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Fiber Reinforced Concrete to Mitigate Hazards of Tunnel Linings

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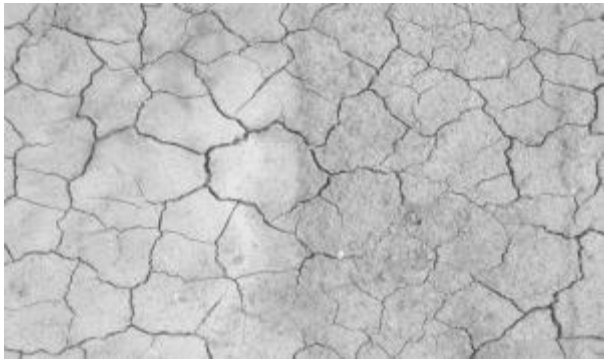
Introduction

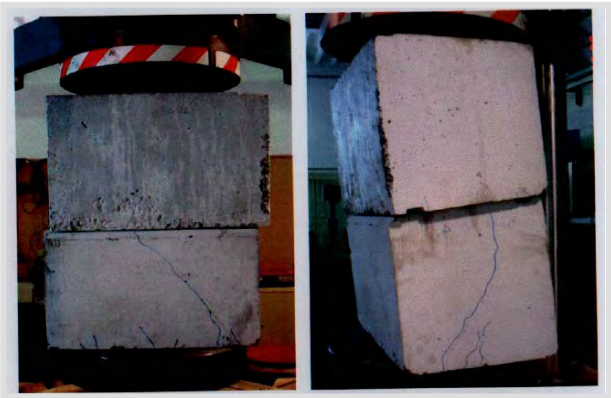
Concrete – Strong in compression but **Weak in..**



Plastic shrinkage

Explosive spalling

Bending



Shear / splitting

Performance improvements by fibers

- **Micro-synthetic fibers:**
  ➔ Material enhancement

- **Steel fibers:**
  ➔ Structural enhancement

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Introduction

Fiber Reinforced Concrete (FRC) containing fibrous material which increase its structural integrity. It contains short discrete fibers that are uniformly distributed and randomly oriented.

Types of Fibers;

- Steel Fibers

- Synthetic Fibers

Introduction (Cont...)

Fibers are usually used in concrete;

1. To inhabit cracking due to plastic shrinkage and drying shrinkage, to improve toughness and or to increase shear of the concrete.
2. Reduce the permeability of the concrete and thus reduce bleeding of water.

Fibers are not to be seen as replacement for rebars.

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Introduction (Cont...)

Advantages Of Fiber

1. Polypropylene and Nylon Fibers

- Improve mix cohesion and pump ability over long distances
- Improves freeze-thaw resistance
- **Improves resistance to explosive spalling in case of a severe fire:**
  1. Internationally proven to limit the occurrence of explosive spalling
  2. Recognized by designers and fire fighting authorities to protect the integrity of the concrete structure
  3. Mitigates damage and loss and Protect lives
- **Increase resistance to plastic shrinkage during curing**

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Introduction (Cont...)

Advantages Of Fiber (Contd..)

***2. Steel Fibers*;**

- Improve structural strength
- Reduce steel reinforcement requirements
- Reduce crack widths by holding it tightly, thus improve durability
- Improve impact and abrasion resistance
- Improve freeze-thaw resistance

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Steel Fiber Reinforced Concrete (SFRC)

Toughness and post-cracking behavior.

- After first cracking of concrete, steel fibers sew the cracks and give an extra strength. This deformation capacity provides ductility (toughness).
- The addition of fibers substantially improves the concrete characteristics transforming its behavior from elastic-fragile (Brittle)to elastic-plastic (ductile), making it suitable for structural applications.

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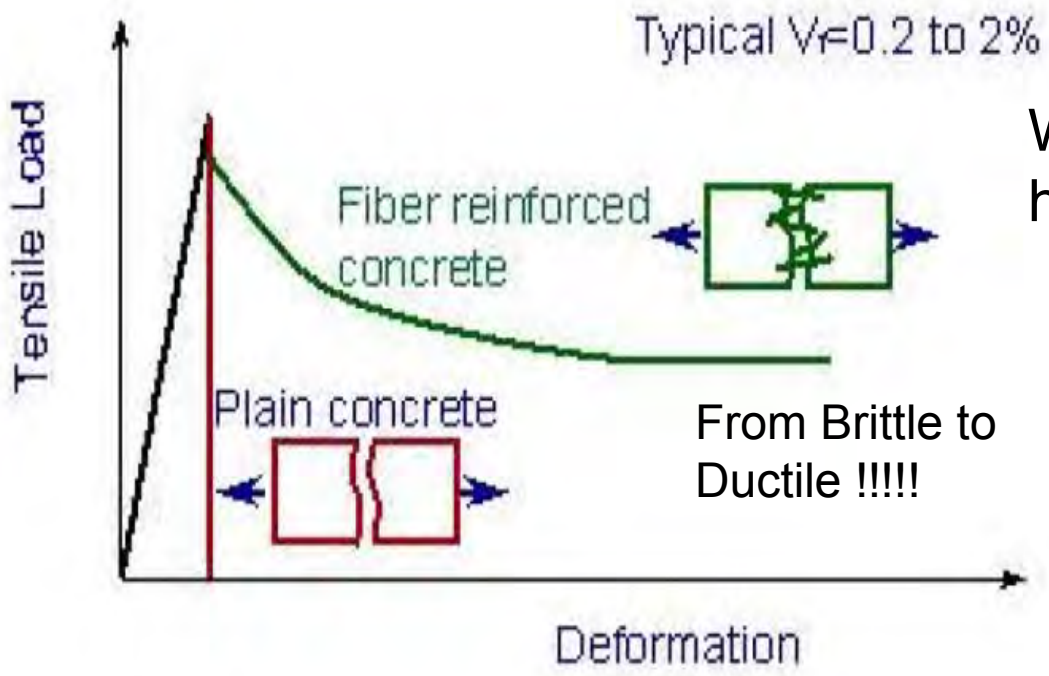
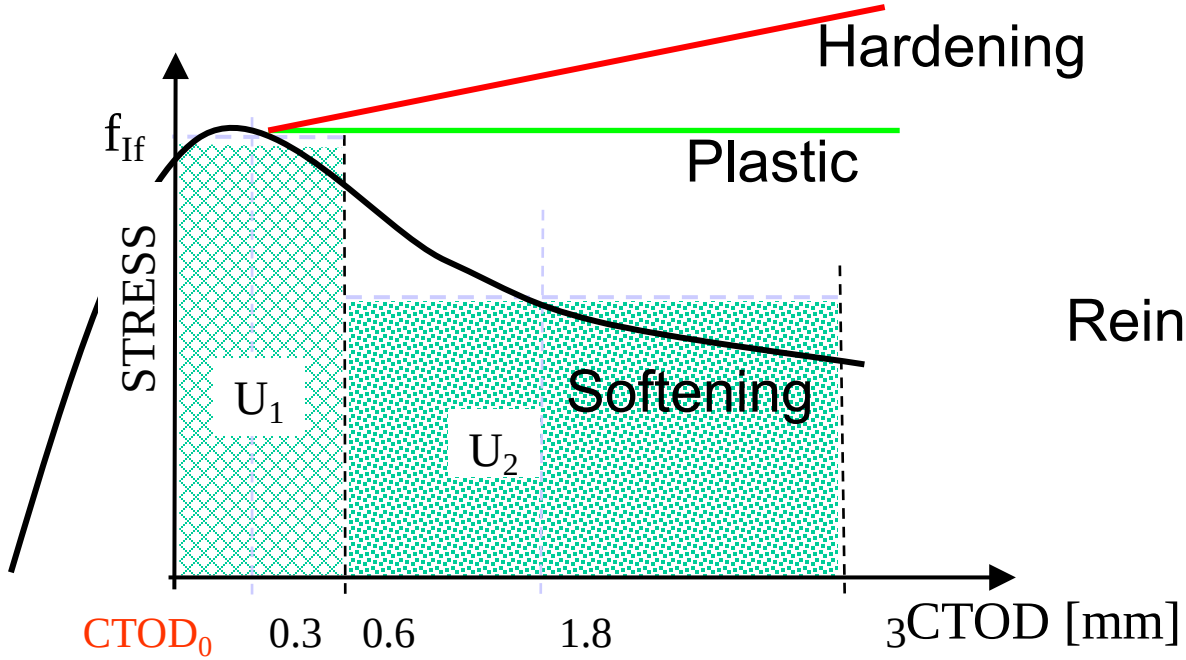
Fiber Reinforcement of Concrete



We can easily reach hardening behavior

From Brittle to Ductile !!!!!

Figure 1. Tensile Load versus Deformation for Plain and Fiber Reinforced Concrete.



Steel Fiber Reinforced concrete behavior

% feq

- >100% Hardening
- =100% Plastic
- <100% Softening

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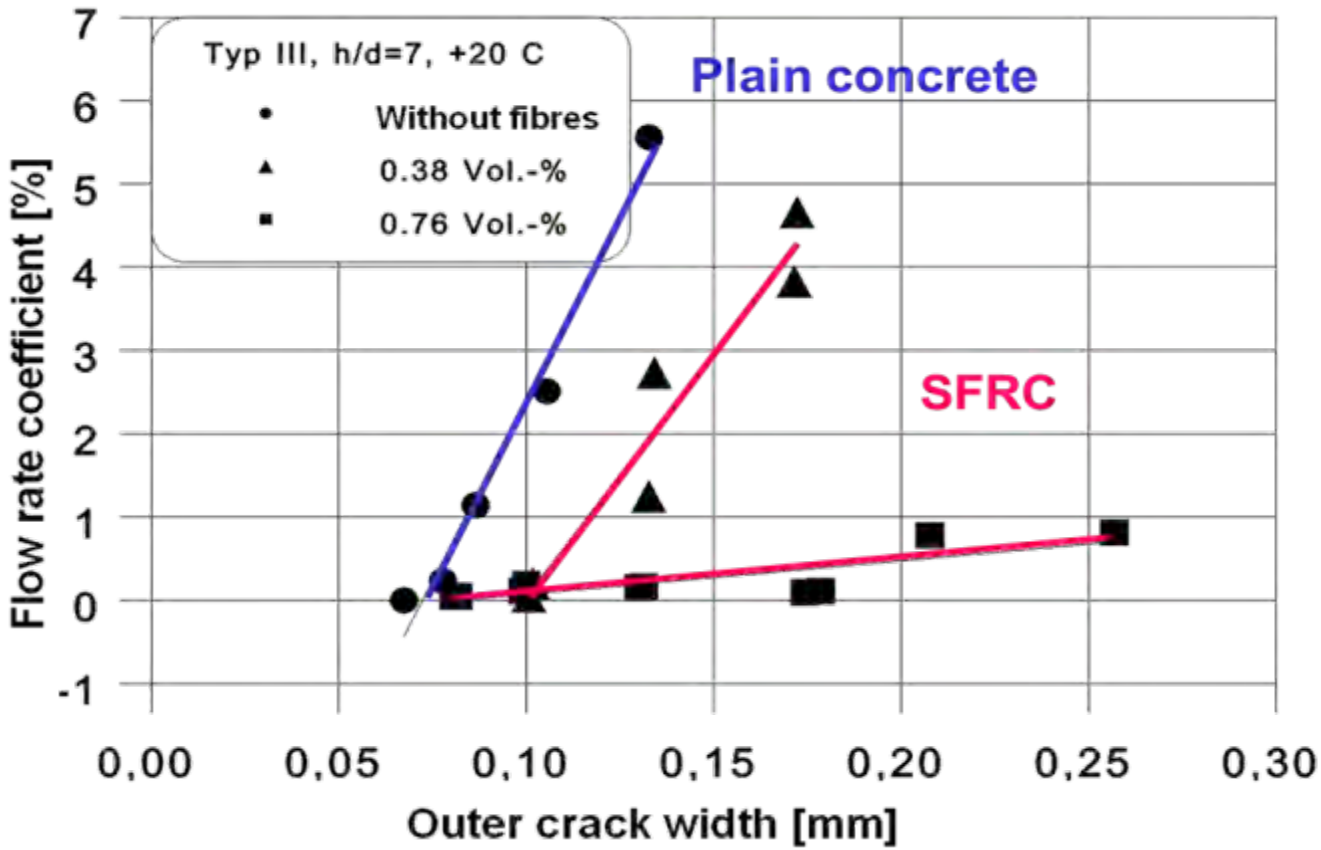
Flow Rates Of Water Through Separation Cracks



SFRC shows up to ***95%*** reduced flow rate coefficients

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Steel Fiber Reinforced Concrete (SFRC)

For design and the structural point of view the most important parameters to define the fibers' performance are:

1. Residual Strength Factor
2. Types and shape of the elements
3. Fiber length (L), diameter (D) and the Aspect ratio (L/D)
4. Strength and quality of the base material
5. Number of fibers per dosages weight (fiber count per weight)

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Fire Resistance

Concrete with Traditional Rebar

Fiber Reinforced Concrete

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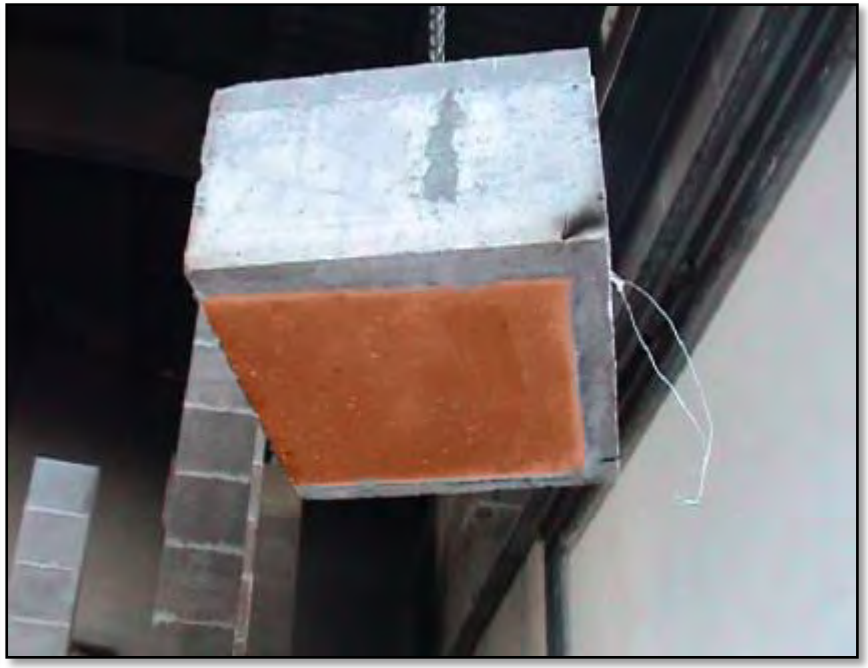
Test Results

Surface immediately after firing;

Plain Concrete



2kg/m3 of PP Fiber RC

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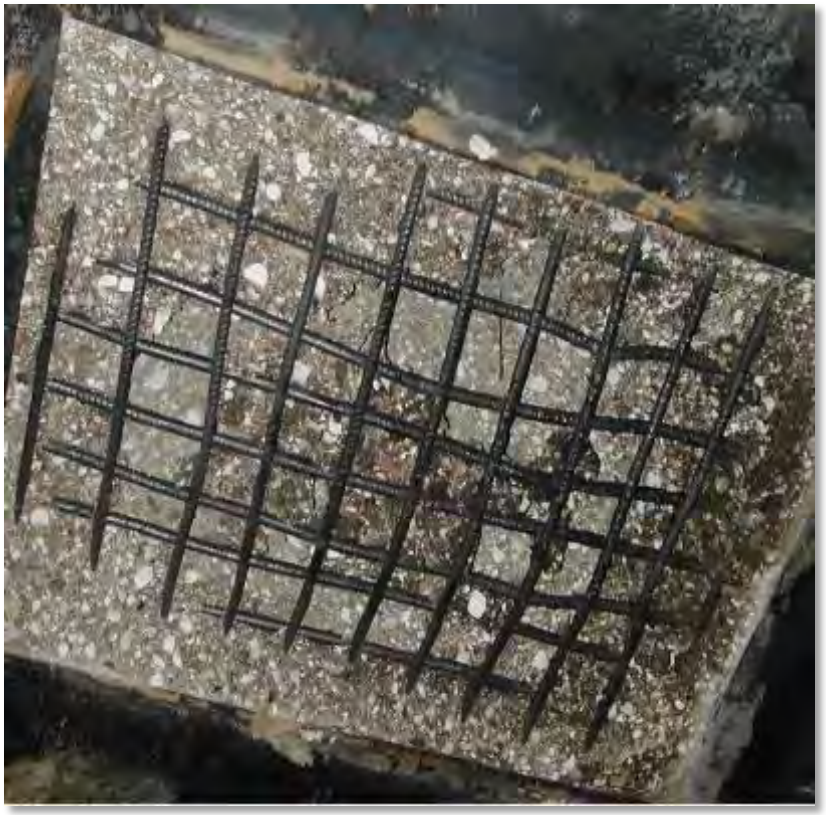
Test Results



Traditional RC

3kg/m3 of PP Fiber RC

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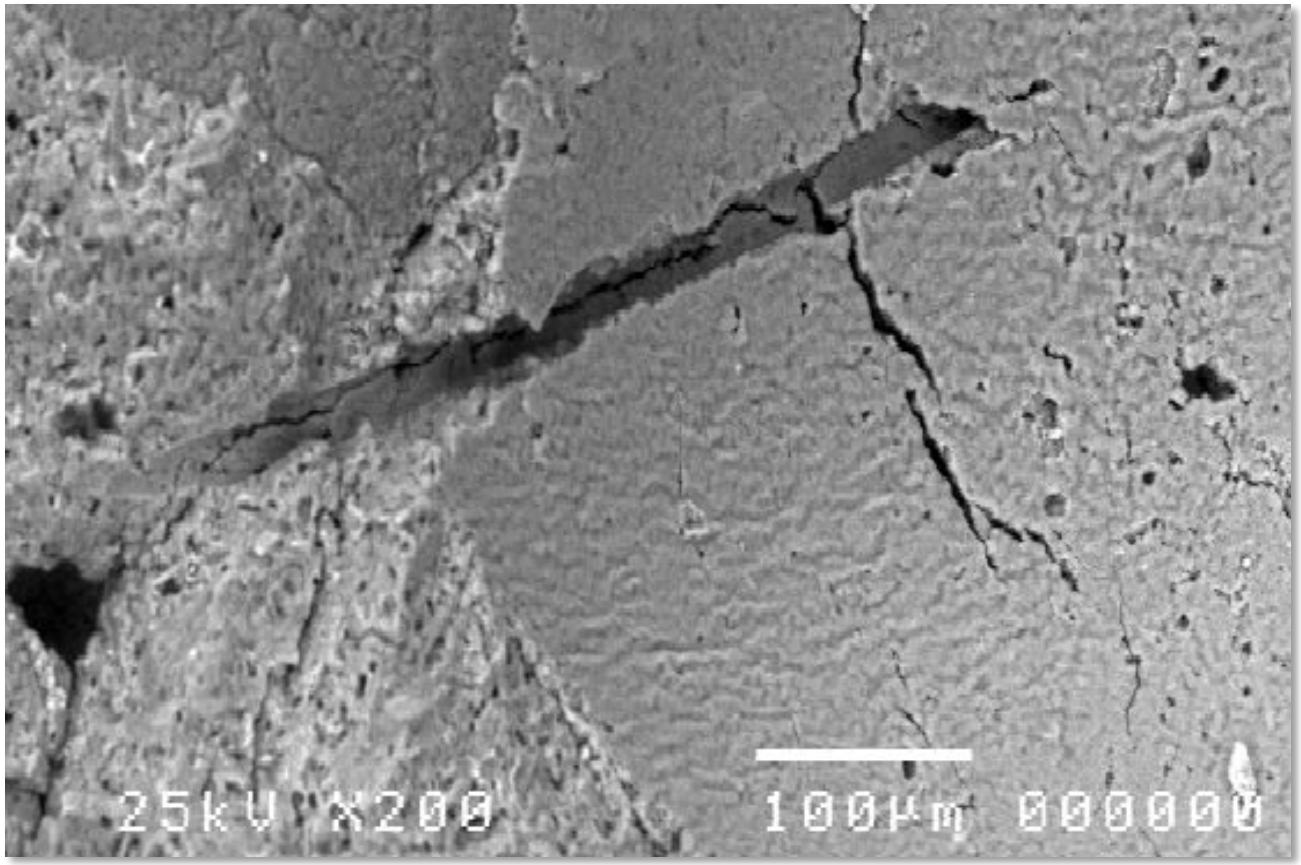
Test Results



Microscopic view of a void, created by a degraded micro-PP fibers

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Choice of PP Fibers

Primary requirement to reduce explosive spalling;

1. Fineness of the fibers
   - High number of individual fibers per unit weight
   - Large specific surface area per unit weight
   - Diameter of PP fiber < 20 microns

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Application of Micro Synthetic Fibers for Resistance to Explosive Spalling In Fires

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Tunnel Fires

- Great Belt Tunnel (Denmark, 1994)
- Channel Tunnel (UK-France, 1996)
- Mont Blanc (Italy-France, 1999)
- Kaprun (Austria, 2000)
- Gotthard (Italy-Switzerland, 2001)
- Baltimore Rail Tunnel (2002)

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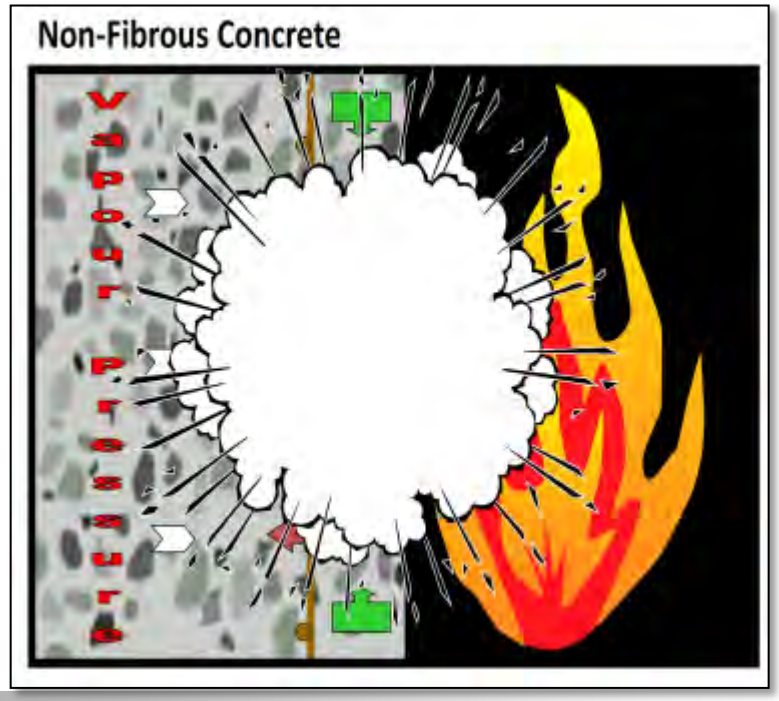
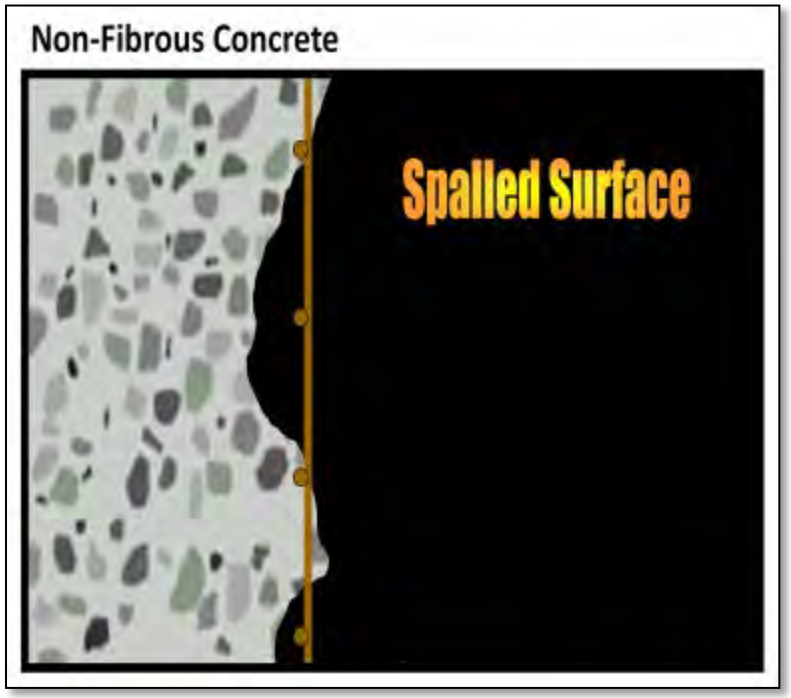
Explosive Spalling

- Most DANGEROUS form of spalling occurs during first 20-30 minutes when rapid heat rise is encountered
- Characterized by forcible separation of pieces of concrete and accompanied by a loud bang





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PP Fiber Degradation

- How PP Fiber Helps Against Fire?
- 160˚C ➔ Melting Temperature
  ➔ Creation of Voids
- Gases given off are burnt away by the fire or will dissipate into the atmosphere
- Toxic gas given off by the fire is so small that meets Health and Safety Regulations

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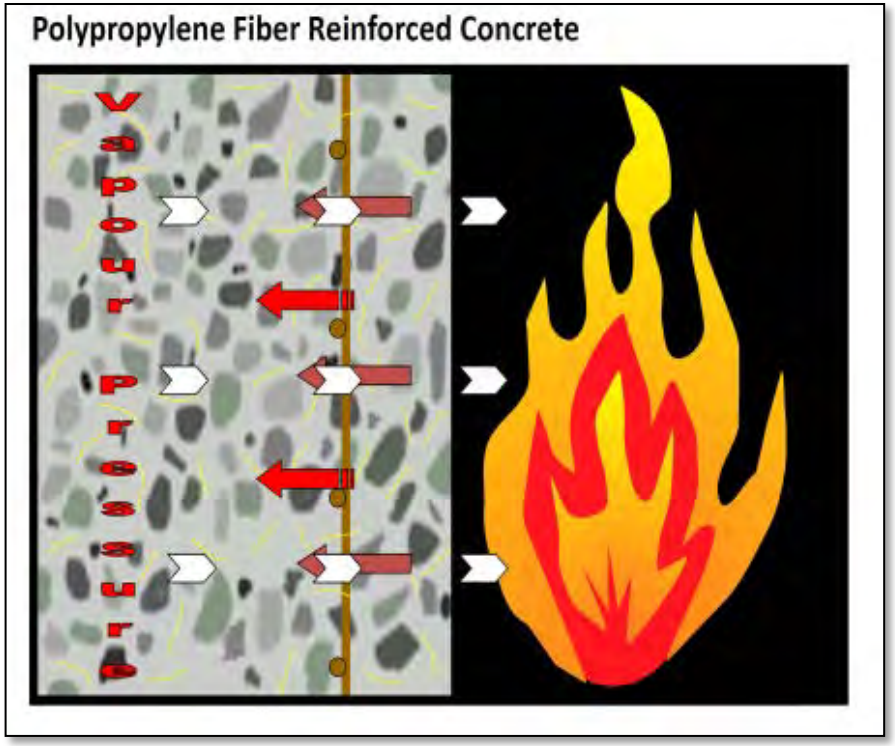
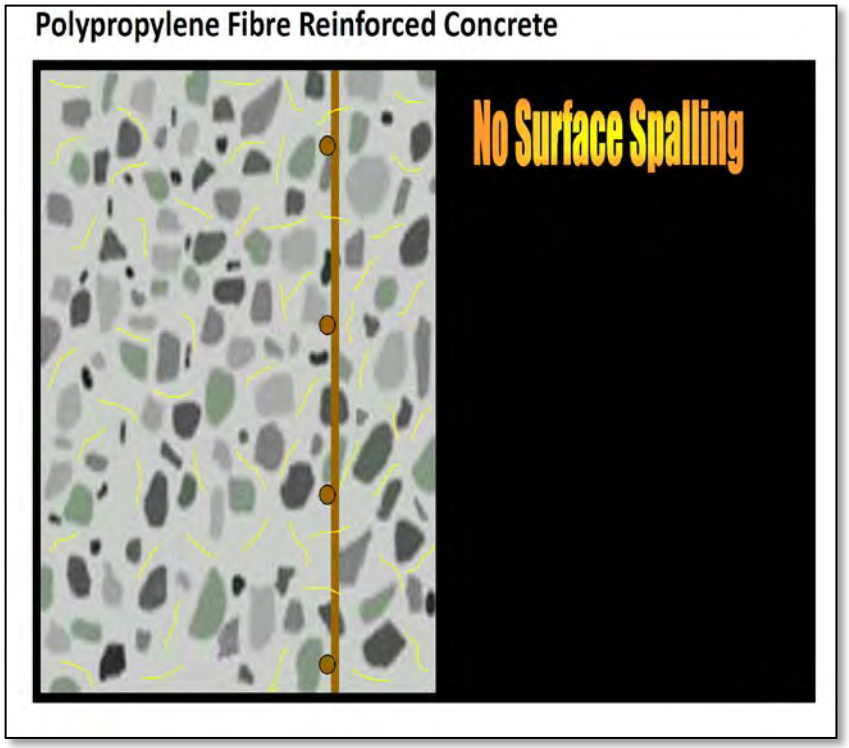
Behavior of Polypropylene Fiber Reinforced Concrete in Fire





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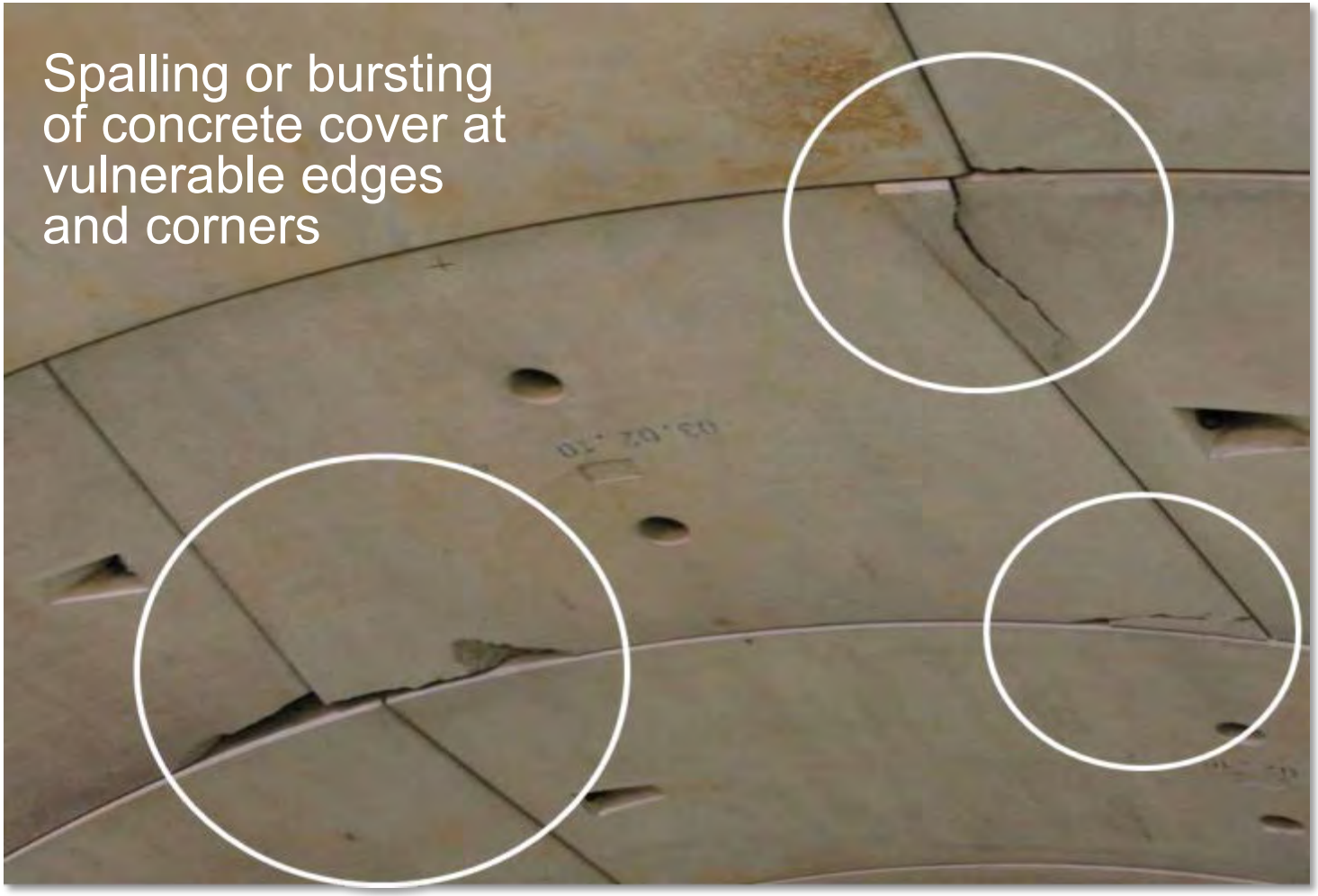
Problems of Conventionally Reinforced Concrete



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Precast segmental linings

Tunnel Linings

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Advantages of SFRC in Precast Tunnel Segments

1. SFRC is a **ductile and robust** material
2. Reduction of **crack widths**
3. High resistance against impacts during handling and placing of the segments
4. reduced risk of unexpected collapse or failure of the lining
5. Improved precast production efficiency by partial or total elimination of ordinary steel reinforcement

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Why using Fiber Reinforcement for Linings?

- Less steel ➔ lower carbon footprint
- Less production time ➔higher productivity
- Lower production costs ➔ less labor (i.e. less human errors)
- Ease of accuracy of reinforcement placement
- Higher robustness due to fiber reinforced cover concrete
- High crack resistance, better crack control (i.e. better durability)

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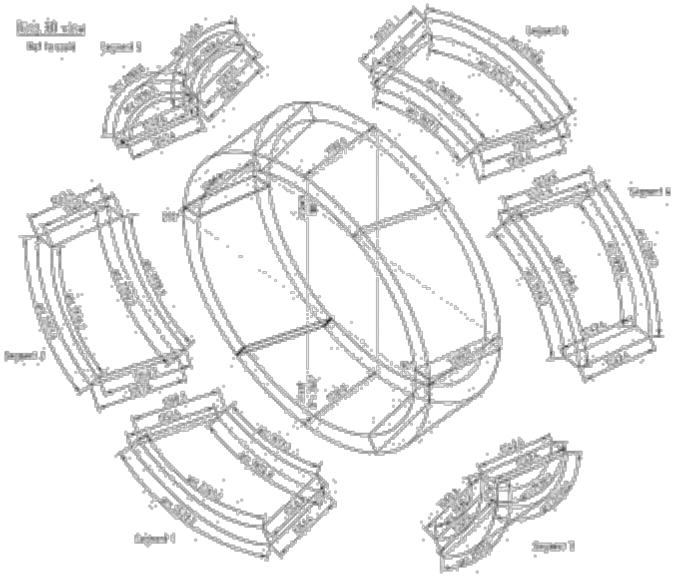
CASE STUDY
Hobson Bay Tunnel Lining, New Zealand

Geometry of the Tunnel and the segments

- Tunnel Length 9843 ft. (3.0 km)
- Internal diameter 12 ft. (3.70 m)
- Wall thickness 9.84 in. (250 mm)
- Ring setup 4+2
- Segment slenderness 8.3
- Ring width 3.9 ft. (1.20 M)



- Conventional reinforcement: 184 kg/m3 (tender design)
- **Alternatively chosen SFRC solution: 40 kg/m3 of Wirand FF3**

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Production Highlights

Quality Assessment:

- 15,000 segments produced
- 7 segments rejected as defective (0.05%)
- 6 damaged during installation (0.04%)

Total Reject Rate < 0.1%

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Production Highlights

Cost Assessment:

- 50% time saving on segment production
- 10% cost saving on total project cost (NZ$118.6 million)

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Preparation of Specimens

Cube - Compressive strength

3 cubes @ 1 day

6 cubes @ 7 days

12 cubes @ 28 days

6 cylinders @ 7 days

12 cylinders @ 28 days

12 beams @ 28 days

Cylinder - Tensile splitting strength

Beam - Flexural Strength

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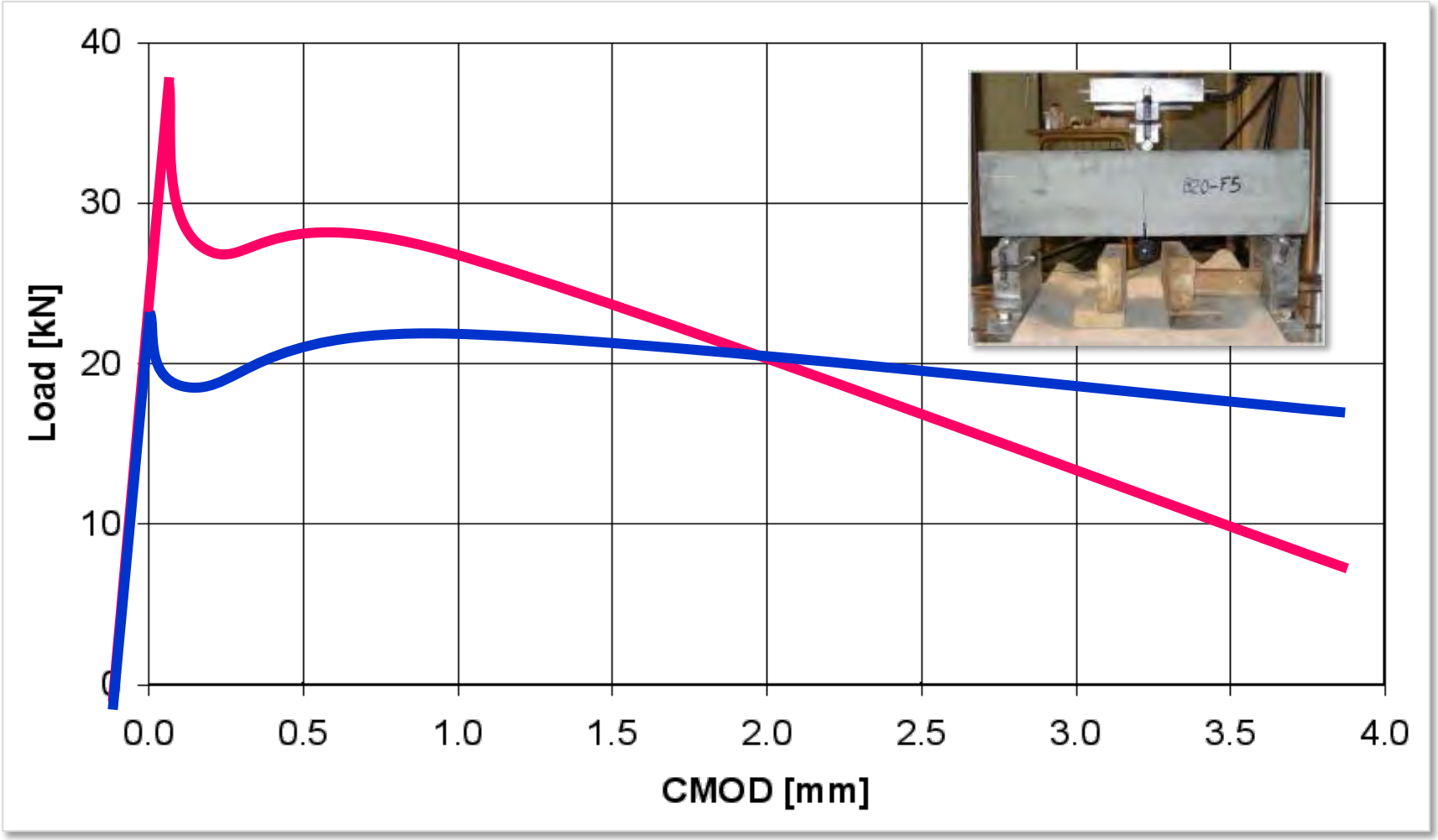
Higher Strength ➔ Higher Brittleness



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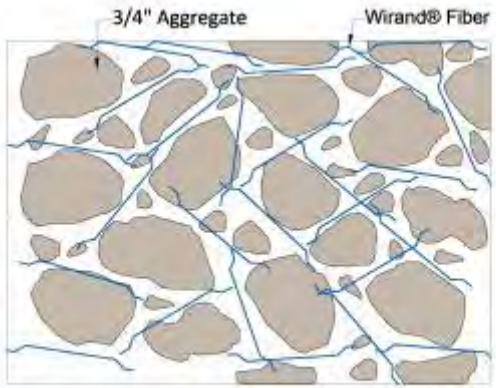
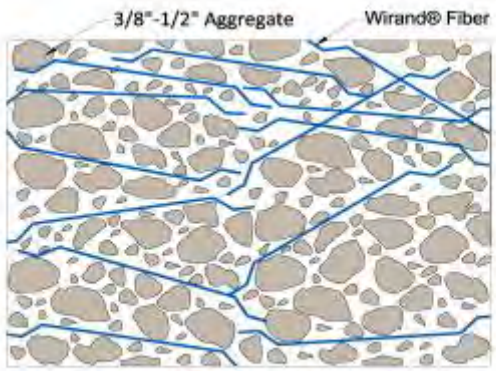
Concrete Mix Design is Very Important to Create a Well Performing Composite



Incorrect Fiber to Aggregate Ratio:
Inefficent Space Overlaping



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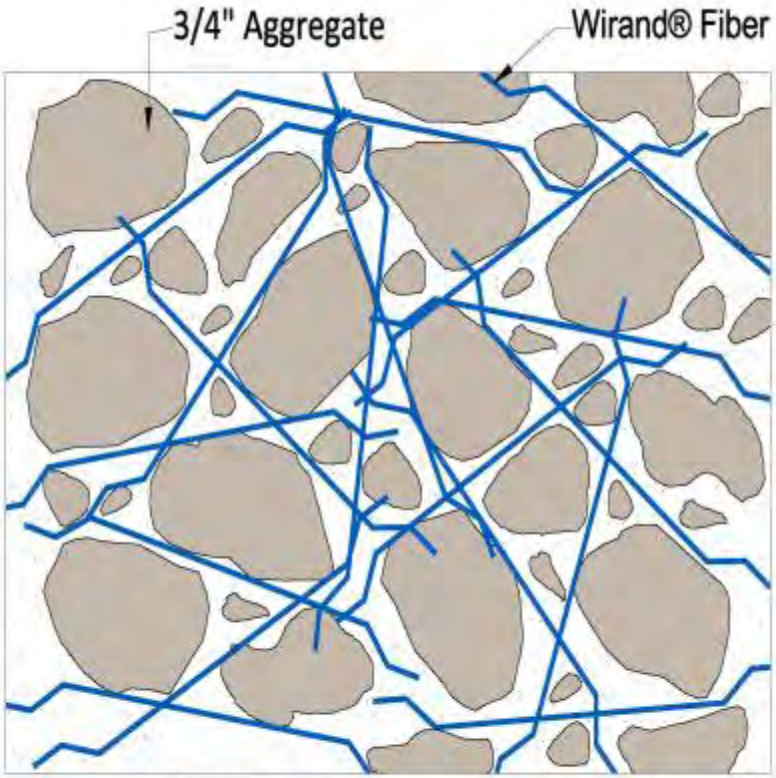

Correct Fiber to Aggregate Ratio:
Efficent Space Overlaping

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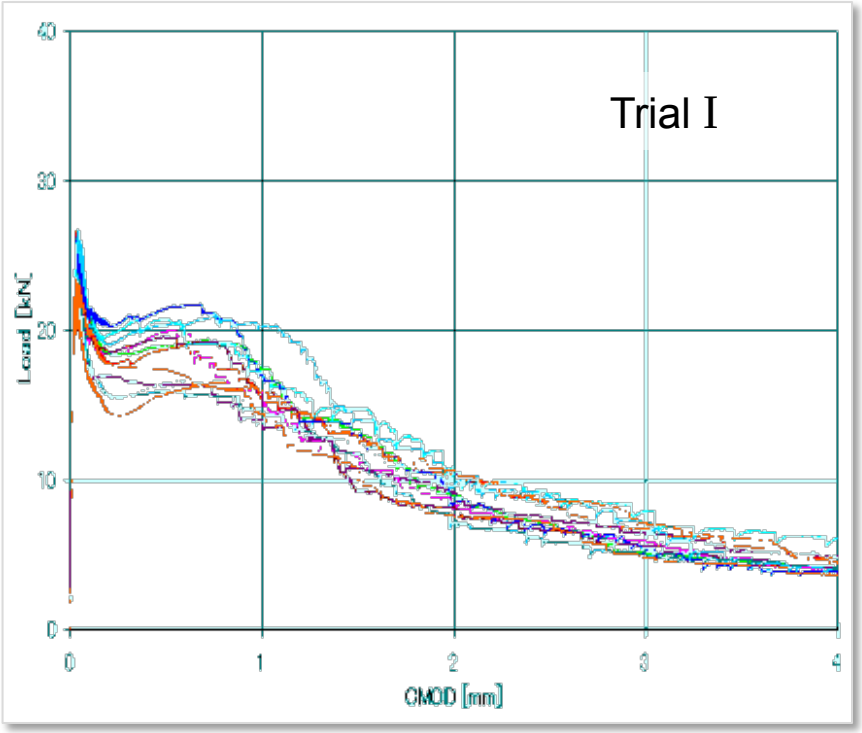
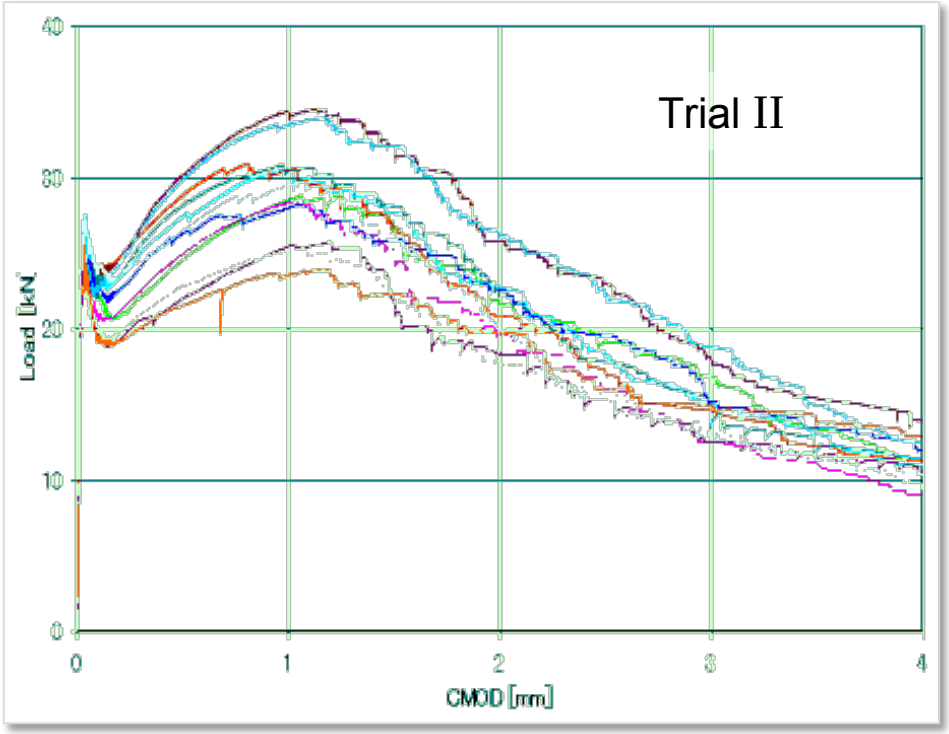
LOAD vs CMOD (Graphs)





Identical mix design, just different grade and quality of aggregates

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General Dosage and Typical Lining Thickness by Energy Absorption Test

TUNNELING - SHOT CRETE			
Usual dosage and typical lining thickness by Energy Absorption Test			
Fiber Type	ASTM C1550 = 225 J	ASTM C1550 = 350 J	ASTM C1550 = 450 J
	Dosage kg/m³ (lb/y³)	Dosage kg/m³ (lb/y³)	Dosage kg/m³ (lb/y³)
Wirand® FS1	25 (44)	30 (50)	35 (60)
Wirand® FS3N	35 (60)	40 (67)	45 (75)
Wirand® FS4N	30 (50)	35 (60)	40 (67)
Wirand® FS7	25 (44)	30 (50)	35 (60)

Notes: The predominant aggregate recommended for the concrete mix design is 1/2". The values consider the experience with concretes from 4000 psi to 5000 psi of compression resistance.

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Steel Fiber In Precast Tunnel Segments

PRECAST TUNNEL SEGMENTS

Usual dosage and thickness by application

Fiber Type	Mix RR + SFRC		SFRC	
	Dosage kg/m³ (lb/y³)	Thickness mm (in)	Dosage kg/m³ (lb/y³)	Thickness mm (in)
Wirand® FF1	25-35 (44-60)	250-400 (10-16)	40-60 (67-100)	250-400 (10-16)
Wirand® FF3	20-30 (34-50)	250-400 (10-16)	35-50 (60-85)	250-400 (10-16)

Notes: The predominant aggregate recommended for the concrete mix design is 1". The values consider the experience with concretes from 4000 psi to 6000 psi of compression resistance. RR=Rebar Reinforcement SRFC=Steel Fiber Reinforced Concrete

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Case Study: Blue Plains – DC Clean River Project

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Blue Plains Tunnels

- The DC Water Clean Rivers Project (Combined Sewer Overflow Control Program) is an activity of DC Water's Long Term Control Plan (LTCP).
- The LTCP is required by the US Environmental Protection Agency to reduce pollution from combined sewer overflows (CSOs) to Rock Creek and the Anacostia and Potomac rivers.
- In achieving this goal, DC Water will implement a system of tunnels, sewers and other division structures to control and capture throughout the city.
  - 13 miles tunnel system for the Anacostia is divided into 3 segments
  - The TBM is making its way along the first segment, more than four miles along the Potomac and the Anacostia rivers
  - At a depth of approximately 100 feet.

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Technical Characteristics

The Scope of the Blue Plains Project Materials:

- Precast Segments are 14” thick
- Tunnel Outside Diameter 25’ 4”
- Tunnel Inside Diameter 23’ 0“
- Tunnel Segments are fully reinforced with Wirand® FF3 HS

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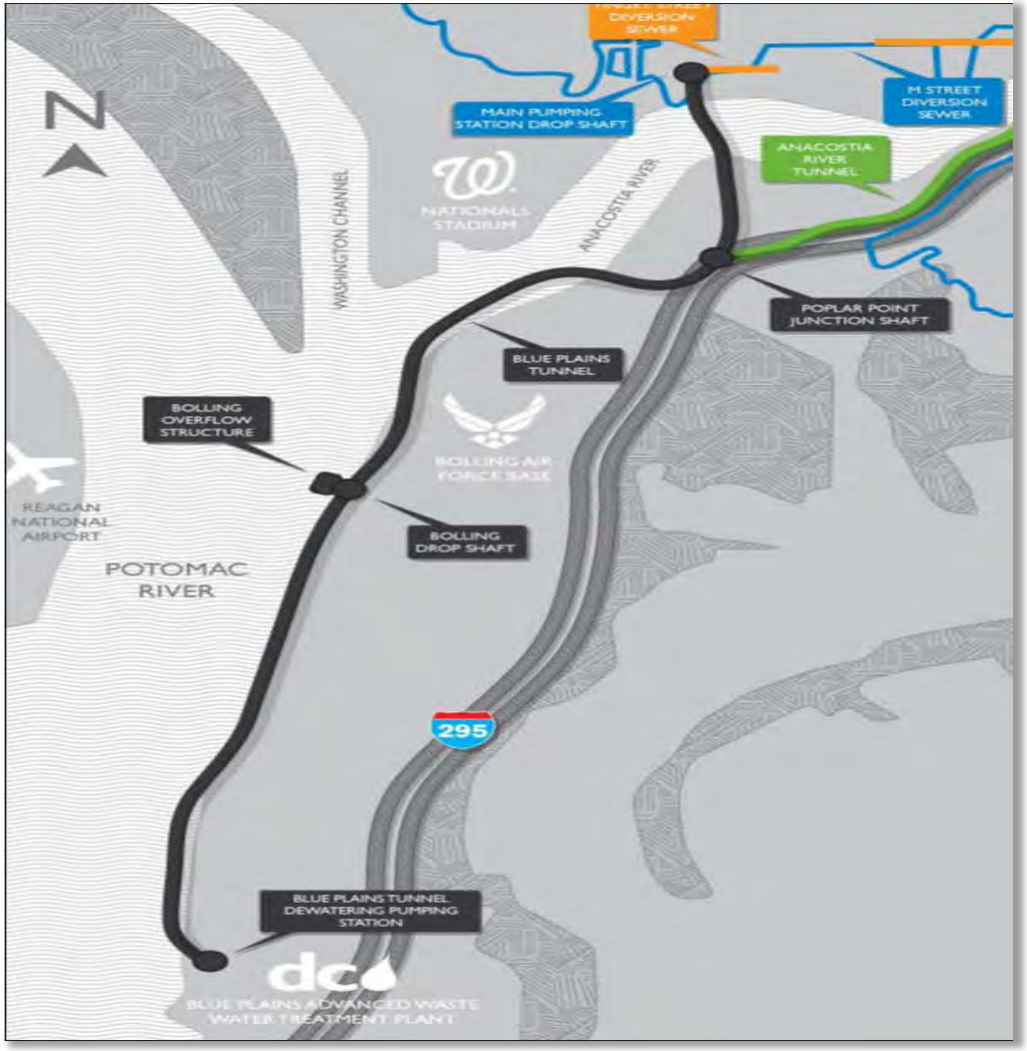
Location Map Blue Plains Tunnel



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Precast Segmental Lining

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THANK YOU FOR YOUR ATTENTION!!!!!
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