

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

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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

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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):

1a. 1994 Bridge, bonded deck overlay

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.

1b. 1994 Bridge, thin bonded asphalt overlay bridge approach

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.

1c. 1994 Bridge, Jersey barrier walls (Figure 4)

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.

2a. 1995 Bridge, Full depth deck

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).

2b. 1995 Bridge, Jersey barrier walls

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.

3. 1995 Pavement full depth

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.

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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

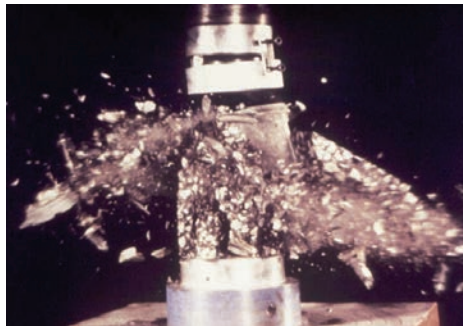


Figure 2 – No fiber concrete cylinder break Figure 3 – FRC extended cylinder break



Figure 4 – Steel reinforced Jersey barrier Figure 5 – Thin overlay residential driveway

Improving the Plastic Shrinkage Cracking Resistance of Self-Consolidating Concrete with Fiber Addition

Dr. Dean Forgeron P.Eng., and Dr. Jean Francois Trottier P.Eng.

SYNOPSIS:

Self-consolidating concrete has become an important material in the concrete construction industry, however the modifications required to produce self-consolidating concrete (SCC) can significantly increase its susceptibility to cracking. This is an important durability issue when SCC is considered for use in reinforced concrete marine and highway structures.

A common method of increasing the resistance of concrete to cracking is the addition of discrete monofilament macro-synthetic fiber reinforcement. However, the addition of fibers to SCC has the negative effect of reducing its self-consolidating characteristics. An experimental program was conducted to investigate the mixture modifications required to maintain the self-compactability of SCC with the addition of various rates between 0.2% and 0.4% by volume (1.8kg/m^3 (3.0 lbs/yd^3) - 3.6kg/m^3 (6.0 lbs/yd^3)) of a commercially available monofilament self-fibrillating macro-synthetic fiber. The effect of fiber addition rate on the plastic shrinkage resistance of SCC was also evaluated.

The addition of fiber volume fractions ranging from 0.2% to 0.4% by volume were easily incorporated into several SCC mixtures ($w/c = 0.4, 0.42, 0.45$) with adjustments made to the coarse/fine aggregate ratio and high range water reducer dosage rates. Interestingly, the addition of as little as 0.2% by volume of the monofilament self-fibrillating macro-synthetic fiber resulted in a 44.6% decrease in plastic shrinkage cracking area, when compared to its unreinforced counterpart, while also reducing the maximum observed crack widths by 43%. The addition of a higher fiber dosage (0.4% by volume) resulted in as much as a 70.4% reduction in cracking area and a 62% reduction in maximum crack widths for SCC mixtures with w/c ratios ranging from 0.4 to 0.45. From this study, it can be concluded that monofilament self-fibrillating macro-synthetic fiber reinforcement can be successfully incorporated into an SCC mixture to significantly increase its resistance to plastic shrinkage cracking while maintaining the workability expected from this type of concrete.

KEYWORDS: Plastic Shrinkage Cracking, Self-Consolidating Concrete, Self-Fibrillating Macro-Synthetic Fibers, workability.

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INTRODUCTION

Self-Consolidating Concrete (SCC) should flow easily and completely fill spaces between reinforcement and forms under its own weight without vibration. In addition, SCC mixtures must resist aggregate settlement and bleeding, during and after the concrete placement. Typically, SCC mixtures have lower coarse aggregate content, smaller maximum aggregate size and higher paste content than conventional concrete mixtures. These modifications are typically associated with reduced volumetric stability and increased potential for cracking than conventional concrete. SCC mixtures typically also contain supplementary cementing materials which can further increase its potential for cracking.

Typically, micro-synthetic fibers are used to reduce plastic shrinkage cracking of conventional concrete^{1,2} but they provide little reinforcing ability in the hardened state and are therefore normally used in conjunction with conventional steel reinforcement. On the other hand, macro-synthetic self-fibrillating fibers have been shown to reduce plastic shrinkage and drying shrinkage cracking while providing post cracking strength similar to conventional light gauge steel reinforcement^{3,4}. However, the addition of macro fibers (Steel and Synthetic) to SCC has the negative effect of reducing its self-consolidating characteristics. This reduction has been attributed to an increase in internal friction due to the presence of fibers which have the effect of reducing the fluidity of SCC. Some adjustments to the mixture composition of SCC are required to reduce this effect. Changes such as reducing the fiber length and reducing the size and content of coarse aggregates seem to be necessary to maintain adequate flow properties of Fiber Reinforced Self-Consolidating Concrete FRSCC^{5,6}.

An experimental program was conducted to investigate the modifications required to maintain the self-compactability of SCC with the addition of various rates (0.2% to 0.4% by volume) of a commercially available monofilament self-fibrillating Polypropylene/polyethylene blend macro-synthetic fiber. The effect of fiber addition rate on the plastic shrinkage resistance of SCC was also evaluated.

TEST PROGRAM

Plain SCC used in structural applications typically must have a slump flow of between 620 mm (24.4") and 720 mm (28.3"), a filling capacity greater than 70%, a L-box blockage ratio ($H_2/H_1 \geq 0.7$), and V-funnel flow time of between 2 and 4 seconds. In practice FRSCC mixtures should also meet the flow requirements of plain SCC. All concrete mixtures in this study were proportioned to meet these specified requirements.

In this study, a total of 18 non-air-entrained SCC mixtures were investigated. To evaluate the effect of fiber addition in a wide variety of SCC mixtures, several mixtures with various water to cement (w/c) ratios were investigated. The SCC mixtures were proportioned with w/c ratios of 0.40, 0.42, and 0.45 and labelled as Series 1, Series 2, and Series 3, respectively. The range of water to cement ratios used in this study represents a typical range seen in SCC concretes used in commercial applications such as precast concrete. All three mixtures contained the same water content of 190 kg/m³. Each series contained six SCC mixtures, one reference plain SCC and five FRSCC labelled as FRSCC 1, FRSCC 2, FRSCC 3, FRSCC 4, and FRSCC 5, which contained fiber volume fractions of 0.20%, 0.25%, 0.30%, 0.35%, and 0.40%, respectively.

Improving the Plastic Shrinkage Cracking Resistance of Self-Consolidating Concrete with Fiber Addition

It is important to note that prior to conducting this test program, many trial mixtures were conducted to evaluate the optimum coarse to fine aggregate ratio which would allow the macro-synthetic fiber used in this study to be added at a fiber volume fraction of up to a maximum of 0.4% by volume. To evaluate the influence of fiber content on the cracking resistance of SCC, the fiber volume fraction was varied between the minimum fiber dosage suggested by the fiber manufacturer (0.2% by volume) to the maximum fiber dosage that could be added while maintaining adequate flow characteristics (0.4% by volume). The optimum coarse to fine aggregate ratio was found to be approximately a 50% split between the volume of fine and coarse aggregate. It is also important to note that the coarse to fine aggregate ratio chosen was based on ease of fiber addition and the resulting effect on workability with no consideration being given to plastic shrinkage cracking potential. The mixture proportions for each SCC mixture used in this study are shown in Table 1.

In this study, commercially available ternary blended cement containing 6% silica fume and 25% fly ash by weight was used in all SCC mixtures. The SCC mixtures were proportioned with crushed coarse aggregate (rounded river stone) having a maximum size of 12 mm and fine aggregate (washed natural sand) with a fineness modulus of 3.0. The shape and the size of the coarse aggregate were selected to enhance the flow characteristics of SCC. The specific gravity and absorption values of the coarse aggregate and fine aggregate were 2.74 and 2.6, and 1.0% and 1.5%, respectively. The grading of the 12 mm coarse aggregate and the fine aggregate (solid lines), used in this study, are both within ASTM C 33 Standard requirements (dashed lines) as shown in Figure 1 and 2. A polycarboxylate based, high range water reducer admixture that fully complies with the requirements of ASTM C 494, and AASHTO M 194 for Type F admixtures, was used in this project. The dosages of high range water reducer were adjusted in each mixture to provide the desired flow characteristics.

A commercially available self-fibrillating macro-synthetic fiber was selected for this study. This fiber is unique in that it is a monofilament fiber that partially fibrillates when mixed in concrete. The geometry, specific gravity, tensile strength, modulus of elasticity of the fiber are given in Table 2.

Prior to mixing, the moisture content of all aggregates was precisely measured allowing for accurate adjustments to the water content in each mixture. All 18 mixtures (0.15 m^3 each) were prepared in a 0.25 m^3 (9.5 ft^3) laboratory drum mixer. After batching and mixing, the various workability tests were conducted in the following sequence: slump flow, filling capacity (34mm between bars), L-box (34mm spacing between bars) and V-funnel, concrete unit weight, air content (ASTM C 231), and concrete temperature. In addition to fresh properties, test specimens were cast for plastic shrinkage resistance, compressive strength (ASTM C 39). Plastic shrinkage cracking tests were conducted by the procedure recommended by ACI Committee 544 (Rectangular Shape).

The plastic shrinkage cracking test was conducted immediately after the fresh properties were evaluated. Two identical concrete slab specimens were cast in plywood moulds 610mm x 915mm x 50mm (24" x 36" x 2") with internal and side restraints. The specimens were exposed to uniform drying conditions for 24 hours. The temperature during testing ranged from 21 °C to 23 °C (70°F -73°F). The relative humidity was monitored during all tests and ranged from 65% to 75% during the period of testing. Two fans were used to generate a constant air speed of approximately 4 m/s (13.1fps) over the surface of the specimens. The fans were placed at the short edge of each plate. After 24 hours of exposure, the total area of cracking, the total number of cracks, and the average crack widths were measured and the results were averaged. The total area of cracking of each specimen was calculated by summing up the product of the length and average width of each crack on the surface of the specimen.

TEST RESULTS AND DISCUSSIONS

The concrete density, air content and compressive strength of all mixtures are shown in Table 3. The air content of all mixtures ranged from 2.3% to 4.4%. The variation in entrapped air was attributed to changes in fluidity of each mixture and as expected was not significantly affected by the addition of self-fibrillating macro-synthetic fiber reinforcement. The measured fresh density was relatively consistent within batches, indicating the level of attention given to controlling mixture components was adequate to produce repeatable mixtures. In fact, all FRSCC mixture exhibited equal or slightly higher compressive strength than the plain control SCC mixture in each series. Fiber distribution in all mixtures conducted in this study was considered excellent with no balling or entanglement. This supports previous findings that this type of fiber reinforcement can be added to properly designed SCC without causing detrimental effects to its mechanical properties.

The slump flow, filling capacity, L-box, and V-funnel tests are shown in Table 4. . All SCC and FRSCC mixtures were easily handled and finished, even at the highest fiber volume fraction of 0.40% by volume (3.7 kg/m^3 (6.24 lbs/yd^3)). The results of the slump flow, filling box, L-box and V-funnel and plastic shrinkage cracking resistance is presented in the following section.

Slump flow test results

All mixtures were adjusted to meet the slump flow requirements of SCC with slump flow ranging from 625 to 715 mm (24.6" to 28.2"). The HRWRA (Plastol 5000 SCC) demand are shown in Table 1 and the results of slump flow tests on each mixture are shown in Table 4. The slump flow was adversely affected by the addition of fibers in series 1, 2 and 3. For example, at a constant HRWR dosage, the increase of fiber volume fraction from 0.20% to 0.25%, in Series 1, caused a reduction in the slump flow from 705 mm (27.75") to 628 mm (24.7"). The effect of fibers on slump flow can also be noted from the HRWRA demand. For mixtures FRSCC1-1 and FRSCC1-5 which had similar slump flow values of about 700 mm (27.6"), the increase of fiber volume fraction from 0.20% to 0.40% required an increase in HRWRA dosage of about 0.75 l/m^3 (33.3 fl oz/yd^3). To evaluate the influence of cementitious content on the high range water reducer demand in FRSCC, the demand must be normalized with respect to cement content and resulting slump flow. Table 1 shows the HRWRA content expressed in litres per 100kg of cement and per 100mm of slump flow. Further normalizing the HRWRA content per 100mm of slump flow allows the effect of mixture proportions on HRWRA demand to be determined for all mixtures. Interestingly, when expressed in this fashion, the HRWRA demand of plain SCC mixtures from series 1, 2 and 3 are similar. In general, an increase in HRWRA content is required to meet plain SCC requirements when fiber content is increased. Despite the increase in internal friction caused by the inclusion of fibers, the unconfined unobstructed flow of the fiber reinforced concrete under gravity in this test was easily achieved with adjustments made using HRWRA.

Filling capacity test results

The results of the filling capacity test, performed on all SCC and FRSCC mixtures, are given in Table 4. All of the concrete mixtures (SCC & FRSCC) exhibited acceptable filling capacity which ranged from 76% to 93.6%. The filling capacities of both plain SCC and FRSCC mixtures were clearly dependent on the fluidity of the concrete mixture. Generally speaking, the mixtures exhibiting high filling capacities had high slump flow values. For example, in Series 2, FRSCC2-3 and FRSCC2-4, which had a slump flow of 680 mm and 700 mm respectively, exhibited filling capacity values of 90.5% and 91.7%, respectively. Whereas, SCC2, FRSCC2-1 and FRSCC2-2 mixtures from the same series, which had lower slump flow values of 625 mm, 640 mm, and 625 mm respectively, exhibited lower filling capacities of 78.4%, 82.6%, and 82.7%, respectively. The same type of observation was made in Series 1 and Series 3. From the results, it appear that the plain and fiber reinforced concrete mixtures possessed moderate to excellent deformability allowing easy placement among closely spaced obstacles. It's important to note that in the slump flow test the concrete flows due to gravitational force from a static position in the slump cone. In the Filling box test the concrete is added for the duration of the test which produces continuous pressure that forces the concrete through the closely spaced reinforcement. Although the addition of fibers is known to increase the internal friction, the nature of this test shows that if the mixture is kept in motion, FRSCC can be easily made to spread through closely spaced obstacles.

L-box test results

The results of the L-box test, performed on all SCC and FRSCC mixtures, are also given in Table 4. For the plain SCC mixtures, the results obtained demonstrate that SCC 3 possessed the greatest passing ability measured with an L-Box ratio of 0.86. This is followed by SCC1 which had a L-Box ratio value of 0.74 and then SCC2, with a L-Box ratio of 0.70.

Many of the FRSCC mixtures that exhibited acceptable slump flow and filling capacity did not meet the minimum L-box ratios of 0.70. By definition this indicates that the mixture has a low ability to spread through reinforcing bars when not consolidated by external forces. From the visual observation during the L-Box tests conducted on fiber reinforced concrete mixtures in series 1 and 2, a small shelf of concrete (10-25mm) remained just beyond the row of reinforcing bars at the end of the test, as shown in Figure 3. It appears that the slight increase in internal friction

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caused by fiber addition lead to a situation where no real blockage occurred, however the application of the test procedure criteria resulted in computed blockage ratios below that deemed acceptable for plain SCC.

The addition of up to 0.4% by volume of self-fibrillating macro synthetic fibers to mixture SCC1 resulted in only a slight decrease in blockage ratio. The lower paste content of SSC2 could only accept up to 0.35% by volume of self-fibrillating macro synthetic fibers without a significant change in blockage ratio. The addition of fibers to mixture SCC3 resulted in the largest decrease in blockage ratio despite the fact that non-fiber reinforced mixture SCC3 had the highest blockage ratio of 0.86. The addition of as little as 0.2% by volume of self-fibrillating macro synthetic fibers to this mixture caused a reduction in blockage ratio to 0.63. The results show the importance of mixture proportions when adding fiber reinforcement to self consolidating concrete mixtures. It appears that a minimum cement paste content is required to allow fiber reinforcement to be present and still maintain a blockage ratio of approximately 0.7 or greater.

V-funnel flow time test results

The test results of the V-funnel flow test for each SCC and FRSCC mixture are presented in Table 4. The V-funnel flow test was conducted to measure the ability of concrete mixtures to alter their path through a narrow section without exhibiting segregation or blockage.

The test results demonstrate that both SCC and FRSCC mixtures exhibited a V-funnel flow time of less than 3.0 seconds. According to previous research, V-funnel flow time should range from 2 to 4 second to possess adequate stability and good resistance to segregation and blockage⁷. The mixture proportions and fiber content seem to have little effect on the flow time for stable concrete mixtures that possess adequate fluidity.

Plastic shrinkage cracking properties

A summary of the plastic shrinkage cracking test results of all concrete mixtures are presented in Table 5. The results represent the average values of the total crack area and average crack width of two plastic shrinkage slabs cast from each mixture. The reduction in the total crack area, due to the inclusion of fibers, was calculated as a percentage of the total crack area of the plain SCC mixture in each series.

For specimens in Series 1 ($w/c = 0.40$), the addition of 0.20% by volume of fibers in (FRSCC1-1) reduced the total crack area, the average crack width, and the maximum crack width by 21 %, 13 %, and 25 %, respectively, when compared to the plain SCC1 specimens. An increase in fiber addition rate to 0.40% (FRSCC1-5) led to 70.4% reduction in the total crack area and a 52% reduction in average crack width and 59% reduction in maximum crack width compared to SCC1. The incorporation of 0.40% fiber volume fraction (FRSCC1-5) reduced the maximum crack width from 0.4 mm (0.0157") to only 0.15 mm (0.0059") as shown in Figure 4.

For specimens in Series 2 ($w/c = 0.42$), the incorporation of 0.20% by volume of fibers (FRSCC2-1) reduced the total crack area, the average crack width, and maximum crack width by approximately 44.6%, 28%, and 25%, respectively, when compared to the SCC2 specimens. An increase in fiber volume fraction to 0.40% in mixture FRSCC2-5 led to a reduction in maximum crack width from 0.4mm (0.0157") to 0.15mm (0.0059") and a 59% reduction in total crack area as compared to mixture SCC2.

For specimens in Series 3 ($w/c = 0.45$), the incorporation of fibers at a fiber volume fraction of 0.20% by volume in mixture FRSCC3-1, reduced the total crack area, average crack width and maximum crack width by approximately 34%, 13%, and 43%, respectively. An increase in fiber content to 0.4% by volume (FRSCC3-5) led to a reduction in maximum crack width from 0.35mm (0.0138") to 0.15mm (0.0059") and a 43% reduction in the total crack area as compared to control mixture SCC3.

Interestingly, a reduction in w/c ratio from 0.45 to 0.40 resulted in a modest increase in compressive strength of 5MPa while the total area of plastic shrinkage cracking increased by four times for plain SCC. The average crack width observed in the panels also increased by a factor of two. The increase in plastic shrinkage cracking is attributed to the increase in paste volume and decrease in the volume stabilizing coarse and fine aggregate content in the lower w/c ratio mixtures. This is in agreement with finding by Loser and Leemann who noted that shrinkage potential of SCC was strongly related to paste volume and not w/c ratio⁸.

In general, increases in fiber content resulted in improved cracking resistance. The addition of as little as 0.2% by volume (1.8kg/m^3 (3.0 lbs/yd^3)) resulted in as much as a 44.6% drop in crack area for series 2 and 25% reduction in maximum crack width observed in series 1 and series 2. A slight increase in fiber dosage to a modest 0.3% by volume (2.7kg/m^3 (4.5lbs/yd^3)) resulted in as much as 57% reduction in crack area for series 2 and a 50% reduction in crack width for series 1 and Series 2.

CONCLUSIONS

In general, the negative effect of self-fibrillating macro-synthetic fiber addition on the flow characteristics of SCC can be countered with proper mixture proportioning and the use of additional HRWRA. Changes in coarse to fine aggregate ratio approaching a 50/50 split as well as an increase in cementitious content and HRWRA content may be required to maintain self-compactability after fiber addition. Fiber volume fractions of up to 0.4% by volume were successfully added to all three mixtures (W/C ratios = 0.4, 0.42 and 0.45) in this study while maintaining adequate slump flow, filling capacity and V-funnel time.

The plastic shrinkage resistance of the SCC was greatly enhanced by the addition of self-fibrillating macro-synthetic fibers. The addition of dosages up to 0.40% by volume resulted in a significant reduction in the total area of cracking, maximum crack width and average crack width of 70.4%, 50%, and 50%, respectively. Such a reduction in cracking potential is expected to translate into a significant increase in durability of structures containing self-fibrillating macro-synthetic fiber reinforced self consolidating concrete.

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Table 1 -- SCC Mixture Compositions.

Mixture No.	Fiber Volume Fraction (%)	Cement [†] kg/m ³ (lbs/yd ³)	Fine Agg. kg/m ³ (lbs/yd ³)	Coarse Agg. kg/m ³ (lbs/yd ³)	Water L/m ³ (gal/yd ³)	HRWR* L/100kg (fl.oz/100lbs)
SCC 1	-	475(800)	800(1348)	843(1420)	190(38.34)	0.67(10.3)
FRSCC1-1	0.20	475	800	843	190	0.74(11.3)
FRSCC1-2	0.25	475	800	843	190	0.74(11.3)
FRSCC1-3	0.30	475	800	843	190	0.79(12.1)
FRSCC1-4	0.35	475	800	843	190	0.84(12.9)
FRSCC1-5	0.40	475	800	843	190	0.89(13.7)
SCC 2	-	450(758.5)	810(1365)	854(1440)	190(38.34)	0.67(10.2)
FRSCC2-1	0.20	450	810	854	190	0.72(11.1)
FRSCC2-2	0.25	450	810	854	190	0.78(11.9)
FRSCC2-3	0.30	450	810	854	190	0.83(12.8)
FRSCC2-4	0.35	450	810	854	190	0.93(14.3)
FRSCC2-5	0.40	450	810	854	190	0.89(13.6)
SCC 3	-	423(713)	825(1391)	869(1465)	190(38.34)	0.68(10.4)
FRSCC3-1	0.20	423	825	869	190	0.69(10.5)
FRSCC3-2	0.25	423	825	869	190	0.71(10.9)
FRSCC3-3	0.30	423	825	869	190	0.77(11.8)
FRSCC3-4	0.35	423	825	869	190	0.80(12.3)
FRSCC3-5	0.40	423	825	869	190	0.83(12.7)

[†] Ternary Blended Cement (St. Lawrence Cement)

* High Range Water Reducer (L/100kg of cement (fl oz/100lbs cement))

Table 2 -- Properties of Self-Fibrillating Macro-Synthetic Fiber.

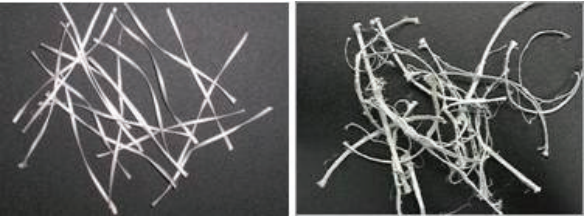
Specific Gravity	0.92		
Material	Polypropylene/ Polyethylene Blend		
Fiber Length	40 mm (1.57")		
Area of Fiber	0.3 x 1.1 mm (0.012 x 0.043 ")		
Modulus of Elasticity	7.8 GPa (1133ksi)		
Tensile Strength	690 MPa (100ksi)	Before Mixing	After Mixing

Table 3 -- Concrete Density, Air Content and Compressive Strength of all Mixtures.

Mix No.	Fiber Volume Fraction (%)	Concrete Density kg/m ³ (lbs/yd ³)	Air Content (%)	Compressive Strength MPa (PSI)
SCC 1	-	2300 (3877)	3.0	48.20 (6991)
FRSCC1-1	0.20	2301 (3878)	3.5	48.20 (6991)
FRSCC1-2	0.25	2303 (3882)	3.8	49.40 (7165)
FRSCC1-3	0.30	2310 (3894)	3.8	49.4 (7165)
FRSCC1-4	0.35	2320 (3910)	2.5	52.70 (7644)
FRSCC1-5	0.40	2320 (3910)	3.7	50.50 (7325)
SCC 2	-	2308 (3890)	4.4	44.10 (6396)
FRSCC2-1	0.20	2319 (3909)	4.0	44.6 (6469)
FRSCC2-2	0.25	2323 (3915)	4.4	44.50 (6454)
FRSCC2-3	0.30	2310 (3894)	3.5	45.30 (6570)
FRSCC2-4	0.35	2311 (3895)	3.5	46.6 (6759)
FRSCC2-5	0.40	2312 (3897)	4.0	45.6 (6614)
SCC 3	-	2322 (3914)	3.5	42.00 (6092)
FRSCC3-1	0.20	2314 (3900)	4.0	42.70 (6193)
FRSCC3-2	0.25	2320 (3910)	2.3	42.5 (6164)
FRSCC3-3	0.30	2311 (3895)	4.0	45.00 (6527)
FRSCC3-4	0.35	2318 (3907)	4.3	42.60 (6179)
FRSCC3-5	0.40	2305 (3885)	4.0	43.70 (6338)

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Table 4 -- Slump Flow, Filling Capacity, L-Box , V-Funnel and HRWRA Demand.

Mix No.	HRWRA Effectiveness*	Slump Flow mm (in.)	Filling Capacity (%)	L-Box Blockage Ratio	V-Funnel Flow Time (sec)
SCC1	0.106	637 (25.1)	85.1	0.74	2.3
FRSCC1-1	0.105	705 (27.8)	86.8	0.67	2.9
FRSCC1-2	0.117	628 (24.7)	79.6	0.70	2.9
FRSCC1-3	0.119	665 (26.2)	82.6	0.67	3.0
FRSCC1-4	0.118	715 (28.1)	89	0.67	3.0
FRSCC1-5	0.128	700 (27.6)	93.9	0.70	2.8
SCC2	0.107	625 (24.6)	78.4	0.70	2.9
FRSCC2-1	0.113	640 (25.2)	82.6	0.74	2.9
FRSCC2-2	0.124	625 (24.6)	82.7	0.67	2.6
FRSCC2-3	0.123	680 (26.8)	90.5	0.73	2.4
FRSCC2-4	0.133	700 (27.6)	91.7	0.67	2.6
FRSCC2-5	0.133	668 (26.3)	82.6	0.60	3.0
SCC3	0.101	675 (26.6)	84.7	0.86	2.0
FRSCC3-1	0.108	635 (25)	76.8	0.63	2.5
FRSCC3-2	0.106	667 (26.3)	79	0.63	2.6
FRSCC3-3	0.122	632 (24.9)	79.7	0.60	2.8
FRSCC3-4	0.126	640 (25.2)	82	0.53	2.7
FRSCC3-5	0.126	655 (25.8)	76.1	0.53	2.7

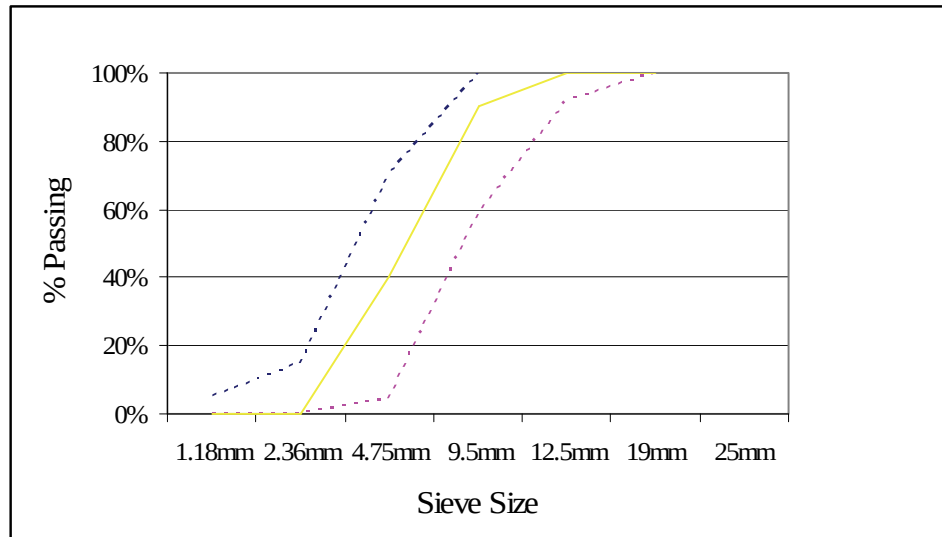
* HRWRA / (cement content (kg)/100) / (slump flow (mm)/100)

Table 5 -- Summary of Plastic Shrinkage Test Results.

Mix No.	Fiber Volume Fraction (%)	Total Area of Cracking (mm²)	Reduction in Total Crack Area (% Control)	Average Crack Width (mm)	Max Crack Width (mm)
SCC1	-	490	-	0.31	0.40
FRSCC1-1	0.20	387	21.0	0.27	0.30
FRSCC1-2	0.25	308	37.1	0.25	0.30
FRSCC1-3	0.30	220	55.0	0.20	0.20
FRSCC1-4	0.35	176	64.0	0.15	0.20
FRSCC1-5	0.40	145	70.4	0.15	0.15
SCC2	-	287	-	0.25	0.40
FRSCC2-1	0.20	159	44.6	0.18	0.30
FRSCC2-2	0.25	150	47.7	0.15	0.20
FRSCC2-3	0.30	123	57.1	0.18	0.20
FRSCC2-4	0.35	122	57.5	0.15	0.20
FRSCC2-5	0.40	117	59.2	0.15	0.18
SCC 3	-	123	-	0.15	0.35
FRSCC3-1	0.20	81	34.1	0.13	0.20
FRSCC3-2	0.25	74	40.0	0.13	0.20
FRSCC3-3	0.30	71	42.3	0.13	0.20
FRSCC3-4	0.35	66	46.3	0.13	0.20
FRSCC3-5	0.40	70	43.1	0.10	0.15

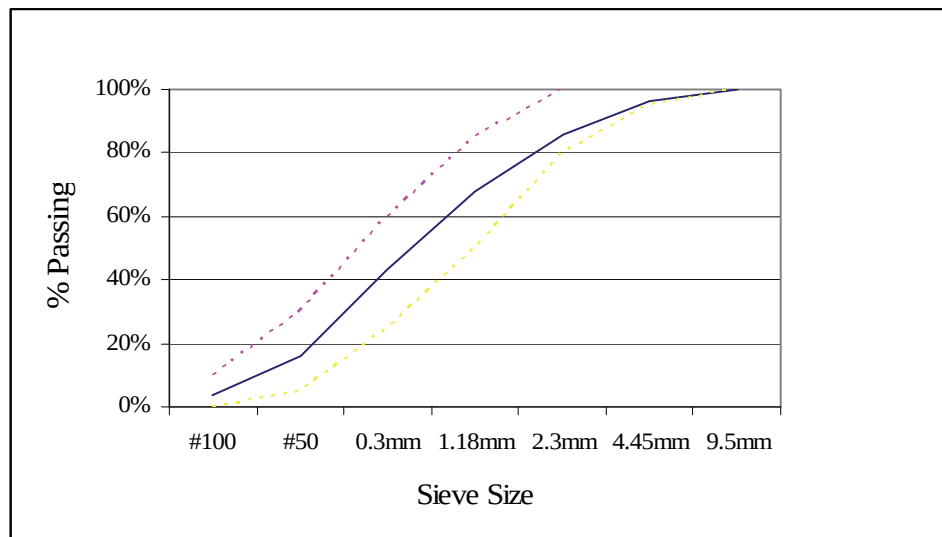
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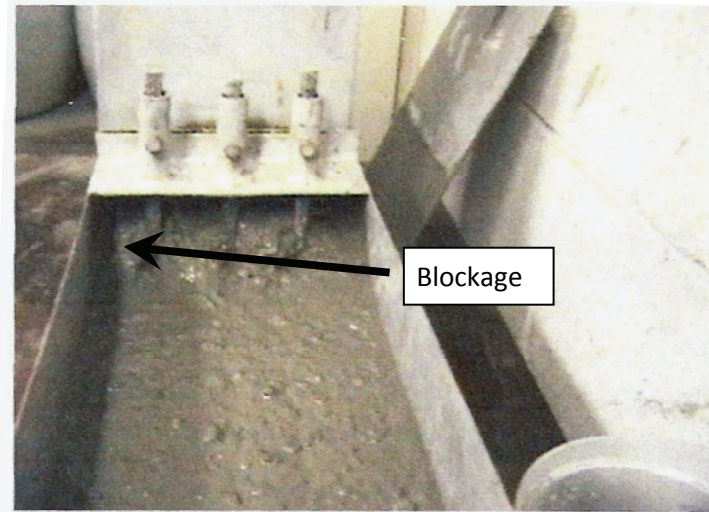
Dashed lines = ASTM C 33 Standard requirements (upper and lower limit for 12mm coarse aggregate)
Solid line = 12mm coarse aggregate grading curve

Figure 1 -- (12 mm) Coarse Aggregate Grading Curve.

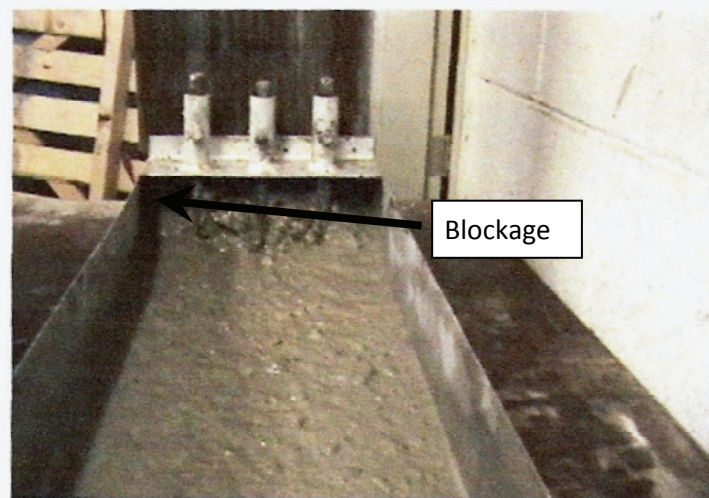


Dashed lines = ASTM C 33 Standard requirements (upper and lower limit for fine aggregate)
Solid line = fine aggregate grading curve

Figure 2 -- Fine Aggregate Grading Curves.



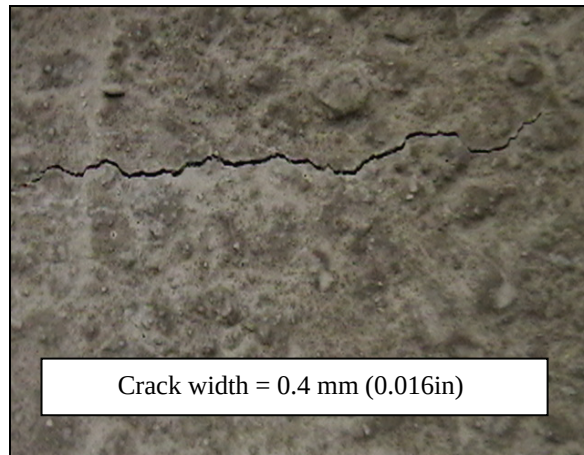
FRSCC 1 ($H_2/H_1 = 0.67$), Fiber Volume Fraction 0.20 %



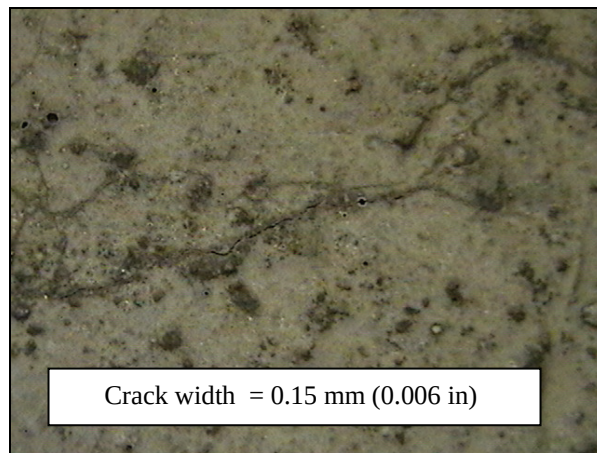
FRSCC 3 ($H_2/H_1 = 0.67$), Fiber Volume Fraction 0.30 %

Figure 3 -- L-box Photos from Series 1.

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Maximum Plastic Shrinkage Crack width, SCC 1



Maximum Plastic Shrinkage Crack Width, FRSCC1-5, Fiber Volume Fraction 0.4 %

Figure 4 -- Typical Example of Maximum Plastic Shrinkage Crack Width.

DURABILITY ENHANCEMENTS OF CRACKED CONCRETE BY FIBERS

Corina-Maria Aldea and Surendra P. Shah

Synopsis: Permeability and cracking affect the durability and integrity of a structure. The addition of reinforcing fibers changes the cracking process in cement based composites. The goal of this paper was to review the research work related to the effect of fiber reinforcement on tensile cracks and water permeability of cementitious composites. Factors affecting this relationship included matrix type, fiber type, geometry and volume fraction, and crack width. Water flow was studied through individual fiber and hybrid fiber reinforced composites. Width-controlled tensile cracks were induced for the polyvinyl alcohol (PVA) and steel fiber reinforced composite samples by feedback-controlled split tension or by feedback controlled wedge splitting. Then water flow was measured with a low pressure test set up. For the hybrid fiber reinforced composites containing blends of macro- steel and micro-steel and PVA fibers tensile cracks were induced by uniaxial tension, while water was forced through the samples under a relatively low pressure. The addition of fibers had beneficial effects on water flow for cracks in the micron range. This was mainly due to changes in crack morphology compared to unreinforced composites and multiple crack development. Permeability thresholds were identified for the crack widths, which varied with the matrix type and the fiber type. Synergistic effects of micro- and macrofibers were obtained through engineered composites mix designs, and hybrid fiber reinforcement showed improved results in terms of mechanical performance and permeability of cracked cementitious composites compared to single fiber reinforcement.

Keywords: cracking, durability, fibers, hybrid fibers, PVA fibers, steel fibers, tension, water permeability.

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INTRODUCTION

Material transport properties, especially permeability, affect the durability and integrity of a structure. High permeability due to porosity and cracking provides a pathway for water, chlorides and other corrosive agents. If these agents reach reinforcing bars within the structure, the bars corrode, thus compromising the ability of the structure to withstand loads, which leads to structural failure.

Building codes require that cracks exposed to weathering be no larger than specified widths in order to ensure structural and mechanical integrity. If tolerable crack widths significantly increase permeability and allow corrosive agents to reach steel reinforcement, the cracks are clearly too large, and the codes should be revised. Knowledge pertaining to permeability can help determine the maximum allowable width of exposed cracks in structures.

ACI 318 [1] procedures only deal with conventionally reinforced concrete. According to section R10.6.4, ACI 318 [1] and in the past ACI 318-95 [2] allowed for exterior exposure a crack width of 0.33 mm (0.013 in). Since 1999 [3] surface cracks are limited “to a width that is generally acceptable in practice, but may vary widely in a given structure”. Meanwhile, no distinction is made between interior and exterior exposure.

Other North American organizations limit crack widths for specific applications as follows. AASHTO Standard Specification for Highway Bridges [4] limits crack widths for concrete decks to 0.30 or 0.38 mm (0.012 or 0.015 in) depending on exposure conditions. As per Section 27, AASHTO LRFD Bridge Design Specifications [4] cracks in concrete culverts are limited to 2.5 mm (0.10 in), whereas cracks for reinforced concrete pipe are limited to 1.6 mm (0.06 in), as per the American Concrete Pipe Association [5].

Crack control recommendations proposed in the European Model Code for Concrete Structures apply both to prestressed and reinforced concrete [6]. According to CEB-FIP 1990 provisions [7] the characteristic crack width (w_k) cannot exceed the limiting crack width (w_{lim}). The limiting crack width is the nominal limit value of the crack width specified for cases with expected functional consequences of cracking, as per Table 1 [6]. In the absence of specific requirements in terms of water tightness, class of exposure, or other factors, a limiting value of 0.30 mm (0.012 in) is satisfactory with respect to appearance and ductility.

Eurocode E2 provisions [8] require that cracking should be limited to a level that does not impair the proper functioning of the structure, or cause its appearance to be unacceptable. Crack width for sustained load and normal environmental conditions is limited to 0.30 mm (0.012 in). This is satisfactory with respect to appearance and durability. For cracks caused principally by flexure the widths are also limited to 0.30 mm (0.012 in).

Previous studies have shown the effect of tensile cracks ranging from 25 to 550 microns (0.001 – 0.022 in) on water permeability and chloride ion penetration of unreinforced cementitious composites, such as paste, mortar, normal and high strength concrete [9-12]. Tensile cracks of desired widths were induced by feedback controlled split tensile tests or by feedback controlled wedge splitting tests. Water permeability of the cracked specimens was measured, on vacuum saturated samples using a low pressure (2.9 kPa (0.42 psi) or 30 cm (12 in) water head) water permeability

test set up, as described in [9, 10]. The results suggested that there is a permeability threshold for the crack width, which is independent of material type (paste, mortar, normal and high strength concrete): for cracks below ~100 microns (0.004 in) there is little effect on water permeability, whereas above this limit there is a significant effect on permeability.

Cracking of fiber reinforced concrete (FRC) is different from unreinforced concrete. It has been reported that adding fibers to concrete is beneficial for its durability, as the fibers reduce the cracking tendency by bridging cracks and reducing the permeability of cracked concrete [14, 15]. Banthia and Bhargava studied the effect of the addition of cellulose fibers on water permeability of compression cracks in the unstressed and stressed state. Collated cellulose fibers at volume fractions up to 0.5% were used and cracks were induced by loading the samples at different levels of compressive stress, which represented fractions of the ultimate strength of concrete in compression (f_u) [16]. It was concluded that fiber reinforcement reduced the permeability of concrete in the unstressed state. A threshold value of compressive stress of $0.3f_u$ was found. Above this threshold an increase in permeability was observed, while the permeability remained below the unstressed level.

Charron et al. investigated the effect of tensile cracking on permeability of ultra high performance fiber reinforced concrete (UHPFRC) [17]. Steel fibers were used for the UHPFRC tested. Tensile cracks were induced and glycol penetration was monitored for unstressed cracked specimens using a water permeability test set up similar to that used in [9-12]. The permeability results were converted from glycol to water transport, which showed that the equivalent water permeability was not affected until a residual tensile deformation of 0.13% was reached, or by a cumulated crack opening below 130 microns (0.005 in). Based on the results of the investigation serviceability limits were defined for the UHPFRC with or without reinforcement bars.

Lepech and Li reported water permeability results of cracked engineering cementitious composites (ECC) and wire mesh reinforced mortar [18]. Tensile cracks were induced by subjecting the samples to elongations of 1.5%. The crack widths induced were closely spaced microcracks of approximately 60 microns (0.002 in) in the ECC and cracks ranging between 150 microns (0.006 in) to 2.5 mm (0.1 in) in the reinforced mortar. Water permeability was measured for unstressed specimens using a test set up similar to that used in [9-12, 17]. The finely cracked ECC maintained the permeability coefficient within the range of the unreinforced mortar, whereas the wire mesh reinforced mortar with larger crack widths exhibited significantly higher permeability.

RESEARCH SIGNIFICANCE

For the purpose of enhancing serviceability, durability and transport properties, e.g. permeability, there is a high interest on how fibers can control cracks in the micron range. The objective of the paper was to review the research work related to the effect of fiber reinforcement on tensile cracks and permeability of cementitious composites. A number of factors which may influence the relationship between crack width and permeability were examined: material type (paste, mortar and concrete), fiber type (PVA, steel and hybrid fibers), fiber length or aspect ratio, volume fraction and crack width.

WATER FLOW THROUGH CRACKED CONCRETE REINFORCED WITH INDIVIDUAL FIBERS

PVA fibers

Experimental program: Shah et al. [19] and Aldea et al. [20] studied the effect of PVA fibers on the relationship between cracking and water permeability. For studying the effect of fiber length, PVA fibers 2 and 6 mm (0.08 – 0.24 in) long were used. Table 2 presents the properties of the PVA fibers used. Test series included reinforced paste and mortar produced by casting. The mix design for reinforced paste used a water-to-cementitious ratio (w/cm) 0.26, PVA fibers 3%, cement 43%, silica fume 11% solid and superplasticizer (SP) 2% by volume. For the reinforced mortar, preliminary work conducted at ACBM Northwestern University using a traditional cement-to-sand ratio (C:S) of 1:3, w/cm=0.45 and no admixtures did not show a clear effect of PVA fibers on cracking and water permeability. Meanwhile, Akkaya et al [21] have shown that sand has a detrimental effect on mechanical properties of the PVA cementitious composites as a result of differences in fiber distribution, an increase in total porosity, and interaction between the matrix and the fibers. Therefore, the reinforced mortar mix design used a C:S=1:0.5, a

w/cm=0.31, PVA fibers 2%, silica fume 11% solid, fly ash class F 9% and SP=2% solid. 100 x 200 mm (4 x 8 in) cylinders were cast for tensile and water permeability tests. All the specimens were demolded after 24 hours and cured at 20°C (69°F) and 100% RH until the age of 28 days. 100 x 50 mm (4 x 2 in) discs were sawn from the cylinders. Cracks of desired widths, ranging between 50 and 300 microns (0.002-0.012 in), were induced by feedback controlled split tension following ASTM C496 [13], as fully described in [9, 10]. One crack was induced in the center of each disc; the specimens were then unloaded and tested for water permeability. The cracks partly closed after unloading. C-scan was used to visualize the crack pattern for the reinforced mortar surfaces of the samples tested after unloading [20]. C-scan is a nondestructive evaluation technique able to distinguish the difference in elastic properties of the materials and results in radiograph-like images highlighting the mechanical defects of the samples. Although companion plain paste and mortars were cast, they were extremely brittle. Only fiber reinforced composites could be tested for split tension and water permeability. Water permeability of the cracked specimens was measured on vacuum saturated samples using a low pressure (2.9 kPa (0.42 psi) or 30 cm (12 in) water head) water permeability test set up, as described in [9, 10]. Water permeability was monitored up to 30-35 days for most of the specimens tested. The permeability coefficient was calculated to quantify the water flow, assuming laminar flow through the cracked material, based on Darcy's law and the continuity of flow [9, 10].

Test results: Figure 1 presents typical stress – average crack width, or crack opening displacement (COD) curves for the PVA composites tested. The addition of fibers changed the trend of the curves compared to previous tests conducted for unreinforced paste and mortar [10]. The ductility of the PVA reinforced paste was improved and cracks up to 300 microns (0.012 in) under load were induced, where as only cracks up to 200 microns (0.008 in) under load could be induced for plain paste in the previous study. The PVA reinforced mortar showed a significant drop in load immediately after the peak load and the first crack formed, for both 2 and 6 mm (0.08 – 0.24 in) fiber reinforced mortars. The drop in load after crack initiation was higher and the crack growth was more unstable for the composite with 6 mm (0.24 in) fibers. With increasing crack widths, the cracks were visible, as developed along the loading diameters for paste and mortar reinforced with both fiber lengths. However, the addition of fibers changed the crack pattern in the higher cracking range compared to plain composites, where multiple cracking was observed for reinforced paste and mortar reinforced with 2 mm (0.08 in) PVA fibers, while mortar with 6 mm (0.24 in) fibers still revealed one well defined crack. The single cracks developed along the diameter of the mortar samples reinforced with longer fibers suggest that the composite experienced a higher damage level compared to that of the mortar reinforced with shorter fibers. The COD measurements for the composites that experienced multiple cracking represent a sum of several narrow cracks induced. The cracks partly closed after unloading and the crack recovery ranged between 60 and 75% for both materials tested. Figure 2 presents the effect of fiber length on crack recovery. No material effect or fiber length effect was observed in terms of crack recovery. C-scan images revealed the differences in crack pattern between the mortar reinforced with 2 and 6 mm (0.08 and 0.24 in) PVA fibers after unloading [20].

Figure 3 presents the effects of fiber length and material type on water permeability coefficient as a function of unloaded average crack widths. Water permeability coefficients of the uncracked plain and reinforced composites were comparable, and the addition of fibers did not change the water flow significantly. All composites were affected by cracking and PVA fiber reinforced composites presented a threshold for the crack width: 50 microns for pastes and 25 microns for mortar. As previously observed for unreinforced cementitious composites [9, 10], for cracks below the threshold the permeability coefficient increased within an order of magnitude compared with that corresponding to uncracked material, whereas above the threshold water permeability increased rapidly. This trend was more pronounced for the mortars compared to the paste, and for the composites with longer fibers compared to those with shorter fibers. The improved performance provided by the short fibers compared to the longer fibers was likely due to a difference in crack morphology induced by a better fiber dispersion and crack bridging of the shorter fibers [19]. Surface crack patterns observed using C-scan suggested that the cracking mechanism was different for the mortars with different crack lengths. Since the rate of flow through a crack with parallel walls is directly proportional to the crack width cubed [12], the reduction in water flow for reinforced paste and mortar with 2 mm (0.08 in) PVA fibers, which exhibited multiple cracking, was a result of the fact that the water flow occurred through multiple narrow cracks. Therefore, a system of narrow cracks is preferable to a single large crack because the total water permeation through the material is reduced. The lower water permeability of the cracked PVA reinforced pastes compared to the mortars within the same cracking range was likely due to the difference in crack morphology, as a result of better fiber dispersion in the absence of sand in the matrix, as well as to the higher volume fraction of PVA fibers.

Good agreement of the results obtained for the mortar from the present study with other results in the literature obtained for high performance fiber reinforced cementitious composites is shown by Figure 4. The materials compared include PVA reinforced mortar from the present study, ECC using PVA fibers and wire mesh reinforced mortar [18], and UHPFRC using steel fibers [17]. The common points of the results compared include the following: the mix designs used sand and no large aggregates, the cracks were induced by tension and the water flow was measured for unloaded, relaxed cracks using the same water permeability test set up. The effect of material type on water permeability coefficient was represented as a function of crack width under load, as measured in [17, 18]. All the curves indicate similar trends; the material was affected by cracking, while permeability coefficient increased with increasing crack width. There may be an effect of the reinforcement type, especially for the wider crack widths. However, for a given crack width the results for these materials range within an order of magnitude.

Steel fibers

Experimental program: Aldea et al. [22] and Rapoport et al. [23] studied the effect of steel fibers on cracking and water permeability of concrete. Two types of hooked steel fibers with different aspect ratios were used: 25/50, 25 mm (1 in) long and 50 microns (0.002 in) diameter, and 50/500, 50 mm (2 in) long and 500 microns (0.02 in) diameter. Three test series with steel fiber volume fractions of 0%, 0.5% and 1% were used. The mix design used a $w/cm=0.45$, cement-to-sand-aggregate ratio (C:S:A) 1:2:2 and SP=1.5% solid by weight. 50 mm (2 in) samples were prepared from 100 x 200 mm (4 x 8 in) cylinders and tested at ages ranging between 2 and 10 months after the casting date. Tensile cracks ranging between 0 and 500 microns (0.02 in) were induced for the concrete reinforced with 50/500 steel fibers by a feedback-controlled split tensile test, as described in [9, 10], where as cracks between 0 and 300 microns (0.012 in) were induced by a feedback-controlled wedge splitting test for the concrete reinforced with 25/50 steel fibers, as described in [12]. The discs 10 cm (4 in) in diameter and 5 cm (2 in) thick used for wedge splitting tests were equipped with special loading brackets in order to sustain the prescribed crack mouth opening displacement (CMOD). The wedge splitting test was feedback controlled and speckle interferometry was used to monitor the crack history throughout the test, as fully described in [12]. Speckle interferometry is an imagery technique using laser light and displaying and quantifying movements at the surface of an object between two different states. Once the desired CMOD was achieved, the screws on each side of the sample bracket were tightened to hold the target CMOD, which was maintained during the water permeability test. Low pressure water permeability tests were conducted on cracked discs following the procedure described in [9, 10].

Test results: The cracks induced to a pre-determined width in the concrete samples reinforced with 50/500 steel fibers partly closed after unloading and the crack recovery ranged between 41 and 77%. Figure 5 presents the effect of the 50/500 steel fibers volume fraction on crack recovery. A material effect was observed in terms of crack recovery, as follows: plain concrete showed the most crack recovery among the materials tested, with an average 62% width recovery, where as steel fiber reinforced concrete underwent more unrecoverable deformation in the wider cracking range. As in the case of using PVA fiber reinforcement for a similar sample geometry and tensile test method, a change in crack pattern was observed for 50/500 steel fiber reinforced concrete samples from a single large crack to multiple smaller cracks [23].

The test results suggest that the aspect ratio of the steel fibers affected cracking and permeability. The addition of 25/50 fibers slightly improved the permeability of sound concrete, where as an improvement was visible up to a 200 microns (0.08 in) cracking level and no clear improvement was observed for larger crack widths [22]. A lower volume fraction of steel fibers (0.5%) showed a significant improvement compared to a higher volume fraction of steel fibers (1%). Figure 6 presents the water permeability coefficient of the 50/500 steel fiber reinforced concrete samples as a function of unloaded crack widths [23]. Statistical tests were conducted on the slope of the permeability lines, which confirmed at a confidence level of 95% that cracks below 100 microns (0.004 in) did not affect the permeability of concrete, whereas at larger crack widths steel fiber reinforcement reduced the permeability of cracked concrete. The higher the volume fraction of 25/50 steel fibers, the more reduction in permeability was observed. It is believed that the improvement in water flow provided by the addition of steel fibers was due to a change in crack morphology, crack stitching and multiple cracking, which resulted in reduced water permeation through the cracked concrete samples. Steel fiber reinforced concrete confirmed previous results for unreinforced [9, 10] and PVA reinforced cementitious composites presented in this study, that a crack threshold exists, below which the composites permeability coefficient is not affected by cracking.

WATER FLOW THROUGH CRACKED CONCRETE REINFORCED WITH HYBRID FIBERS

Fracture process

The mechanism by which fibers influence the failure process in concrete differs depending on the material properties and the geometry of the fibers. Microfibers and macrofibers act differently during the cracking process due to their differences in size scales. Previous studies have shown that the efficiency of fibers in concrete can be optimized by using two or more types of fiber blends. Lawler et al. [24-26] studied the development of cracking in microfiber and macrofiber hybrid fiber reinforced concrete. Subregion Scanning Computer Vision (SSCV) was used to examine the role of the fibers in the fracture process, as fully described in [27]. SSCV is a digital image based method for measuring surface deformation that allows capturing images at loading steps chosen to describe the fracture process. Figure 7 presents the stages of the crack development in concrete under tensile loads and the effect of micro- and macrofibers throughout the process, as observed using SSCV.

- Pre-peak stage or microcrack formation. Fine, discontinuous microcracks develop as the stress is applied. During the pre-peak regime of the stress-strain relationship the discontinuous microcracks link to form longer, narrow coalesced cracks. In this stage microfibers control microcrack formation and interact with fracture evolution by delaying the coalescence of microcracks and hampering the widening of coalesced cracks.
- Peak stage or crack localization. A crack evolves that is long enough to govern the stress in the surrounding material.
- Post-peak or macrocrack formation. The crack widens, becoming a macrocrack. In this stage macrofibers, due to their larger size, are more efficient at carrying load across the wide macrocrack as it opens compared to microfibers, and they control macrocrack formation, thus contributing to the post-peak ductility of the materials.

The synergistic effects of micro- and macrofibers on concrete crack development have implications on durability of hybrid fiber reinforced concrete, since water permeability of cracked cement-based composites is significantly reduced if multiple cracking occurs, as shown for the composites reinforced with individual PVA or steel fibers in this paper. Therefore, research was conducted to evaluate the potential of hybrid fiber blends in terms of water flow through cracked hybrid fiber reinforced cementitious composites. These results are presented below.

Experimental program

Lawler et al. studied the effect of hybrid fiber blends on cracking and water permeability of cementitious composites [25-27]. Table 3 presents the properties of the steel macrofiber and steel or PVA microfiber blends used. Test series included plain and reinforced mortar and concrete using individual and hybrid fibers, as detailed in Table 4. The mix designs were developed in order to minimize the paste volume, while optimizing the workability, fiber dispersion and flow [25-27]. Class C fly ash was used in the concrete hybrid mixes due to its beneficial effect on increasing workability [26]. Preliminary studies showed limited improvements for hybrid fiber reinforced concrete with aggregates larger than 4 mm (0.16 in). Consequently, the reinforced mortar used C:S=1:1 by weight. The aggregates in the reinforced concrete was composed of fine aggregate with particle size <4 mm (<0.16 in) and coarse aggregate with particle size 4-8 mm (0.16 – 0.31 in), which represented 42% and 58% of the total aggregate by weight, respectively. Due to limitations in workability associated with using microfibers, there are fundamental differences between the mortar and concrete mix designs in Table 4 in terms of w/cm, ratio of the fiber blends and the dosage of the macrofiber. Water permeability of cracked samples was measured under tensile load. Tensile cracks were induced by uniaxial tensile loading of unnotched 50 x 100 x 120 mm (2 x 4 x 4.72 in) specimens, while water was forced through the specimens under a pressure of 13.8 kPa (2 psi), which is equivalent to a water head of ~1.40 m (4.60 ft), as described in [25]. The relative displacement of the platens was measured with linearly variable displacement transducers (LVDT) and was used as feedback control for the tensile tests.

Test results

Figure 8 presents the uniaxial tensile stress and water flow versus axial displacement results for hybrid fiber reinforced mortar [28]. The effect of the addition of fibers on tensile performance was as follows: 0.50% steel macrofiber had a minimal benefit compared to unreinforced mortar; 0.50% PVA microfiber resulted in improved tensile strength compared to unreinforced mortar, however, it had a minimal effect on ductility; hybrid 0.50% steel

macrofiber and 0.50% PVA microfiber improved significantly both the tensile strength and ductility of the composite compared to unreinforced mortar. A similar trend was observed for water permeation, where macrofibers provided marginal improvement compared to plain mortar, microfibers provided a significant improvement and hybrid blends of micro and macrofibers provided further improvement compared to unreinforced mortar. 0.50% steel macrofiber and 0.50% PVA microfiber reinforced mortar required an axial displacement of 250 microns (0.01 in) before flow was appreciable. This axial displacement was similar to the crack threshold observed in previous studies for unreinforced and individual fiber reinforced composites, where below this displacement the flow rate was not affected by cracking. The test results showed a synergistic effect in terms of mechanical performance and resistance to water permeability when micro and macrofibers were combined. Hybrid steel macrofiber and PVA microfiber reinforced mortar outperformed the constituent fiber types, when examined individually.

Figure 9 presents the uniaxial tensile stress and water flow versus axial displacement results for hybrid fiber reinforced concrete [26]. The effect of the addition of fibers on tensile strength was as follows: hybrid 0.50% steel macrofiber and 0.29% microfiber blend had some benefit on tensile strength and ductility compared to unreinforced concrete; where as 0.82% steel macrofiber improved significantly both the tensile strength and ductility of the composite compared to unreinforced concrete. A similar trend was observed for water flow, where the addition of fiber reduced the permeability of the cracked concrete. The hybrid fiber blend showed an improved performance compared to plain concrete, but it was outperformed by 0.82% steel macrofiber reinforced concrete. For steel macrofiber reinforced concrete, there was a significant increase in flow rate at displacements over 100 microns (0.004 in). Similar to the hybrid PVA microfiber reinforced mortar, this axial displacement was similar to the crack threshold observed in previous studies for unreinforced and individual fiber reinforced composites, where below this displacement the flow rate was not affected by cracking. The reduction in water flow in the fiber reinforced concrete compared to the plain concrete was likely due to an increase in tortuosity of the cracks produced by fibers. Since the water flow in a crack with parallel sides is proportional to the cube of the crack width, the reduction in water permeation through cracked steel macrofiber reinforced concrete compared to that through the hybrid fiber blend reinforced concrete can be explained by the difference in the crack patterns observed during the test. The macrofiber reinforced specimens exhibited multiple cracking, where the displacement measured during the test was a sum of narrow cracks. Instead, a single crack was observed in the hybrid fiber reinforced concrete.

The effectiveness of the hybrid fiber blend differed in the mortar and concrete matrices tested. As previously mentioned, due to limitations in workability associated with using microfibers, the ratio of the blends, the dosage of the fiber and the w/cm were different for the reinforced mortar and concrete. The water permeability of the plain mortar and concrete tested were comparable. The cracked permeability of the PVA hybrid reinforced concrete was marginally superior to that of the unreinforced matrix, whereas PVA hybrid reinforced mortar was significantly superior to that of the PVA hybrid reinforced concrete. The difference in PVA microfiber hybrid reinforced mortar and concrete cracked permeability was likely due to the difference in the failure mechanism in the composites [26]. The concrete matrix had a lower w/cm compared to the mortar matrix, and the cracks traveled through the aggregate. This type of fracture suggests that the presence of aggregates in the concrete matrix contributed to a reduced performance of the microfibers in the composite. Due to the increased bond strength, as a result of the low w/cm and the addition of fly ash, the mechanism of failure of the fibers in the concrete matrix was breaking. Fiber breaking is known to consume less energy than debonding and pull out, which are desirable failure modes for maximizing the effectiveness of the fibers.

CONCLUSIONS

Durability enhancements in terms of water flow through cracked concrete by individual and hybrid fibers, respectively, were studied. A number of factors which may influence the relationship between crack width and permeability were examined, such as material type, fiber type, fiber length or aspect ratio, volume fraction and crack width. Based on the experimental test results, the following conclusions can be made:

- Fiber reinforcement improves the resistance to water permeation of cracked cementitious composites compared to plain composites.
- A crack width threshold exists both for fiber reinforced and unreinforced composites, above which the flow rate increases significantly. Depending on the material type the threshold crack width can be either a single crack or a sum of multiple cracks.

- Improved performance is obtained through blending micro and macrofibers. The effectiveness of the hybrid fiber blends studied was more pronounced in mortar compared to concrete. This was due to fundamental differences in the mix designs used, associated with the use of microfibers, the fracture mode of the composites and the mechanism of failure of the fibers.
- Hybrid fiber reinforced mortar outperformed the constituent fiber types, when examined individually. This was mainly due to a change in crack topography and an increase in tendency for multiple cracking.

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