Fibre orientation and rheological behaviour of self-compacting FRC

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Outline presentation

- Fibre concrete
- Fibre orientation
- Case-studies
- Fibre orientation in standards
- Conclusions
Fibre concrete

Interaction

Material

Production

Fibre concrete

Structure
Fibre concrete

Thin plates: contribution of fibres

OL13/0.20
Fibre dosage: 0/77.5/155 kg/m³
Fibre concrete

Thin plates: failure pattern
Fibre concrete

Relationship between direct tensile strength and fibre factor

Sato & Walraven
TU Delft, Befib 2000
Fibre concrete

Maximum fibre content: Deviating flow pattern of flowable concrete
Fibre concrete

Prediction of the yield value

Total relative packing fraction (TRPF) =

\[ \phi_f \cdot \frac{r}{4} + \phi_s / \phi_{ms} \]

Optimum TRPF: 0.8-1.0

(L. Martinie and N. Roussel, 2010)
Fibre concrete

Normalized yield value

Max. TRPF self-compacting: 0.957
Min. TRPF not self-compacting: 0.878
Highest NYV: 69.3
(plastic viscosity: 143.1 Pas)
Fibre orientation

Fibre orientation - involved phenomena:

- **Flow-type:** 1) Free surface-flow & 2) Confined flow

- **Shear-induced fibre orientation**
  (rheological characteristics concrete, geometry of element and casting circumstances)

- **Wall-effect**
  (geometry, flow circumstances)
Fibre orientation

Mechanism of fibre orientation (Roussel & Martinie, 2011):

- Fibres rotate due to torque cause by the fluid (fibre geometry)
- (Unstable) shear stress minimum in direction parallel to the flow
- Almost instantaneous orientation ($T=0.5-5$ s, dependent on shear rate); $T$ is short related to casting process
- No preferred orientation in an area with ‘plug flow’ or ‘dead zone’ (not sheared area)
- High shear rate close to boundaries (walls, bottom of mould, rebars)
- Due to a high fibre content the tendency of fibres to align is reduced
Fibre orientation

Motor of orientation:

- Stress/pressure gradient (i.e. vicinity to surface, height difference of concrete, vibration energy, rebars)

- Hinderance by: stress below yield stress other particles (fibres/large aggregates)
Fibre orientation

Simulation: effect yield stress:

Orientation factor relative to the flow direction z; yield stress of concrete, left: 800 Pa, right: 50 Pa (Martinie & Roussel, 2010).

Traditional vibrated concrete  Self-compacting concrete
Fibre orientation

Bending behaviour of SCFRC

Strength class: C55/67, Dramix 80/60 BP, $V_f=60$ kg/m$^3$
Fibre orientation

Single fibre pull-out: SCC versus CC
Fibre orientation

Average fibre orientation

\[ \eta_\varphi = \frac{1}{N_{sf}} \cdot \sum_{1}^{N_{sf}} \cos \varphi \]

\[ y = 0.00177x + 0.698 \]
Fibre orientation

Possible positions of fibres in space:
0,5 - isotropic 1,0 – aligned situation
Fibre orientation

Distribution profile: Gaussian
(Researcher: F. Laranjeira/UPC)

Example:
hooked-end steel fibres
($L_F=41.2$ mm,
Dramix BN 65/40 C steel fibre,
$V_F=100$ kg/m$^3$,
strength class: C55/67)
Fibre orientation

F. Laranjeira / UPC Barcelona:
Distribution of fibre orientation: **Gaussian distribution**

\[CV(\eta_\theta) = 1 - \eta_\theta\]

\[\sigma(\eta_\theta) = \eta_\theta \times (1 - \eta_\theta)\]
Fibre orientation

Fibre efficiency

Fracture energy (N.mm)

Maximum Fibre orientation angle, \( \theta ^{\circ} \)

[P. Robins, S. Austin & P. Jones, 2002 - hooked-end steel fibres (\( L_{F}=30 \text{ mm}; D_{F}=0.5 \text{ mm} \))]
Fibre orientation

Predicted fibre orientation profile:
Fibre orientation

Prediction of fibre orientation - Martinie & Roussel (2011):

- Traditional vibrated concrete

\[ \alpha = 0.7 - 0.4 \cdot \frac{\tau_0}{\rho g e} + 0.05 \cdot \frac{L_f}{e} \]

- Self-compacting concrete

\[ \alpha = 0.7 - \frac{\tau_0}{\rho g e} + 0.05 \cdot \frac{L_f}{e} \]
Fibre orientation

Comparison of methods to determine fibre orientation

\[ \alpha = 0,7 - 0,4 \cdot \frac{\tau_0}{\rho_{ge}} + 0,05 \cdot \frac{L_f}{e} \]

\[ \alpha = 0,7 - \frac{\tau_0}{\rho_{ge}} + 0,05 \cdot \frac{L_f}{e} \]

\[ N_F = \frac{V_F}{A_F} \cdot \eta_\varphi \]

\[ \eta_\varphi = \frac{1}{N} \cdot \sum_{i=1}^{N} \cos \varphi \]
Fibre orientation

DESTRUCTIVE METHODS
- Manual counting
- Weighting partial volumes
- Image Analysis
- X-Ray methods
- Computer tomography (CT-Scans)
- Uniaxial tensile test
  - Bending test
  - Round panel test
  - Barcelona test

NON-DESTRUCTIVE METHODS
- Alternate Current Impedance Spectroscopy (AC-IS)
  - Open Coaxial Transmission Line (OCTL)
    - Dielectric waveguide antennas
      - Electrical resistivity
Case-studies: tunnel segment

Experimental set-up (2 tunnel segments)

Steel fibres: 60 kg/m³
L: 30 or 60 mm, C50/60

<table>
<thead>
<tr>
<th>Mixture composition</th>
<th>[kg/m³]</th>
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<tbody>
<tr>
<td>CEM III 42.5 N</td>
<td>382</td>
</tr>
<tr>
<td>Fly ash</td>
<td>179</td>
</tr>
<tr>
<td>Sand (0.125-4 mm)</td>
<td>1044</td>
</tr>
<tr>
<td>Coarse aggregates (4-16 mm)</td>
<td>489</td>
</tr>
<tr>
<td>Water (incl. superplasticiser)</td>
<td>183</td>
</tr>
<tr>
<td>Superplasticiser LR</td>
<td>(2.43)</td>
</tr>
<tr>
<td>Superplasticiser HR</td>
<td>(1.17)</td>
</tr>
<tr>
<td>Steel fibres</td>
<td>60</td>
</tr>
</tbody>
</table>
Case-studies: tunnel segment

X-ray and splitting tensile testing

Concrete slice
\( d = 18 \text{ mm} \)
Case-studies: tunnel segment

Casting with a truck mixer
Case-studies: tunnel segment

Casting / tensile strength

Free-surface flow & walls cause shear-induced fibre orientation
Case-studies: tunnel segment

Post-cracking splitting tensile strength

Dramix 45/30 BN

Dramix 80/60 BN
Case-studies: tunnel segment

Maximum splitting tensile strength (first crack/post crack)

Dramix 45/30 BN
AV: 4,66 MPa (STD: 0,83 MPa)

Dramix 80/60 BN
AV: 4,98 MPa (STD: 1,32 MPa)
Case-studies: tunnel segment

Effect of production and element shape

60 mm steel fibres

\[ \eta_{\theta} = 0.24 \]
perpendicular

\[ \eta_{\theta} = 0.91 \]
parallel
Case-studies: tunnel segment

Two directions: splitting tensile strength

> 80% Perpendicular to the wall

Parallel to the wall
Case-studies: beams

2 beams, 3.70 m each
- 50 kg/m³ steel fibres –

Beam A: Dramix 45/50 BN
$L_f = 50 \text{ mm}$

Beam B: Dramix 45/30 BN
$L_f = 30 \text{ mm}$
Case-studies: beams

Direction of plane:
parallel to the wall

Direction of plane:
parallel to bottom of mould

$$\eta_\varphi = \frac{1}{N_{sf}} \cdot \sum_{i=1}^{N_{sf}} \cos \varphi$$
Case-studies: beams

Direction of plane:
perpendicular to the flow

\[ \eta_\varphi = \frac{1}{N_{sf}} \cdot \sum_{1}^{N_{sf}} \cos \varphi \]
Fibre orientation in standards

fib TG 8.8 ‘Structural design with flowable concrete’

- ECC, plastic fibres
- Special applications
- T. fibre concrete
- UHPC, French guideline

Fibre content [Vol.-%]

Compressive strength [MPa]
Fibre orientation in standards

\[ \sigma_{ct} \] [MPa]

\[ \frac{f_{ctfm}}{K} \]

\[ f_{ctfm,el} \]

\[ f_{ctfm,1\%} \]

\[ K \]

\[ E_c \]

\[ \varepsilon_{ctfm,el} \]

\[ w = 0.3 \]

\[ w_{1\%} \]

\[ \ell_f/4 \] [mm]

\[ \sigma-\varepsilon \] relation for hardening behaviour

\[ \sigma_{ct} \] [MPa]

\[ f_{ctfm,el} \]

\[ f_{ctfm} \]

\[ f_{ctfm,1\%} \]

\[ K \]

\[ E_c \]

\[ \varepsilon_{ctfm,el} \]

\[ w = 0.3 \]

\[ w_{1\%} \]

\[ \ell_f/4 \] [mm]

\[ \sigma-\varepsilon \] relation for softening behaviour
Fibre orientation in standards

Figure 5.23 Division of slabs in zones depending on fibre orientation.
Fibre orientation in standards

Year 2000: 2 Viaducts in France
Bourg lès Valence

Variation in flexural strength
(w = 0.3 mm)
within an element:
K local: 1.25
K global: 1.75
Fibre orientation in standards

**Period 2007-2008:**
2 bridges (Pont Pinel/Pont Sarcelles): span 28 m, 125 m³ UHPC
Fibre orientation in standards

Test elements: Bridges Pont Pinel/Pont Sarcelles
Conclusions

- The structural behaviour of FRC depends on material properties, processing and structural boundary conditions.

- In the past years: Understanding of fibre orientation is greatly improved; tools will become / became available to measure and simulate fibre orientation. Standards follow-up the research efforts.

- Outstanding structures can be realized with tailor-made FRC.