Cracking Histories of Synthetic Fiber Reinforced Concrete Applications

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Synopsis: In 1994, the bridge over Interstate 90 at mile marker 212 in South Dakota, USA, used synthetic fiber reinforced concrete in the approach, deck topping, and Jersey barriers. Crack widths were measured and counted on the three applications with a histogram developed for the Jersey barrier. The synthetic fiber dosages were 1.3% and 1.6%. This location and applications have been monitored almost yearly and more thoroughly in 2007. Comments, including crack history, on other applications placed 1994 to 1995 and 2002 to 2006 are included for comparison. Further comparisons include synthetic fiber reinforced concrete with and without conventional steel reinforcing, and with plain concrete. There is a significant measurable difference in crack frequency and width with a decided benefit from synthetic fiber reinforcement. The historical and philosophical review is accomplished with selected examples of synthetic fiber reinforced concrete projects to allow for a generalized beneficial conclusion.

Keywords: fiber reinforced concrete, FRC, synthetic FRC, theoretical mechanics, projects

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INTRODUCTION

A good design for construction has to do with best fit, or conformance to the existing conditions, and results in a desired outcome by following a generally understood set of activities to establish some constraints and parameters. For a designer, this begins with determining the customer's softer issues such as needs, wants, and desires. From this then, hard measurable criteria are established to meet the project cost, schedule, and performance. Before the project begins, the risk is getting enough information about these issues without dictating to the customer the designer's preferences. When the materials have been chosen and design is complete, the information is usually transmitted to construction by contract (legal verbiage about relationship conduct) including specifications (criteria generally and specifically about materials and execution issues on pages, copies, cut sheets, etc.) and graphical representations (drawings, sketches, etc.) of the work to be done. By definition, the amount of these documents is the level of quality control the designer wants for the project. Further risks associated with the construction have to do with labor, equipment, materials, weather, and then also incorporating and ensuring the designer's intent.

The benefit associated with this entire process is that it can be repeated for other projects. Further, a person's philosophical understanding coupled with his belief systems, education, and experience will significantly influence and drive this design construction process (White 2003). The use of fiber reinforced concrete (FRC) is no less challenging to consider for projects.

The philosophical and case histories cited are based on experience and intended for educating others on what was done by generalizing a simple conclusion (MacDonald 2005). Numerous diverse applications are included to conclude that fibers influence concrete by reducing cracking incidence and width. None of the concrete mixture information, strength, or load information is presented in this paper for comparison and analysis. The variables considered were concrete with fibers or not and what dosage of fibers to significantly influence the concrete as a variable rather than just a random exception.

PAST FRC

ACI Committee 544 Fiber Reinforced Concrete (FRC) cites in the 1966 State of the Art report that the concept of straw in mud from Biblical times seems tied to fiber reinforced concrete (ACI Committee 544 1966). Figure 1 – shows a photograph taken in Egypt in the 1990's of a straw and mud wall that was reported to the photographer as near 2,000 years old. Further, comparisons of the 1966 and 1996 State of the Art reports from 544 FRC Committee show that nothing changes, although some of the issues will always be of concern.

What have probably changed are the performance, schedule, and cost that bring definition to any project. Hence, FRC of years ago is probably the same in composition as today, but how FRC has been used in projects by changing the performance, schedule, and cost is where the innovation and change can be discussed. Hence, the great pyramids as an example could be built today, but the discussion would be about performance (would the new behave the same), schedule (would the new last as long and how long to build), and the costs would be significantly higher (is it worth it).

Generally speaking, most people – not including engineers – have zero tolerance for cracks and believe any cracked concrete has failed. Regardless of definition of failure, there are correlations that can be established regarding tolerable crack widths as described in ACI 224 Cracking committee documents (ACI Committee 224 2001). Relating the crack widths to durability only seems technically sound because of the obviousness that a crack of greater width allows faster intrusion, meaning whatever is detrimental to the concrete would have been kept out if the concrete crack had been narrower.

Further, an FHWA Manual identifies numerous causes of early and later cracking of concrete. The durability issues for hardened concrete properties are to minimize permeability, cracking, and alkali-silica reaction, and to maximize frost, abrasion, and sulfate resistance. The FHWA Manual reports early age cracking (for pavements) can be caused by concrete mixture proportions, sawing, curing, insufficient joint depth, excessive joint spacing, warping (curling), high temperature, too many lanes tied together, edge restraint, slab/base bonding (high frictional restraint), misaligned dowel bars, and temperature changes (shock from cold front with or without a rain shower). Hardened concrete cracks from applied loads, loss of support, reflective cracks from stabilized bases, slab/base bonding (high frictional restraint), mortar penetration (joint closure penetration), differential environmental support, misaligned dowel bars, alkali-silica reaction, chemical attack, and frost related (Taylor et al. 2007).

In 1984 at the first CANMET conference about Durability, MacDonald presented a paper describing the inspection of hundreds of FRC applications at 3 chemical plant sites in 2 states. The FRC applications were better than the no fiber applications, but the FRC technology was too young then and just the added attention to the projects using fibers might have resulted in better concrete anyway compared to the no fiber concrete (MacDonald 1984).

SOME THEORETICAL AND PRACTICAL DISCUSSIONS ABOUT FRC

Figures – 2 and 3 show the failure modes and behavior of brittle concrete cylinders in compression. Figure – 3 the cylinder has fibers in the concrete matrix and Figure – 2 the cylinder does not have fibers in the concrete. The fiber concrete material behavior can be categorized as follows: tough, ductile, load carrying after it cracks, holds broken brittle material together. Regardless of the words used to describe the observed phenomena, the next scientific method type question is why and from what theoretical basis can this be modeled or described.

The basic concepts about FRC theoretical mechanics and behavior are shown in Table – 1 from the ACI 544 committee short course on FRC. There are some corollaries and subsets that follow: reinforced concrete, development length, engineering mechanics, materials engineering, structural engineering, and macro versus micro views. Frequently during discussions and extended times of reasoning, engineers will change their own arguments regarding a belief in fracture mechanics or strength of materials. (And upon further discussion, the basics or background of these two theoretical views, strength of materials and fracture mechanics, are not relationally understood with the corollaries and subsets previously identified. Neither theoretical view is right or wrong, just different and again only theoretical! The purpose of illustrating these two worldviews of FRC is to add honesty to the conversation between the seller and buyer of FRC).

Any reinforcement can behave with a slip or grab, stretch or break. Both slip or grab and stretch or break behaviors are desired, but not exclusively either one. Too much of one or the other will result in behavior too brittle or too elastic and essentially not provide any reinforcement. This is similar to under and over conventional steel reinforced concrete (Wang and Salmon 1973). So theoretically, there is only a scale difference between understanding models of conventional and fiber reinforced concrete.

The definition and features of fibers for reinforced concrete is small (significantly less than conventional reinforcing steel), discrete (discontinuous), higher aspect ratio (length divided by width), distributed 3 dimensionally and homogeneously, imparts isotropic (uniformly consistent not significantly separate or anisotropic) behavior to the concrete, and just like conventional reinforcing, carries load after the concrete cracks.

SIGNIFICANT FRC DEVELOPMENTS

A concrete project responsibility and process life is shown in Table – 2. The purpose of this table is to broadly outline steps and commitments in the project, and to show how affecting the performance-schedule-cost in these areas for those responsible for projects can define value to the fiber industry.

In 1977 at the South Dakota School of Mines and Technology, steel fibers were tested that were glued, side-by-side (Ramakrishnan et al. 1980). The significant difference between this solution and other available steel fibers that were also tested was fiber efficiency and ease of batching. The loose fibers, ‘not collated’ or glued, had to be hand shuffled into the mixer, like cards, in small quantities to inhibit balling and clumping of the fibers. The collated or glued fibers were easily added, dumped, or just put into the mixer ‘all-at-once.’ This fiber collation significantly reduced time for the batching and mixing of the fiber concrete. The significant performance improvement, or increased fiber efficiency, was accomplished by improved anchorage of the steel fiber in the concrete matrix. The cost difference between the steel fibers was insignificant compared to the added performance and to the reduced time that translated into added assurance that what was desired was more easily obtainable.

In about 1993, the first work was done with synthetic fibers that mimicked the concrete load carrying behavior after cracking of steel fibers. Previous attempts at increasing the synthetic fiber dosage were like the 1977 steel fiber batching and addition issues, balling and clumping of fibers. A dispersible circumferential wrap of paper to encase the synthetic fibers overcame the batching addition issues of these larger synthetic fibers (Ramakrishnan 1997). Later in about 1999, the synthetic fibers accomplished collation by another means, twisting the fibers into bundles and also packaged in a dispersible bag. The notable performance issue with the synthetic fibers was no corrosion. The schedule or time difference was comparable to the 1977 improvements by that collation approach, loose versus glue.

FRC PROJECT BENEFITS

From Table 2, the concrete project responsibilities and project process life were significantly affected in all areas by the 1977 and 1993 improvements to FRC but could be focused as remarkable and outstanding in design and analysis, materials, batching, and testing. The other areas were affected like most goal driven methodologies. There were some affects and trade-offs, but very little was compromised overall regarding performance, schedule, and cost, which generally improved the projects.

The following applications illustrate the improvements when compared to alternate means to accomplish these improved results. The following examples show the effect of the addition of fibers on cracking in these 7 applications (3 for 1994 to 1995 and 4 for 2002 to 2006):

<u>1a. 1994 Bridge, bonded deck overlay</u>
This thin bonded overlay was on a bridge at Exit 212 on Interstate 90 in South Dakota. It was the first to use 1.7% synthetic fibers in an application 340 ft by 48 ft by 2 in. (104 m by 14 m by 50 mm). It was transit ready mixer supplied and not a mobile mixer. There are no apparent cracks in the overlay from a ‘not official’ casual walk over inspection of the bridge in 2007.

<u>1b. 1994 Bridge, thin bonded asphalt overlay bridge approach</u>
This was the first to use 1.3% and 1.7% in two panels about 50 ft by 14 ft by 2.5~4.5 in. (15.2 m by 4.3 m by 63 to 114 mm), transit truck supplied. There was a significant crack in the underlying asphalt that was not filled before the overlay. There is one crack in the 1.3% concrete panel but it is not near the asphalt crack below.

<u>1c. 1994 Bridge, Jersey barrier walls (Figure 4)</u>
Three types of concrete were placed into two Jersey barriers on the sides of one bridge: no fibers, 1.3% and 1.7% synthetic fibers. No conventional steel reinforcement was removed. Crack width histograms showed significantly reduced crack widths and incidents (number of cracks) with increasing fiber dosage. The crack widths were compared to ACI 224R-01

Table 4.1- Guide to reasonable crack widths, reinforced concrete under service loads (ACI Committee 224 2001). The table lists five exposure conditions and related crack widths and includes some caveats about sound engineering judgment regarding cracks in concrete. Crack widths wider than the maximum crack width value do not meet an exposure condition. The listed exposure condition and crack width value and narrower crack widths meet that exposure condition. The narrowest crack width exposure condition is for 'Water-retaining structures' with crack widths less than 0.004 in. (0.10 mm). The exposure condition for 'Deicing chemicals' is crack widths 80% more than the narrowest. Only 15% of the no fiber concrete crack widths and 93% of the fiber concrete crack widths met the 'Deicing chemicals' exposure condition. The average crack width of the no fiber concrete was 300% of the narrowest or exposure condition 'humidity, moist air, soil'. The 1.3% fiber concrete average crack width equaled the narrowest crack width and the 1.7% fiber concrete was 50% of the narrowest crack width.

<u>2a. 1995 Bridge, Full depth deck</u>

There are two bridges side by side at Exit 12 on Interstate 90 in South Dakota. The west bridge was built in 1994 with no fiber and the east bridge was built in 1995 using 1.7% synthetic fiber as supplemental to the steel epoxy coated rebar. There were too many cracks in the west bridge to document very accurately. This was the first fiber application on a full depth deck 340 ft by 40 ft by 10 in. (104 m by 12.2 m by 254 mm). The east bridge had six cracks topside, 1 crack 0.004 in. (0.10 mm) width and 1 ft (305 mm) long, and five cracks that were 25% less crack width. The underside had 32 cracks, 28 cracks less than 0.016 in. (0.41 mm) width for dry air exposure, and four cracks 6%, 25%, 31%, and 100% greater width averaging in length 4.5 ft (1.4 m).

<u>2b. 1995 Bridge, Jersey barrier walls</u>

This second Jersey barrier wall application was for both sides, meaning two applications 340 ft (104 m) long. Again, no rebar was replaced by using the fibers. There were 25 cracks that were all considered as Water-retaining for the Exposure condition.

<u>3. 1995 Pavement full depth</u>

This was an experiment to place a continuously reinforced concrete pavement with fibers rather than steel rebar. The synthetic fiber reinforced concrete was 1,320 ft (402 m) of centerline tied two lanes in each direction, each lane 12 ft (3.7 m) width, and 6.5 in. (165 mm) thickness. The other pavement was not reinforced and was 8 in. (203 mm) thickness. This is a 'go to market' road and located north of Pierre, South Dakota, near the town of Onida. Temperature ranges are between minus 40 and plus 130 °F (minus 40 to plus 54 °C) on the open prairie. Within 2 weeks of the fall season placement, cracks occurred at an average 89 ft (27.1 m) on center almost perpendicular across both lanes. For unknown reasons surmised to be 'this is what has always been done,' the cracks were immediately routed and sealed with a bitumen sealer. The state wide paving representative indicated the concrete would be cracked significantly by next year at best 20 ft (6.1 m) on center. The 2007 inspection of the pavement showed no additional cracks have occurred since the original concrete placement.

4. 2002 Manufacturing pallets floor
The four slabs are located near Grove City, Pennsylvania, in a single building used to manufacture pallets. The four slabs are 30 by 90 ft by 5 in. (9.2 m by 27.4 m by 127 mm). The slabs were all placed as identical as possible except for fiber length, 1.5 and 2.1 in. (38 and 54 mm), and dosage, 0.25% and 0.50%. There is one crack in the middle of the slab with the lowest dosage and shortest length fiber.

5. 2003 Not-bonded floor overlay
The roller skating rink overlay is located in Atlanta, Georgia, and has rounded corners but is generally 87 by 167 ft by 4 in. (26.5 m by 50.9 m by 102 mm) placed on a thick plastic type slip-sheet using a synthetic fiber dosage of 0.5%. There are no joints and no cracks and no steel was used at all.

6. 2004 Warehouse slab on ground
The warehouse slab on ground was 6 in. (152 mm) thickness, and had no joints and no significant cracks in the 60 by 130 ft layout (18.2 by 39.6 m). The slab had 0.5% synthetic fiber dosage. The adjacent 85 by 115 ft layout (25.9 by 35.1 m) had one mid panel crack due to settlement from fill materials. The performance of the slab has been outstanding – no cracks and a better fork truck ride – and the costs were significantly reduced by no saw cuts (1,850 ft – 563.9 m).

7. 2005 and 2006 Concrete overlay of a residential asphalt driveway (Figure – 5)
An ultra thin “whitetopping” overlay of a residential driveway was done on a 17% slope and built the wrong way - top down instead of bottom up. The slab is minimally 1.5 in. (38 mm), 250 ft long (76.2 m) and about 9.5 ft width (2.9 m). No surface preparation was used for adhering the concrete except to blow off leaves and no filling of the significant potholes from the loose asphalt. There are no saw cuts and minimal cracking from using a 0.67% synthetic fiber dosage. There are more cracks in the placement done in 2005 than the 2006 placement. The additional cracks are from the less strong concrete put into service too soon due to the colder weather because everything else was essentially the same with both placements. This concrete placement would not have been tried without fibers because the thin section would have behaved just like the asphalt: once cracked, dislodge pieces and reduce the serviceability.

FRC FUTURE AND CONCLUSION

Future improvements in FRC will come and are inevitable and will focus just as in the past on performance, schedule, and cost. These issues and how these benefit the various parties involved in the concrete project process life will no doubt be significant and will improve testing to understand the behaviors and refine the models. Since concrete is second to water as the most widely consumed material in the world, there appears to be no shortage of future opportunities.

It is believed these case histories should be sufficient to prove that the use of synthetic fibers (at sufficient dosages) can minimize and reduce cracking in concrete and therefore increase the concrete durability.

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FRC Theoretical Mechanics		
Aspects	Theory 1	Theory 2
Basic Conceptions	Reinforcement	Fracture toughening
Background	Strength of Materials	Fracture Mechanics
Emphasis	Bond and anchorage	Energy absorption
Requirement	Strong stiff fibers	Adequate numbers of fibers
Fiber Functions	Spans over cracks	Matter states and ages
Resultant Objective	Significant matrix damage	Matrix integrity
Force Conductors	FIBERS	MATRIX

Table 1 – Aspects and 2 theories of FRC theoretical mechanics

Generalized Concrete Project: Successive Responsibility and Process Life			
Designer	Supplier	Constructor	Owner
Material selection	Mixture proportions	Placing	Service
Design and analysis	Batching	Finishing	Repair
Materials	Mixing	Curing	Removal
	Delivery	Testing	Recycling
			Disposal

Table 2 – Successive responsibility and process life of a generalized concrete project

Figure 1 – Straw and mud personal photograph from Egypt in the 1990’s

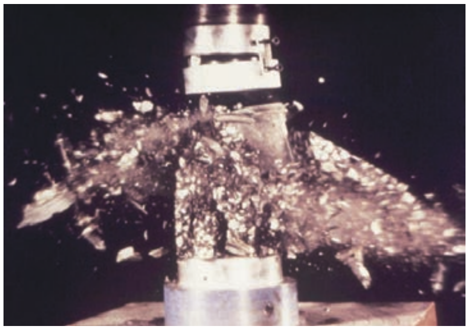

Figure 2 – No fiber concrete cylinder break

Figure 3 – FRC extended cylinder break

Figure 4 – Steel reinforced Jersey barrier

Figure 5 – Thin overlay residential driveway