Chapter 21: Special Concrete and Concreting Methods – Fiber-Reinforced Concrete (FRC)

Introduction

Traditional concrete, although strong in compression, exhibits poor tensile strength and is brittle in nature. To overcome this limitation and improve the toughness, ductility, and post-cracking behavior, fiber-reinforced concrete (FRC) is developed. In FRC, short discrete fibers are uniformly dispersed throughout the concrete mix to bridge cracks and provide improved mechanical performance.

Fiber-reinforced concrete is a composite material that combines the cement matrix with fibrous materials to form a more durable and impact-resistant material suitable for structural and non-structural applications. Depending on the type, volume, and orientation of fibers, the concrete's tensile strength, flexural strength, toughness, and resistance to dynamic and static loading can significantly improve.

21.1 Types of Fibers Used in FRC

Fibers are broadly categorized based on their material composition:

1. Steel Fibers

- **Properties**: High tensile strength (1100–2000 MPa), modulus of elasticity (~200 GPa), good bonding with cement paste.
- **Shapes**: Straight, crimped, hooked-end, twisted.
- **Applications**: Industrial flooring, tunnel linings, shotcrete, precast segments.

2. Glass Fibers

- **Types**: Alkali-resistant (AR) glass fibers are commonly used.
- **Properties**: Tensile strength ~1700 MPa, modulus of elasticity ~70 GPa.
- **Limitations**: Susceptible to alkali attack unless treated or used with pozzolanic cement.
- **Applications**: Decorative panels, façade elements, precast cladding.

3. Synthetic Fibers

a. Polypropylene (PP)

- **Advantages**: Excellent resistance to chemical attack, corrosion-free.
- **Properties**: Low modulus (~4 GPa), used for plastic shrinkage control.

- **Forms**: Microfibers and macrofibers.

b. Nylon

- **Absorbs water** and can affect water-cement ratio slightly.
- Good flexibility and tensile strength.

c. Polyvinyl Alcohol (PVA)

- Strong bonding with cement, used in engineered cementitious composites (ECC).

4. Natural Fibers

- Examples: Coir, jute, sisal, bamboo fibers.
- **Limitations**: Biodegradability, variability in properties.
- **Applications**: Low-cost housing, rural infrastructure.

21.2 Fiber Characteristics Influencing Performance

Aspect Ratio (Length to Diameter)

- Typical range: 30 to 150.
- Higher aspect ratios increase efficiency but may reduce workability.

Volume Fraction

- Generally ranges from 0.1% to 2.0%.
- Excessive volume reduces workability and increases voids.

Orientation and Distribution

- Randomly oriented fibers provide isotropic behavior.
- Proper mixing ensures uniform dispersion and crack bridging.

Bond Strength with Matrix

- Determines load transfer efficiency.
- Surface deformations (hooked ends, rough texture) improve bonding.

21.3 Mix Design Considerations for FRC

1. **Water-Cement Ratio (w/c)**: Should be optimized to maintain workability and reduce bleeding.

2. **Use of Superplasticizers**: Recommended to improve flow without increasing w/c ratio.
3. **Aggregate Gradation**: Well-graded aggregates improve packing and reduce voids.
4. **Mixing Time**: Extended mixing ensures uniform fiber dispersion.
5. **Fiber Dosage**: Should be within optimal limits to prevent balling or segregation.

21.4 Properties of Fiber-Reinforced Concrete

Fresh Properties

- **Workability**: Reduced due to the fiber network. Measured using slump, compaction factor.
- **Segregation & Bleeding**: Controlled effectively by fibers.

Hardened Properties

- **Compressive Strength**: Slightly improved or unaffected.
- **Tensile Strength**: Significant improvement due to crack bridging.
- **Flexural Strength**: Enhanced due to post-crack ductility.
- **Impact Resistance**: Increased toughness under dynamic loading.
- **Shrinkage and Crack Control**: Fibers restrain plastic shrinkage and microcracking.
- **Durability**: Depends on fiber type; steel fibers must be protected against corrosion.

21.5 Testing of Fiber-Reinforced Concrete

1. Flexural Strength Test (ASTM C1609)

- Measures load vs. deflection curve.
- Important parameters: First crack strength, toughness index.

2. Compressive Strength (IS 516 or ASTM C39)

- May show minor improvements with fibers.

3. Split Tensile Strength (IS 5816)

- Provides insight into improved tensile resistance.

4. Toughness Index (ASTM C1018)

- Area under load-deflection curve normalized against first-crack strength.

5. Impact Resistance (Drop Weight Test)

- Measures number of blows required to crack or fail the specimen.

21.6 Applications of Fiber-Reinforced Concrete

- **Pavements and Industrial Floors**: Enhanced fatigue resistance and jointless construction.
- **Shotcrete**: Tunnel linings, slope stabilization.
- **Precast Elements**: Pipes, panels, manhole covers.
- **Seismic-Resistant Structures**: Increased ductility.
- **Repair Works**: Retrofitting damaged concrete.
- **Bridges and Marine Structures**: Steel and synthetic fibers enhance durability and strength.

21.7 Advantages of Fiber-Reinforced Concrete

- Better control over cracking.
- Improved toughness and ductility.
- Higher resistance to dynamic loads and fatigue.
- Reduction in reinforcement in certain applications.
- Improved shrinkage control and reduced permeability.

21.8 Limitations and Challenges

- Reduced workability; may require admixtures.
- Higher material and labor cost.
- Uniform fiber dispersion is critical; poor mixing causes weak zones.
- Specialized equipment may be needed for placing and finishing.
- Durability issues with steel fibers in aggressive environments unless protected.

21.9 Recent Advances and Research Trends

1. Engineered Cementitious Composites (ECC)

- Also known as bendable concrete.
- Uses PVA fibers with special cementitious matrix for strain-hardening behavior.

2. Hybrid Fiber Systems

- Combination of fibers (e.g., steel + PP) to balance toughness, strength, and ductility.

3. Nano-fiber Reinforced Concrete

- Use of carbon nanotubes, nanocellulose for enhanced microstructural properties.

4. 3D Printed FRC

- Optimized rheology and fiber content enable structural 3D printing applications.

21.4 (continued): In-Depth Analysis of Hardened Properties

21.4.1 Stress-Strain Behavior

Fiber-reinforced concrete displays a markedly different stress-strain behavior compared to plain concrete:

- **Plain Concrete**: Linear elastic until peak, then sudden brittle failure.
- **FRC**: Shows non-linear strain hardening after first crack. Fibers bridge cracks, allowing for energy dissipation and strain capacity beyond peak load.
- **Post-Cracking Behavior**: Often categorized as:
  - **Deflection Hardening**: Load continues to increase after first crack.
  - **Deflection Softening**: Load decreases but concrete retains some post-crack load-carrying capacity.

Stress-Strain Curve Phases for FRC:

1. Elastic behavior up to matrix cracking.
2. Multiple cracking as fibers begin to engage.
3. Fiber pull-out or rupture depending on bond and length.
4. Final failure after loss of fiber effectiveness.

21.4.2 Fracture Energy (GF)

Fracture energy is a key parameter in characterizing fiber-reinforced concrete toughness.

- **Definition**: Energy absorbed per unit area of crack surface.

- **Influencing Factors**:
  - Fiber volume and orientation.
  - Fiber aspect ratio.
  - Matrix composition.
- **Measurement**: Determined from the area under load-CMOD (crack mouth opening displacement) curve.

FRC typically shows **2 to 10 times** higher fracture energy compared to conventional concrete.

21.4.3 Fiber Pull-Out Mechanism

The fiber pull-out mechanism dominates energy absorption in FRC. Instead of fiber rupture, controlled pull-out is often preferred due to higher energy dissipation.

- **Bond Mechanisms**:
  - Chemical bond (adhesion with matrix).
  - Frictional resistance (during sliding).
  - Mechanical anchorage (hooked or deformed ends).
- **Pull-Out vs. Rupture**:
  - Pull-out allows for multiple cracking and toughness.
  - Rupture is common in high-strength fibers like carbon or PVA.

Designing fiber length, surface texture, and embedment length is essential to optimize pull-out resistance.

21.4.4 Durability of FRC

Durability varies based on fiber type:

Steel Fibers:

- Corrosion prone, especially near surface or in chloride environments.
- Corrosion leads to rust expansion and internal cracking.
- Protective measures:
  - Use of coatings (epoxy).
  - Adequate concrete cover.
  - Use in non-aggressive environments or interior applications.

Polymeric Fibers:

- Chemically inert, corrosion-resistant.
- UV degradation can be a concern for surface-exposed fibers.
- Temperature limitations depending on the polymer type (e.g., melting of PP fibers above 160°C).

Glass Fibers:

- Alkali-resistant glass (AR-glass) required for concrete.
- Use of pozzolanic materials like silica fume can reduce alkalinity and enhance durability.

Natural Fibers:

- Susceptible to biodegradation, fungal attack, and loss of strength over time.
- Require pretreatment or surface coatings for long-term use.

21.4.5 Thermal Properties

- **Thermal Conductivity**: Slightly reduced due to fiber-induced porosity.
- **Fire Resistance**:
  - Polypropylene fibers melt (~160–170°C), creating microchannels for vapor escape and reducing explosive spalling in high-strength concrete.
  - Steel fibers improve fire performance by increasing tensile strength at elevated temperatures.
- **Thermal Compatibility**: Differential thermal expansion between fiber and matrix must be considered to avoid interface cracking.

21.4.6 Creep and Shrinkage

- **Creep**: Long-term deformation under sustained load.
  - Fibers reduce microcracking, thus **reduce creep** especially under flexural stress.
  - Synthetic fibers (e.g., PP) exhibit some creep themselves at elevated temperatures.
- **Shrinkage**:
  - Plastic shrinkage (first few hours): Fibers reduce cracking by bridging early tensile stresses.

– Drying shrinkage (long-term): Effect is modest, but hybrid fiber systems can enhance control.