Fiber Reinforcement in Lieu of Welded Wire Reinforcement? Is the design as easy as advertised?

In last year's March 2022 WRI Technical Blog, we briefly discussed fiber reinforcement as a replacement for WWR or rebar in nominal slabs, with a high-level discussion of some of the attributes of a fiber solution that can, at times, be overlooked when it comes to implementation.

As a quick refresher, here are some notable attributes of fiber reinforcement in concrete.

1. Fiber reinforcement is a dosed, additive material that is intended to be part of the concrete mix. Its uniform distribution within the concrete mix is critical for proper performance. Measures must be in place to prevent the fiber material's natural tendency to ball up and clump together.
2. Special attention may be required during the finishing process to ensure fiber material is sufficiently buried, otherwise "hairy" slabs can result.
3. Special attention to and timing of the introduction of contraction joints can be required for slabs reinforced with fiber material, otherwise, the fibers can be pulled up during the saw-cutting operation resulting in spalling or raveling at the joint.
4. The proper design of slabs with fiber is a performance-based exercise, and is entirely contingent upon test data that is specific to the project's defined concrete mixes.

It is Item #4 that deserves a deeper dive in today's blog, the simple goal of which is to show that a fiber-reinforced concrete (FRC) solution as a replacement for conventional reinforcement is not an "easy button" design exercise.

Several direct excerpts from ACI 544.4R-18 "Guide to Design with Fiber-Reinforced Concrete" are presented below for consideration and as basic context for the remaining discussion.

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EXCERPT 1
Standard tests are used for characterizing the performance of FRC, and the results are used for design purposes, including flexure, shear, and crack-width control.

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EXCERPT 2
The decision on the type, material, size, geometry, and dosage for fibers depends on the application as well as the environmental exposure. Ultimately, the performance

of FRC should be evaluated using standard test methods for the application for which it is used.

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EXCERPT 3

Material properties such as residual strength are determined from standard beam tests.

These properties are then inserted into the equations for determining the performance of the FRC and the corresponding load-carrying capacity. Test programs should be conducted in such a way that an appropriate design strength can be established, which includes proper allowance for the uncertainties covered by the partial safety factors in conventional design. Generally, it will be necessary to establish the influence of material strengths on the behavior and their variability so that a characteristic (and thus design) response can be derived. When testing is carried out on elements significantly smaller or larger than the prototype, size effects should be considered in the interpretation of results. Attention should be paid to material behavior at both limit states: ultimate limit state (ULS) for strength requirements as well as serviceability limit state (SLS) for crack width and deflection limits.

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EXCERPT 4

At higher dosages and depending on the fiber type, some adjustments to the mixture design become necessary. This includes adding or increasing the amount of water-reducing admixture (plasticizer) to maintain workability and slump without changing the water-cement ratio (w/c). At much higher dosages, an increase in the paste volume (cementitious materials) and using more fine aggregates can ensure proper accommodation and dispersion of the fibers in the concrete mixture.

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EXCERPT 5

A test or trial mixing is always recommended to ensure that the mixture will support the fiber type/dosage and the batching sequence will not cause any problems.

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EXCERPT 6

Depending on the application and the familiarity of the concrete producer and contractor with FRC, some checks have to be made at a reasonable frequency. The quality control system should include both material control and process control. Material control primarily focuses on controlling the material properties of the delivered product.

Continuous testing of post-crack residual strength would be a suitable option for this approach. A process control-based approach, however, would focus on *controlling all steps when making FRC, rather than testing only the outcome or the final product. Once the residual strength has been determined (initial testing), providing that neither concrete composition, fiber type, or dosage are changed, control of fiber content and distribution will ensure the required performance. Testing post-crack residual strength would, of course, still be essential, but the frequency could be reduced if there is confidence in the reliability of the process.*

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EXCERPT 7
Parameters affecting the performance of FRC include fiber type (material, size, and geometry), as well as bond characteristics and concrete mixture design.

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In the simplest of terms, it is impossible to carry out a calculation on the capacity of a particular fiber reinforced concrete (FRC) slab in the absence of laboratory test data that is specific to the fiber reinforced concrete itself.

Without laboratory test data, there is no FRC design.

Without an FRC design, there is no reliable way for a manufacturer or designer to recommend an FRC solution.

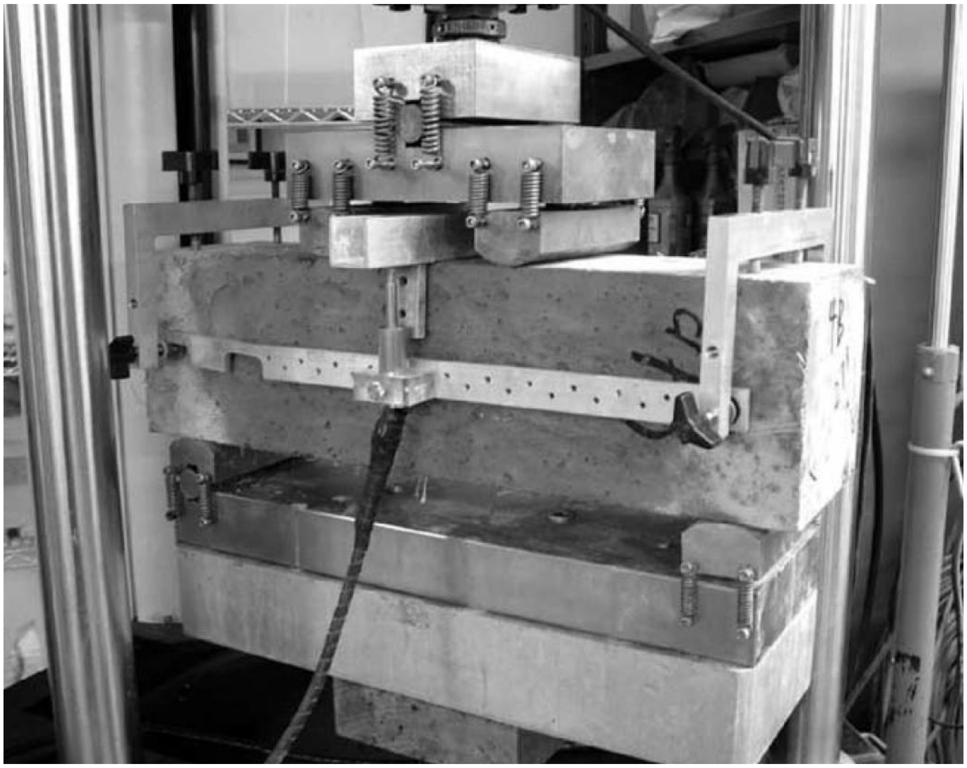
Contrast this with a conventional reinforced concrete design using WWR. For a known cross-sectional area and positioning of reinforcing steel, combined with a known steel yield strength and concrete compressive strength, capacities are easily calculated using longstanding and well-established design equations, with no contingency predicated on validation through testing of purpose-made concrete specimens.

Project stakeholders should be asking questions and receiving transparent guidance on design matters such as those discussed below.

1. What does FRC design look like?

<u>Step #1:</u>
For a specific concrete mix design reinforced with a specific fiber type and dosage, a sample beam is tested in accordance with ASTM C1609 *“Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading)”*, and a plethora of benchmark load values, strengths, and stresses are documented and reported.

Note that per ACI 544.4: *“At least three replicate beams should be tested for determining these parameters, though testing six beams is recommended for achieving a representative average value for residual strength of FRC”*.



ASTM C1609 test configuration
(*image from ASTM C1609, ASTM International*)

Step #2:
With an FRC equivalent flexural strength / residual strength value established through testing as noted in Step #1, and in conjunction with design equations in ACI 544.4, the designer can in turn, calculate capacities relevant to the slab application under consideration and compare these capacities to the slab's load/force demand. The slab would then be proportioned and specified to ensure that demand-to-capacity ratios are acceptable.

2. How is FRC specified?

The Fiber Reinforced Concrete Association (FRCA) recommends that the specification of steel fiber reinforced concrete to be done as follows:

- The "average equivalent flexural strength" must be specified on the contract documents.
- The contract documents must include language requiring fiber type conformance with relevant ASTM material standards.
- The contract documents include language that defers the required fiber dosage to the manufacturer.

With the above definitions established by a designer, a manufacturer, in turn – *typically based on previous ASTM C1609 test results they already have on file* – will offer up a fiber reinforcement type and dosage that has a corresponding "equivalent flexural strength" to that which is specified on the contract documents.

3. ***As the design professional of record (DPOR), how do I know that the project-specific concrete mix designs on my job are compatible with and accurately represented by the manufacturer's "on-file" ASTM C1609 test data?***

The short answer is that you don't, at least not with categorical certainty.

While it is not unreasonable to expect manufacturers to keep extensive records of past ASTM C1609 FRC tests and to have something on file that could end up serving as a fair representation of your project's requirements, a certain amount of disparity between the "on-file" reference FRC test result and the DPOR's project-specific FRC is inevitable.

Concrete mix design is really an art unto itself, with adjustments in proportioned materials and admixture types and dosages resulting in significant differences in performance to suit project-specific needs. It is possible that a manufacturer's on-file ASTM test results, carried out on a generic concrete mix "A", will not fully capture the subtle nuances of the DPOR's project-specific concrete mix "B". And if one reads the fine print associated with any reputable fiber producer's performance data, there is typically language to this end stating that the test results could vary depending on things like mix design, cure time, and size effects.

So if the DPOR elects to rely on a manufacturer's pre-existing (non-project specific) ASTM C1609 test results as being representative of the project-specific FRC design, the matter of whether or not disparities between the two are cause for concern must be navigated and reconciled by the DPOR, as it is the DPOR who is ultimately responsible for the design, not the material manufacturer.

4. *Is there any alternative to relying on one of the manufacturer's "on file" ASTM C1609 test records so that I can eliminate the grey areas mentioned in Item #3?*

To minimize the uncertainty discussed in Item #3, the DPOR can dictate that ASTM C1609 tests be carried out on a project- or case-specific basis, using the same exact concrete mix design as that which is to be specified on the contract documents and slated for use on the project. This purpose-made approach is in good alignment with the basic tenets of of specificity and quality control alluded to in the previously-shared ACI 544.4r excerpts (particularly Excerpts 2, 3, 4, 6, and 7).

Put plainly, project specificity is paramount. And while there are undoubtedly some time and cost ramifications of having an ASTM C1609 test program carried out specific to a particular project's concrete mixes, this is the purest representation of properly-validated FRC.

5. Is it expensive to use project-specific ASTM C1609 testing?

Designers should familiarize themselves with the cost and time premium associated with project-specific ASTM C1609 testing, as there are financial and schedule ramifications when contrasted with project applications using conventional reinforcement.

Test specimens have to be batched and molded using the project-specific mix (including fiber reinforcement), sufficiently cured, transported, loaded, monitored, and reported upon, with the results compiled and then submitted to the appropriate project stakeholders. It is a highly-controlled operation because it is being relied upon to inform downstream design decisions. So naturally, there are cost and time premiums that must be considered.

Note, too, that not all material testing laboratories are equipped and/or accredited to carry out this testing. The designer should confirm ahead of time the availability of testing resources to do the actual work. For example, at the time of this writing, there are only six (6) laboratories in the United States listed as having AASHTO-accreditation (http://www.aashtoresource.org/) for this testing procedure.

6. In Items #1 and #2 above, the term "equivalent flexural strength" is mentioned? If, as the DPOR I am not familiar with what this is, can I still use FRC?

It could be argued that if a designer doesn't have a reasonable working knowledge of FRC design methodology, the material's intended behavior and performance, and the terminology used to describe those attributes, then the designer might end up operating outside of their area of specific and stated expertise. This could not only constitute the offering of an inadequate design service, but could also result in some additional professional liability exposure for the designer.

The simplest solution for a design professional is to abide by their profession's standard of care and avoid the specification of components and materials for which they lack the appropriate level of professional design expertise.

With that said, it is not uncommon for certain fiber producers to promote themselves as design facilitators or delegated designers, with the primary and obvious goal seemingly being to sell more product by assisting with the "simplification" of the DPOR's efforts. Some manufacturers may even employ technical staff and licensed professionals to seal and sign "FRC designs". Depending on the scope and execution of certain contract agreements, there could of course, be some design culpability on the part of the fiber manufacturer such that liability exposure is shared, but it wouldn't be accurate to suggest that full ownership of a design could ever be transferred over entirely to the manufacturer in their role as facilitator or delegated designer.

<u>In the end, FRC design is the responsibility of the DPOR.</u>

7. What Phi factors (strength reduction factors) should be used in FRC design?

There are no published strength-reduction factors for FRC like there are for conventional reinforced concrete design. As such, the values for these factors used in the derivation of capacities are largely selected based on the designer's own discretion / judgment depending on the criticality of the design application.

8. How do I know that the ASTM C1609 test result values correspond to serviceability levels that would be satisfactory for my project? For example, If I'm trying to minimize crack size in a slab, which of the C1609 reported characteristics should I be using?

This is a scenario where a DPOR's own engineering comprehension and judgment are critical, and it highlights some of the complexity of the FRC design process that tends to be overlooked and undersold.

Average equivalent flexural strength typically corresponds to a test specimen mid-span crack size of 0.12", which for an 18-inch long ASTM C1609 test beam span correlates to a deflection ratio of L/150.

For nominal slabs-on-ground in service, the control of crack size is a primary consideration in design. Depending on the sensitivity of the project and the slab's intended utility, the average equivalent flexural strength that corresponds to an L/150 deflection ratio may not be appropriate, and instead a flexural residual strength value corresponding to a much smaller deflection (say, L/600) might be better suited. As it relates to calculations, the strength value corresponding to an L/600 deflection will be considerably smaller than the more commonly advertised equivalent flexural strength that corresponds to an L/150 deflection. If a lower FRC strength (at L/600) is used in calculations in order to better represent smaller crack widths at service level, the result would be a need to increase the thickness of the concrete slab.

Again, the DPOR has an obligation to understand FRC design and the ASTM C1609 test result values that serve as critical inputs for that design. If crack control at the serviceability state is a primary focus, simply running numbers based on FRC strengths at an L/150 deflection level may not yield acceptable results.

As noted in ACI 544.4:

"If FRC is designed for smaller crack widths under serviceability limit state requirements, other parameters such as flexural residual strength at L/600 can be used that correspond to smaller deflection in the (ASTM C1609) beam test. The choice of the design limit (ultimate versus serviceability) and the related design parameter depends on the application and serviceability requirements."

9. Because the ASTM C1609 test specimen is so small, how certain can the FRC designer be that it is truly representative of what likely would be significantly larger expanses and geometries of FRC on the project?

Refer to Excerpt 3 shared previously.

Both ACI 544.4 and ASTM C1609 acknowledge the potential difference in performance - arising from size effects - between the molded test specimen and the FRC poured on site that the specimen is intended to represent. The matter of whether or not the size effects are cause for concern must be navigated and reconciled by the DPOR, as it is the DPOR who is ultimately responsible for the design, not the material manufacturer or the testing laboratory.

To be clear, this blog is not an attempt to discredit or disparage FRC as an unviable nominal slab solution. That the product has its place is not in dispute.

Rather, the point being made through observation is that FRC is not the "easy button" replacement for conventional reinforcement that promotional outlets often present it to be. There are detailed engineering design routines and unique considerations that must be made.

FRC can only be reliably deployed as a solution when the appropriate steps are taken to validate and support the subsequent design, and those steps are predicated entirely on the presence of relevant data taken from a rigorous ASTM C1609 testing program that is representative of the specific application in which the FRC is proposed for use.

DPORs who consider using FRC on their projects have an obligation to familiarize themselves with the requirements of the ASTM C1609 specification as well as the FRC design methodology outlined in ACI 544.4, and should proceed cautiously in those instances where the delegation of FRC design responsibility is presented to them as a method of simplifying or reducing their role and responsibility in FRC design.

References:

1. ACI Committee 544, "Guide to Design with Fiber-Reinforced Concrete (ACI 544.4R-18)", American Concrete Institute, Farmington Hills, MI, 2018

2. "Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading) (C1609/C1609M-19)", ASTM International, West Conshohocken, PA, 2019.

3. "Fibers-in-Practice FIP 8 – Design and Specification of Fiber-Reinforced Concrete", Fiber Reinforced Concrete Association, Murfreesboro, TN, 2018