Characterization and Testing of Fiber Reinforced Concrete (*American Standards*)

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Fibers mixed into concrete can provide an alternative means of reinforcement to partially or fully replace steel bars or welded wire mesh in certain applications.

Fibers can contribute to the improved performance of concrete members in two different ways: by resisting tensile stresses and therefore playing a structural role, or by controlling crack development and therefore improving the quality of concrete.

When fibers are intended to contribute to the structural performance of an element or structure, the FRC needs to be designed accordingly and the fibers contribution to the load-bearing capacity needs to be properly assessed and justified.
Advantages of using fibers

**Economic**
- Significant decrease in production cycle time
- Reduced labor costs
- Reduction in breakage and repair costs
- Reduce potential for corrosion (only polymeric)

**Technical**
- Crack - reduction
- Increased ductility and flexural toughness
- Good impact resistance
- Prevention of concrete spalling
- Provide Residual strength
Fiber Reinforced Composites

- **FRC**: Substantially enhance the post-cracking response of the composite (toughness).
- **Post-cracking response**: is evaluated through toughness testing
- **Toughness**: area under the load deformation curve

![Graph showing strain-hardening and strain-softening responses](image)

**Fig. 1.1—Range of load versus deflection curves for unreinforced matrix and fiber reinforced concrete**
Toughening Modes for FRC

Depending on the type, length, properties, and content of fibers, the tensile (or flexural) response of FRC may vary.

1) Damage of the matrix
2) Fiber/matrix debonding
3) Fiber bridging
4) Fiber failure
5) Fiber pull-out
KEY PROPERTY: Stress-strain diagram

Fiber Reinforced Concrete

\[ F_{ct,eq,3} \] Equivalent strength at deflection of 3 mm (L/150)

\[ F_{ct,eq,1.5} \] Equivalent strength at deflection of 1.5mm (L/300)

Plain Concrete

RILEM TC162
Post-cracking behavior

• The cracked section of fiber-reinforced concrete (FRC) does carry tensile load while plain concrete becomes ineffective after cracking as indicated in the stress-strain diagram.

Conventional RC  
FRC  

Need to be characterized
Configurations of tensile test

Direct tensile test on FRC is difficult, instead, the residual tensile strength is derived from the measured flexural strength by means of conversion factors.

Tensile Test is not Standard

Difficult to perform in a consistent way
Toughness tests

• **ASTM C1609/C1609M (JCI-SF4)** (Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading))
  - 100 mm by 100 mm by 350 mm beam
  - 150 mm by 150 mm by 500 mm beam

• **ASTM C1399/C1399M** (Test Method for Obtaining Average Residual-Strength of Fiber-Reinforced Concrete)
  - 100 mm by 100 mm by 350 mm beam

• **ASTM C1550** (Standard Test Method for Flexural Toughness of Fiber-Reinforced Concrete (Using Centrally Loaded Round Panel))
  - 75 mm thick, 800 mm diameter round panel

• **ASTM C1018-97** (Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading))
This test method evaluates the flexural performance of fiber-reinforced concrete using parameters derived from the load-deflection curve obtained by testing a simply supported beam under third-point loading using a closed-loop, servo controlled testing system.

- $L$ = Span length
- $P_p = P_r$ = Peak Load = First-Peak Load
- $\delta_p = \delta_1$ = Net deflection at Peak and First-Peak Loads
- $f_p = f_1$ = Peak Strength and First-Peak Strength
- $P_{600}^D$ = Residual Load at net deflection of L/600
- $f_{600}^D$ = Residual Strength at net deflection of L/600
- $P_{150}^D$ = Residual Load at net deflection of L/150
- $f_{150}^D$ = Residual Strength at net deflection of L/150
- $A_{150}$ = Area under the load vs. net deflection curve 0 to L/150

### Equations

1. $P_p = P_r$
2. $f_1 = \frac{P_1 L}{bd^2}$
3. $f_{600}^D = \frac{P_{600}^D L}{bd^2}$
4. $f_{150}^D = \frac{P_{150}^D L}{bd^2}$
This test method provides for the determination of first-peak and peak loads and the corresponding stresses calculated by inserting them in the formula for modulus of rupture. It also requires determination of residual loads at specified deflections, and the corresponding residual strengths calculated by inserting them in the formula for modulus of rupture. At the option of the specifier of tests, it provides for determination of specimen toughness based on the area under the load-deflection curve up to a prescribed deflection.

To determine the first-peak, peak and residual strengths the respective load value is substituted in the modulus of rupture formula:

\[ f = \frac{PL}{bd^2} \]

Where:
- \( f \) = the strength, MPa (psi),
- \( P \) = the load, N (lbf),
- \( L \) = the span length, mm (in.),
- \( b \) = the average width of the specimen, mm (in.),
- \( d \) = the average depth of the specimen mm (in.),

at the fracture, and

Values of loads at specified deflection points are used for measuring residual strength of FRC.
## Residual Loads and Corresponding Residual Strengths

### 350 x 100 x 100 mm (14 x 4 x 4 in.)

- **$P_{150,0.75}$** — the load value corresponding to a net deflection equal to 1/600 of the span (or 0.75mm - 0.03 in.) using a specimen with a depth of 150 mm (6 in.).
- **$f_{150,0.75}$** — the stress value obtained when the residual load $P_{150,0.75}$ is inserted in the formula for modulus of rupture.

### 500 x 150 x 150 mm (20 x 6 x 6 in.)

- **$P_{100,0.5}$** — the load value corresponding to a net deflection equal to 1/600 of the span (or 0.5mm - 0.02 in.) using a specimen with a depth of 100 mm (4 in.).
- **$f_{100,0.5}$** — the stress value obtained when the residual load $P_{100,0.5}$ is inserted in the formula for modulus of rupture.

### 350 x 100 x 100 mm (14 x 4 x 4 in.)

- **$P_{150,3.0}$** — the load value corresponding to a net deflection equal to 1/150 of the span (or 3.0mm - 0.12 in.) using a specimen with a depth of 150 mm (6 in.).
- **$f_{150,3.0}$** — the stress value obtained when the residual load $P_{150,3.0}$ is inserted in the formula for modulus of rupture.

### 500 x 150 x 150 mm (20 x 6 x 6 in.)

- **$P_{100,2.0}$** — the load value corresponding to a net deflection equal to 1/150 of the span (or 2.0mm - 0.08 in.) using a specimen with a depth of 100 mm (4 in.).
- **$f_{100,2.0}$** — the stress value obtained when the residual load $P_{100,2.0}$ is inserted in the formula for modulus of rupture.
Residual Strength at 3 mm deflection depends on the dosage of fibers
Specimen toughness, \( T_{150,3.0} \) – the energy equivalent to the area under the load-deflection curve up to a net deflection of \((1/150)\) of the span (3.0 mm – 0.12 in.) using a specimen with a depth of 150 mm (6 in.).

Specimen toughness, \( T_{100,2.0} \) – the energy equivalent to the area under the load-deflection curve up to a net deflection of \((1/150)\) of the span (2.0 mm – 0.08 in.) using a specimen with a depth of 100 mm (4 in.).
Equivalent flexural strength, $f_{e,3}$

ASTM C1609-06  
JSCE, JCI-SF4  
NBN B15-238

$$f_{e,3} (\text{MPa}) = \frac{L(\text{mm}) \cdot T_{150,3.0} (\text{Nmm})}{150 \cdot W(\text{mm}) \cdot D(\text{mm})^2}$$

For Span, $L = 450$ mm

$$f_{e,3} = \frac{450 \cdot T_{150,3.0}}{3 \cdot W \cdot D^2} = \frac{150 \cdot T_{150,3.0}}{W \cdot D^2}$$

**Equivalent Flexural Strength:** Have the same toughness, $T_{150,3.0}$, obtained from experiment to a deflection of $L/150$ (same area under load-deflection curve)

$$R_{e,3} (%) = \frac{f_{e,3}}{f_p} \cdot 100$$
‘Small’ (100 mm) versus ‘big’ (150 mm) flex beam

ASTM C1609-12
‘Small’ (100 mm) versus ‘big’ (150 mm) flex beam

Residual strength is lower when measured with ‘big’ flex beams!!
ASTM 1609 Provides

• **Equivalent Flexural Strength** $F_{e,3}$ for Strength Design

• **Residual Strength of FRC**
  • At L/600 deflection (for serviceability design)
  • At L/150 deflection (for ultimate strength design)
  • Used to characterize stress strain curve for section analysis

• **Toughness** (area under the load deflection curve)

• Compare performance of different fibers

• Care must be practiced when assess flexural beams with small size
Test Method for Obtaining Average Residual-Strength of Fiber-Reinforced Concrete

(100 mm x 100 mm x 350 mm) Flexural Beam

The testing shall be done using the third-point loading apparatus specified in Test Method C-78 with the modification of the steel plate used in the initial loading cycle.

The steel plate is used to help control the expected high rate of deflection when the beam cracks.

Closed-loop feed-back controlled deflection apparatus is not required.
Average Residual Strength Evaluation ASTM C1399

Initial loading Curve
(Stop initial loading after beam cracking or 0.5 mm deflection)

ASTM C1399-98
Average Residual Strength (ARS)

ARS = ( (PA + PB + PC + PD) / 4 ) x K
K = L / bd^2
PA + PB + PC + PD = sum of recorded load at specified deflection, N
Test Method for Obtaining Average Residual-Strength of Fiber-Reinforced Concrete

Two stage test:

1. Using a steel plate underneath the entire length, the beam is initially cracked from an applied load up to a deflection of between a minimum of 0.25 mm (0.01 in.) and a maximum of 0.5 mm (0.02 in.).

2. The steel plate is then removed and the cracked beam then reloaded up to a deflection of 1.25 mm (0.05 in.) as measured from the beginning of reloading.
Test Method for Obtaining Average Residual-Strength of Fiber-Reinforced Concrete

Two curves plotted:

1. Initial loading curve – the load-deflection curve obtained by testing an assembly that includes both the test beam and a specified steel plate.

2. Reloading curve – the load-deflection curve obtained by reloading and retesting the pre-cracked beam, that is, after the initial loading but without the steel plate.
Test Method for Obtaining Average Residual-Strength of Fiber-Reinforced Concrete

The average residual strength is calculated using loads at reloading deflections of 0.50, 0.75, 1.00, and 1.25 mm

\[
ARS = \left( \frac{P_A + P_B + P_C + P_D}{4} \right) \times k
\]

where:
- \(k = \frac{L}{bd^2}, \text{ mm}^{-2} (\text{in.}^{-2})\)
- \(ARS = \text{average residual strength, MPa (psi)}\),
- \(P_A + P_B + P_C + P_D = \text{sum of recorded loads at specified deflections, N (lbf)}\),
- \(L = \text{span length, mm (in.)}\),
- \(b = \text{average width of beam, mm (in.) and}\)
- \(d = \text{average depth of beam, mm (in.)}\)

Note. This test cannot determine the flexural strength of the FRC.
Important points to remember:

• If ASTM C1018-97 / C1609/C1609M test on small flex beams (100 mm x 100 mm x 350 mm) can be controlled in terms of crack development, the equivalent flexural strength, $f_{e,2}$, and Average Residual Strength, $ARS$, are within 10% and therefore can be considered equivalent.

• Disadvantages of ASTM C1399/C1399M:
  • Does not tell you flexural strength
  • NO information about what happens right after crack initiation
  • Only uses small flex beams

• Larger specimens are more representative for slab on ground applications
  • Similar specimen thickness (150 mm thickness is common)
  • Less ‘artificial’ fibre alignment caused by the specimen molds and therefore more realistic fibre performance measurement
  • Larger fibres (50 mm and more in length) require larger crack surface area
ASTM C 1550

- Determination of flexural toughness of fiber-reinforced concrete (FRC) expressed as energy absorption in the post-crack range.
- Toughness is measured using a round panel supported on three symmetrically arranged pivots and subjected to a central point load.
- Load and deflection are recorded simultaneously up to a specified central deflection.
- The energy absorbed by the panel up to a specified central deflection is representative of the flexural toughness.
ASTM C 1550

• Such a test panel experiences bi-axial bending which exhibits a mode of failure related to the *in situ* behavior of structures.

• The nominal dimensions of the panel are 75 mm in thickness and 800 mm in diameter.

• The testing machine should operated such that the piston advances at a constant rate of 4.0 +/- 1.0 mm/min up to a central displacement of at least 45.0 mm.
• Larger fracture surface area minimizes standard deviation
• Behaviour of thin panel does not simulate slab-on-ground action
Third Point Loading Test (ASTM C 1018-97)

\[ \delta \quad \text{Deflection at first} \]

**toughness indices** - the numbers obtained by dividing the area up to a specified deflection by the area up to first crack.

\[ I_s = \frac{\text{Area}(3 \, \delta)}{\text{Area}(\delta)} \]
\[ I_{10} = \frac{\text{Area}(5.5 \, \delta)}{\text{Area}(\delta)} \]
\[ I_{20} = \frac{\text{Area}(10.5 \, \delta)}{\text{Area}(\delta)} \]

**Residual strength factor**

\[ R_{5,10} = 20 \times (I_{10} - I_s) \]
\[ R_{10,20} = 10 \times (I_{20} - I_{10}) \]
Definition of toughness indices

<table>
<thead>
<tr>
<th>Area Basis</th>
<th>Index Designation</th>
<th>Deflection Criterion</th>
<th>Values of Toughness Indices</th>
<th>Observed Range for Finite Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>GA</td>
<td>I_{OA}</td>
<td>38</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>GB</td>
<td>I_{OB}</td>
<td>5.58</td>
<td>1.0</td>
<td>10.0</td>
</tr>
<tr>
<td>GC</td>
<td>I_{OC}</td>
<td>10.58</td>
<td>1.0</td>
<td>20.0</td>
</tr>
</tbody>
</table>

*Indices calculated by dividing this area by the area to the first crack OAB.

**FIG. X1.1 Definition of Toughness Indices in Terms of Multiplies of First-Crack Deflection and Elastic-Plastic Material Behavior**
Third Point Loading Test (ASTM C 1018-97)

Toughness Performance Levels for a design flexural strength of 4 MPa

- Level V
- Level IV
- Level III
- Level II
- Level I

Load (kN) vs. Deflection (mm) graph with percentage levels.
Level system template was developed by Rusty Morgan et. al. *(not part of ASTM)*
Toughness Level and Residual Strength Depends on the type and dosage of Fiber
Problems

• Instability issues - low stiffness of the testing apparatus and poor control of the test can cause brittle failure (sudden drop of load)

• Toughness indices and residual strength values are not size-independent - values measured on 4” by 4” by 14” beam are much bigger compared to values measured on 6” by 6” by 20” beams (alignment of fibers)

• Crack pattern varies (starting point, end point), which causes high standard deviation

• Small fracture surface area compared to large volume of concrete - low number of fibers are bridging the crack
Beam deflection (mm)

0.00 0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08 0.09 0.10 0.11 0.12

0.0 0.5 1.0 1.5 2.0 2.5 3.0

Flexural stress (MPa)

0.0 1.0 2.0 3.0 4.0 5.0 6.0

Beam deflection (inches)

f'_c = 50 MPa (7,250 psi)

0.20% STRUX = 3.10 lb/ft² = 1.8 kg/m²
0.33% STRUX = 5.17 lb/ft² = 3.1 kg/m³
0.50% STRUX = 7.75 lb/ft² = 4.6 kg/m³

ASTM C 1018-97
6" by 6" by 20" beam
150 mm by 150 mm by 500 mm beam

Level IV

Level III

Level II

Level I
Toughness Measurement using the area under the load deflection curve - ASTM C 1018

- Problems included:
  - Determination of first crack point using the test equipment
  - Uncertainty of the location of cracking, Size effect
  - Point of deviation from linearity
  - Closed loop testing vs. open loop
  - Relevance of termination of the load,
  - Normalization of the test results with respect the a very small number
  - Lack of consistency in the utilization of the test results as a qualitative measure.
  - Different samples with different fibers could give same results

![Load vs. Deflection Graph]
Thank you!

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