An Update on Fiber Reinforcement for Concrete Design

EUCLID CHEMICAL

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Dedicated to Cast-in-Place Concrete

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New ACI Design Guides for Fiber Reinforced Concrete, and Other Developments in FRC

Fiber Reinforced Concrete continues to evolve and become more common place in everyday concrete construction. The new ACI 544.4R document and successful examples of FRC can help ready-mix producers, engineers and contractors by providing a roadmap to designing FRC for many applications including wall systems, floors, precast, shotcrete and paving applications.

Your Speaker
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Director of Marketing and Technology, Fiber Reinforced Concrete, Euclid Chemical

- Responsible for marketing and development of FRC markets working with ready-mix producers, contractors, engineers and owners
- 25+ years experience with fibers, R&D, testing and concrete engineering
- Past President of Fiber Reinforced Concrete Association and currently serving on various committees with ACI, ASTM and NPCA

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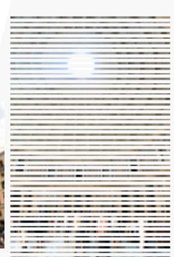
A little levity…..

Some fun facts on concrete



The Roman Pantheon is the largest unreinforced concrete dome in the world – built in 126 AD

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Concrete Firsts

The Federal-Aid Highway Act of 1956 called for 41,000 miles of Interstate roadways to be constructed at an estimated cost of $41 billion;

- 60% of the initial work was constructed with concrete

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Oldest Concrete Street in America

- “Artificial Stone” street in Bellefontaine, Ohio
- George Bartholemew, 1891
- Posted a 5 year bond guaranteeing performance

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Worlds First Concrete Skyscraper

Ingalls Building
Cincinnati, OH

- 15 storey reinforced concrete structure, first of its kind in the world.
- Concerns that it would collapse after bracing was removed

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The Hoover Dam

- Authorized by President Coolidge in 1928; referred to as Boulder Dam; renamed Hoover Dam in 1947 by President Truman
- Secretary of Commerce, Herbert Hoover took active part in development and engineering; oversaw construction during his presidency.Constructed through the 1930's; largest federal works project of its time
- 20,000 workers at height of construction; wages varied from $0.50 to $1.25/hr
- 96 workers died during construction
- 726 feet high, 45 feet thick at the top and 660 feet at the bottom
- Larger than the Great Pyramid of Cheops.
- **3.25 million cubic yards of concrete**, enough to pave a strip 16 feet wide and 8 inches thick from San Francisco to New York City.
- If the heat produced by the curing concrete could have been concentrated in a baking oven, it could have baked 500,000 loaves of bread per day for three years.

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Largest Dam in the world

Three Gorges Dam, Yangtze River, China

- Largest power station in the world – 22,500MW
- 7,661 ft long and 594 ft in height
- 35 million cubic yards of concrete used in construction

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More cool concrete structures

Sydney Opera House, Australia
- roof structure comprises precast concrete shells; entire building sits on 588 concrete piers

Petronas Towers, Kuala Lumpur, Malaysia
- worlds deepest foundation system with piles up to 375 ft deep and a concrete raft mat measuring 15 ft thick using 17,400 yd^3 of concrete

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Concrete Homes

In 1908, Thomas Edison designed and built the first concrete homes in Union, New Jersey. These homes still exist today

100 years later:

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Concrete is Everywhere!

Concrete will continue to be the dominant building material of the future

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The Business of Fiber Reinforced Concrete

A strong future

Although FRC has been used since the 1960's, there have been little to no-agreed upon design approaches in North America for many of their potential applications…. Until now.

New developments in materials technology and the addition of field experience to the engineering knowledge base have expanded the applications of FRC to include design guides that are now material independent and recognized by the engineering community.

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Why use Fiber in Concrete?

Short answer:

To control cracks from forming in concrete during both the plastic and hardened state

Concrete is strong in compression but weak in tension. Like the placement of steel rebar, fibers are placed in concrete to transfer stress, modify the cracking behavior and possibly increase strengths and long term performance.

Quality Fiber Materials

- types of fibers
- shapes of fibers
- quantity of fibers

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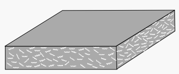
Benefits of Using Fiber Reinforced Concrete

During construction
- Reduced labor and costs
- Reduced construction time
- Increased safety
- Potential reduction in thickness
- Added value for RM



After construction (in service)
- Three dimensional reinforcement
- Shorter and thinner cracks (if any)
- Less spalling and chipping
- Increase in long-term durability
- Lower maintenance costs

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How to Differentiate the Fiber Types – *micros & macros*

steel macro-fibers and micro-synthetic fibers (fibrillated, monofils, etc) are not used under the same conditions.

Micro-synthetics – "secondary" reinforcement; plastic shrinkage only

Steel fibers – industrial floor design; replacement of heavier reinforcing configurations

Synthetic macro-fibers can be thought of like steel fibers, but simply not made of steel. The physical characteristics of these fibers (length, tensile strength, diameter, etc.) are all different, when compared to traditional micro-synthetics.

– dosages of macro-fibers should be calculated by engineering requirements.

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Typical Fiber Types & Dosage Rates

Micro-Synthetic Fibers
- monofilament polypropylene and other synthetic materials
  0.5 to 1.5 pcy for control of plastic shrinkage cracking only

Micro-Synthetic Fibers
- fibrillated polypropylene
  1.0 to 1.5 pcy for control of plastic shrinkage and some temperature and shrinkage cracking as a replacement for very light WWM (6x6 10 gage)

Macro-Synthetic Fibers
- monofilament polypropylene and other synthetic materials
  3.0 to 20 pcy for temperature and shrinkage cracking control and limited structural reinforcement – highly engineered calculations

Steel Fibers
- deformed geometry drawn steel wires
  15 to 100 pcy for temperature and shrinkage cracking control and limited structural reinforcement – highly engineered calculations

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Performance and Specifications

Calculated fiber dosages are becoming more prevalent in the specification community with required testing and compliance. Different fiber types may be more suited to specific applications.

- fiber alternate shall be macro-fiber (steel or synthetic) complying with ASTM C1116 and provide equivalent tensile and/or bending resistance to # 4 rebar (Grade 60) placed 2" from top of a 6" slab or mid-depth in a 8" wall……….

and / or

- "A minimum fe3 of *xxx* psi
- Approved dosage rate for BRAND 'X' by MANUFACTURER 'Y' is 'Z' lb/cy;
  Dosage rate for other products shall satisfy the performance requirements".

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ACI - A wealth of information on fibers…

544.1R	Fiber-Reinforced Concrete
544.2R	Measurement of Properties of Fiber-Reinforced Concrete
544.3R	Guide for specifying, proportioning, mixing, placing, and finishing FRC
544.4R	Design Guide for Fiber-Reinforced Concrete
544.5R	Report on the Physical Properties and Durability of Fiber-Reinforced Concrete
544.7R	Report on Design and Construction of Fiber-Reinforced Precast Concrete Tunnel Segments
544.8R	Report on Indirect Method to Obtain Stress-Strain Response of Fiber-Reinforced Concrete
544.9R	Report on Measuring Mechanical Properties of Hardened Fiber-Reinforced Concrete
506R	Guide to Shotcrete
506.1R	State-of-the-art report on Fiber-Reinforced Shotcrete
506.2	Specification for Shotcrete
440R	State-of-the-art report on Fiber-Reinforced Plastic (FRP)
302.1R	Guide for concrete floor and slab construction
325.10R	State-of-the-art report on roller compacted concrete pavement
207.5R	Roller compacted mass concrete
330R	Guide for design and construction of concrete parking lots
330.1	Standard specification for plain concrete parking lot
332.1R	Guide to Residential Concrete Construction
360R	Design of slabs-on-grade
116R	Cement and concrete terminology

New

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Guide to Design with FRC

Scope of Document

This guide is intended for designers who are familiar with structural concrete containing conventional steel reinforcement, but who may need more guidance on the design and specification for FRC.

In this document, fibers are treated as reinforcement in concrete and not as admixture. The design guides in this document have been derived and verified for FRC with steel and synthetic macrofibers only.

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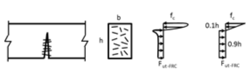
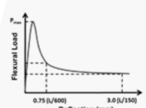
A New Approach for FRC Design

- Chapters 1 & 2 – Definitions, Notations and History
- Chapter 3 – Characteristics of FRC
- Chapter 4 – Design Concepts
- Chapter 5 – Specific Applications
- Chapter 6 – Construction Practices



Classification of fibers based on size and type (micro vs. macro)
ASTM requirements for each fiber type and evaluation methods
Real world examples and techniques for use



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Document Overview

Introductions, Scope, Notations and Definitions

- Introduction and background for this document
- Basic information about fibers and FRC
- History of advancements in FRC
- Engineering and Calculations
- Design and Testing
- Applications and Examples

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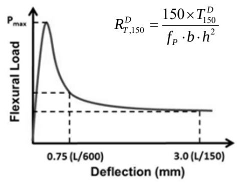
Standardized Testing of FRC

ASTM C1609

- Four point bending test
- Closed-loop control
- Typically strain-softening behavior

$$R^D_{T,150} = \frac{150 \times T^D_{150}}{f_P \cdot b \cdot h^2}$$



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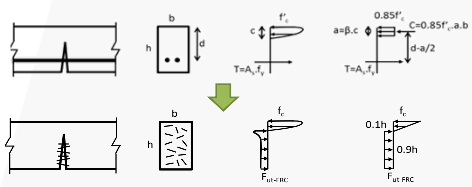
Design of FRC for Flexure

Typical rectangular stress block



$$M_{n-RC} = A_s \cdot f_y \cdot (d - \frac{a}{2}) \qquad M_{n-FRC} = f^D_{150} \times \frac{bh^2}{6}$$

Schematics of stress block for a cracked RC and FRC flexural member.

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Solved Examples

Real world conversions of steel to FRC

Example: Assume an 8" (200 mm) precast panel reinforced with #4@16" placed in mid-section to provide post-crack moment capacity. Find the value of f^D_{150} for FRC to provide the same level of post-crack flexural strength as rebar. Assume 5,000 psi concrete and grade 60 steel and a moment capacity factor of 0.9 for steel.

$$\varphi.M_{n-RC} = \varphi.A_s.F_y.(d - \frac{a}{2}) = 0.9 \times 0.147 \times 60{,}000 \times \left(\frac{8}{2} - \frac{0.17}{2}\right) = 31{,}120 \ \ lb - in$$

$$a = \frac{A_s.F_y}{0.85\ f'_c.b} = \frac{0.147 \times 60{,}000}{0.85 \times 5{,}000 \times 12} = 0.17 \ in$$

$$\varphi.M_{n-FRC} = \varphi.M_{n-RC} = 31{,}120 \ \ lb - in = \varphi.f^D_{150}\ \frac{b.h^2}{6}$$

$$\rightarrow f^D_{150} = \frac{6M_{n-FRC}}{\varphi.b.h^2} = \frac{6 \times 31{,}120}{0.9 \times 12 \times 8^2} = 270 \ \ psi \ \ (1.86 \ \ MPa\ )$$

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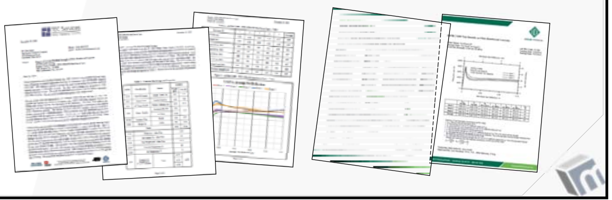
Where to from here?

Verify and Trust

Independent test lab data with specific concrete mix designs can then be used to check compliance and residual strengths of FRC to match design considerations



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Construction, elevated

Safety, speed and cost savings

- IBC 2015 permits fiber for temp / shrinkage steel replacement on c-m-d projects
- Concrete is a wearing surface, usually non-structural
- Need to call on DB and GC's

- Available tools:
  - Tech Data sheets, certification letters
  - UL listings, SDI Manual
  - CMD Sell Sheet, Project profiles

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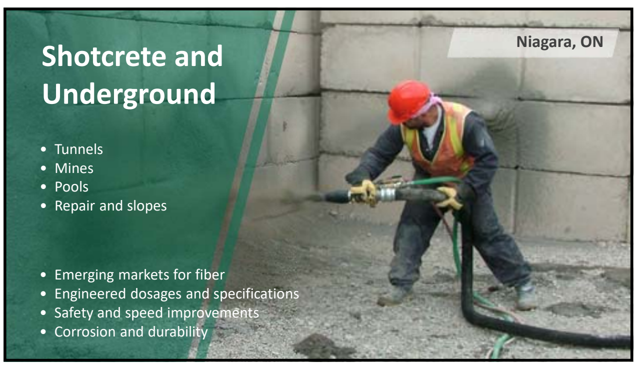

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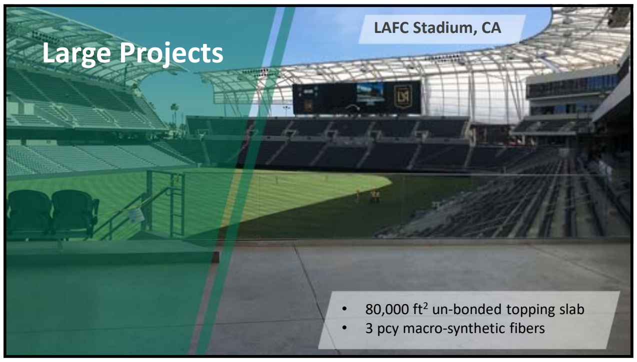

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Indiana DOT

Simple, effective FRC specification

912.06 Synthetic Fibers for use in PCC

(a) General

Synthetic, non-metallic, fibers are used for concrete three-dimensional reinforcement to promote post-crack control, and improve the long-term performance of PCC. Synthetic fibers shall be introduced into PCC mixtures at a dosage subject to required properties in the table below, a dosage no less than 4 lb/cyd, at the batching plant or a ready-mix truck.

(b) Acceptance

Synthetic fibers for use in PCC shall be selected from the Department's list of approved materials. A list of approved Synthetic Fibers will be maintained by the Department. Synthetic fibers may be added to the approved list by completing the requirements in ITM 806, Procedure F.

(c) Requirements

Synthetic fibers shall be Type III in accordance with ASTM C 1116 and ASTM D 7508 with the following exceptions:

1. Aspect Ratio – Length Equivalent Diameter, min. 70
   max. 100
2. Tensile Breaking Strength, min. .... 70,000 psi
3. Modulus of Elasticity, min. .... 800,000 psi
4. Length: 1.5 to 2.25 in

(d) Acceptance Testing of Hardened Fiber-Reinforced Concrete

Testing in accordance with ASTM C 1609 and ASTM C 1579 shall be performed by a recognized laboratory regularly inspected by the CCRL for PCC materials and for specifications listed in this section.

Required Hardened Fiber-Reinforced Concrete Properties

PHYSICAL TEST	SPECIFICATION	REQUIREMENT
Equivalent Flexural Strength Ratio ($R^{D}_{T,150}$)*	ASTM C1609	Minimum of 25%
Crack Reduction Ratio (CRR)	ASTM C 1579	Minimum reduction >85%

*The specimens shall be tested when the concrete flexural strength at first crack (f_1) is a minimum of 600 psi. For 6 x 6 x 20 in FRC beam the maximum required net deflection value of 1/150 of the 18 in span length is 0.12 in.

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Residential Construction
ICF Home, PQ
• Engineered dosage rates
• National potential
• State Revised Code requirements
• PE stamp letters usually needed

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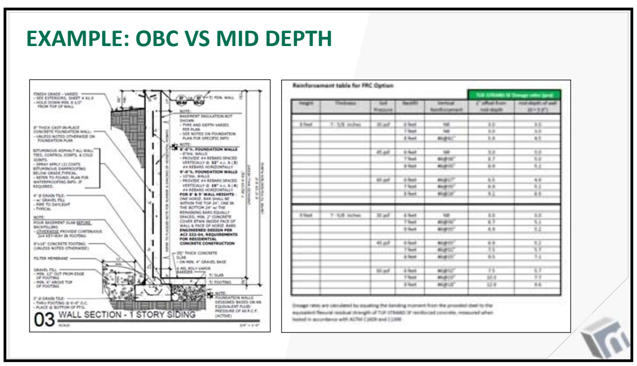
EXAMPLE: OBC VS MID DEPTH
03 WALL SECTION - 1 STORY SIDING

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Bridge Decks
Desert Center, CA
CALTRANS spec:
1 lb/yd³ micro
3 lb/yd³ macro fibers
¾ gal SRA (0.032% shrinkage)
• High Performance Modified Concrete Mixture
• Research projects funded at various Universities
• Increase durability and service life through reduction of cracking

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US23 Bridge, Toledo, OH

OHIO DEPARTMENT OF TRANSPORTATION

- 4 pcy macro-synthetic fiber dosage
- 4500 psi concrete design, 600 psi flexural in 3 hrs
- Replace 20% FA with LWAS for better internal curing
- Wanting better performance, fast turn on construction




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CR44 Bridge, Hinckley, OH

OHIO DEPARTMENT OF TRANSPORTATION

- 10 pcy macro-synthetic fiber dosage
- designed with University of Akron to combat cracking issues in bridge deck construction


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Back to Pavements and Floors

- Concrete floors and pavements must resist dynamic wheel loads, static rack loads and uniformly distributed loads. They must also withstand the damaging effect of fork truck traffic and impact from falling loads or equipment
- Fiber reinforced concrete, which is designed as a homogeneous material, combines easy processing and high reliability

Applications

- Factories & Warehouses
- Hangers
- Concrete overlays
- Bridge Decks
- Pavements and Parking areas
- Rehabilitation projects


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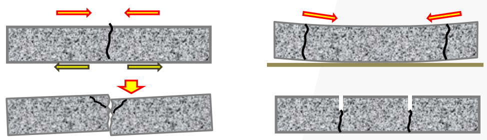
Concrete Shrinkage and Cracking

Understanding failure mechanisms

- restraint - caused by subgrade, curing, mix design, others.
- curling - long term serviceability issue
- load transfer - design, performance and maintenance
- joint spacing - mitigate cracking, design implications



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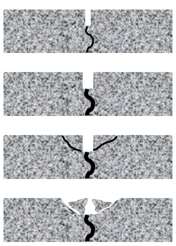
Typical Pavement and Floor Failures



new pavement, conventional sawcut
w/wo dowel baskets
tight crack with aggregate interlock

shrinkage = wider joint opening;
loss of aggregate interlock and load transfer
more moisture accessibility to base

additional cracking at joints,
loss of ability to transfer load
early stages of failure

concrete loss and spall
accelerated failure
typical pavement deterioration

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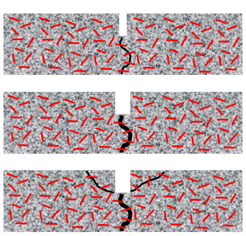
Fiber Reinforced Advantage



fibers provide crack control, improved durability and load re-distribution

if shrinkage occurs, load transfer can still be maintained; 3D reinforcing is maintained throughout matrix

If edge loading causes cracks along joints, concrete integrity is maintained preventing spalling and loss

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RTA Park ‘n Ride – Akron, OH

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Additional FRC Topics

Construction Practices

- Mix Design Recommendations for FRC
- Workability of FRC
- Adding and Mixing Fibers
- Placing, Consolidation and Finishing FRC
- Quality Control for FRC
- Contraction (Control) Joints
- Specifying FRC

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Adding and Mixing Fibers

Different methods, different costs

Considerations – speed, costs, safety, fiber type, job site, specifications

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Placing, Consolidating and Finishing FRC

Same as conventional concrete

FRC can be finished with similar tools as used for unreinforced concrete.

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Common Mix Design Issues when using Fibers

Common mistakes made during batching and placement of FRC mixes

- Insufficient cement / fines to coat extra surface area of fibers
- Incorrect use of fiber types (micro / macros)
- Batching fibers – ensuring non-zero slump conditions
- Adding water to offset slump reductions
- Using slump cone to evaluate workability*
- Timing of finishing (affects water demand)
- Finishing techniques on job – textured and / or troweled
  - Always recommended to have fiber manufacturer present at pre-job
  - When in doubt, conduct a trial mix / placement

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Adjustments

One click away…

- Fiber manufacturers and the FRCA have a series of technical guides, tips, tricks and recommendations on how to work with FRC:
  - Adjusting concrete mix for high volume steel and macro-synthetic
  - Finishing practices – broom vs hard trowel surfaces
  - Selecting the correct fiber type and dosage
  - Navigating the technical language and testing requirements

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Specifying FRC

Summary of Fiber Reinforcement Tests & Parameters

	Reinforcement Purpose	
	Shrinkage/Temperature Crack Control	Post-Crack Tensile/Flexural Capacity
Fiber Type	Synthetic microfiber Steel and synthetic macrofiber	Steel and synthetic macrofiber
Test Method	ASTM C1579 or ASTM C1581*	ASTM C1609 or ASTM C1550 **
Test / Spec Parameter	% in crack width reduction	Flexural residual strength or toughness

* Prescriptive (dosage based) language may be used instead.
** Equivalent BS tests are EN 14651 and EN 14488

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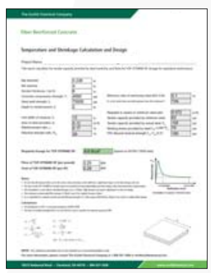
Engineered Solutions

PDF Report, submittal ready

Temperature / Shrinkage
OR
Bending Moment Design



- Follows ACI formulas
- Provides extra calculation steps
- Shows true cost per ft^2
- Ability to save, send and store

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Advanced Floor Designs (Structural)

Chapter 11 - Design Principles
The design principles for micro polymeric FRC are the same as those used for unreinforced concrete.

Macro polymeric fibers provide increased post-cracking residual strength to concrete slabs-on-ground. The same design principles for steel fibers can be used for macro polymeric FRC.

Various fiber manufacturers are now supplying and developing software based design packages for providing optimum thickness & fiber dosage for specific job site requirements.

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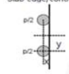
Required Input for Design

- Concrete properties
- Subgrade properties
- Loading conditions
- Curing and saw-cut conditions
- Load patterns
- Dynamic and Static repetitions
- Safety factors

Slab edge/contraction joint



$$R_{e3} = 100 \cdot \left[\frac{3 \cdot z \cdot P_e}{h^2 f_r} - 1\right]$$

-Center of Slab

$$R_{e3} = 100 \cdot \left[\frac{P_c}{6\left\{\left(1 + \left(\frac{2a_c}{L_k}\right)\right) \cdot \left[\frac{f_r t^2}{6}\right]\right\}} - 1\right]$$

-Edge of Slab

$$R_{e3} = 100 \cdot \left[\frac{P_{ce}}{3.5\left\{\left(1 + \left(\frac{3a_c}{L_k}\right)\right) \cdot \left[\frac{f_r t^2}{6}\right]\right\}} - 1\right]$$

-Corner of Slab

$$R_{e3} = 100 \cdot \left[\frac{P_{cc}}{\frac{3}{2}\left\{\left(1 + \left(\frac{4a_c}{L_k}\right)\right) \cdot \left[\frac{f_r t^2}{6}\right]\right\}} - 1\right]$$

where:

a_c = Contact radius of the applied load (mm)
L_k = Relative slab stiffness (resilient subgrade)
t = Slab thickness (mm)
f_r = Flexural strength (MPa)
P_c = Applied load to the center of the slab (N)
P_{ce} = Applied load to the edge of a slab (N)
P_{cc} = Applied load to the corner of a slab (N)

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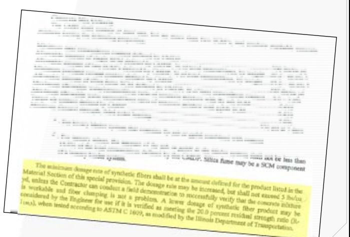
Testing leads to Specs

What to look for…

- Performance criteria will be the new norm in fiber specs
- Language and testing requirements will be more consistent
- Look or search for key words:
  - Residual strength
  - Fiber dosage
  - Manufacturer names
  - C1609



… Silica fume may be a SCM component …

The minimum dosage rate of synthetic fibers shall be at the amount defined for the product listed in the Material Section of this special provision. The dosage rate may be increased, but shall not exceed 5 lb/cu yd, unless the Contractor can conduct a field demonstration to successfully verify that the concrete mixture is workable and fiber clumping is not a problem. A lower dosage of synthetic fiber product may be considered by the Engineer for use if it is verified as meeting the 20.0 percent residual strength ratio (R… (m,s)), when tested according to ASTM C 1609, as modified by the Illinois Department of Transportation.

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Expanding the market from 'Specs'

O. **Macro-Synthetic Fiber Reinforcement**

Macro-Synthetic Fiber Reinforcement shall be used for the purpose of controlling temperature and drying shrinkage cracking. Fibers shall provide a minimum post-crack residual strength value (fe3) of 200 PSI when measured by ASTM C1609, and shall meet the requirements of ASTM C1116 for Type III synthetic fibers. Minimum fiber length shall be 1.5-inches, minimum tensile strength shall be 70 KSI, when tested by ASTM D2256, and minimum aspect ratio shall be 70.

FedEx Ground

B. Macro Synthetic Fibers: Provide high strength. Macro Synthetic Fibers conforming to ASTM C1116, ASTM D7508, and a UL rating.
1. Minimum fiber length shall be 2 inches (50mm)
2. Aspect ratio shall be between 50 and 90
3. Subject to compliance with requirements, products incorporated in work are limited to the following:
   a. Euclid Chemical Company, "Tuf-Strand SF"

C. Minimum Fiber Dosage
1. Provide a minimum dosage of fibers (pounds per cubic yard) to insure a minimum post crack equivalent flexural strength of 200 psi in accordance with ASTM C1609, unless noted otherwise in the following table. The following table defines the requirements for determining the minimum fiber dosage based on specific project criteria:

GM

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Where are these methods now in practice?

Projects are already out there

- Many DOT's are now developing QPL driven, performance based specs
  - Testing programs and specifications are in place in OH, IL, IN, CO and NH
  - Project specifications are in place in CA, NV and UT
- Testing laboratories are better equipped today than ever before
  - ASTM C1609 is becoming the "go to standard" for fiber performance in floors and precast
  - Design methods and specs can now reference this test method
- These Codes and standards are leveling the playing field for FRC producers
  - No more BS marketing
  - RM producers are protected with Engineering support and services

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What does this all mean……

What else needs to be done…..

- New design tools for engineers
- More horsepower for specifying fibers
- Fair game with the same set of performance criteria

- Educating engineering community
- Educating the industry (RM, precast, contractors)
- Working with other ACI committees

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Summary and Conclusions

A good time to be in the business of FRC

- The use of macro-synthetic fiber reinforced concrete for pavements, floors, overlays and bridge decks has been shown to be both feasible and economical while providing a more durable concrete for surface traffic conditions.
- Engineering calculations and codes are becoming more accepted and recognized for design and construction compared to traditional steel
- ACI and other technical organizations will continue to revise, update and publish work related to FRC and disseminate through education with more standards and approvals to come.
- Certified test results with statistical data and field trials should be performed comparing fiber types and reinforcement requirements. There are currently several manufacturers and distributors of macro-synthetic fibers who are successfully marketing these newest reinforcing materials along with the concrete producers who use them.

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