

Distribution of Fiber-Reinforcement in Thin Concrete Overlays

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Abstract

The spatial distribution and orientation of fibers in concrete materials can be linked with the measured fracture performance of the fiber-reinforced concrete (FRC). For FRC pavements, the improved toughness performance is used for adjusting the structural design and expected service life of the pavement. The prediction of toughness performance and pavement serviceability can be improved with a better characterization of fiber dispersion in the concrete pavement. In this research study, a flowable fibrous concrete (FFC) mixture was developed containing a synthetic macro-fiber at a volume fraction higher than found with existing thin concrete pavements. This FFC mixture is anticipated to have greater toughness induced by more fiber alignment in a thinner (5 cm thickness) concrete inlay pavement. Quantification of synthetic fiber dispersion and alignment in the FFC mixture was made using x-ray computed tomography and imaging analyses. The influences of placement technique and proximity of cast or mold surfaces were investigated and found to impact the fiber spatial distribution and orientation. The image analysis revealed that the number of fibers crossing any vertical plane, which increased for FFC placed under directional flow, was directly related to the measured fracture performance. Fibers were verified to have the desired alignment, allowing more fibers to become engaged in crack opening resistance, when the FRC was placed as a thinner pavement layer and therefore resulting in a more cost-effective use of FRC for pavements.

Introduction

Thin Concrete Pavements and Fiber-Reinforcement

Concrete pavements less than 7.5 cm have been constructed in the past, e.g., slabs of 6.3 cm height with 4.6 m slab lengths were constructed as part of the AASHO road test (Highway Research Board 1961). Recently, ultra-thin whitetopping (UTW) technology has gained acceptance as a thin concrete overlay (7.5 to 15 cm) bonded to an existing asphalt pavement (Gucunski 1998, Harrington 2008, Mack et al. 1998). High shear stresses can exist at the thin concrete-asphalt interface due to large surface-to-volume ratios with the temperature contraction of the surface layer (Harrington 2008, Mack et al. 1997). Yet with UTW, the magnitude of these interface stresses are reduced by decreasing the slab size to less than 1.8 m (ACPA 1998). Challenges still remain, such as rapid deterioration rates of thin un-reinforced

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concrete slabs and an intense joint saw-cutting requirement (potentially 0.6 x 0.6 m slab sizes for a 5 cm thick pavement) (Harrington 2008, Roesler et al. 2008), which have prohibited widespread acceptance of even thinner concrete overlay (≤ 5 cm) technologies.

Current performance-based fiber-reinforced concrete (FRC) design for UTW pavements allows for a pavement thickness reduction based on the measured mixture residual flexural strength properties (Roesler et al. 2008). An equivalent flexural strength ratio, $R_{T,150}^{150}$ – defined as the toughness measured at a midspan deflection of 3 mm divided by the modulus of rupture from a 150 mm standard flexural beam depth (ASTM Standard C1609 2010) – of 20 percent is used by the Illinois Department of Transportation as the recommended minimum for FRC overlay pavement designs (Bordelon and Roesler 2011). Using this design methodology, a reduction in the required pavement thickness is anticipated by increasing the amount of macro-fibers in a paving mixture, with the magnitude of reduction related to the equivalent flexural strength ratio from the flexural beam test. Typically for thin concrete pavements, a reduction in thickness brings down the total cost for construction materials and makes thin concrete overlays/inlays economically competitive. FRC has also been considered a feasible option for thinner (38 to 50 mm) bridge deck overlay projects (Carlsward 2006, Kunieda and Rokugo 2006, Zhang and Li 2002). As the concrete slab thickness is reduced to 5 cm or less, a mixture with higher macro-fiber content is required to achieve both the necessary slab load capacity and design life serviceability requirements. For these new thinner concrete pavements, a minimum recommended equivalent flexural strength ratio needs to be established.

The fracture energy (G_{TOTAL}) and toughness performance ($R_{T,150}^{150}$) properties, among other benefits, significantly increase compared to that of un-reinforced UTW pavement mixtures through the implementation of economical dosages of macro-fiber-reinforcement. It has been well documented that an increase in the dosage of fiber reinforcement, for the same fiber type and for similar concrete mixture strengths, results in an increase in the post-cracking performance ($R_{T,150}^{150}$ or G_{TOTAL}). A challenge of increasing the dosage of fibers in the concrete mixture is this can lead to fiber clumping, reduced workability, non-uniform dispersion, and poor consolidation. Due to any poor consolidation, one can expect to have a reduction and higher variation in toughness performance. Therefore, in order to achieve optimal toughness performance, it is important to have a reasonable fiber-reinforcement dosage and a concrete mixture which can be placed rapidly and with little need for consolidation.

Mixture Design

A concrete mixture was created to improve consolidation and counteract workability loss from the addition of fiber-reinforcement. This research utilized the technology of self-consolidating concrete (SCC), which was developed for highly reinforced concrete structures, in combination with FRC and UTW technology as seen in Figure 1. SCC mixture designs often consist of higher cementitious contents (Assaad et al. 2003, Carlswärd 2006, Kosaka et al. 1996, Nehdi and Ladanchuk 2004, Wang 2005) and well-graded aggregate blending (Hu 2005, Koehler 2007, Shen 2007) to improve workability of a concrete mixture.

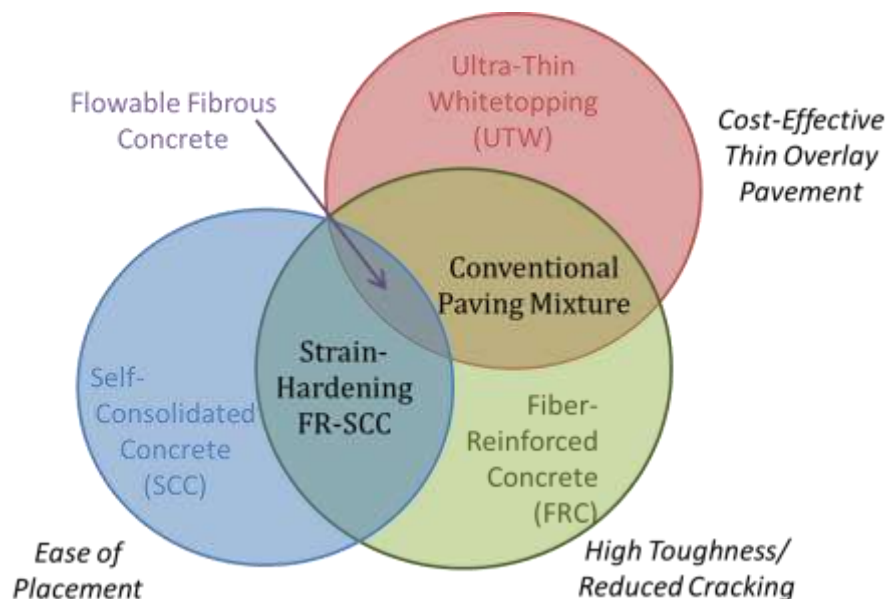


Figure 1 – Diagram illustrating the combination of research technologies (UTW, SCC, and FRC) used to classify flowable fibrous concrete (FFC).

The mixture design of flowable, fibrous concrete (FFC) along with measured fresh and hardened properties are described in Table 1. The FFC mixture (Bordelon 2011b) for this study contained a w/c ratio of 0.4 with 30% slag replacement of cement, a volume fraction of macro-fibers at 0.46%, and well-graded aggregate blending. The measured strengths and fracture properties of the FFC mixture are slightly higher, but not significantly different than some UTW mixtures used. By utilizing a more flowable concrete mixture in combination with the addition of fibers, the likelihood of voids from poor compaction/consolidation efforts is reduced and the toughness performance can be maintained. The adjustments to the concrete mixture proportioning allow for the FFC to have a higher slump, and thus standard slip-form paving is no longer applicable for placing a pavement with this mixture. Instead, the FFC can be placed directly from the back of the concrete truck as an inlay (as demonstrated in the field project described by Bordelon 2011a) or as an overlay with the use of formwork. Additional benefits of using a flowable concrete material are the rapid placement capability during construction (Bordelon 2011a, Bordelon

2011b), with minimal consolidation energy and increased contact area of the concrete on the existing asphalt interface.

In addition to improved workability, the FFC can have more superior toughness and fracture energy performance by casting the fiber-reinforced concrete mixture (at similar volume fraction of fibers as some UTW mixtures) into a 5 cm thick concrete inlay and inducing more alignment of the macro-fibers. The degree of alignment was studied for different FFC placement techniques in different specimen geometries.

Table 1 – Mixture Designs and Average Properties

Material		FFC Mixture	UTW Mixtures†
Water	kg/m ³	187	132 to 161
Type I Cement	kg/m ³	328	257 to 310
Type C Fly Ash	kg/m ³	140	80 to 83
Limestone Coarse Aggregate (9.5 mm maximum size)	kg/m ³	1052	1145 to 1186
Natural Sand	kg/m ³	857	596 to 730
Macro-Fiber*	kg/m ³	4.6	0 to 3.6
Water Reducer	mL/m ³	0	0 to 808
Polycarboxylate-based Super-Plasticizer	mL/m ³	1028	0 to 606
Air Entraining Admixture	mL/m ³	107	100 to 400
Vertical Slump	cm	-	1.2 to 2.5
Inverted Slump Flow Diameter	mm	509	-
Compressive Strength	MPa	42	36 to 40
Split-Tensile Strength	MPa	4.3	4.0 to 4.1
Equivalent Flexural Strength Ratio ($\square_{\square,150}^{150}$)	%	28	0 to 18
Initial Fracture Energy (G_f)	N/m	53	34 to 65
Total Fracture Energy (G_{TOTAL})	N/m	3175	0 to 3553

w/cm $\approx$ 0.4 for all mixtures shown here. Strengths are reported for 28 days based on 10x20cm cylinders or 15x15x53cm beams. Fracture properties are reported for 28 days based on a 15cm SEN[B].

† Example concrete overlay mixtures are restated from (Roesler et al. 2008).

* The polymeric macro-fibers added to the FFC mixture is a bi-tapered “BT” ($L_f = 48\text{mm}$, $L_f/d_f = 97$) fiber. The UTW mixtures shown utilize a straight fibrillated macro-fibers ($L_f = 40\text{ mm}$, $L_f/d_f = 90$, $E_f = 9.5\text{ GPa}$).

Placement Influence on Fiber Orientation

The most efficient use of fibers in the concrete would be created by having fibers oriented perpendicular to any expected cracking plane such that the fracture performance of the concrete will be maximized. The orientation of fibers in concrete has been found to be influenced by the casting technique. Past research has indicated that steel fibers in SCC mixtures cast into plates, long beams, or vertical walls can have a significant variation in the measured toughness performance based on specimens cut at different orientations relative to the flow direction (Barnett et al.

2010, Ferrara et al. 2007, Torrijos et al. 2010). Regardless of casting direction or technique, fibers located close to a mold surface have been shown to rotate and become more parallel with that mold surface (Moses et al. 2001, Stähli et al. 2008). This phenomenon of fiber alignment near a cast or mold surface is referred to as the boundary wall effect.

In this study, a random placement of concrete was attempted by placing small mounds of concrete near each other and continuously adding concrete at random locations to fill the form. The random placement technique likely simulates a field application of placing concrete in a sweeping pattern from the back of a truck chute, wheel barrow, or by shovelful amounts at random locations. Conversely, a directional flow placement technique referred to in this article is having concrete placed in one location, such as an edge or corner of a mold, and allowing the concrete head to push the flowable material down and outwards to fill the entire mold or formwork. In the field, this directional placement could be done by placing the concrete chute in one location and allowing gravity and momentum to assist in filling the form.

For a thin pavement, the orientation of fibers either parallel or perpendicular to the direction of traffic is not a crucial concern. However, it is important to gain an understanding of casting placement technique effects on the expected net fiber orientation with regards to a vertical plane of the slab at the joint or potential crack location in order to predict the thin FFC inlay pavement fracture performance.

Fracture Performance

In order to determine whether placement technique affects the FFC fracture performance, specimens were cast with different placement techniques, both with random placement or directional flow, and as different geometries (15x15x53 cm beam or 5x20x34 cm plates) as shown in Figure 2. A single-edge-notched beam (SEN[B]) fracture test was performed on 5x5x23 cm beams (Bordelon 2011b) cut from within each specimen geometry and each casting technique. Fracture test results shown in Table 2, indicate that the specimen's initial fracture properties (peak strength, stress intensity factor K_{IC} , crack tip opening displacement $CTOD_c$, and initial fracture energy G_f) were not influenced by the placement techniques or original specimen construction size. On average, the measured fracture energy of these mixtures was similar when cast under directional flow, near 6,000 N/m. In fact, by merely placing the FFC concrete under some directional flow, regardless of the specimen geometry, the range of measured total fracture energy was between 3,270 and 13,458 N/m, which all specimens measured considerably higher than many UTW mixtures with fiber-reinforcement (Bordelon 2011b, Roesler et al. 2008). A comparison of fracture curves for cast plate specimens, as shown in Figure 3, illustrates the specimens from plates cast under directional flow had on average five times the fracture energy than those under random placement.

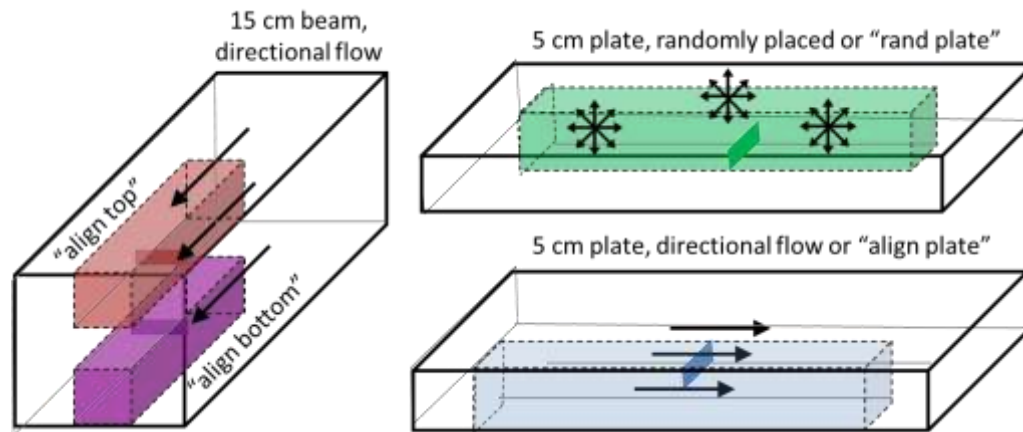


Figure 2 – Schematic of extracted 5 cm specimens cast either into a 15 cm beam or 5 cm plate with different placement techniques.

Table 2 – Fracture Results for 5 cm FFC Beams

Placement Technique	Original Cast Specimen	Number of replicates	$\frac{1.5P_{max}S}{b(d - a_0)^2}$ (MPa)	K_{Ic} (MPa- $m^{1/2}$)	CTOD _c (mm)	G_{Ic} (N/m)	G_{TOTAL} (N/m)
Rand	5 cm plate	5	4.47 (5%)	0.75 (11%)	0.012 (40%)	29 (26%)	1105 (86%)
	15 cm beam	8	5.03 (9%)	0.81 (10%)	0.011 (23%)	29 (16%)	3954 (60%)
Align	5 cm plate	3	4.77 (7%)	0.76 (11%)	0.012 (10%)	30 (10%)	5702 (51%)
	15 cm beam	8	4.68 (8%)	0.73 (7%)	0.010 (12%)	26 (14%)	6376 (56%)

SEN[B] specimens were 5x5x23 cm and tested at 7 days.

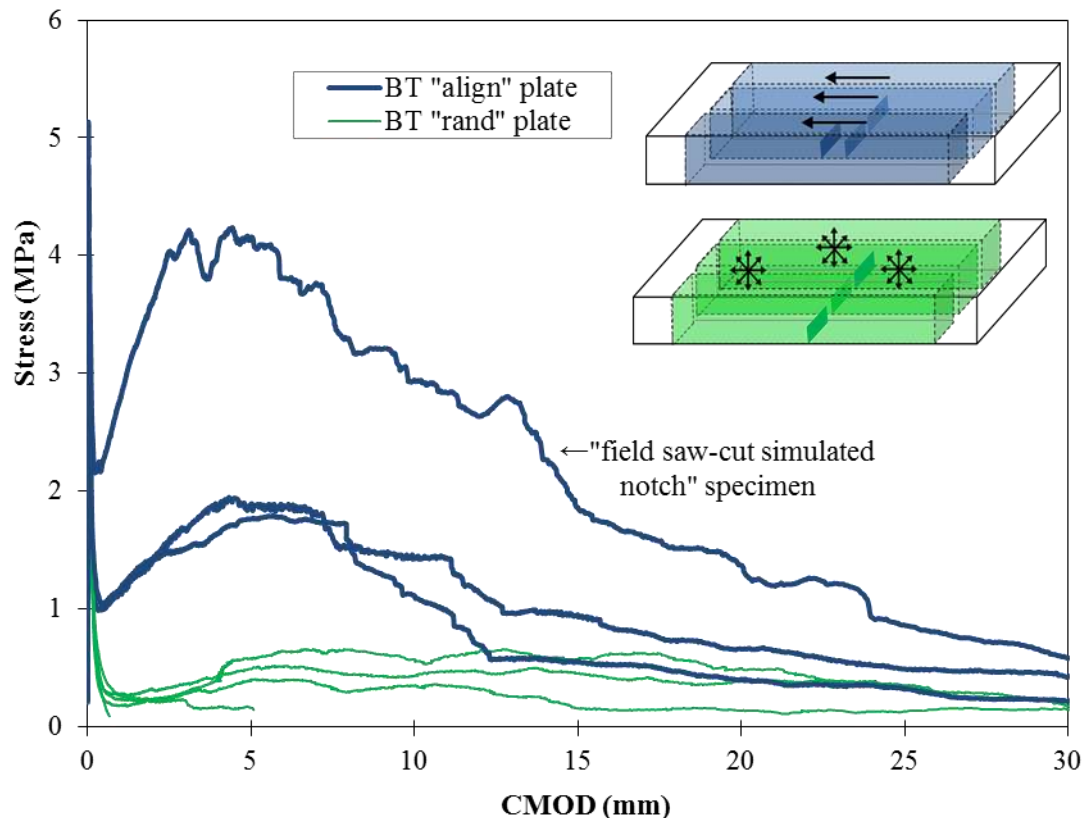


Figure 3 – Fracture curves for the FFC mixture tested as 5 cm SEN[B] specimens cut from 5 cm plates comparing directional versus random placement. All specimens consisted of a notch cut on the molded surface, except one “field saw-cut simulated notch” aligned plate specimen as indicated.

There is a high variability among the fracture properties as reported in Table 2. Past researchers have similarly found when performing a SEN[B] test that there can be high coefficients of variability of 21 to 37% for $CTOD_c$, 18% for G_f , and 30% for G_{TOTAL} values (Bažant and Becq-Giraudon 2002, Jansen et al. 2001). The FFC mixture studied in this research exhibited an even higher coefficient of variation in the measured total fracture energy of 51% or 86% for 5 cm plate specimens when cast under directional flow or placed randomly, respectively. Therefore, a larger sample set of FFC specimens would be required to predict the expected fracture performance with higher confidence.

The highest measured fracture curves resulted from the FFC fracture specimens cut from within 5 cm of either the cast or molded surfaces of the 15 cm beam. This improved performance was hypothesized to be related to either the boundary wall effect or a non-uniform distribution of fibers. Additionally, one of the FFC plate fracture specimens cast under directional flow was tested with the notch on the cast surface as would be similar to a saw-cut notch in a field inlay pavement. This specimen referred to as “field saw-cut simulated notch” (shown in the illustration for Figure 2 and with the indicated test result in Figure 3), represents crack growth that mimics the cracking of a saw-cut inlay, performed with a much higher post-cracking fracture curve comparable with the superior fracture energy of specimens cut from the

top of the 15 cm beam. It also appeared that the fibers in this FFC mixture cast under directional flow either segregated to the top cast surface or became more aligned near this cast surface in order to produce such high fracture energy.

A hypothesis was also made that the increased toughness could be a result of more effective alignment and re-distribution of the fibers as the concrete flowed into the cast inlay or forms, particularly because the height of the slab was on a scale proportional to the fiber length. Further information on the fiber orientation and distribution within the concrete would be useful to provide more insight into the measured fracture responses of these specimens.

Fiber Spatial Distribution

To properly characterize the alignment or dispersion of the fibers of FFC mixture in thin inlay pavement, a means to identify the fiber location within the concrete was required. Once fibers are identified within the concrete, it is essential to quantify the net orientation of fibers, the spatial distribution of fibers, and the expected number of fibers crossing any given fracture plane.

The majority of research to detect fibers in three-dimensions from within concrete or cement has been performed using steel fibers. Primarily, rigid steel fibers have been selected in analysis of FRC mixtures because of the greater contrast with x-rays (Redon et al. 1999, Redon et al. 1998, Stroeve 1985), electrical resistivity (Lataste et al. 2008), electrical impedance (Ozyurt et al. 2006), or visual contrast through scanning electron or optical microscopes (Chermant et al. 2001, Gettu et al. 2005, Shen et al. 2008, Torrijos et al. 2010). X-ray computed tomography (CT) is useful for not only detecting steel fiber content (Barnett et al. 2010, Benson et al. 2005), but also can be used in quantifying fiber orientation (Krause et al. 2010, Stähli et al. 2008).

Locating the synthetic fibers in a 3D space was desired for this work especially using a non-destructive technique, such as the x-ray CT. Although there has been research using x-ray CT to successfully locate steel fibers within concrete (Stähli et al. 2008), there has been no published work to locate synthetic fibers within concrete. The significant challenge addressed by this research is the detection of polymer fibers in the concrete, which are flexible, non-magnetic, and non-conductive, eliminating the application of most common detection techniques. There has been research studying synthetic fiber dispersion (Rapoport and Shah 2005, Shen et al. 2008), however none of these publications characterize the fiber's spatial distribution and individual fiber's orientation within the concrete. Thus, the a technique was developed of using x-ray CT with a fine image resolution combined with computer software post-processing to successfully locate and identify individual synthetic fibers in the FFC.

X-ray Computed Tomography and Image Analysis

A benefit of performing x-ray CT over other stereological techniques is the entire internal structure can be determined without destroying the specimen (i.e., without cutting and preparing slices). For detecting synthetic fibers in concrete, a higher

power x-ray tube source was needed to penetrate through concrete, particularly for thick samples (Masad et al. 2002), and still display enough grayscale resolution to differentiate slight variations in densities. The x-ray attenuation of the polymeric fibers was found to be similar in magnitude to the air voids, despite different material densities.

X-ray CT samples were scanned at the Washington State High-Resolution X-Ray CT machine at Washington State University in Pullman, WA. The x-ray source has a capacity of 420 kV and can scan up to 20 cm thickness of concrete, producing a 3D reconstruction voxel size resolution of 0.127 mm. For this research, the 52x52x229 mm notched specimens were first tested in fracture, and then each half of the specimen beam was scanned in the x-ray CT. The X-ray CT energy settings (Bordelon 2011b) were determined through trial and error such that there was sufficient energy for distinguishing fibers and voids in the concrete matrix without oversaturating the detector by absorbed x-ray energy.

Image processing through grayscale or contrast filters are typically performed to segment an image for locating components with unique x-ray attenuations. The IMARIS[®] software (Bitplane 2009) was selected over other 3D imaging programs as it provided the ability to apply filters and thresholds to select individual fibers within the concrete (image analysis can be found in (Bordelon 2011b)). The accuracy of locating fibers within the concrete was verified by crushing the concrete samples and counting fibers.

Four previously-tested fracture beam specimens were selected to be scanned and image post-processed (two half-beam specimens were scanned to make a total of eight x-ray CT 3D images). The goals of selecting specific samples were to cover the entire range in fracture response and to provide insight on the cracking resistance based on the number of fibers at the fracture plane, fiber spatial distribution, and net orientation of these fibers.

Imaging Result

The image analysis of the net orientation of synthetic fibers was performed to test the hypothesis that a directional flow during casting enabled more parallel fiber alignment and thus contributed to higher fracture responses. The higher flexural stiffness of the BT fibers enabled the fibers to be rotated parallel to the direction of the flow and to remain relatively straight after placement of the FFC into the molds. After thresholding and shape-filtering the x-ray images, the fibers were visualized, as demonstrated in Figure 4, within the concrete for the two half-beams (shown for a plate specimen cast under directional flow).

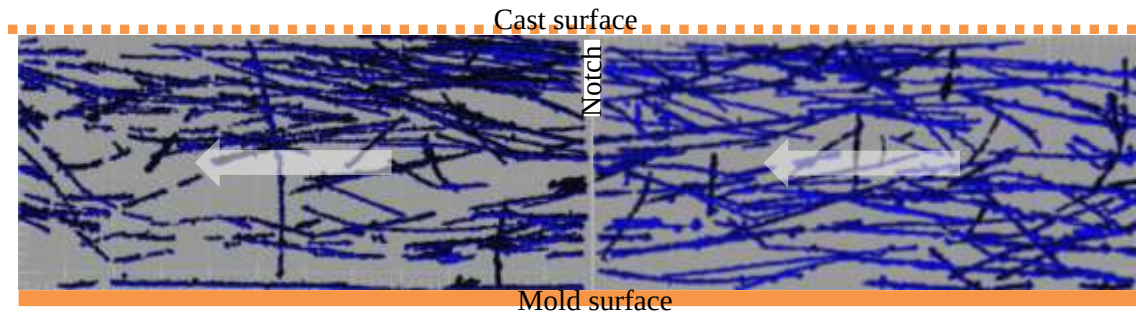


Figure 4 – Side view of the x-ray CT imaged FFC sample cast as a 5 cm height plate under directional flow with BT fibers.

Accuracy of X-ray CT Imaging

It was important to understand the limitations and repeatability of the x-ray CT imaging and post-processing in order to have an accurate estimation on the number of fibers found in the concrete and their respective orientations. With very few specimens (eight half-beam samples) scanned in the x-ray study, accurate image verification was needed to be sure that the reported fiber distributions and orientations were valid.

The number of fibers found within the specimen is directly linked with the estimated fiber volume fraction V_f (Bentur and Mindess 1990, Hannant 1978). The estimated volume for each fibril object based on IMARIS[®] software was on average (19.24 mm^3) slightly lower than the theoretical manufactured BT50 fiber volume (23.04 mm^3). An increase in the fiber volume estimation exists for any attached air voids on the fiber surface. There was also an expected reduction in the estimated volume for fibers which were broken into short fibril segments, during contrast image thresholding. The computed volume fraction $V_{f,est}$, as listed in Table 3, is based on the total volume of fibers within the image and is expected to represent the realistic volume fraction estimation within each specimen.

Table 3 – Imaging Accuracy and Fiber Volume Fraction Estimations

		BT align top		BT align plate		BT align bottom		BT rand plate	
Half beam replicate:		1	2	1	2	1	2	1	2
Number of Fibers From Image Analysis	N_{obj} (-)	164	125	141	131	124	82	95	66
Number of Fibers After Crushing The Concrete	N_{actual} (-)	139	-	149	132	-	-	96	-
Image Analysis Accuracy	(%)	10.1	-	5.4	0.8	-	-	1.0	-
Volume Fraction From Image Analysis	$V_{f,est}$ (%)	0.86	0.86	0.63	0.87	0.60	0.47	0.71	0.19
Average $V_{f,est}$		0.86		0.75		0.53		0.45	

All fibers were manually confirmed using the imaging software and by crushing up the concrete to count the number of fibers. The number of fibril objects,

N_{obj} , based on imaging was found to be anywhere from 0.8 to 10% lower than actual number of fibers determined by breaking the samples apart, as listed in Table 3. Clumped fibers had to be manually separated using the imaging software cutting tool, bringing in an element of human error. The specimen containing 10% less identified fibers (by imaging) was from the top of a 15 cm beam and was confirmed to contain a large amount of fiber clumping. This fiber clumping can be seen in the CT images, such as near the top surface in Figure 4. Overall, the image analysis procedure was found to identify at least 90% of the synthetic fibers within the concrete, despite clumping issues.

An interesting observation was that the specimens from the top 5 cm of the cast surface (either from a 15 cm beam or cast as a 5 cm plate) were found to contain almost double the amount of fibers (see $V_{f,est}$ in Table 3) than the 0.46% volume batched in the FFC mixtures. Meanwhile, the randomly placed FFC mixture had a similar volume fraction on average (for both half-beam samples) as was originally batched for the FFC mixture. This finding tends to lead to the theory that these BT fibers may have segregated, floating towards the top cast surface, during the directional placement technique.

These x-ray CT specimens cast under directional flow exhibited on average higher volume fraction estimations by 1.2 to 1.8 times above the batched V_f . Based on the volume fraction findings, it is further hypothesized that portions of the same 15 cm cast beam or 5 cm cast plate must have lower concentrations of the fibers, while the portions cut out and scanned for this study must have contained fiber clumps and a higher concentration of fibers. It appeared there was a gradient in the number of fibers (N_f) within the 15 cm beam. Again, this may have been caused by segregation of the BT fibers in the 15 cm beam as a result of having both a lower specific gravity for the fibers and use of the flowable concrete mixture.

Distribution Analysis

Expected Number of Fibers

It is useful to be able to predict the number of fibers distributed in the FFC in order to improve modeling and design of thin concrete inlays. Most micromechanical models described in the literature include either the volume fraction or utilize the number of fibers to predict the FRC toughness performance (Dupont and Vandewalle 2005, Gopalaratnam and Shah 1987, Krenchel 1975, Li et al. 1993, Li et al. 1991). Several of these models also incorporate the expected values of fiber orientation (Geng and Leung 1997, Li et al. 1991) or expected embedment length (Lange-Kornbak and Karihaloo 1997). However, all of these models assume a uniform distribution of fibers across the entire concrete specimen and do not account for boundary wall effects.

The calculation of expected number of fibers per unit area was presented by Krenchel (1975) as $n = \alpha V_f/A_f$, where α was an orientation factor and A_f was the fiber cross-sectional area. The orientation factor for randomly distributed fibers in a 3D space has been published to be 0.5 (Dupont and Vandewalle 2005, Li et al. 1991, Stroeve and Hu 2006), making the expected number of BT fibers to be 3.75 fibers

per cm^2 in the FFC specimens. Even with a thin pavement, the fibers can still have a random orientation in the vertical plane within the slab. However, it was expected that the magnitude of vertical fibers would be reduced by having the thinner slab. The number of fibers intersecting a vertical plane was used to evaluate the efficiency of the FRC mixture for use in a pavement. The number of fibers intersecting a vertical plane was calculated from the x-ray CT imaged specimens, as seen in Figure 5. A standard normal distribution was found to be sufficient for estimating the number of fibers in the FFC mixture randomly placed. For this randomly placed FFC, the average number of fibers was 3.72 fibers per cm^2 , which was similar to the theoretical expected value of 3.75 fibers per cm^2 . This verifies that the fibers will be randomly oriented within the pavement slab if the FFC were randomly across a pavement section.

Notably, when the thickness of the concrete slab is reduced such that all of the fibers are influenced by the boundary zone, then the distribution of fibers is expected to approach a 2D random planar distribution, meaning all of the fibers are most effective by being perpendicular to any given vertical plane. In this effective fiber alignment case, a fiber orientation factor has been defined and calculated based on other researcher models to be either 0.57 (Soroushian and Lee 1990), 0.60 (Dupont and Vandewalle 2005), or 0.636 (Geng and Leung 1997, Li et al. 1991, Stroeve and Hu 2006). With these fiber orientation factors, the expected number of fibers in the fracture plane was calculated to be from 5.46 to 6.10 per cm^2 for the samples containing 0.46% batched volume fraction of fibers. Therefore, the number of fibers perpendicular to a given crack surface is roughly 1.5 times greater if the pavement thickness is reduced to be approximately the same dimension as the fiber length. Since the actual fiber volume fraction measured from the aligned plate specimen was 0.75% and larger than the batched dosage (see Table 3) with a directional casting, then the number of fibers crossing any vertical fracture plane can be expected to be from 8.91 to 9.95 per cm^2 for random 2D alignment or 7.81 per cm^2 for random 3D distribution. The measured average number of fibers in a vertical cross section as determined using the image analysis for the aligned plate sample was at 8.97 fibers per cm^2 (see Figure 5), which falls within the expected theoretical range. Overall, the FFC mixture was found to match the theoretical fiber 2D or 3D distributions due to the material being cast with direction or random placement techniques, respectively.

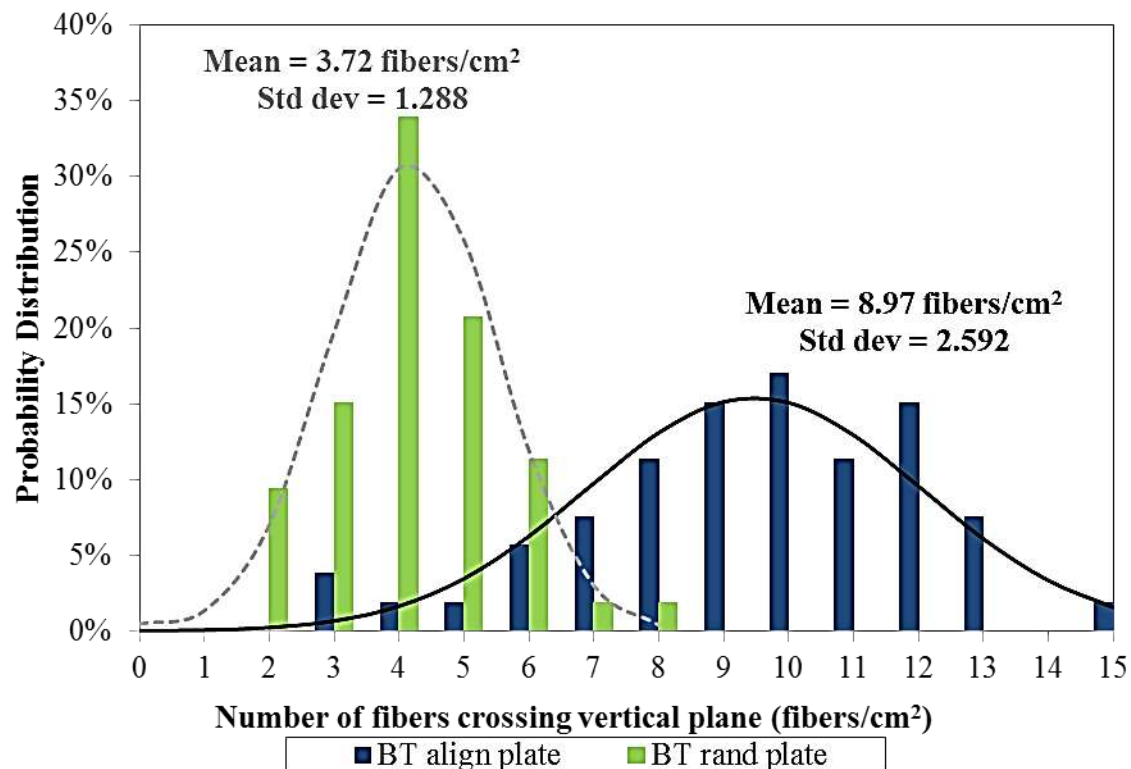


Figure 5 – Distribution of fibers crossing a vertical xy plane at any horizontal position within the sample.

Fiber Orientation

Fibers oriented vertically in the thin plate do not contribute to the measured fracture performance, while fibers oriented with some projected angle in the 2D horizontal plane do contribute to the pull-out fracture resistance. A perfectly “aligned” system of fibers in the thin pavement would be the case if all fibers were oriented at a 90 degree angle from a vertical axis, but can have any angle in the horizontal plane. A polar angle from the vertical can therefore be used to describe the alignment of fibers, where 0 degrees polar angle is a vertical fiber (no contribution to fracture energy) and 90 degrees polar angle is perfectly aligned parallel with the cast surface. The probability of a fiber being randomly oriented in a 3D space follows a sinusoidal function with the expected mean orientation value of 57.3 degrees from the vertical polar axis (Dupont and Vandewalle 2005, Jain and Wetherhold 1992, Li et al. 1990, 1991, Stroeve and Hu 2006). It is anticipated that fibers within the thin FFC plate specimens will have 2D in-plane dispersion and an expected polar angle closer to 90 degrees, while larger 15 cm cast FFC beams were expected to have a 3D random dispersion of fibers with a mean polar angle closer to the 57.3 degrees.

The polar angle of each fiber within the FFC was computed and plotted versus its height within the specimen, as shown in Figure 6. A moving average over a 2 mm height of the fiber polar angles was plotted versus beam depth to aid in visualizing the variation in fiber orientations exhibited by these test specimens. In comparing placement techniques of thin plates, the randomly-placed concrete resulted in more

random fiber orientations on average (76 degrees), than when cast under directional flow (80 degrees). There was also a greater amount of fibers aligned near the boundary surfaces of the plate for both casting techniques, verifying the boundary wall theory. Furthermore, both casting techniques in the plate specimens gave a fiber orientation closer to 2D confined orientation than 3D random, as seen in Figure 6. It is important to state that the amount of variation in fiber orientation is large (standard deviations in polar orientation angle were around 10 to 16 degrees) and therefore no significant statistical difference exists between the two casting techniques and net fiber orientations for plate specimens.

Near the boundary surface, fibers were shown to be more aligned (see Figure 6) and the number of fibers is reduced due to packing particle limit of the fibers. After reviewing fiber orientation and distribution results, it was determined that the number of fibers, specifically those fibers located directly ahead of any crack or notch tip, dominated the fracture response curve of the SEN[B] specimen. Figure 7 illustrates the number of fibers crossing a given fracture plane in the concrete for each of the four analyzed specimens. For the same number of fibers ahead of the crack tip, the fiber orientation does contribute to the measured fracture response. For example, the BT align plate was measured to have a net orientation of 75 degrees polar angle from vertical, while the BT align bottom was measured to have a net orientation of 71 degrees from the vertical. This slight reduction in net polar angle of the fibers found in this BT align bottom sample was enough to reduce the measured fracture energy. Still, the overall volume fraction of fibers within the specimen was the main contributor to fracture response (see insert in Figure 7).

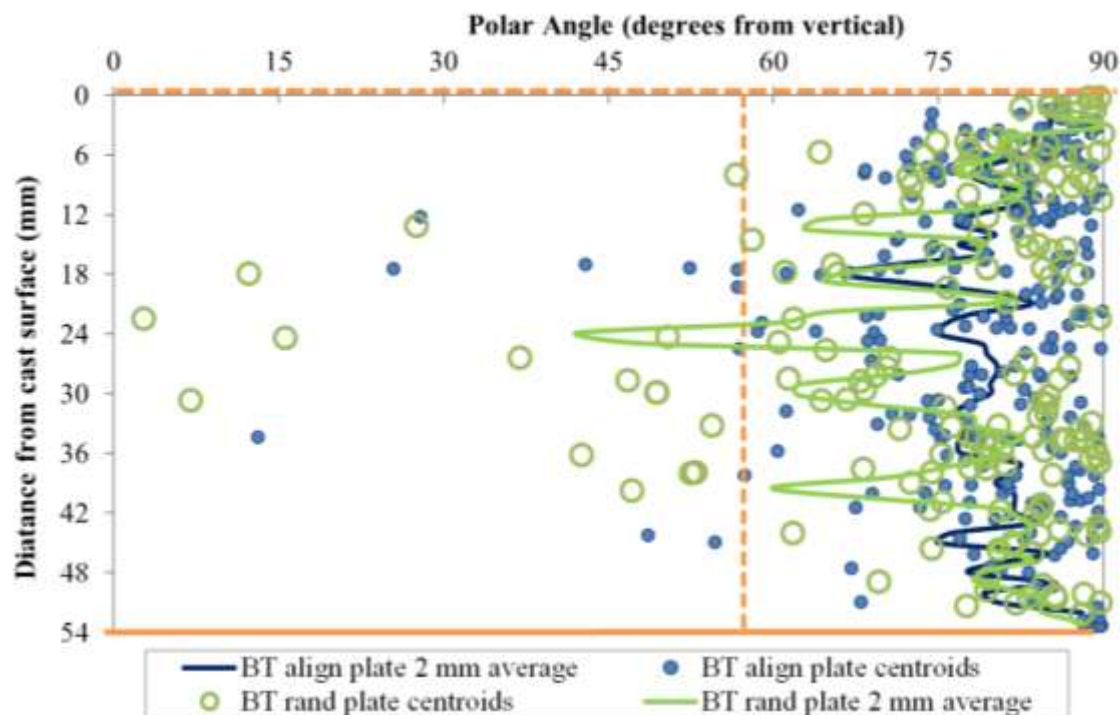


Figure 6 – Polar angles and average orientation for each 2 mm through the specimen depth for the plate specimens.

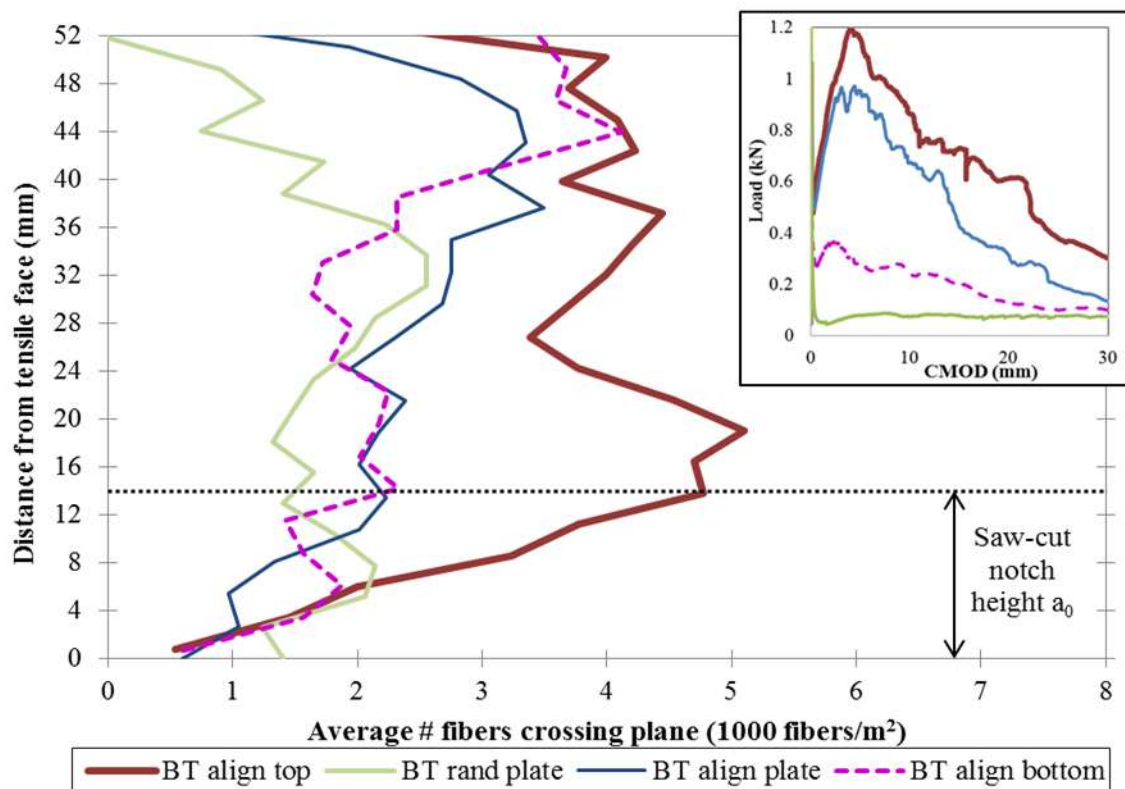


Figure 7 – Average number of fibers found ahead of crack front for each x-ray CT specimen, with superimposed insert of the SEN[B] load versus CMOD curves.

Conclusions

A flowable fibrous concrete (FFC) mixture developed in this research study was found to have improved fracture performance when cast as a 5 cm thin plate, especially under directional flow. The FFC fracture properties measured from standard size beams, with concrete randomly placed, were similar to conventional FRC paving materials. The measured total fracture energy for FFC could be potentially higher as a result of improved fiber alignment if cast as a thinner specimen or as a result of directional flow of the material at placement.

Many techniques exist for locating steel fibers in concrete, but this is the first attempt to locate synthetic fibers within concrete. The technique required a high powered x-ray CT machine coupled with contrast and shape-based filters. This non-destructive technique was verified to be 90 to 99% accurate at identifying the straight synthetic fibers of higher fiber flexural stiffness.

The spatial distribution and orientation of the synthetic fibers in three-dimensions within the FFC were verified using the x-ray computed tomographic imaging and post-processing analysis techniques. Analysis of the fiber distribution from the imaging found a higher concentration of synthetic fibers near the top of the 15 cm cast beam, attributed to synthetic fiber clumping and segregation. The fracture energy performance was found to be highly variable (up to 86% coefficient of variation), yet correlated with the variability in the number of fibers (N_f) found within a given fracture plane. A normal distribution was found to be sufficient in describing

the variation of N_f at any vertical cross-section along a 5 cm thin plate (both random and directional placement). The orientation of each individual fiber was also highly variable and therefore could not be statistically differentiated based on casting technique. On average, the total fracture energy of the FFC cast as a thin 5 cm plate was 6000 N/m, or twice that of conventional pavement FRC, for the same volume fraction of synthetic macro-fibers. For these specimens, the improved fracture response was attributed to the thinner section, greater fiber alignment with the horizontal plane, and uniform spatial distribution of the fibers within a given specimen.

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