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Society for Rock Mechanics & Engineering Geology, Singapore
Technical Seminar on Fiber Reinforced Sprayed Concrete
State of the Art, Specifications, and Standards

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Fibre Reinforced Sprayed Concrete Properties

- **Fibre reinforced sprayed concrete (FRS)** is a **mortar** or **concrete** containing discontinuous **steel or synthetic fibres**, which are pneumatically **projected** at high velocity onto a surface

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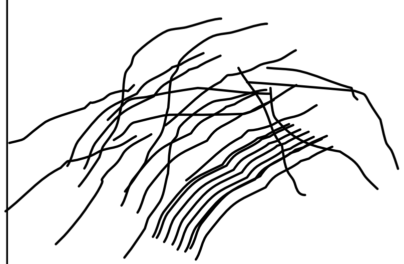
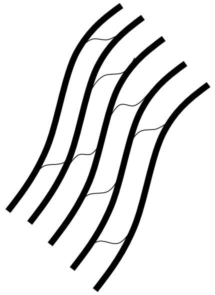
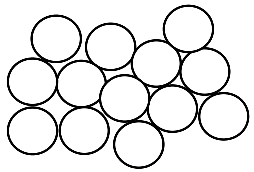
Micro synthetic Fibres

Fibre Reinforced Sprayed Concrete Properties

	multifilament	**fibrillated**
		
fibre section(s)		
# fibres (mio/kg)	200 – 300	10 - 20
specific area (m^2/kg)	200 – 300	40 - 80

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Fibre Reinforced Sprayed Concrete Properties

Macro synthetic Fibres

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Fibre Reinforced Sprayed Concrete Properties

- Modulus of Young – reinforcing ability of the material
  - STEEL = 210 000 MPa
  - POLYPROPYLENE = 3000 – 5000 MPa
  - CONCRETE = 30 000 MPa

- Tensile strength – reinforcing ability of the material
  - STEEL = 1000 – 2000 MPa
  - POLYPROPYLENE = 300-600 MPa
  - CONCRETE = 0 MPa

- Specific density
  - STEEL = 7850 kg/m^3
  - POLYPROPYLENE = 910 kg/m^3
  - CONCRETE = 2400 kg/m^3
  - WATER = 1000 kg/m^3
  - Contra: PP fibres float on water

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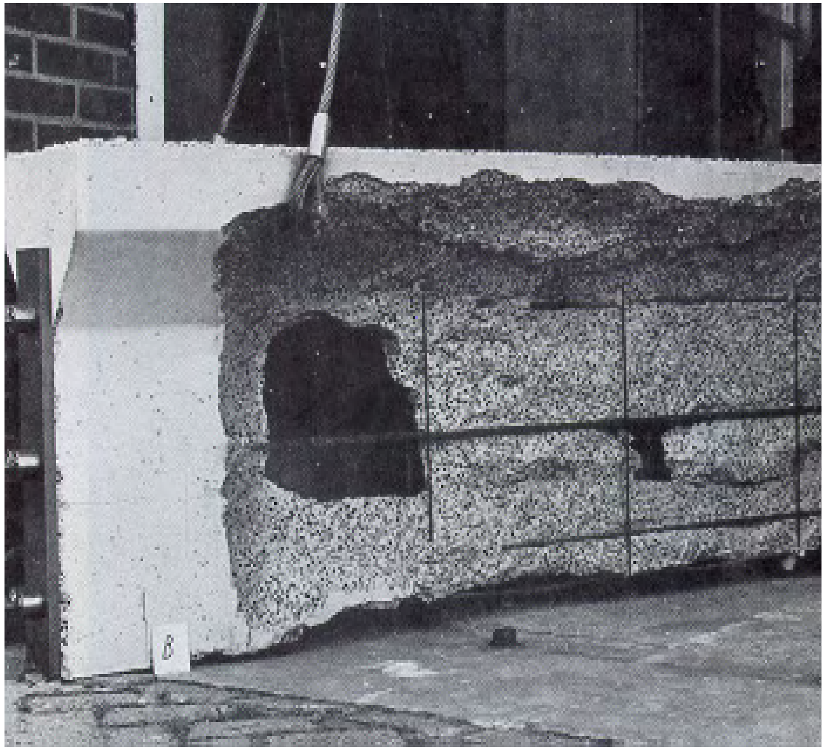
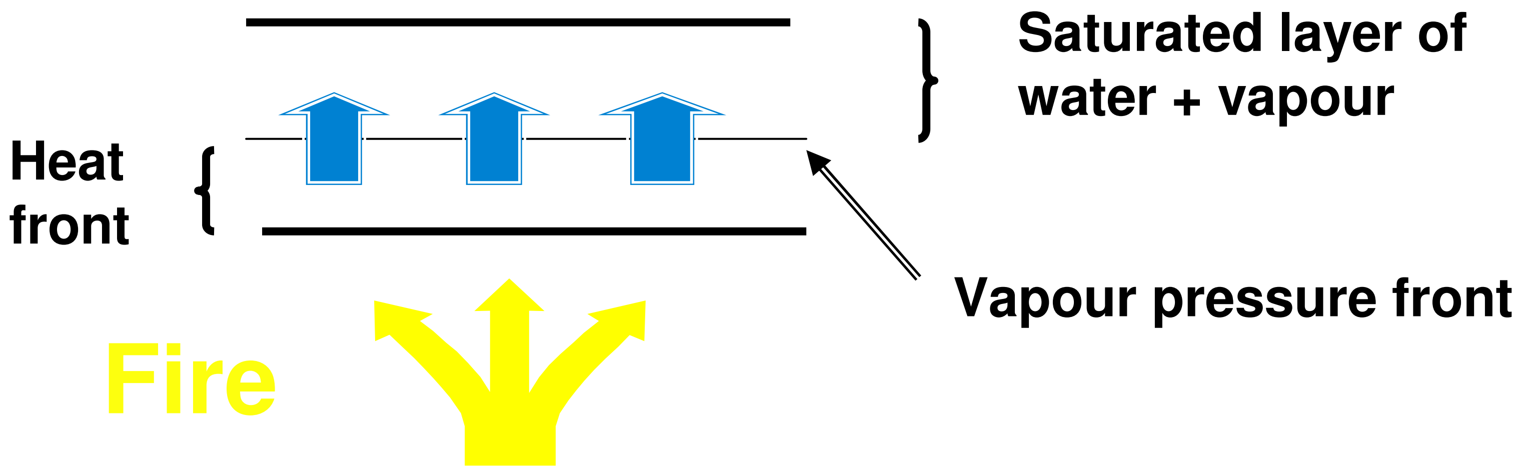


Spalling of concrete

= When concrete is being exposed to fire, small or even big pieces are blown of



Exposed to fire, the water at the heat front evaporates → this vapour will move towards the cold front and will be absorbed in the voids → saturated layer → when this layer cannot move fast enough, the heat front will reach this saturated front → creation of higher vapour pressure will lead to spalling

Fibre Reinforced Sprayed Concrete Properties

- How to avoid spalling of concrete?
  - adding monofilament PP fibres: these will melt (165°C) and create high amount of 'channels' → the vapour pressure can escape more easily → no spalling
  - adding steel fibres: these will not prevent spalling but will hold the pieces together

Fibre Reinforced Sprayed Concrete Properties

	Micro Synthetic Fibre Reinforced Concrete	Steel Fibre Reinforced Concrete
strength and toughness		***
energy absorption		***
resistance to plastic shrinkage	***	
Freeze-thaw resistance	***	
resistance to spalling in a fire	***	*
impact resistance	*	***
resistance to drying shrinkage		***
structural reinforced concrete		***

Micro synthetic fibres = non-structural ; Macro synthetic & steel fibres = structural

⇒ Micro synthetic fibres can never replace macro synthetic or steel fibres

⇒ However, they can be complementary

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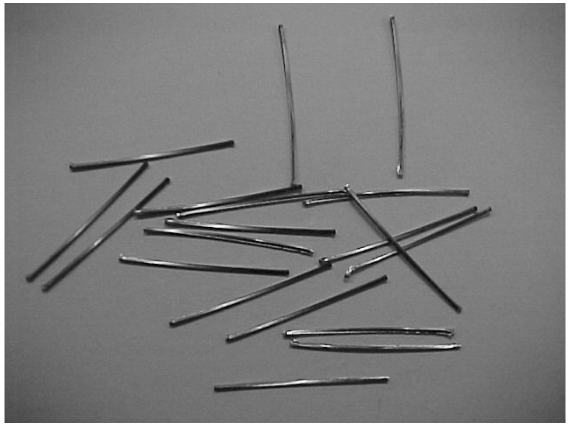
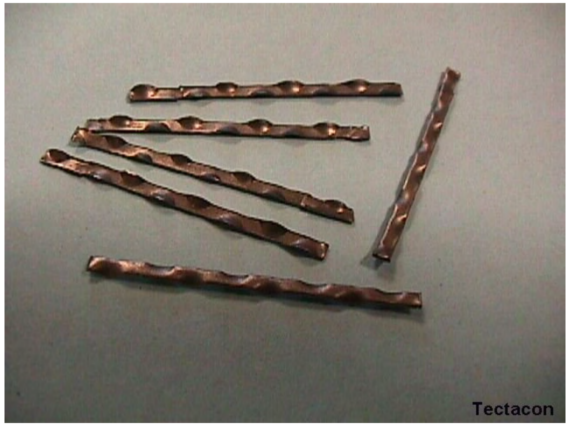
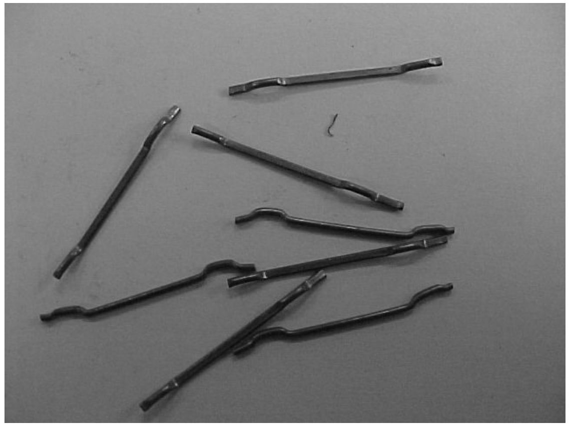
Fibre Reinforced Sprayed Concrete Properties

- Length and diameter: aspect ratio (L/d)
- Shape of the fiber, or the anchorage
- Strength of the fiber
- Strength of the matrix (concrete)







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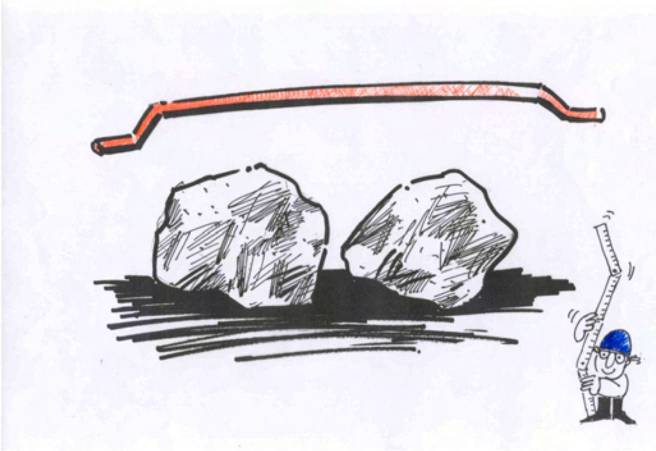
Steel fiber characteristics

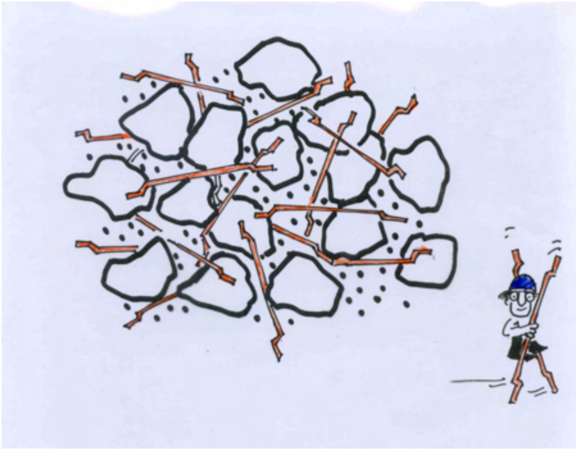
Fiber length

1. Bridge the crack
2. Overlap 2 aggregates
3. Workabilty : pumping, and hose diameter



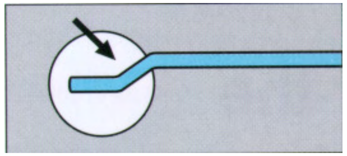
Small fiber section

1. More fibers per kilo
2. Shorter distance between the fibers – networking effect
3. More contact surface steel/ concrete per unit weight

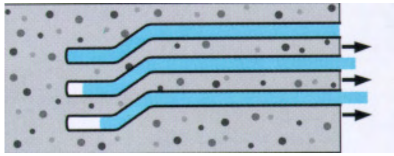


The quality of FRS is due to a combination of factors

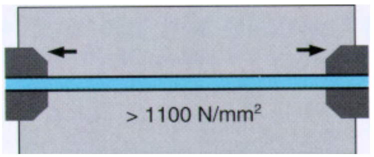
- A **high length-diameter ratio** (L/D ratio)
- **Hooked ends**



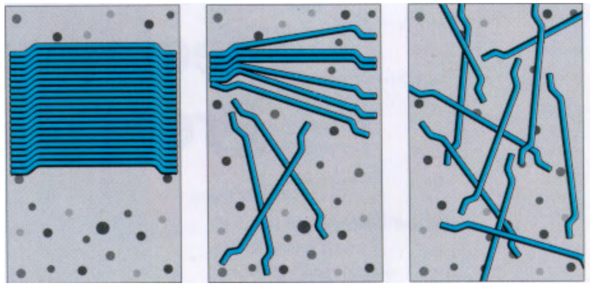
- **Controlled pull-out** (due to deformation of the hook)

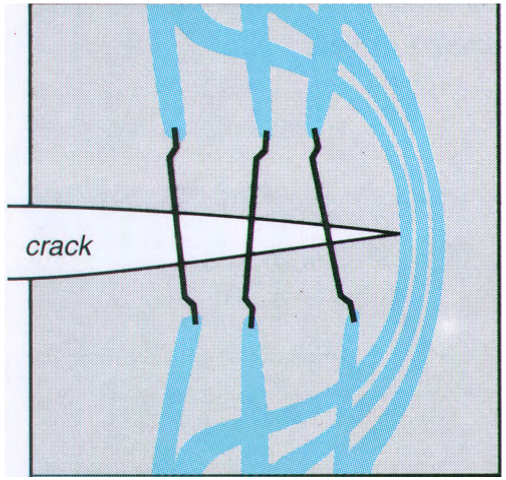


- **High tensile strength steel**



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





Concrete spalling is excluded

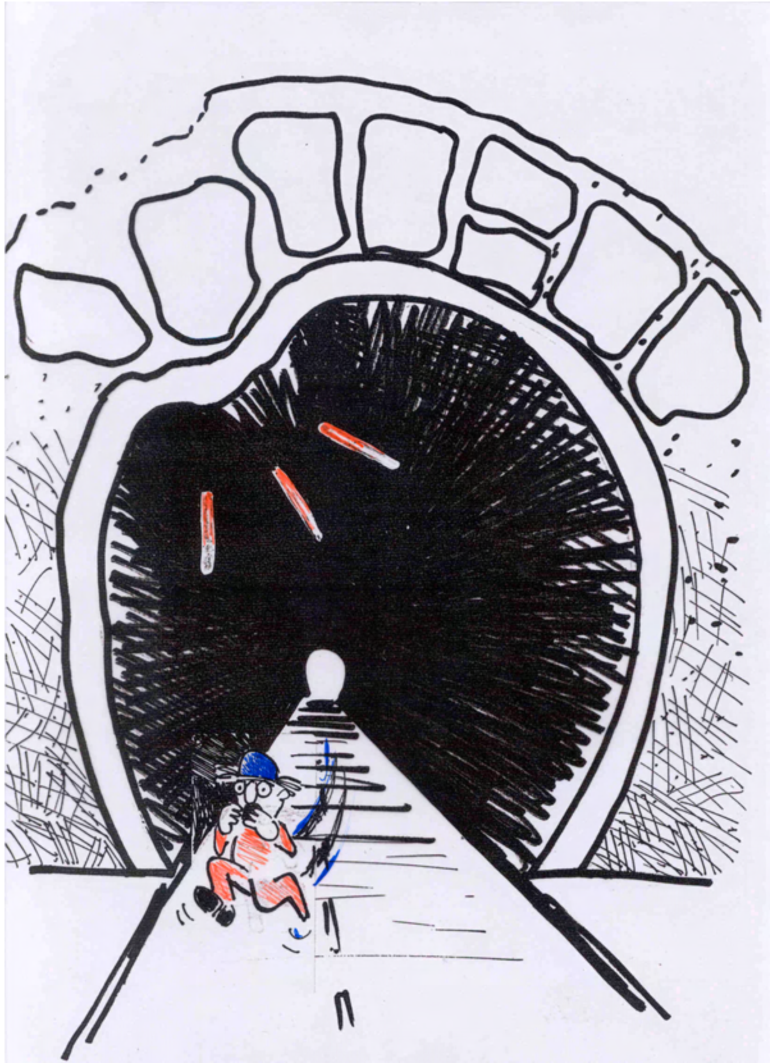
Spalling of concrete caused by rusting reinforcement bars is physically impossible with fibre reinforcement concrete due to :

- small fibre diameter
- non continuous reinforcement
- high surface / volume ratio.

This type of damage is not possible with FRS

Fibre Reinforced Sprayed Concrete Properties

- *Steel fibres are incorporated in the concrete to improve:*
    - the ductility
    - the energy absorption
    - the crack resistance
    - the impact resistance
- *Modern tunnelling methods include mobilising the strength of the ground by promoting ductility of the lining*



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Sprayed Concrete

high initial strength for a good bond to the rock

ductility to absorb and block rock movement

safe working conditions

faster job progress

Fibre Reinforced Sprayed Concrete Properties

Steel or macro synthetic fibres

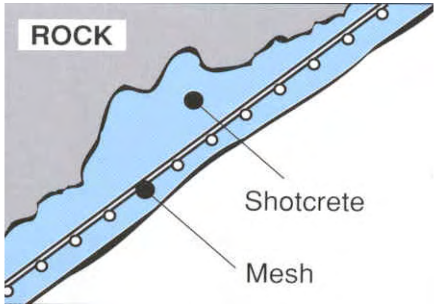
provide a better bond due to a higher crack resistance

a high degree of ductility

incorporated reinforcement reducing the cycle time and increasing the safety for the tunnelling crew

Mesh Reinforced Sprayed Concrete

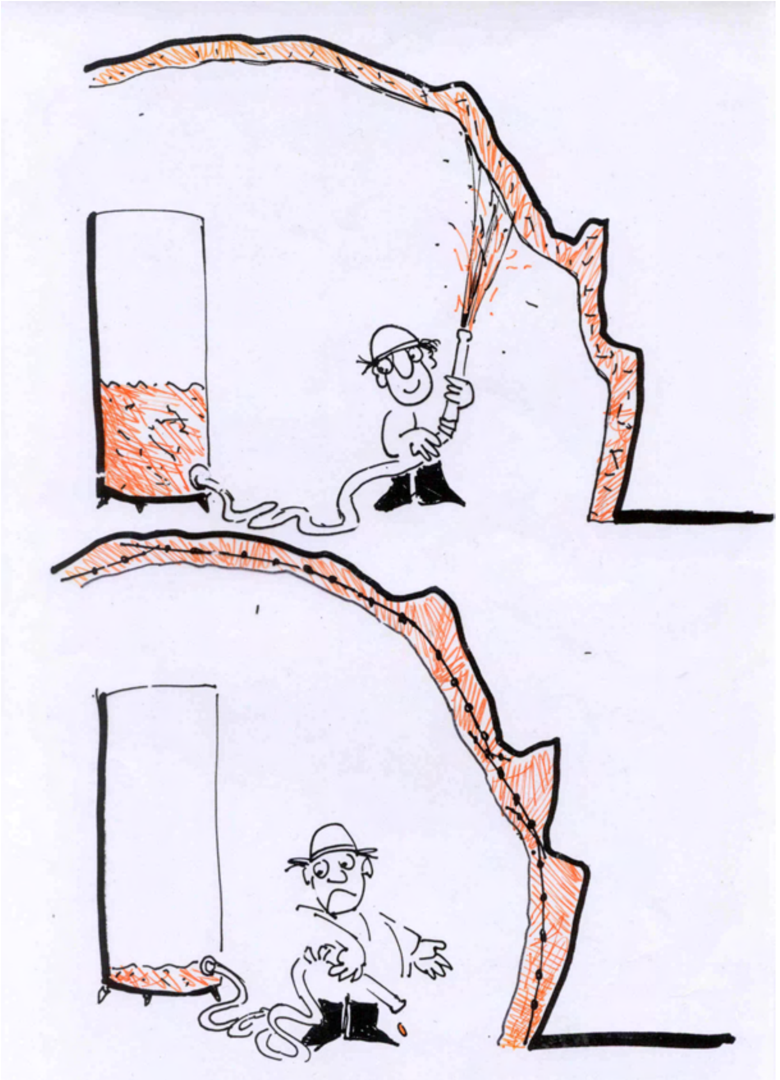
Mesh installation is:



- difficult
- time consuming
- hazardous under loose rock
- costly

Mesh Reinforced Sprayed Concrete

Sprayed concrete consumption is high due to:

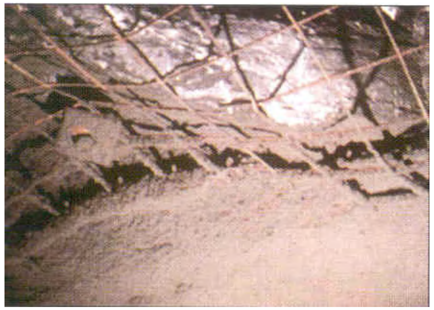


- irregular rock surface
- filling up voids
- high rebound on the mesh wires

Mesh Reinforced Sprayed Concrete

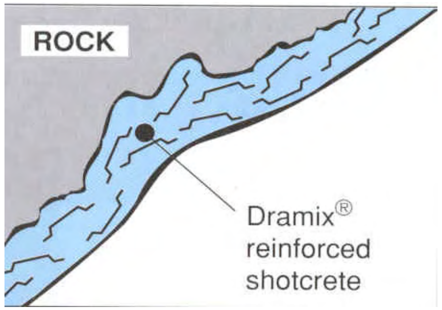
Lining quality can be poor:

- Sprayed concrete builds up on the face of the mesh
- Low quality shadow areas form behind the wire
- Not a uniform bond between sprayed concrete and rock
- Irregular mesh positions do not give an efficient reinforcement



Fiber Reinforced Sprayed Concrete

Advantages of a FRS layer:



- Homogeneous reinforcement
- Can be applied very quickly
- A uniform thickness results in a significant reduction of sprayed concrete consumption
- Strong bond to the surface which is required to make the underground self supporting

Fibre Reinforced Sprayed Concrete Properties

- REBOUND
- Wet sprayed concrete (no silica fume): 15-20%
- Dry sprayed concrete: 20-50%
- Silica fume : improves bond
  - Rebound: 5-7% on vertical wall; 10-12% on ceiling
  - Typical dosage: 6-8% cement weight: makes the sprayed concrete not too strong
- Accelerator (AF)
  - High early strength
  - Improves the bond
  - Increases rebound if overdose

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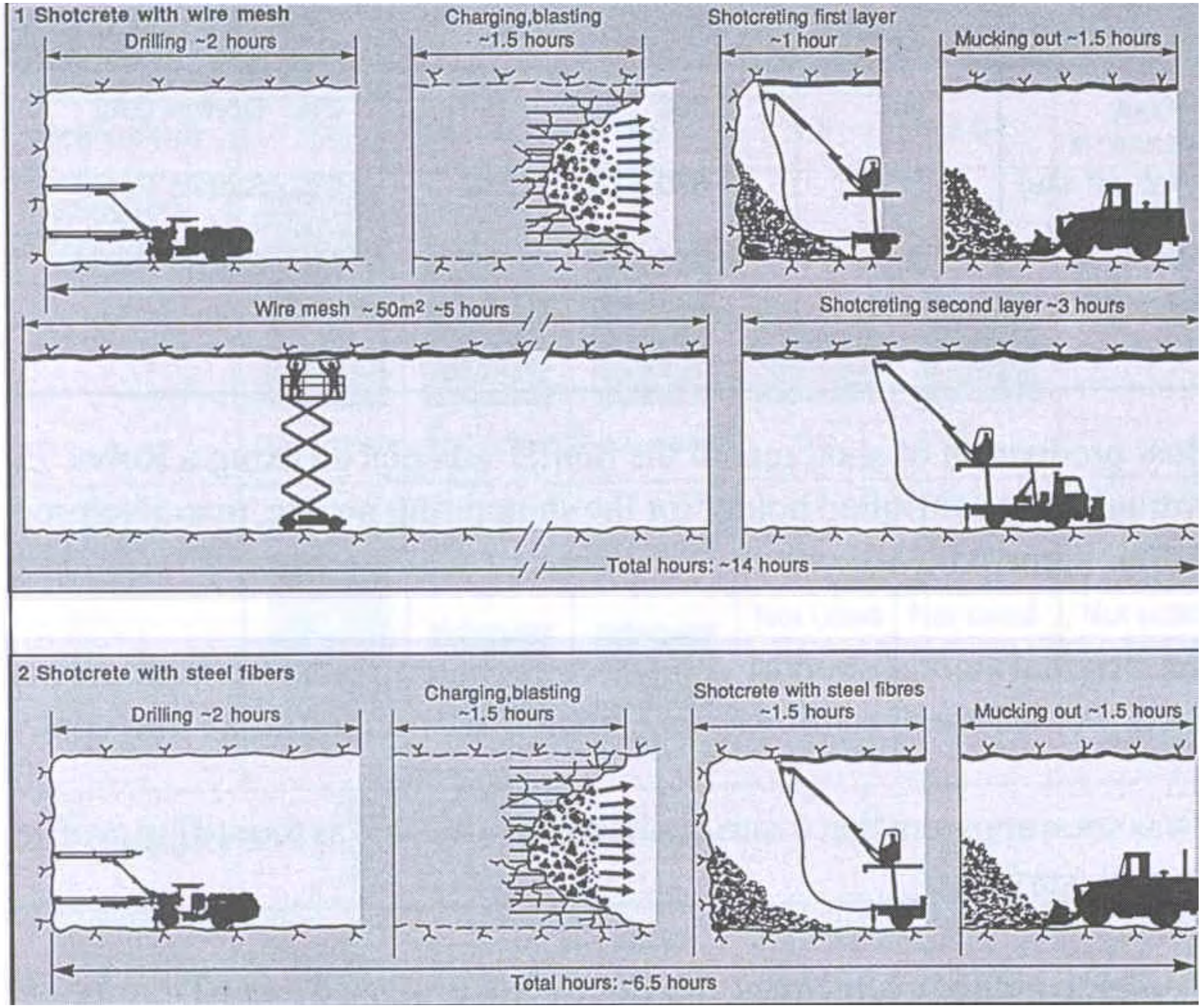
Fibre Reinforced Sprayed Concrete Properties



SAVINGS: - concrete: 33%

- cycle time: 7.5 hrs (64%)

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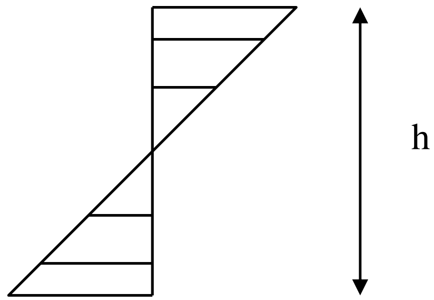
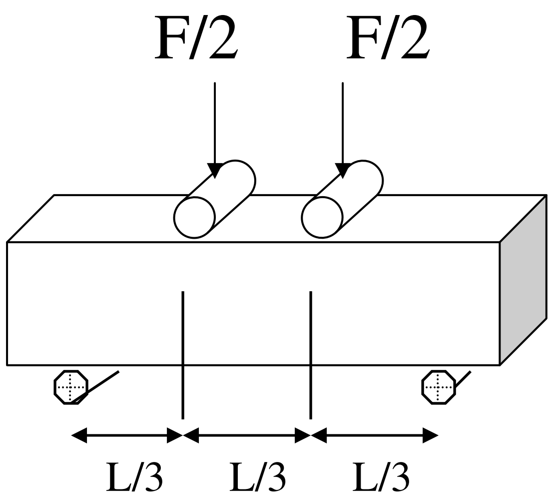
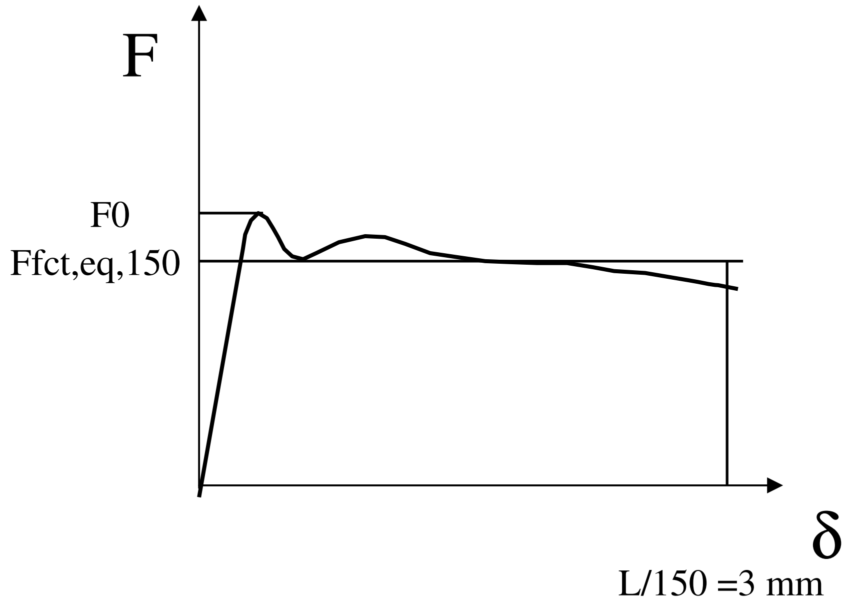
Characterisation of FRS

1. Beam test
2. Efnarc panel test



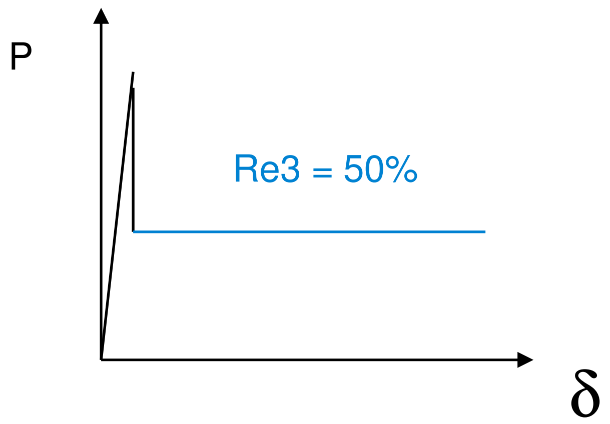


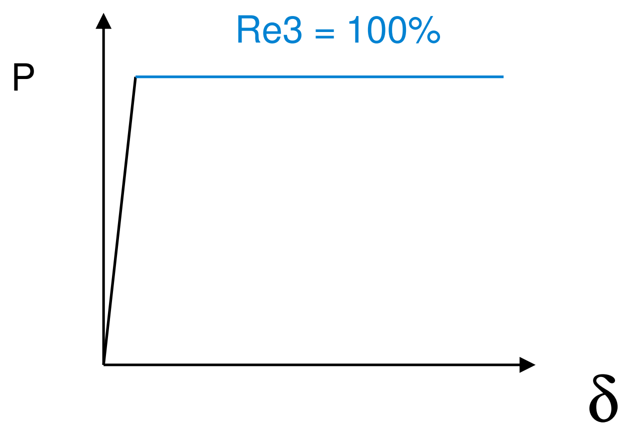
L = 450 mm
b = 150 mm
h = 150 mm

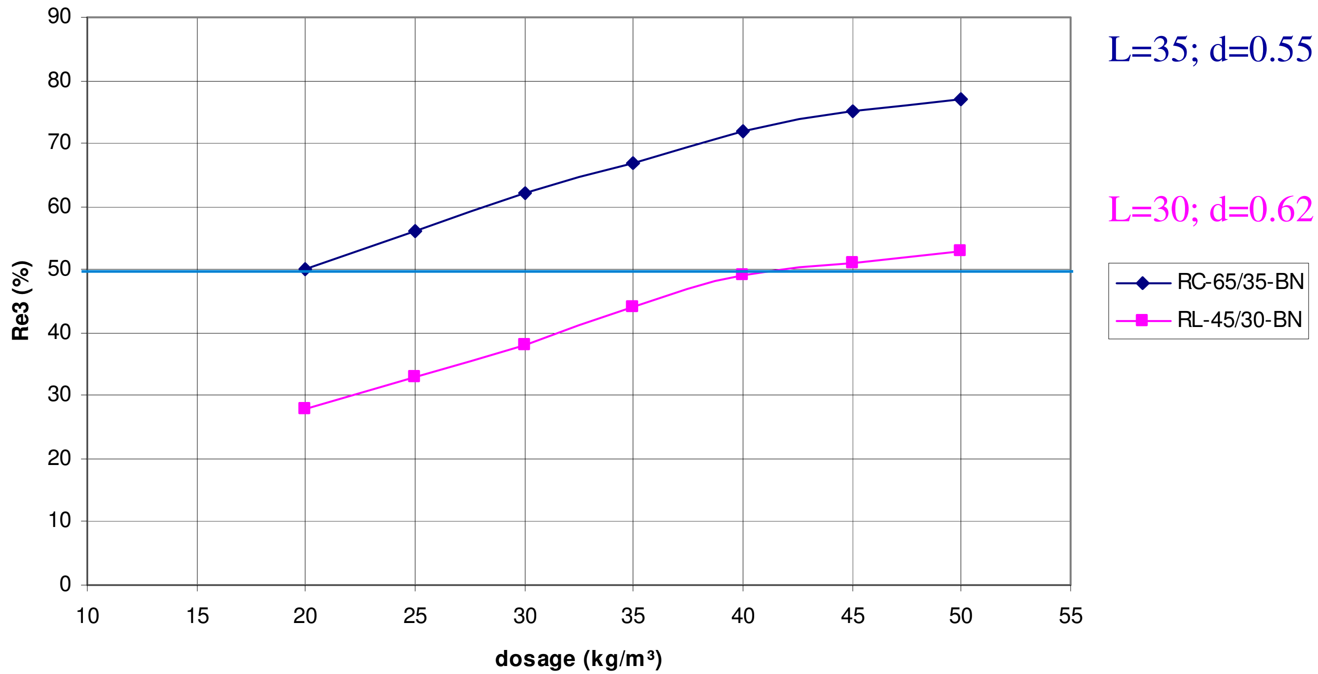


$f_{e150} = F_{fct,eq,150} \cdot L / (b.h^2)$ in Mpa
$R_{e3} = F_{fct,eq,150} / F_o$ in %

Fibre Reinforced Sprayed Concrete Design







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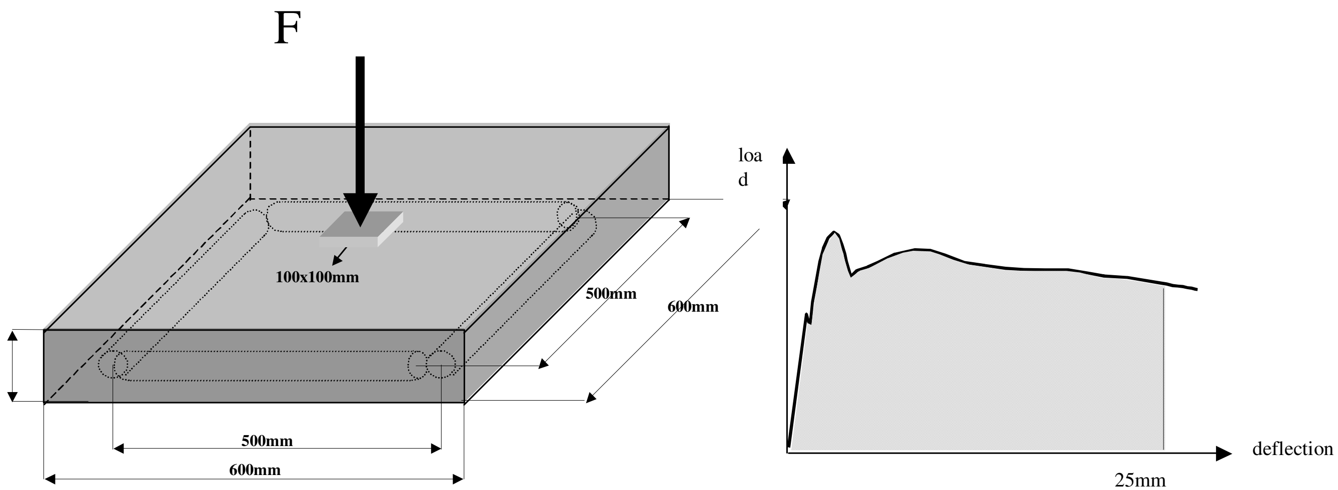
Fibre Reinforced Sprayed Concrete Properties

Efnarc toughness classification:

500	J: min. requirement; rock; small diameter tunnel
700	J: standard; less good rock
1000	J: high ductility for bad soil condition



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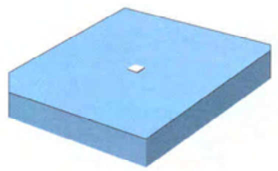
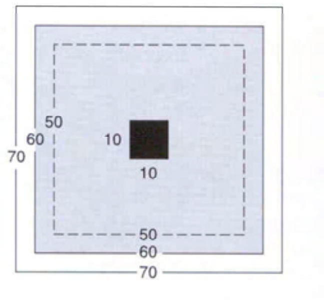
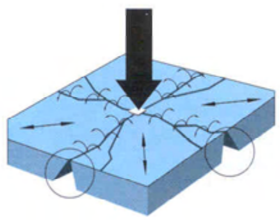
Fibre Reinforced Sprayed Concrete Design

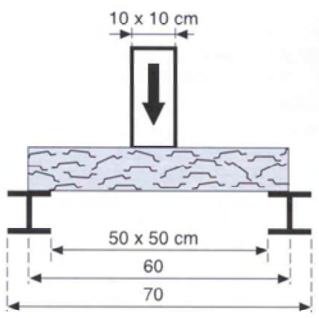
Efnarc panel test

European standard
EN 14488-5







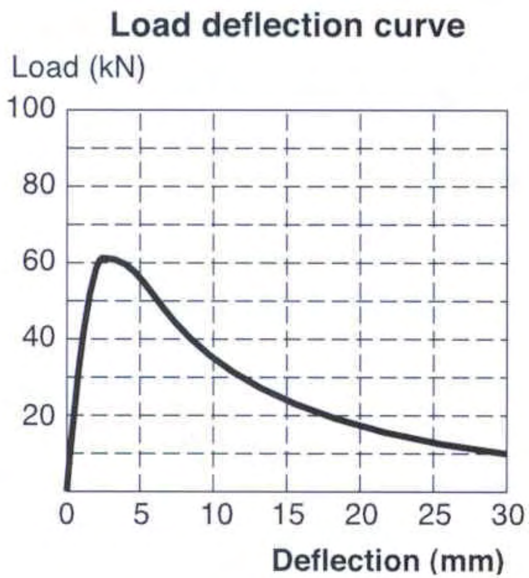


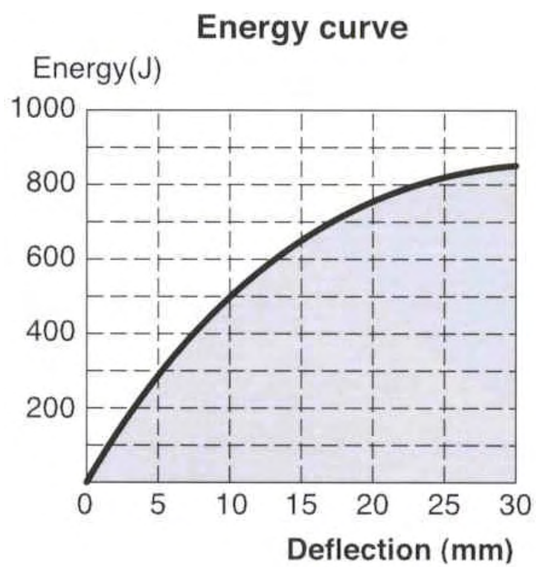
The punching-flexion test is an ideal test to check the FRS behaviour:

1) A sprayed concrete tunnel ling behaves like a slab
2) The hyperstatic test conditions allow load redistribution
3) The test can be carried out with mesh reinforcement

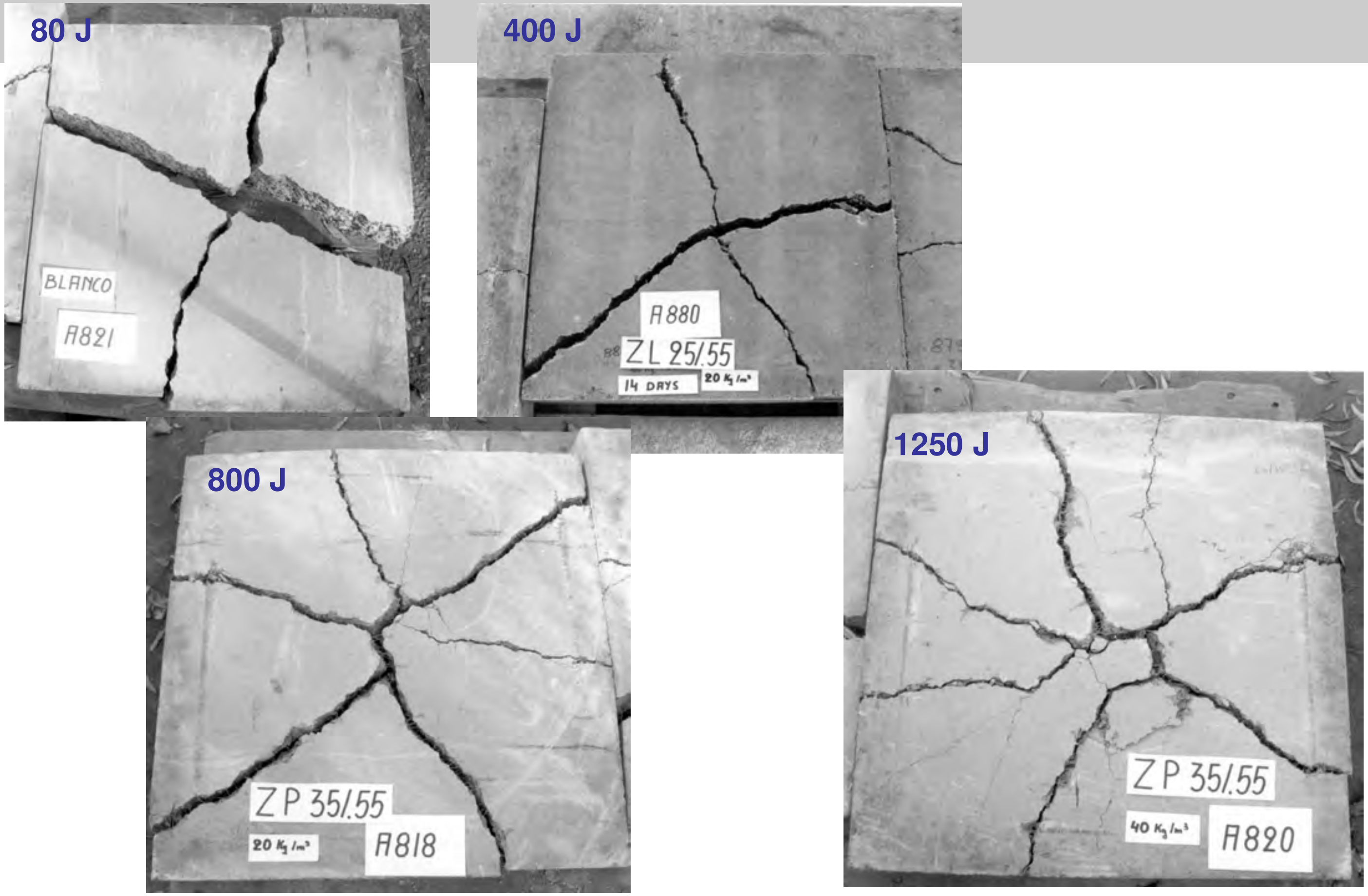
This test is introduced in 1989 by the French railway, and is in the meantime accepted by *Efnarc*, and is proposed in *CEN 104* Shotcrete.

Efnarc panel test

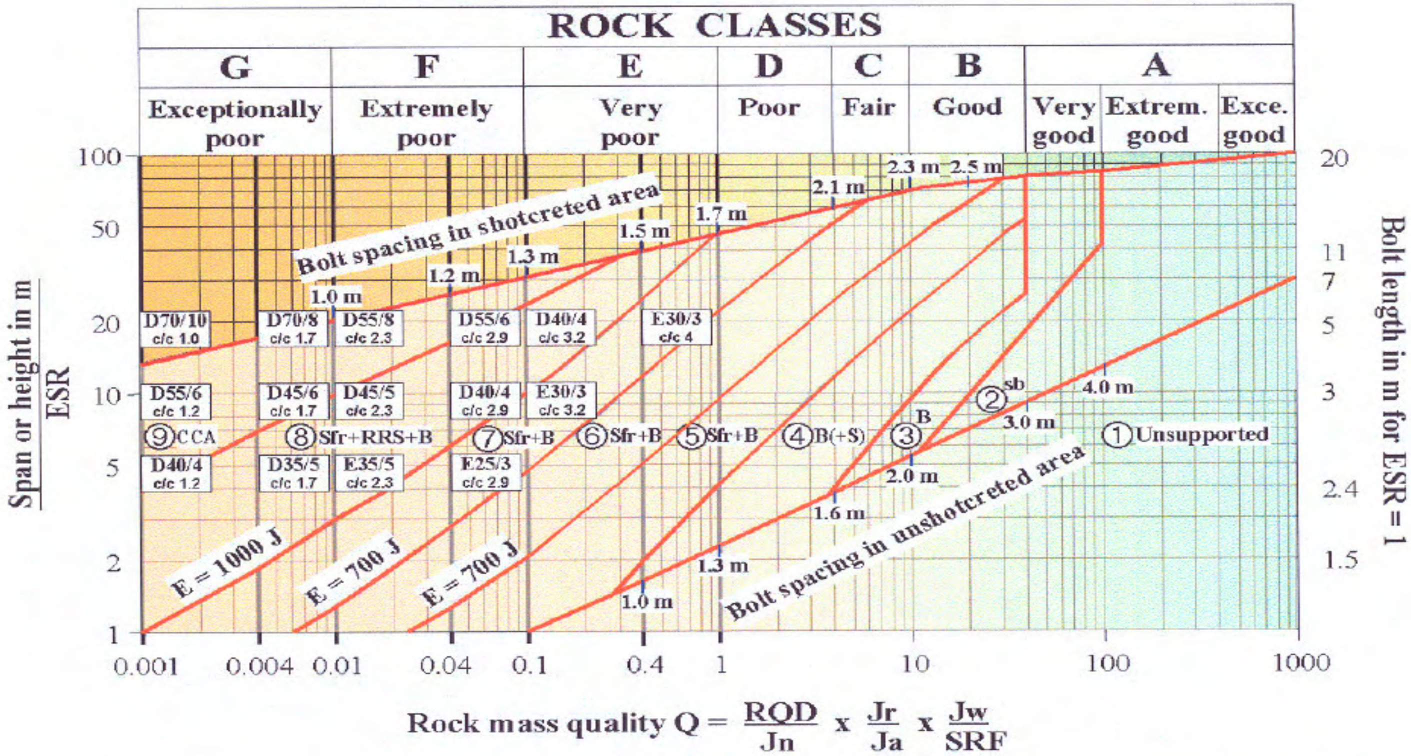




Fibre Reinforced Sprayed Concrete Design



Fibre Reinforced Sprayed Concrete Design



Rock mass quality $Q = \frac{RQD}{Jn} \times \frac{Jr}{Ja} \times \frac{Jw}{SRF}$

REINFORCEMENT CATEGORIES

1) Unsupported
2) Spot bolting, **sb**
3) Systematic bolting, **B**
4) Systematic bolting, (and unreinforced shotcrete, 4-10 cm), **B(+S)**
5) Fibre reinforced shotcrete and bolting, 5-9 cm, **Sfr+B**
6) Fibre reinforced shotcrete and bolting, 9-12 cm, **Sfr+B**
7) Fibre reinforced shotcrete and bolting, 12-15 cm, **Sfr+B**
8) Fibre reinforced shotcrete > 15 cm + reinforced ribs of shotcrete and bolting, **Sfr+RRS+B**
9) Cast concrete lining, **CCA**

e) Energy absorbtion in fibre reinforced shotcrete at 25 mm bending during plate testing

D45/6 c/c 1.7 = RRS with 6 reinforcement bars in double layer in 45 cm thick ribs with centre to centre (c/c) spacing 1.7 m. Each box corresponds to Q-values on the left hand side of the box. (See text for explanation)

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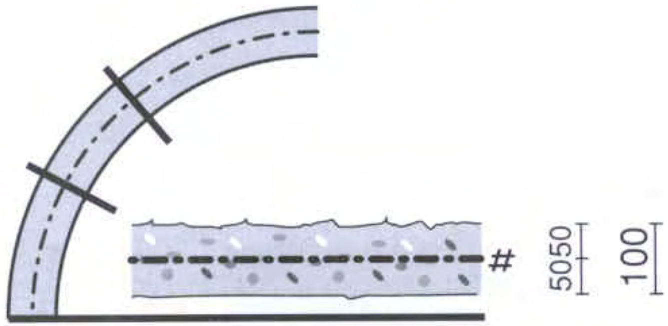
Fibre Reinforced Sprayed Concrete Design

1 mesh reinforced layer versus fibre reinforced sprayed concrete layer

Design of 1 mesh reinforced layer



$$M_{m,u} = 0.9 \cdot \frac{d}{2} \cdot A_s \cdot \sigma_{s,u}$$

whereby

$M_{m,u}$ = ultimate bending moment (Nm/m)

d = total layer thickness (mm)

A_s = steel wire mesh cross secti (mm²/m)

$\sigma_{s,u}$ = ultimate tensile strength of me steel wires (N/mm²)

for d = 100 mm

A_s = 131 mm² (# 150/5)

$\sigma_{s,u}$ = 460 N/mm²

$M_{m,u}$ = 0.9 x 50 mm x 131 mm²/n 460 N/mm²

= 2.711.700 Nmm/m

= 2.712 Nm/m

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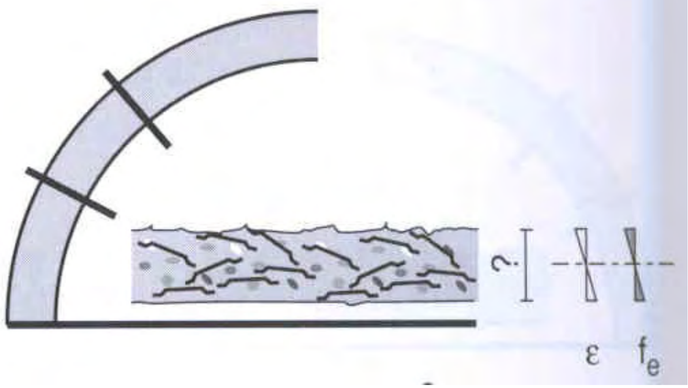
Design of steel fibre reinforced sprayed concrete layer



$$M_{D,1m} = f_e \cdot \frac{b \cdot d^2}{6}$$

hereby

$M_{D,1m} = M_{m,u}$ = bending moment (Nm/m)

f_e = equivalent flexural strength of Dramix shotcrete (N/mm²)

b = width of loaded area (mm)

d = total layer thickness (mm)

for $M_{D,1m}$ = 2.712 Nm/m

b = 1.000 mm

f_e = 0.65 f_u for 40 kg/m³ Dramix ZP 30/.50 (Fig. 21)

f_u = 4 N/mm²

f_e = 0.65 x 4 = 2.6 N/mm²

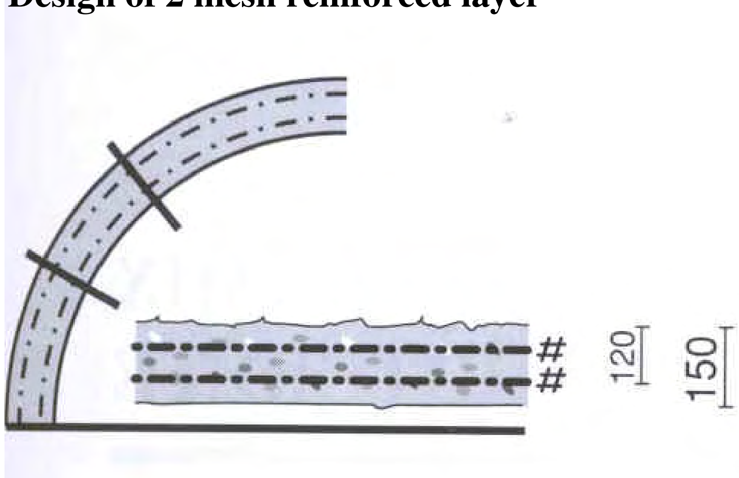
$$d^2 = \frac{6 \cdot M_{D,1m}}{f_e \cdot b} = \frac{6 \times 2.712.000}{2.6 \times 1.000}$$

= 6.258 mm²

d = 80 mm

Double mesh reinforced layer versus fibre reinforced sprayed concrete layer

Design of 2 mesh reinforced layer



$$M_{2m,u} = 0.9 \cdot h \cdot A_s \cdot \sigma_{s,u}$$

$M_{2m,u}$ = ultimate bending moment (Nm/m)
h = d - a (mm)
d = shotcrete layer thickness (mm)
a = shotcrete cover of wire mesh (mm)
A_s = steel wire mesh cross section (mm²/m)
$\sigma_{s,u}$ = ultimate tensile strength of steel mesh wires (N/mm²)

d = 150 mm
a = 30 mm
h = 150 - 30 = 120 mm
A_s = 126 mm²/m (# 100/4)
$\sigma_{s,u}$ = 460 N/mm²

$M_{2m,u}$ = 0.9 x 120 mm x 126 mm²/m x 460 N/mm²
= 6.259.680 Nmm/m
= 6.260 Nm/m

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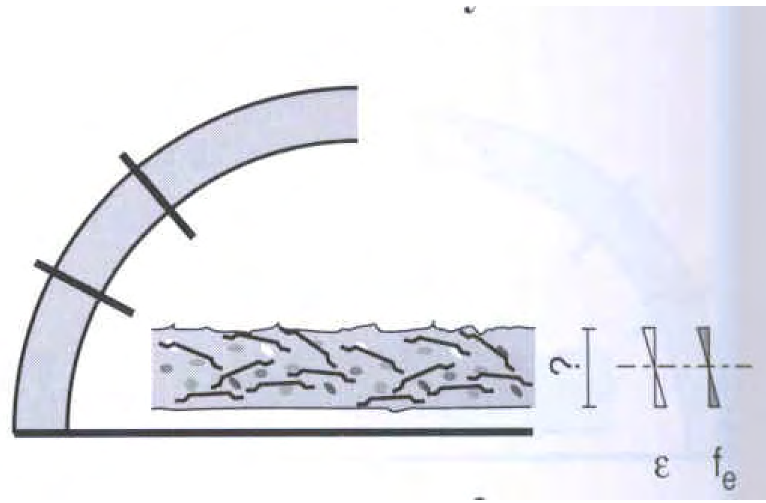
Double mesh reinforced layer versus fibre reinforced sprayed concrete layer

Design of steel fibre reinforced sprayed concrete layer



$$M_{D,2m} = f_e \cdot b \cdot \frac{d^2}{6}$$

$M_{D,2m}$ = 6.260 Nm/m

b = 1.000 mm

f_e = 0.65 f_u for 40 kg/m³ Dramix ZP 30/.50 (Fig. 21)

f_u = 4 N/mm²

f_e = 0.65 x 4 = 2.6 N/mm²

$$^2 = \frac{6 \cdot M_{D,2m}}{f_e \cdot b} = \frac{6 \times 6.260.000}{2.6 \times 1.000}$$

= 14.446 mm²

d = 120 mm

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Fibre Reinforced Sprayed Concrete QA/QC

- EN14488-3 - Testing sprayed concrete - Part 3: Flexural strengths (first peak, ultimate and residual) of fibre reinforced beam specimens
- EN14488-5 - Testing sprayed concrete - Part 5: Determination of energy absorption capacity of fibre reinforced slab specimens
- EN14488-7 - Testing sprayed concrete - Part 7: Fibre content of fibre reinforced concrete

FIBRE COUNTER

1

2

3

4

Fibre Reinforced Sprayed Concrete QA/QC

- 1. Plug into A/C power point. Switch on the fibre counter.
- 2. Determine an amount of Steel Fibre Reinforced Sprayed Concrete (SFRS) in accordance to EN14488-7. Put the SFRS into the top of the fibre counter.
- 3. The SFRS will be vibrated as it passes through the fibre counter. The steel fibres will be stuck to the magnet in the fibre counter while the aggregates, sand and cement will appear at the base of the fibre counter.
- 4. Remove the steel fibres from the magnet. Clean the steel fibres with clean water. Dry the steel fibres. Weigh the amount of steel fibres collected. All other procedures will be in accordance to EN14488-7.
- 5. Clean the fibre counter with clean water after each use.

Fibre Reinforced Sprayed Concrete QA/QC

Time		Wall				Top				Actual steel fibre dosage in mix, kg/m3	Density of plain shotcrete, kg/m3	Density of SFRS, kg/m3
12:00 PM	Shotcrete sample, kg	2.08	2.02	3.32		3.1	2.4	2.02	1.02	30	2200	2230
	Steel fibre weight, g	19.5	24.44	30.58		33.63	23.6	23.5	12.27			
	Steel fibre dosage, kg/m3	20.90625	26.98	20.54		24.19	21.93	25.94	26.83			
	Average steel fibre dosage, kg/m3	**22.80907427**				**24.72222353**						
	Steel fibre rebound, %	23.96975244				17.59258825						
	Energy Absorption, Joules	**>1000**				**>700**				Tested in NTU on 14th August 2007		
	Reqd. Energy Absorption, Joules	**>700**				**>700**						
	Designed steel fibre dosage, kg/m3	**20**				**20**						
4:00 PM	Shotcrete sample, kg	2.26	2.44	2.5	3.08	2.54	2.24	2.2	2.56	40	2190	2230
	Steel fibre weight, g	34.27	30.8	31.22	33.7	35.35	32	22.35	29.79			
	Steel fibre dosage, kg/m3	33.81509	28.15	27.85	24.4	31.04	31.86	22.65	25.95			
	Average steel fibre dosage, kg/m3	**28.55304604**				**27.87435708**						
	Steel fibre rebound, %	28.61738491				30.3141073						
	Energy Absorption, Joules	***>1000 (not tested since the ceiling panel achieved the requirements)***				**1300**				Tested in NTU on 14th August 2007		
	Reqd. Energy Absorption, Joules	**>1000**				**>1000**						
	Designed steel fibre dosage, kg/m3	**30**				**30**						

Based on the above-mentioned results, the spraying trials conducted on 16th July 2007 were successfully completed. The steel fibre rebound were within the designed tolerances.

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Fibre Reinforced Sprayed Concrete Specifications

- Minimum fiber length: 2 times the max. Aggregate size
- Aspect ratio: range 40-80
- Fibre tensile strength: min. 1000 Mpa
- Ductility performance: 500-700-1000 Joules
- EN14487-1 - Sprayed concrete - Part 1: Definitions, specifications and conformity
- EN14487-2 - Sprayed concrete - Part 2: Execution

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