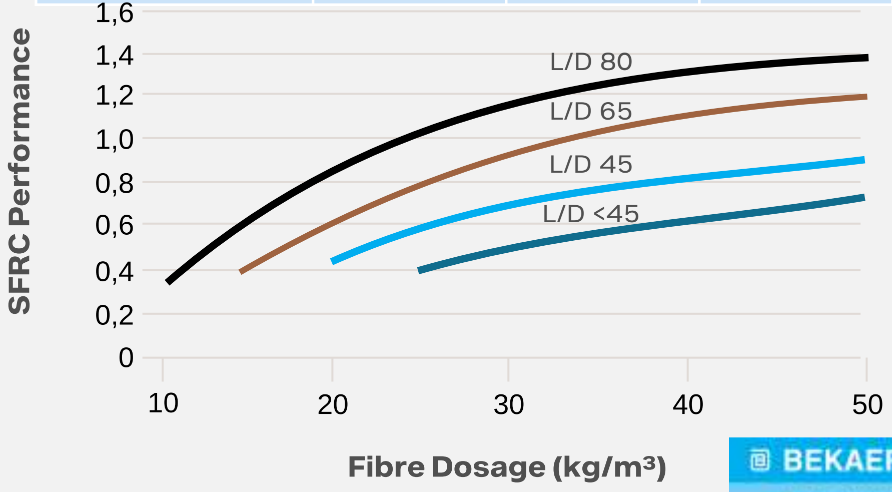
What makes up Dramix®?

- Engineered fibres
- High aspect ratio

Higher aspect ratio = higher performance

- Design software
- Research & Development
- Decades of experience

Aspect Ratio L/D	80	65	45
Length (mm)	60	60	50
Diameter (mm)	0,75	0,90	1,05
Network (m/kg)	276	200	147



BEKAERT
better together

What makes up Dramix®?

- Engineered fibres
- High aspect ratio
- Bundled fibres
- Certified products and production
- Design software
- Research & Development
- Decades of experience

Glued Fibres

Dramix® steel fibres are glued into soluble bundles, which

- avoids balling successfully
- allows to use high performing fibre designs
- allows to distribute the fibres easily, uniformly and reliably

BEKAERT better together

What makes up Dramix®?

- Engineered fibres
- High aspect ratio
- Bundled fibres
- Certified products and production
- Design software
- Research & Development
- Decades of experience

System certificates

ISO 9001
BUREAU VERITAS
Certification

ISO 14001
BUREAU VERITAS
Certification

Product Certificates

Certified and externally controlled products and production - globally

- ISO 13270
- EN 14889-1 / CE
- ASTM A 820
- …

0749-CPD
EN 14889-1

Conforms to
ASTM A820

What makes up Dramix®?

- Engineered fibres
- High aspect ratio
- Bundled fibres
- Certified products and production
- Design software
- Research & Development
- Decades of experience

Own design software

- free of charge
- easy to use
- fast results
- Bekaert supported
- fully integrated Dramix® database

Commercial design software

In cooperation with Bekaert, ADAPT (US-based) and SCIA (Europe-based) developed structural analysis software to design and calculate steel fiber reinforced concrete for structural and non-structural applications.

A NEMETSCHEK COMPANY

BEKAERT
better together

What makes up Dramix®?

- Engineered fibres
- High aspect ratio
- Bundled fibres
- Certified products and production
- Design software
- Research & Development
- Decades of experience

- own research & development
- global network of in- and external experts
- in-house design services
- lab testing

BEKAERT
better together

What makes up Dramix®?

- Engineered fibres
- High aspect ratio
- Bundled fibres
- Certified products and production
- Design software
- Research & Development
- Decades of experience

- ✓ More flexibility
- ✓ Less stock on site
- ✓ More efficient construction techniques
- ✓ Optimized structures
- ✓ Less risks for accidents on site
- ✓ Less problems
- ✓ Less working hours
- ✓ Less repair
- ✓ Higher durability
- ✓ Quicker progress
- ✓ More possibilities

BEKAERT
better together

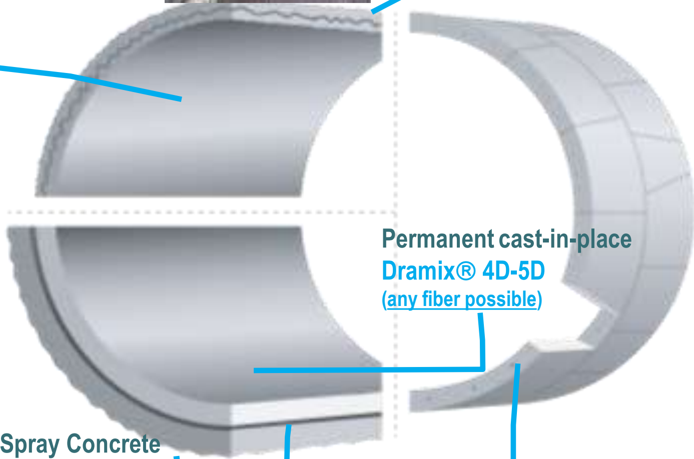
Our product portfolio

Our current offer for undrground

Products per tunneling applications

Permanent Spray Concrete Lining
Dramix® 4D 65/35BG
(any steel fiber possible)

Optional spray membrane (part of Supercon project)
Dramix® 3D 80/30BGP



Permanent cast-in-place
Dramix® 4D-5D
(any fiber possible)

Temporary Spray Concrete
Dramix® 3D 65/35BG if nothing required, any steel fiber possible
Synmix®

Geotextile & sheet membrane

Segmental lining with TBM
Dramix® 4D 80/60BGP 3D 80/60BGP if only 4C required
(any steel fiber possible)

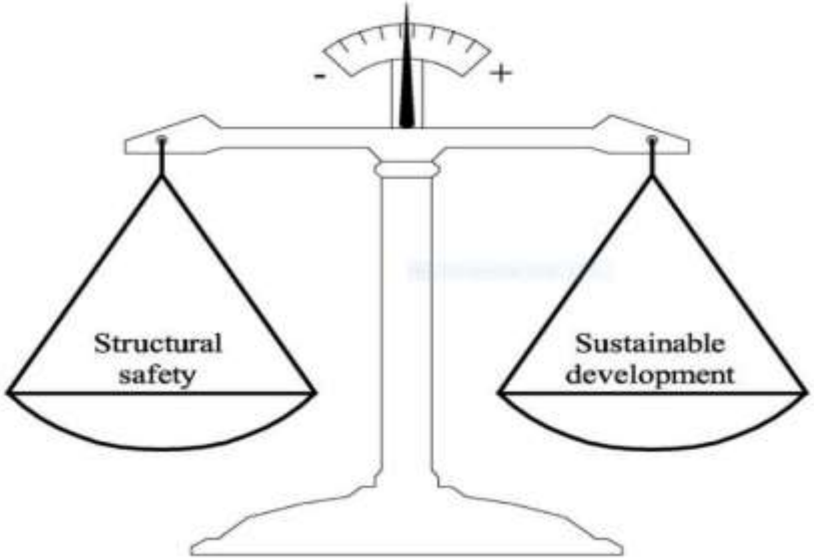
Industry we serve

MINING
ROAD
HYDRO
METRO
RAIL
CSO
UTILITY

Fire resistance & anti-explosive spalling
Duomix® M6 Fire

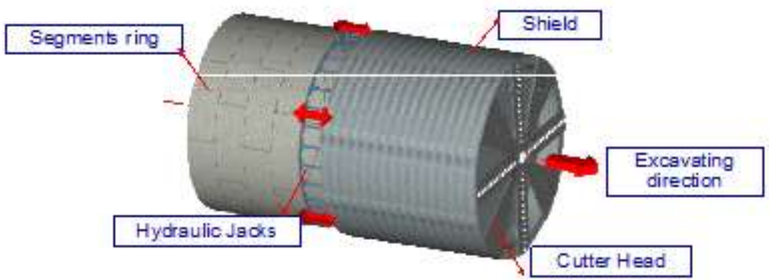
PRECAST SEGMENT STATE OF THE ART

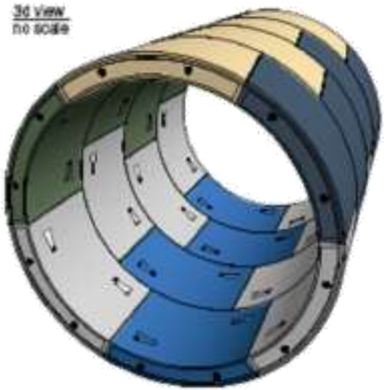
The assessment of concrete linings requires the definition of both the **Sustainability Index and Mechanical Index**



Contemporarily, a low environmental impact guarantees a sustainable development, which is in accordance with the Brundtland Commission of the United Nations (March 20, 1987), the "development that meets the needs of the present without compromising the ability of future generations to meet their own needs”.

MORE AND MORE MECHANIZED EXCAVATION USING TBM





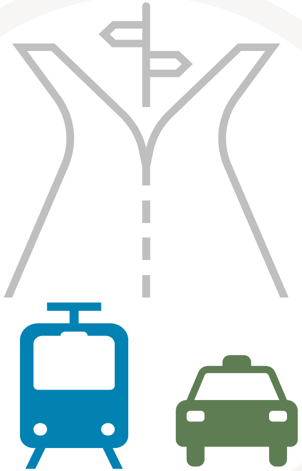
MORE AND MORE FIBRE REINFORCED CONCRETE PRECAST SEGMENT

State of the art summarized by fib bulletin 83 /ACI/ITA

Durability advantages at final stage

Cracking control during construction phases

Higher impact resistance

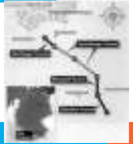


Sustainability advantages

Reduction of costs

Boosting of the production process

Key Underground projects from more 300



pioneering | innovating | expanding | recognition | new design codes | transforming

1990

Munich Water Tunnel, Germany

- Contractor: Bilfinger und Berger
- Designer: C.V. Buchan
- Owner: Munich City Works
- Fiber type: Dramix® RC80/60BN
- Length: 11.8 km
- Diameter: 2.2 m
- Thickness: 180 mm
- Concrete class: C45

- **All start from Heathrow baggage**

2003

CTRL (Channel Tunnel Rail Link), UK

- Client: RLE (Rail Link Engineering Ltd. Designer: Ove ARUP & partners
- Fiber type: Dramix® RC80/60BN
- Length: 40 km
- Diameter: 7,15 m
- Thickness: 35 cm

2006

Singapore Metro Line

- Contractor: Woh Hup – STEC –
- NCC JV – Tasei Corporation
- Fiber type: Dramix® RC65/60BN
- Length: 750 m & 650 m
- Diameter: 5.8 m
- Thickness: 275 mm
- Concrete strength: 60MPa
- Dosage rate: 30 kg/m

2010

Brisbane Airport link, AU

- Client: BrisConnections
- Contractor: TJH JV
- Designer: PBA JV & Hallcrow
- Fiber type: Dramix® RC80/60BN Duomix® M6 Fire
- Length: 15 km
- Diameter: 11,24m

2014

Lee Tunnel, UK Concrete Society Awards

- Contractor: Morgan Sindall/Vinci
- Grand Projets/Bachy Soletanche
- (MVB JV)
- Designer: Aecom/UnPS
- Owner: Thames Water
- Fiber type: Dramix® 3D 8060BG
- Length: 6.9 km
- Diameter: 7.2 m
- Thickness: 350mm
- Concrete class: C50/60

2016

Doha Metro, Qatar

- Contractor: JV Porr – Saudi BinLadin – HBK
- Designer: D&B by JV contractors
- Fiber type: DRAMIX® 4D 80/50 BG
- Diameter: 7.8 m
- Thickness: 350mm
- Length: 34 km

2020

Grand Paris, France

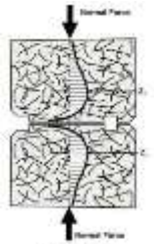
Owner : Société du Grand Paris (SGP)
Designer: Egis
Contractor: Eiffage Génie Civil
Diameter: 9,50m
Length: 16 km
Thickness: 400mm
Concrete quality: C540/50
Fiber type: DRAMIX® 3D 80/60 BGP
First important reference in definitive segments in the French Market

2022

Toronto Project, Canada

Main difficulty with precast segment

Bursting in segments occurs from two different types of loads:



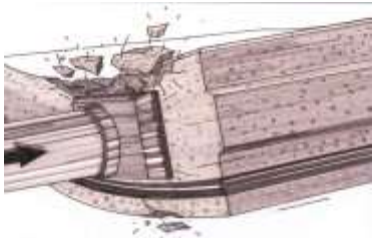
Ring bursting

Ram bursting

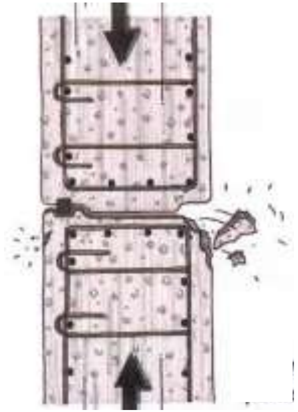
In-place forces due to compression in the ring

During installation by the application of ram loads to the edge of the segments

- Minimal concrete cover requirements for corrosion
  combined with …..
- Particular edge shapes
  leads to……
- Vulnerable edges



Cracking and spalling of the concrete in the cover zone at the joint of a segment.



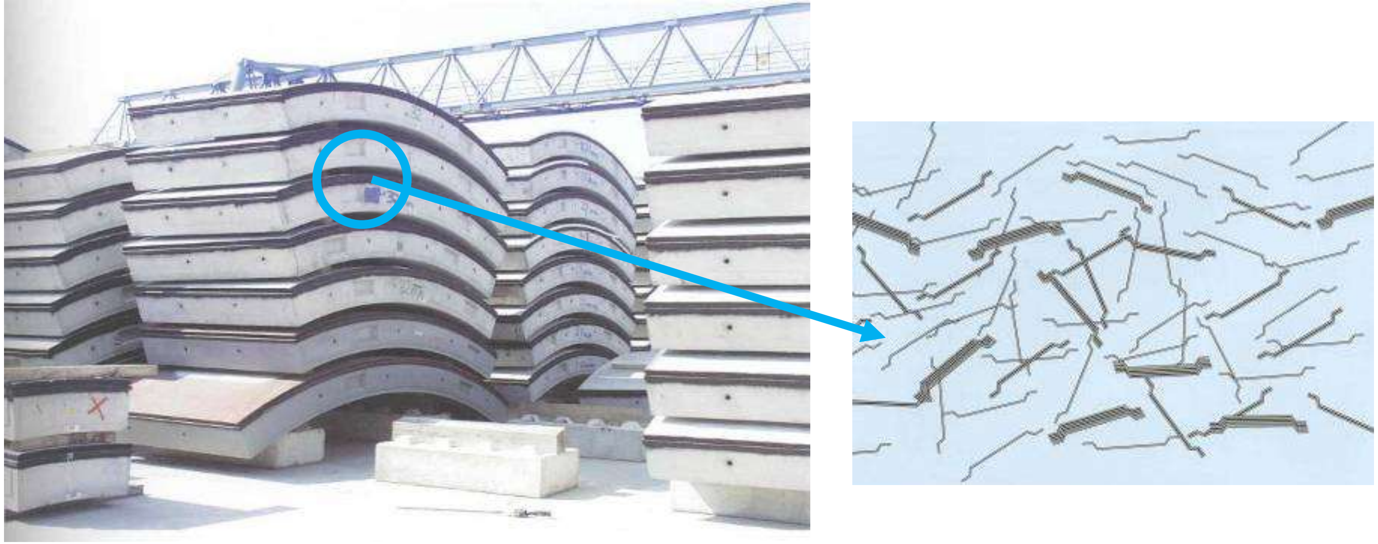
Spalling at a joint with a particularly vulnerable profile

Inadequate reinforcement

Repairs must be made that ensure long term durability

How long will you guarantee this repair?

Steel fibre reinforced concrete (SFRC)



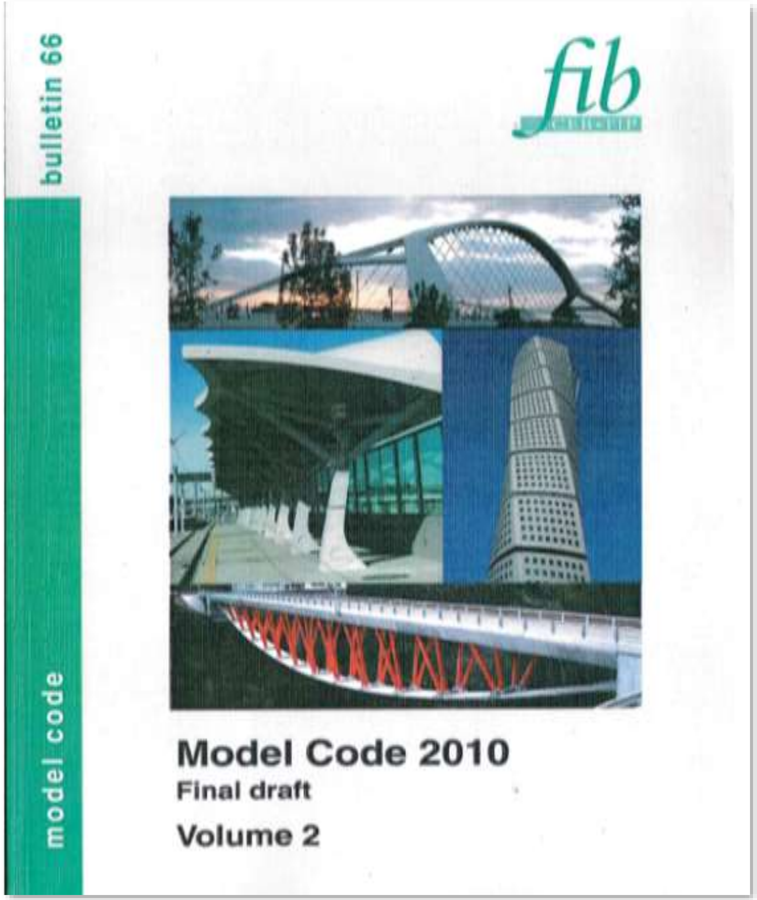
Dramix :CTRL(UK) = A very positive return of experience

Table 1: Overall damage rate to segments CTRL project published in TT magazine					
Manufacturing process			Construction process		
No. of segments made	Rejected	Repaired	Minor damage no repair needed	Minor damage controlled repair	Major repair
(No.)	(%)	(%)	(%)	(%)	(No.)
260,000	0.8	2.8	2.2	0.3	1

PRECAST SEGMENT : STRUCTURAL REQUIREMENT

FRC PRECAST SEGMENT INTERNATIONAL GUIDELINE JOURNEY

2012	2013	2016	2017	2018	2019
Model Code 2010	**AFTES**	**ITA TECH** Volume 1 **ITA WG2** Lesson learn	**ACI 544** **Fib Bulletin 83**	**ITA TECH** Volume 2	**ITA WG2** Design



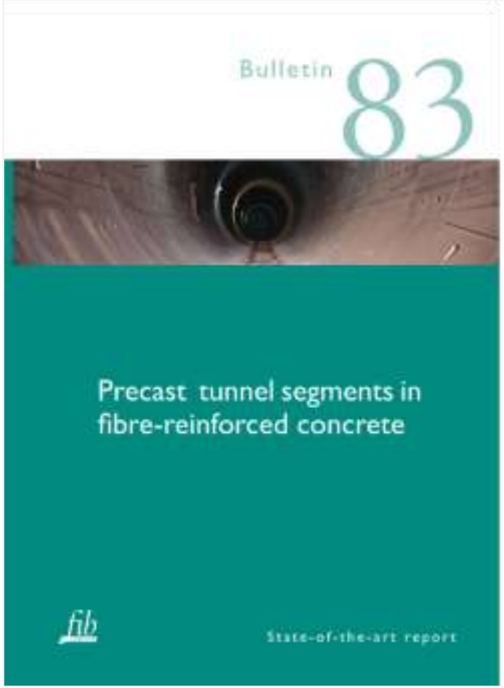
International (2010/2012)

- Published 2012
- Pre-normative (e.g. future Eurocode)
- Proposed by fib as operational document
- Fibres are included in MC2010 which is the base for the future EuroCode Annex L (to be published soon)

FIB Bulletin 83

- Clear guidelines on how to characterize FRC material performance
- Clear state of the art
- Clear design guidelines

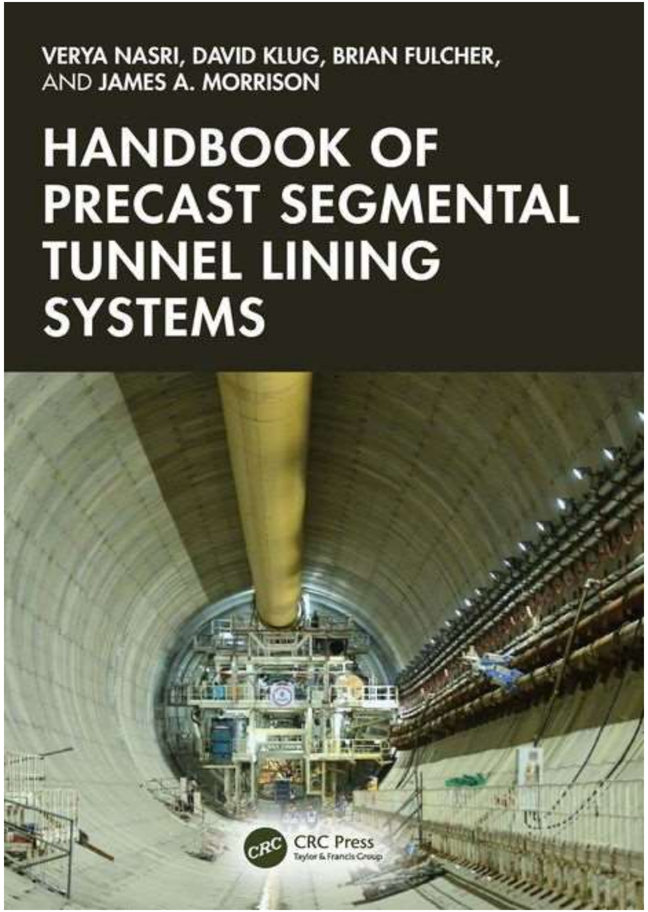
NEW PUBLICATION 2018



Precast tunnel segments in fibre-reinforced concrete

Contents

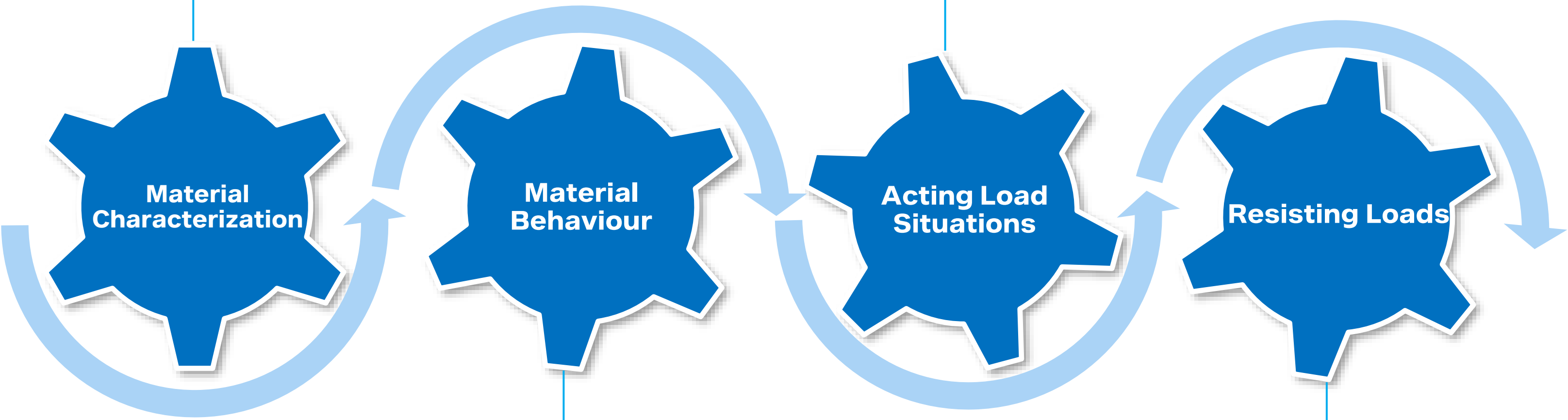
- For the first time, all aspects of design, production, and construction of precast concrete tunnel segmental lining, and best practices in this field, are presented in a single book.



Design Flow

- Beam tests according to EN14651
- Performance classes
- Material requirements

- Demolding
- Stacking
- Transport & Placing
- Service

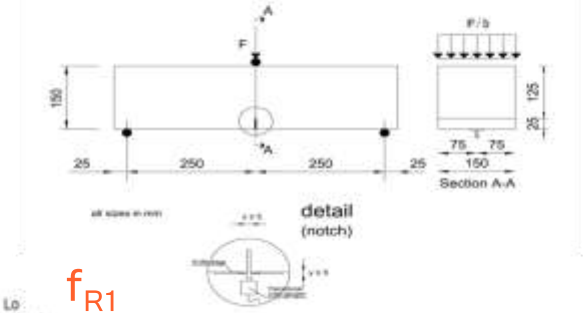


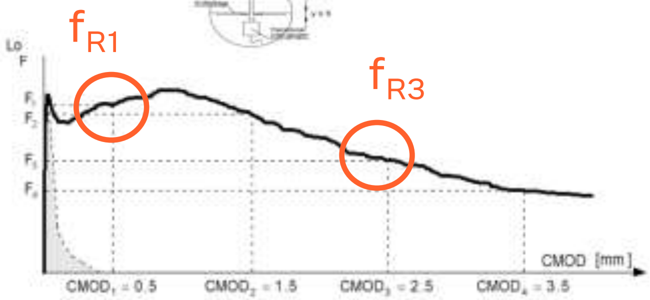
- Constitutive laws
- Material safety factors and other impact factors

- Bending moment capacity
- Shear capacity
- Resistance against spalling/bursting
- Resistance against impact

Standardized beam test

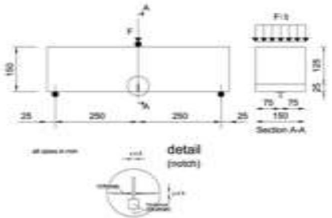
EN 14651





Material Characterization

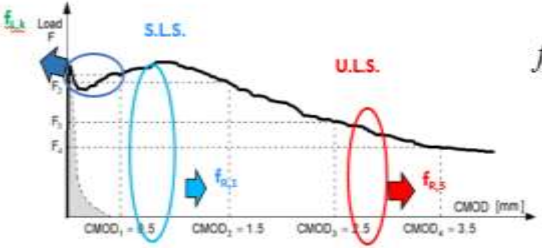
- **Beam test according to EN14651**
- **Classification according to MC2010**



EN 14651

h_{sp} = 125 mm

b = 150 mm



$$f_{R,j} = \frac{3 F_j l}{2 b h_{sp}^2}$$

5d

f_{R1k}	f_{R3k}/f_{R1k}
1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0	a: if $0.5 \leq f_{R3k}/f_{R1} < 0.7$ b: if $0.7 \leq f_{R3k}/f_R < 0.9$ c: if $0.9 \leq f_{R3k}/f_R < 1.1$ d: if $1.1 \leq f_{R3k}/f_{R1} < 1.3$ e: if $1.3 \leq f_{R3k}/f_{R1k}$

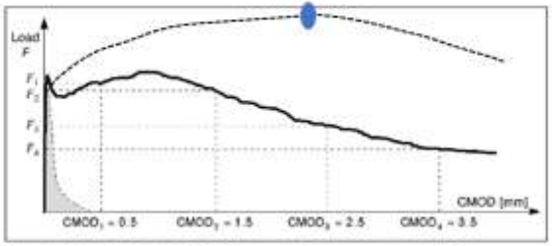
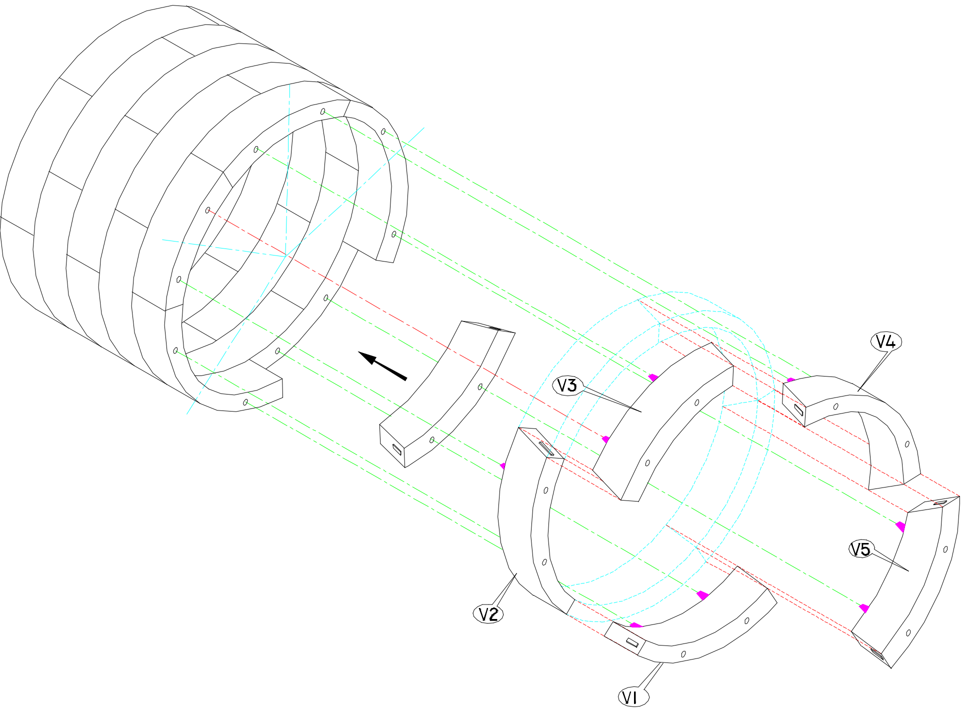


Figure 5.6-6: Typical load F–CMOD curve for plain concrete and FRC

- **Requirements according to MC2010**

$f_{R1k} / f_{Lk} > 0.4$ $f_{R3k} / f_{R1k} > 0.5$	If fulfilled → fibres can substitute conventional reinforcement at ULS

New development in the segmental lining design



Ever increasing concrete compressive strength for fast demoulding

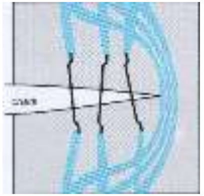
Higher concrete compressive strength

=

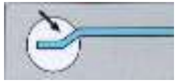
More steel to meet “non brittle failure” requirements

The quality of Dramix® is due to a combination of factors...

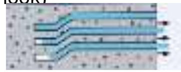
- Wire strength
- Wire elongation
- Shape
- Length
- Diameter
- L/D ratio



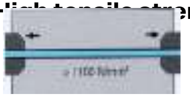
- A **high length-diameter ratio** (L/D ratio)
- **Hooked ends**



- **Controlled pull-out** (due to deformation of the hook)

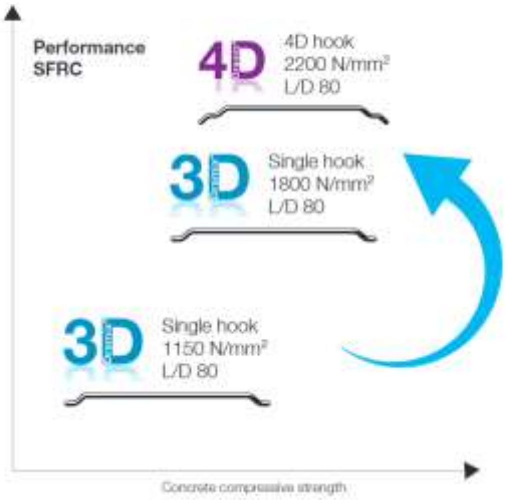


- **High tensile strength steel**



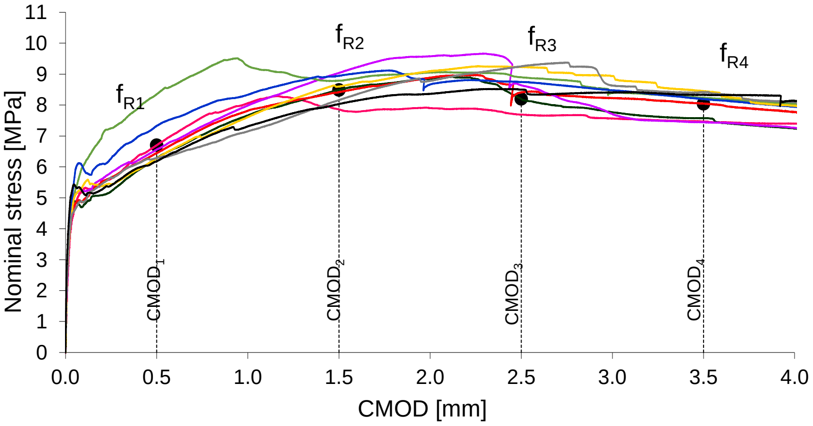
- A system of glued fibre bundles enables fibres with a high L/D ratio to be mixed easily and uniformly throughout the c

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.



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

Material Example 40kg/m3 Dramix 4D 80/60BGP



	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

Hardening post crack behaviour at section level (3PBT) allows immediately:

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

Performance class type 5e according to MC2010

Determination of the characteristic value

In order to define the characteristic value from the tests results, the procedure suggested in Eurocode 0 can be used.

$$X_k = m_x\{1 - k_n V_x\} \qquad V_x = \frac{s_x}{m_x} \qquad s_x = \sqrt{\frac{\sum (x_i - m_x)^2}{(n-1)}}$$

unknown V_x

n	k_n
3	3.37
4	2.63
5	2.34
6	2.18
8	2.01
9	1.96
10	1.92
12	1.87
15	1.82

known V_x

n	k_n
3	1.89
4	1.83
5	1.80
6	1.77
8	1.74
9	1.73
10	1.72
12	1.71
15	1.70

9 to 12 beams recommended

Quality management

The procedures for the control of Fibre-Reinforced Concrete performance should be defined in the design process.

Usually, a quality control procedure considers two steps:

- **initial qualification of the material (trials testing);**
- tests during the segment production (production testing).

Automated dosing equipment

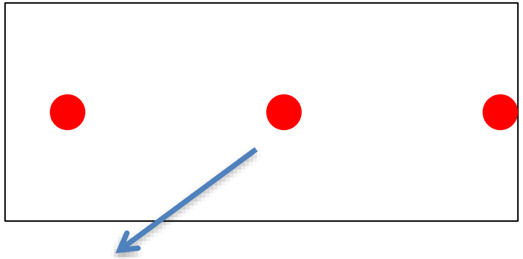
Dosing equipment linked with the control system ready-mix plant

Wash-out test

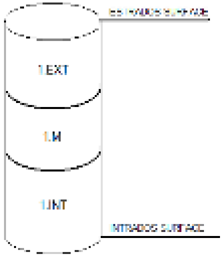
- 8l volume
- Pour through magnet
- Wash out & dry
- Weigh the fibers
- Labor intensive process!

Initial tests

Tests for fibre distribution



Fib Bulletin 83



Usually, a fibre content measured according to EN 14721 can be accepted if this differs less than 20% from the nominal value.

Dramix® eyeD® Analyser

- Dramix® eyeD® Analyser carries out the inductive test to determine the content and orientation of steel fibers in fiber reinforced concrete (FRC).

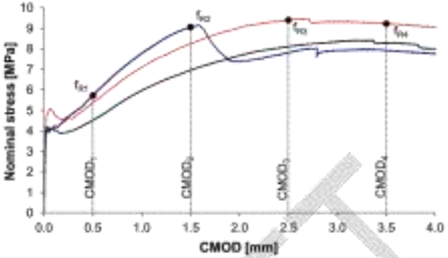
- The equipment **allows to determine the content and orientation of the fibers** present in the concrete from the variation produced by the fibers in the magnetic field generated by the equipment.

Alternatively: design by testing

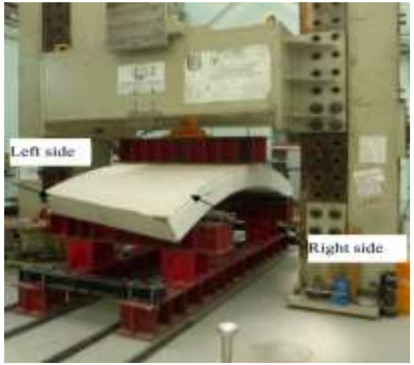
Dramix® 4D 80/60BGP - Tests led by Prof. Meda

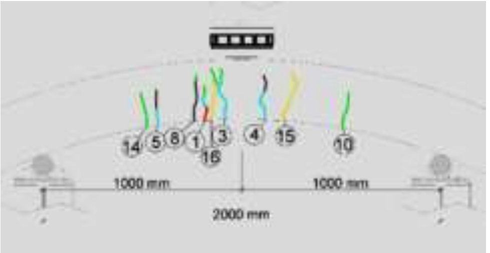
Università degli Studi di Roma "Tor Vergata"
CIVIL ENGINEERING AND COMPUTER SCIENCE DEPARTMENT
TERC – TUNNELLING ENGINEERING RESEARCH CENTRE

Material Characterization

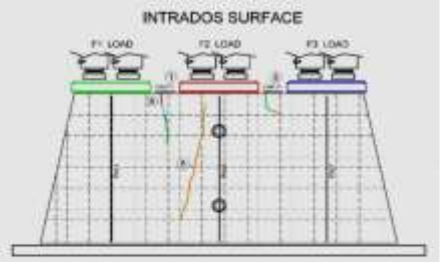


Bending Test





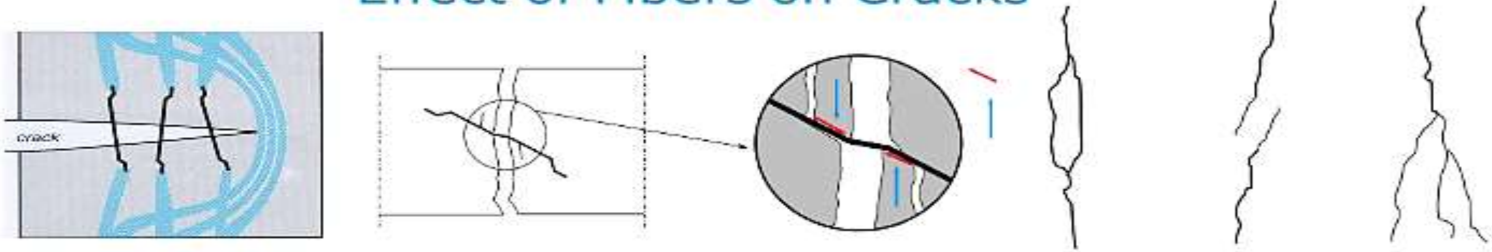
Point Load Test



Durability a key issue : 120 years design life

Solution: Segments reinforced with steel fibers, *having a bending hardening behavior*, contain cracks much thinner Effect of Fibers on Cracks segment reinforced with steel rebar.

Effect of Fibers on Cracks



- "Comparing crack width in RC segments with FRC segments indicate a better performance in favor of fibers by as much as an average value of 43%"

In order to assess the durability of SFRC a number of parameters such as the exposure conditions and concrete quality, have to be considered, in particular with regards to chlorides.

Durability and Steel Fibres

fib Bulletin 83 – Precast tunnel segments in fibre-reinforced concrete
§8 Durability – Literature study

Conclusions

- Uncracked concrete:
  SFRC durability ❯ RC durability
- Cracked concrete:
  SFRC durability ❯ RC durability
- Stray Current induced
  SFRC durability ❯ RC durability

Grand Paris Return of experience

Grand Paris Express in a nutshell

200 km of Automatic Subway Line to Provide New Travel Options

- ✓ 200 km, equivalent to the existing Metro Network
- ✓ Automatic subway lines, almost entirely underground
- ✓ Estimated cost :42 billions euros

Jean François MONTEILS

Board of

Sociéte du Grand

Our innovation policy is above all a lever for making the Grand Paris Express a project in the service of ecological transition and developing practices in the world of public works.

This is why we are orienting many of our projects towards sustainable design and construction, such as reducing concrete, choosing materials or even operating solutions for the metro that consume less energy.

Innovations have already given significant results….

The use of fiber-reinforced concrete for the construction of the segments of part of line 16. *This is a first in France in underground work. Compared to reinforced concrete, fiber-reinforced concrete notably represents* ***savings of around 5,000 tonnes of steel for 10 kilometers of tunnels”***

AFTES CONGRESS/SGP Website

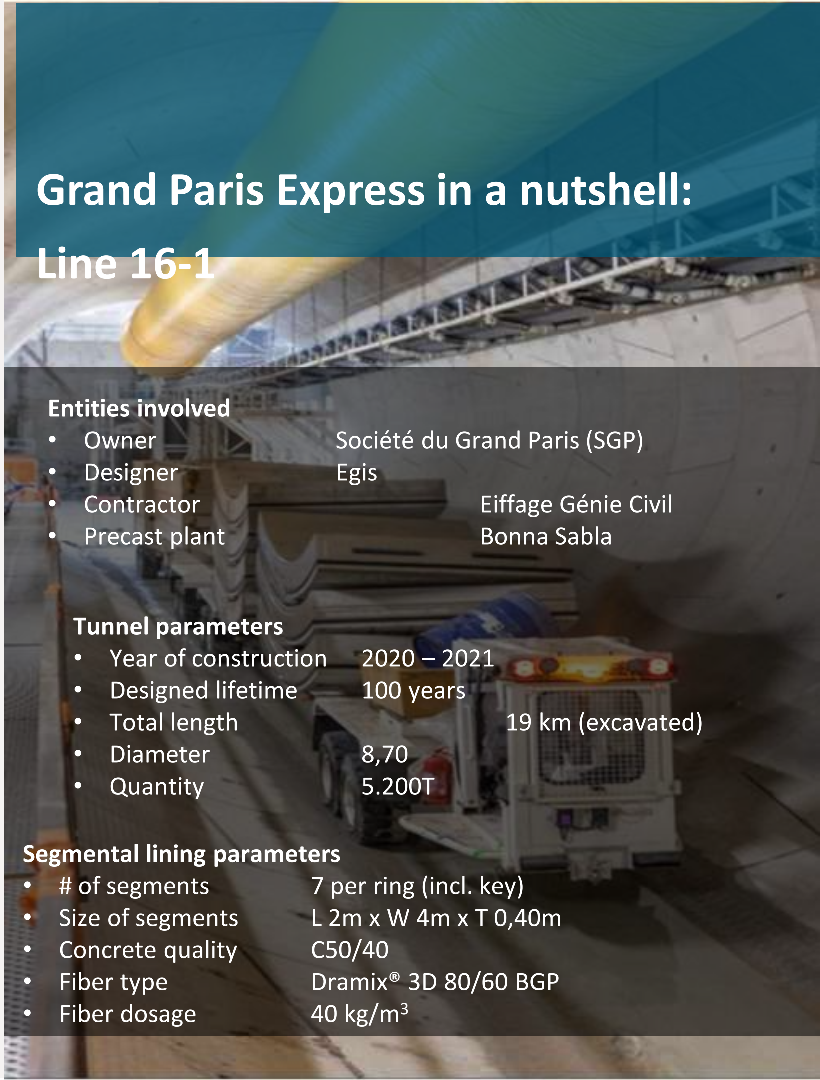
Designers, constructors and suppliers work together to achieve reductions of CO2e emissions in design and construction, and this collaboration must be incentivised by the client.

Fibre-reinforced concrete takes over in Greater Paris

- Futhermore in terms of resources, FRC can reduce the quantities of concrete by 2 to 3 cm segment thickness.

In addition to the quantities of steel and concrete saved, fiber-reinforced concrete also reduces CO2 expenditure, both in cement factories and in steelworks: **10,000 tonnes of CO2 are saved on average for 10 km of tunnels compared to Rebars .**

The twenty-two 1,100kg bulk bags per truck, representing a 24.2 t consignment of fibres, ***allowing the production of nearly 185 segments ,compare with 60 equivalent segments per truck****, representing a 17.85t load of reinforced concrete rebars FEWER TRUCKS ON THE ROAD AND OPTIMISED WASTE management in a large city such as Paris is an important factor that must be taken into account. From an environmental perspective, the impact on the carbon footprint is very positive.*



Grand Paris Express in a nutshell: Line 16-1

Entities involved

- Owner — Société du Grand Paris (SGP)
- Designer — Egis
- Contractor — Eiffage Génie Civil
- Precast plant — Bonna Sabla

Tunnel parameters

- Year of construction — 2020 – 2021
- Designed lifetime — 100 years
- Total length — 19 km (excavated)
- Diameter — 8,70
- Quantity — 5.200T

Segmental lining parameters

- # of segments — 7 per ring (incl. key)
- Size of segments — L 2m x W 4m x T 0,40m
- Concrete quality — C50/40
- Fiber type — Dramix® 3D 80/60 BGP
- Fiber dosage — 40 kg/m^3

Lot 1 of Grand Paris Line 16

Why fiber-reinforced lining segments for Lot 1 of Line 16?

Given its scale, the Line 16-1 project represented a favorable environment for running a validation campaign with a view to the prefabrication and installation of 100% fiber-reinforced lining segments as the permanent structural lining.

EIFFAGE therefore proposed to Société du Grand Paris to implement a 100% FRC segments solution in May 2018. After validation by the EIFFAGE , with the assistance of egis ,the project manager, have together validated the FRC formula in December 2019.

This reference now represents a French first, which, as a world reference, shows that the technical advances in reinforced concrete are perfectly transposable to fiber-reinforced concrete, for better corrosion resistance.

Stakeholders:

TOR VERGATA
BEKAERT better together
CONSOLIS BONNA SABLA
EIFFAGE
egis
CERIB Expertise concrète
BUILDING TRUST Sika

Lot 1 of Grand Paris Line 16

Fiber-reinforced lining segments: what is the process?

Stages of the process

- Implementation of a common standard
- Suitability studies and tests
- Installation of fiber-reinforced concrete rings

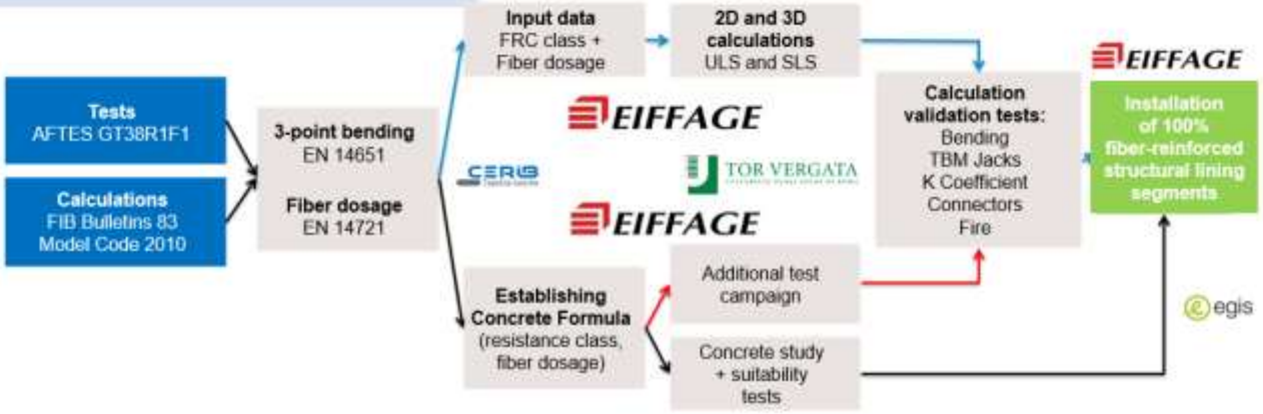
Lot 1 of Grand Paris Line 16

Fiber-reinforced lining segments: validation campaign

Input data

- 3 diameters = 3 types of FRC required
- 4 precast plants = 3 concrete formulas reduced to a single 1
- 3 studies reduced to a single 1
- Contract: reinforced concrete lining segments

Calculations and Laboratory Tests



Lot 1 of Grand Paris Line 16

Fiber-reinforced lining segments: validation campaign

Suitability tests preliminary studies

- Mix: around 90 between 100 and 300 l
- Bending tests:
  - Around 750 preliminary study and study phases
  - 150 to determine K coefficient
  - 100 for suitability test
- Tests conducted at CERIB (concrete laboratory)
- Around 64 tons of materials

Choice of structural fibers

- 2 geometries tested (single and double hooks)
- 2 fiber diameters tested (0.75 and 0.9 mm)
- Multiple tensile strengths for the steel
- Choice: DRAMIX 3D 80/60 BGP,
  - 0.75 mm Glued, 1,800 Mpa, L60 mm
  - 4,584 fibers/kg (network of 183,360 fibers/m3, with dosage 40kg/m3)

Lot 1 of Grand Paris Line 16

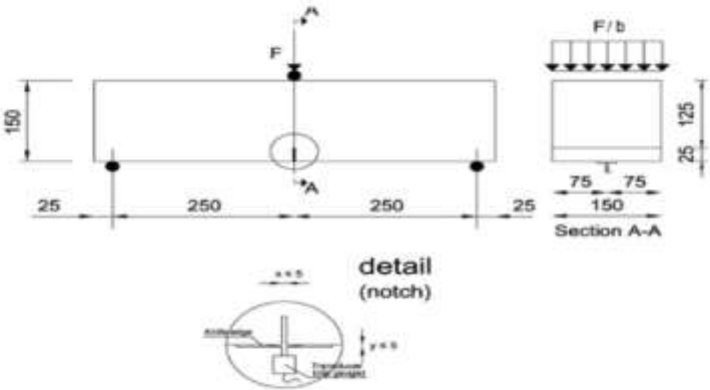
Fiber-reinforced lining segments: validation campaign

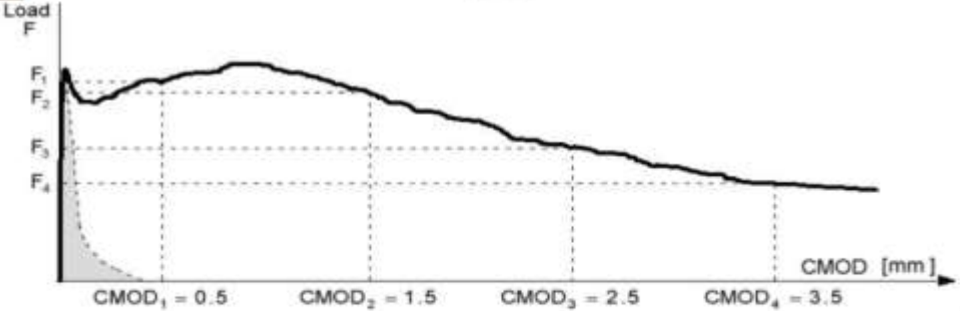
EIFFAGE

3-point bending tests EN 14651

Tests conducted at CERIB laboratory in consultation with University Tor Vergata

CERIB TOR VERGATA





Lot 1 of Grand Paris Line 16

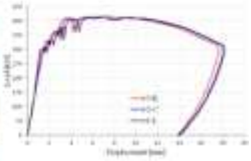
Fiber-reinforced lining segments: validation campaign

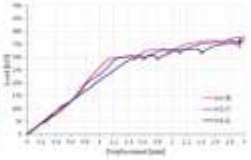
Mechanical behavior

Studies conducted at the University of Rome (Department of Professor Alberto Meda):
- Bending tests on the lining segments
- TBM jacks thrust tests
- Connector pull-out test

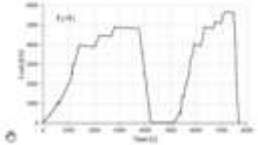
Suitability and control plan:
Tests on around 40 lining segments

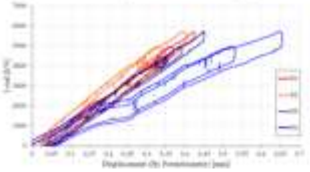
Bending tests





TBM cylinder thrust tests





Connector pull-out test

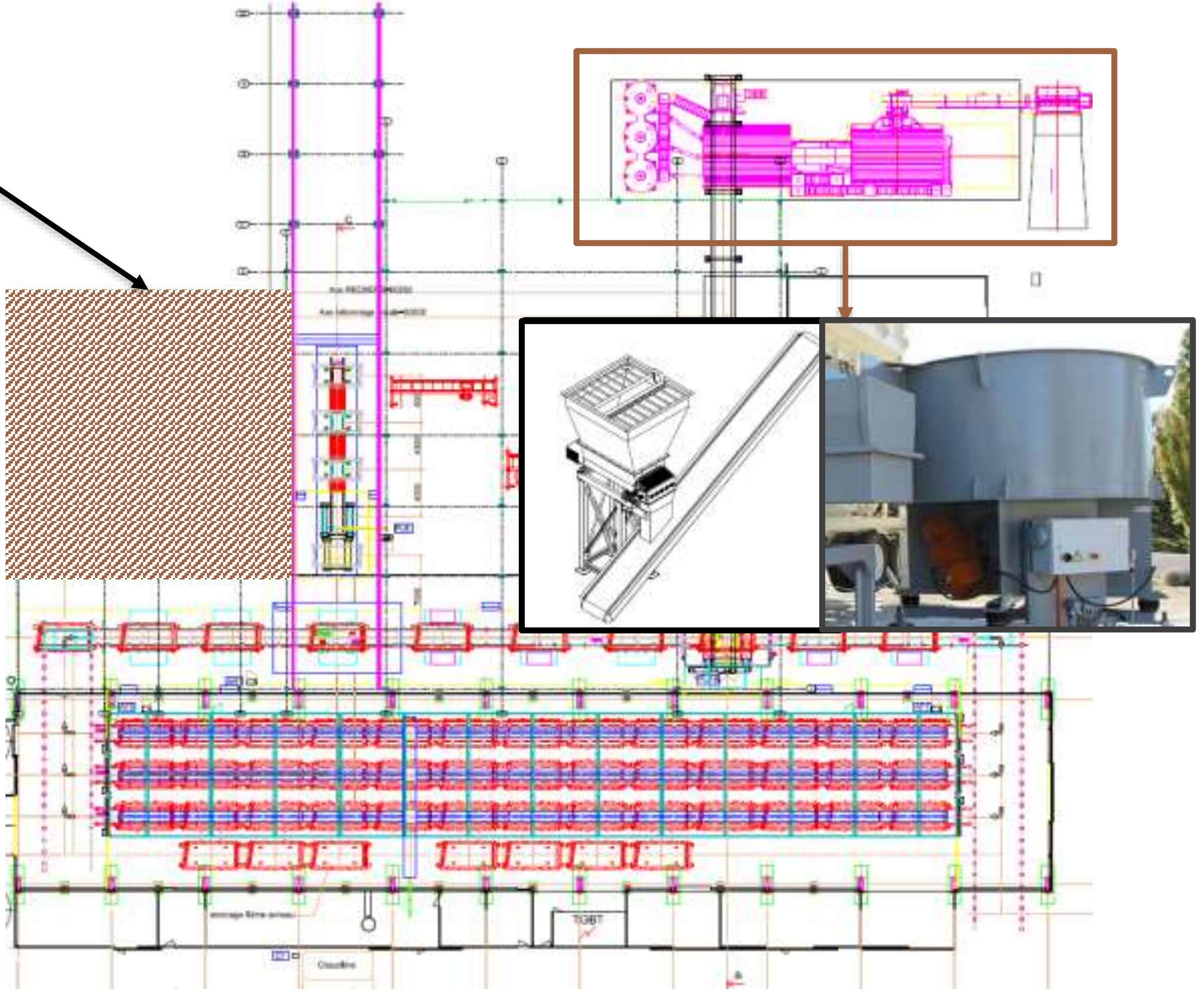
Factory production

Consistency is the key to guaranteeing the result. Careful installation of the concrete batching plant and the fibre batching system will guarantee this consistency:

- Batching machine and buffer
- Triple weighing system with load cells
- Precise water dosing using appropriate probes and a robot

Once this consistency has been ensured, the quality of production is also guaranteed, materialized by the consistency of the Scale 1 tests, the sole and exclusive judge of peace.

Steel cages storage space



Strengthening the control system

- <u>Examples :</u>
  - Triple weighing system with load cells
  - Camera system installation

Complementary systems

– Batching machine and buffer

As regards installation in the tunnel :

- **Reinforced concrete compensates for installation that is not carried out according to the Rules of the Art, whereas FRC imposes rules of the SFRC that tunnel operators neglect in order to improve production** - to the detriment of durability, which as a result is poor - **thinking that SFRC segments are "fragile" and crack, whereas these same FRC segments «repair themselves" more easily than reinforced concrete.**

- **The micro cracking of the SFRC, which guarantees durability, contrasts with the more extensive cracking of the Reinforced Concrete, causing more serious damage.**

- **J.L BISCHOF (EIFFAGE) Tunnel Engineer 16,1**

Lot 1 of Line 16

Conclusion

(FRC lining segments = 12 km over 18.7 km of project L16-1)

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

LEARNING POINTS

- Conclusive experience: 90% of 12 km 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 (jacks stresses)
- Better level of cracking as a percentage as for reinforced concrete:
  - Lower crack size
  - Cracks close up
- The result is improved corrosion resistance (size of fibers/Φ reinforcement) and therefore greater durability of fiber-reinforced lining
- Environmental benefits (reduced consumption of raw materials, manufacture of fibers creates less pollution than rebar, saving on transport of fibers = 300% v. rebar)

Case Studies Carbon counting

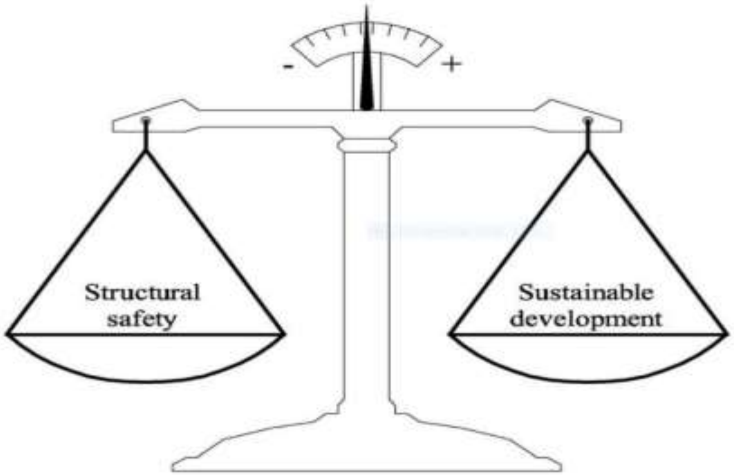
We have commun langage

The assessment of concrete linings requires the definition of both the Sustainability Index and Mechanical Index

DUCTILITY

DURABILITY

SUSTAINABILITY



Designers, constructors and suppliers must work together to achieve reductions of CO_2e emissions in design and construction, and this collaboration must be incentivised by the client.

- **Carbon Emission Throughout the Entire Life Cycle of Infrastructure**
    - Product Stage & Construction Stage (Stage A), Usage Stage (Stage B), End of Life Stage (Stage C)
- **Embodied Carbon**
    - Includes Stage A1 through A5 & Contribute 60 ~80% of Total Carbon Emission of Infrastructure Projects

Construction's Carbon Footprint

The construction industry accounts for **23%** of CO^2 emissions produced worldwide, largely due to the embodied carbon in materials like concrete and steel.

Concrete Emissions

Cement is responsible for at least **one-third** of the construction industry's CO^2 emissions

Rebar's Contribution

Steel rebar alone is reported to account for **1.5%** of worldwide carbon emissions.

Tunnelling

It's no surprise that most of a project's embodied carbon, approximately **two-thirds**, is from concrete in the shaft and tunnel linings.

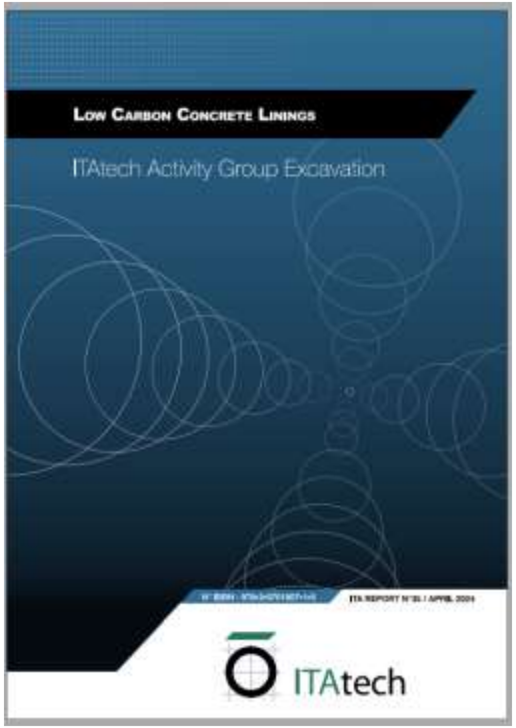
Generic guideline to create awarness

We do tunnels.

Our objective:

Reduce the carbon footprint of tunnel construction and contribute to the prevention of climate change

1. Introduction
2. Where we are now
3. Reducing carbon through contracts and procurement
4. Carbon accounting
5. Selection of low carbon concrete materials
6. Specification
7. Design
8. Construction
9. Operation and maintenance of tunnels with low carbon concrete linings
10. Conclusions
11. Recommendations



Chair:
Dr Benoit Jones

Vice Chair:
Dr Wolfgang Aldrian

Vice Chair:
Benoit de Rivaz
Global Technical Manager,

Be focus

– *We should use every lever available to reduce CO_2e emissions, but we should focus first on the areas we can make the biggest difference*

- **Measures to Reduce Embodied Carbon**
  - Design Optimization
  - Reducing Portland Cement & Steel
  - Enhancing Equipment Efficiency

Measures to Reduce Cement & Steel

- Use of Supplementary Cementitious Materials (SCMs) Such as Slag, Fly Ash, Silica Fume
- **Use of Fiber Reinforcement instead of Rebar**
- Paste Volume Reduction through Aggregate Optimization

How to Calculate Unit Carbon Emission of Concrete


Environmental Product Declaration Type III ITB No. 215/2021

BEKAERT

EPD

Dramix® Steel fibres for Concrete Reinforcement

3D 4D 5D

EPD Program Operator:

Owner of the EPD:

$CO2_{eq}$ Factor: Amount of Equivalent CO_2 Per kg of Material

- Total Mass of $CO2_{eq}$ = Σ ($CO2_{eq}$ Factor x Mass of Material)

This is What We Want to Minimize

From Environmental Product Declarations (EPDs)

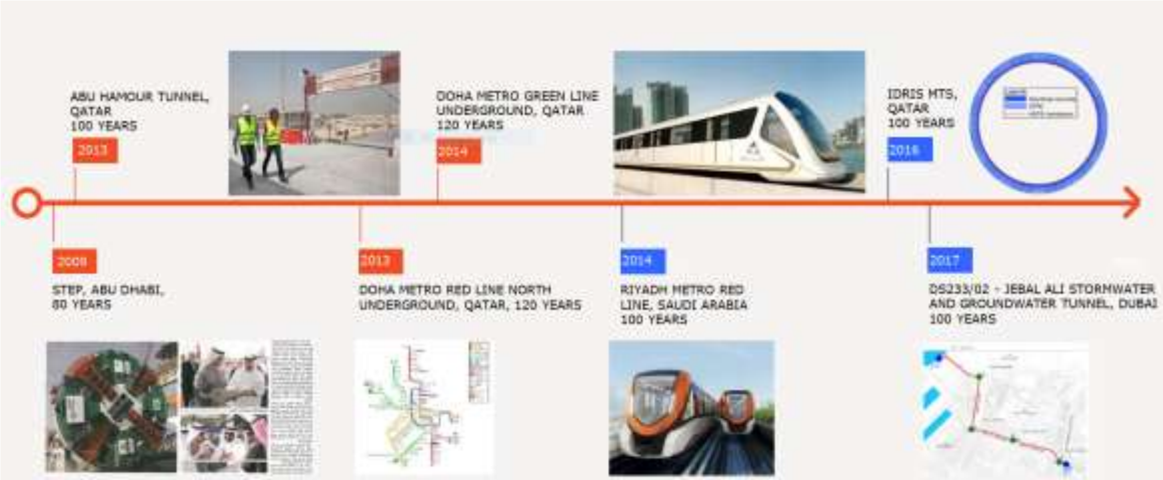
From Mix Design

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

A paper by consultant COWI Denmark entitled **'The consultant's view on service life design" C.** Edvardsen from COWI

Breakthrough in the Middle East - Timeline

Achievements made without sacrificing durability, through:



Main facts Doha

- Internal diameter of 6.17m about
- Design lifetime: 100 years

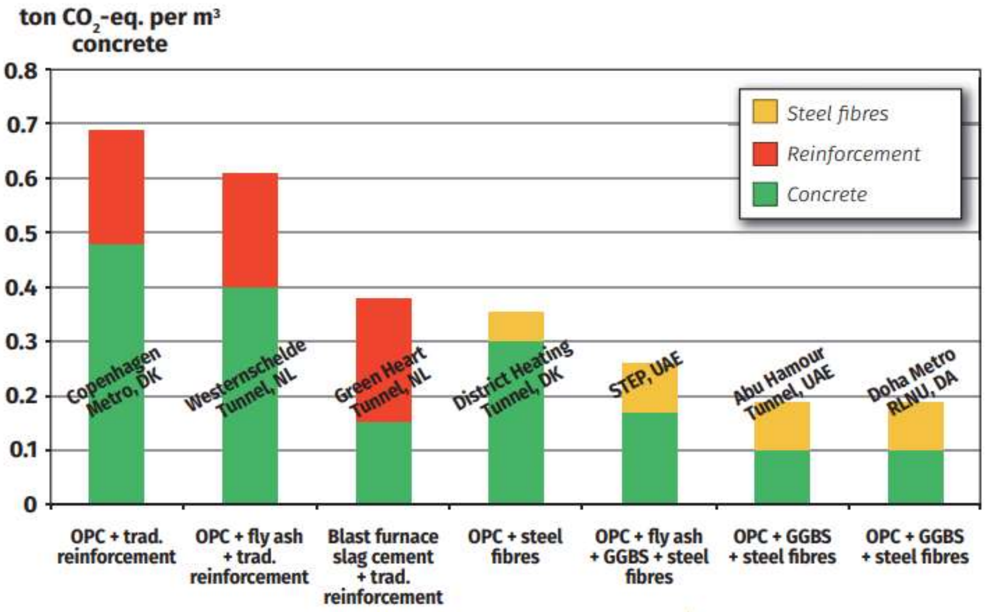
Conditions

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

- **Steel fibre: 100 years design life +Reduced CO2**
- Concrete mix design: High content of sup. Cementitious materials **(GGBS & FA) → 100 Years design life + Reduced CO2 emission**

Lesson learn : Durability and Sustainability goes hand in hand

Low Carbon Concrete Lining for tunnels - voice of the customers



Comparison of embodied CO2 for different types of binder and steel reinforcement used for various major infrastructure projects

A paper by consultant COWI Denmark entitled **'The consultant's view on service life design"** provides this example how much CO2 emission saving was reached by replacing traditional concrete and steel-reinforced with steelfiber reinforcement and adding GBBS/FA to the concrete mix.

- **Use of GGBS & FA: > 75% CO_2 reduction**
- **Use of steel fibres: > 50% CO_2 reduction**

- **Doha Metro have just 0,2to vs 0,7to of CO2 emission which Copenhagen Metro had.**

- **If Doha Metro would be built "traditional"… = 400.000 tons more CO2 emission**

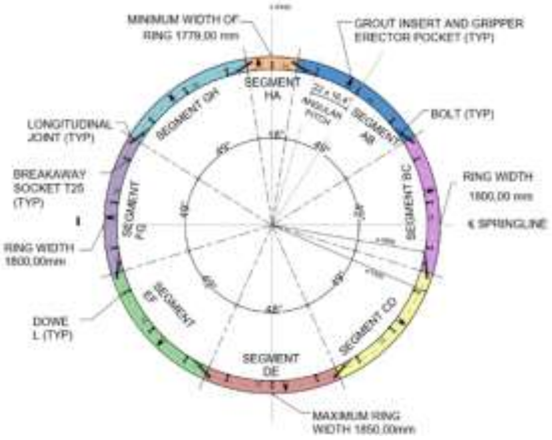
Note:
GGBS (Ground Granulated Blast-furnace Slag) is a cementitious material whose main use is in concrete and is a by-product from the blast-furnaces used to make iron.

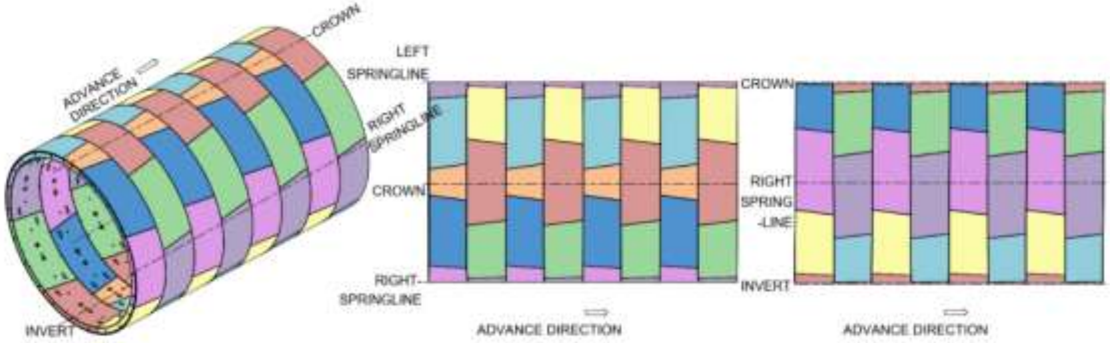
FA (Fly ash) is a particulate material produced from the combustion of coal in thermal power plants. It´s also a by product The fine powder does resemble Portland Cement but it is chemically different. Fly ash chemically reacts with the byproduct calcium hydroxide released by the chemical reaction between cement and water to form additional cementitious products that improve many required properties of concrete.

Montreal Blue Line Extension

AECOM

- 6 km two-track tunnel
- 5 new stations
- Internal diameter 8,6m
- 7+1 segments
- Thickness 350mm
- Only Reinforcement : 40kg/m³ Dramix high performance 4D80/60BGP

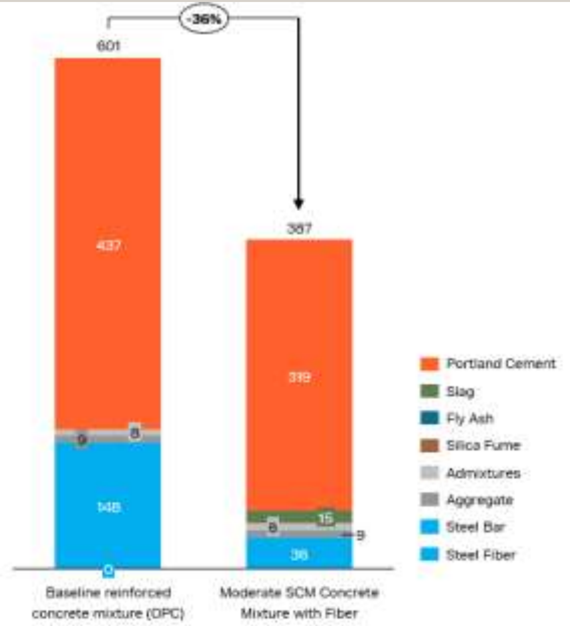




Applying ACI 544.7R for Design and Construction of FRC Tunnel Segments in North America with Fiber-Enabled Carbon Footprint Reduction – M. Bakhshi & V. Nasri

Courtesy of AECOM

Comparison between OPC and SCM concrete for segment design



– Embodied carbon in unit volume for the baseline and optimized final mix designs

<u>Step 1 Optimisation of concrete mix</u>

Partial replacement of OPC with SCM

Slag by 22%

Silica fume by 5%

Total replacement of rebars by 40kg/m3 steel fibre

Mix design components	CO_{2eq} Factor	Mass (kg/m³)	CO_{2eq} (Kg/m³)	% Replacement by Mass	Mass (Kg/m³)	CO_{2eq} (Kg/m³)	% Replacement by Mass
Portland Cement	0.92	475.0	437		346.8	319.1	
Slag	0.1466	0.0	-	0%	104.5	15.3	22%
Fly Ash	0.093	0.0	-	0%	0	0	0%
Silica Fume	0.014	0.0	-	0%	23.8	0.3	5%
Admixtures	1.67	0.0	7.5	1%	4.5	7.5	1%
Aggregate	0.06	4.5	8.6		1430	8.6	
Steel Bar	1.85	80	148.00		-	-	
Steel Fiber	0.7	-	-		40	28	
		Total	**601**			**378,6**	

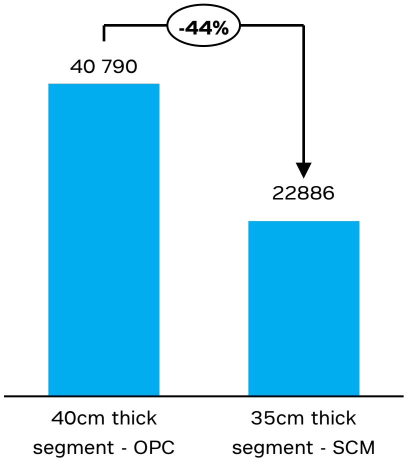
Comparison between OPC and SCM segments

Based on carbon embodied analysis

Step 2 Design optimization

Segment reduction thickness from 40cm design rebars to 35 cm design FRC just by eliminating intrados and extrados cover ref ACI 544

	Ring width (m)	Tunnel Length (m)	D_{ex} (m)	D_{in} (m)	Ring Volume (m^3)	Total Concrete Volume (m^3)	CO_{2eq} (Kg/m^3)	CO_{2eq} per 1 linear meter of Tunnel (ton)	Total CO_{2eq} (ton)
40cm thick segment – OPC	1.8	6000	9.4	8.6	20.4	67 858	601	6.8	**40 790**
35cm thick segment - SCM	1.8	6000	9.3	8.6	17.7	59 046	387	3.8	**22 886**



Total CO2eq (ton)

Total Carbon Saving with Optimized Design Enabled Using Fiber:

- Use of SCM: 8,578 ton (21%)
- Use of Fiber: 9,325 ton (23%)
- Total: 17,904 ton (44%)

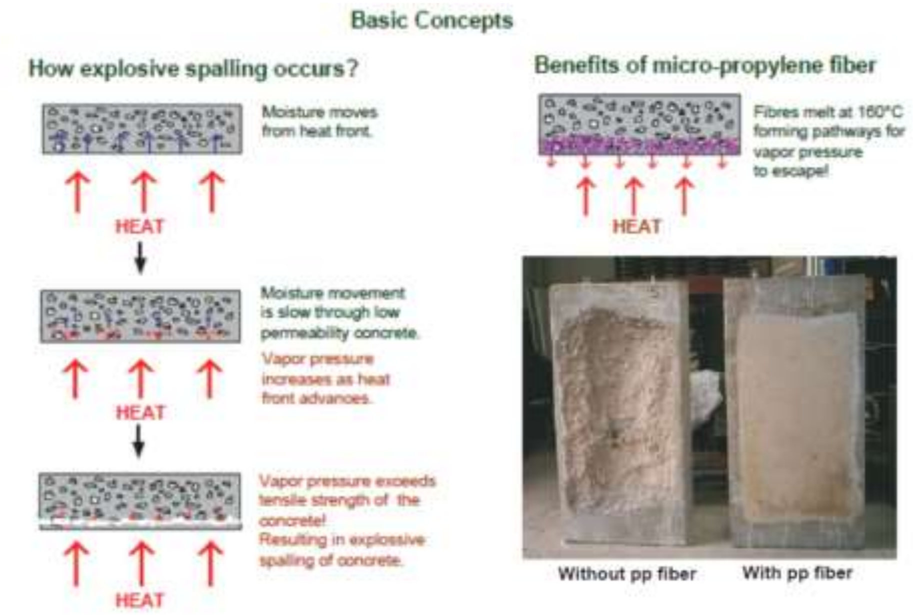
3 000 t C02 saving / km

Fire proctection

History on the Use of Micro-PP Fibers for PFP

A major fire in the Channel Tunnel between France and the United Kingdom in 1996 as shown. It was reported that a significant loss of cross-sectional area in the precast segmental tunnel lining had occurred due to severe spalling of the high strength concrete that had been exposed to very high temperatures. In some sections, the loss of concrete was so great that the embedded reinforcement steel had become so exposed that the structural integrity of the tunnel had been placed at risk. This spalling can not only become a structural issue, but it is also a life safety issue.

Basic concepts of the use of Micro-PP Fibers for PFP



The primary role of the short and very thin micro-PP fibers is to create a network of fibers, that then when exposed to heat will melt and create pathways for the vapor pressure (steam) to escape, thus preventing the explosive spalling. The concept of explosive spalling and prevention using micro-synthetic fibers.

Testing found that by ***inclusion of 1.0 kg/m³ of monofilament polypropylene fibers in the high strength, low permeability mixes significantly the risk of explosive spalling when exposed to a severe hydrocarbon fire was reduced.***

The CTRL project was the first project to use the recommended 1.0 kg/of micro-PP fibers for controlling explosive spalling. In this project 30 kg/m^3 of steel fiber was used as the only reinforcement along with the micro PP fibers as passive fire protection (PFP).

Conclusion

FRC is no more an exotic solution

Sustainability will be a new booster for FRC low carbon lining

High performance to meet structural & sustainable requirement

All the way from project start until its finalization, Bekaert will support you on your sustainability journey with Dramix®.

Thanks for your attention

Contact : benoit.derivaz@bekaert.com

Bekaert