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Cement & Concrete Composites 28 (2006) 161–172
Cement & Concrete Composites
www.elsevier.com/locate/cemconcomp

Aligned kraft pulp fiber sheets for reinforcing mortar

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Received 2 February 2004; accepted 16 August 2005
Available online 6 December 2005

Abstract

In this research program, aligned pulp fiber sheets were used as reinforcement in cement-based matrices. Flexural testing results validate this reinforcement strategy by demonstrating that: (1) fiber sheet alignment does significantly affect mechanical behavior, indicating that fiber alignment is achieved by the production process, and (2) aligned fiber sheet composite exhibited significantly greater toughness than equivalent volumes of distributed fibers. Additional results indicate that the addition of the wet-strength additive Kymene facilitates the handling of fiber sheets, but has no effect on mechanical performance. Addition of fly ash to the fiber sheets also had no effect on composite behavior. Use of fibrillated (beaten) fibers and the introduction of perforations to the fiber sheets appeared to have no effect on flexural strength, while generally decreasing composite toughness. Increasing the fiber sheet basis weight (thickness) produced increases in toughness, with negligible changes in flexural strength. Reinforcement with multiple fiber sheets (total basis weight increasing) was shown to increase toughness, while layering with total basis weight remaining constant improved strength, but reduced toughness.

Keywords: Cement; Composite; Pulp; Fiber; Fly ash

1. Introduction

The relatively low cost of pulp fibers makes them attractive for reinforcing cement-based materials. However, one obstacle to the practical use of these fibers is their poor dispersion in portland cement-based materials. Reinforcement using aligned pulp fiber sheets, rather than discrete fibers, could avoid the problems with workability and fiber dispersion commonly associated with fiber reinforcement. While procedures for producing aligned fiber sheets are known in papermaking, such materials have not been previously investigated for reinforcement of mineral matrices, to our knowledge.

By reinforcing cement-based materials with sheets comprised of aligned pulp fibers additional benefits may be had in terms of tailoring the composite design for the desired mechanical behavior. That is, the functionality of the reinforcement can be tailored to achieve specific performance characteristics in structural and non-structural cement-based materials. For example, by aligning the pulp fibers, strength and stiffness in fiber–cement products can be enhanced directionally. Basic laminated plate theory can be used to infer the mechanical properties of aligned discontinuous fiber composites at various fiber orientations. In unidirectional aligned discontinuous fiber composites, the composite strength and stiffness is generally greatest in the fiber direction, and significantly less in the cross-fiber direction [1,2]. On the other hand, randomly oriented discontinuous fiber composites exhibit three-dimensional isotropy. In other words, the strength and stiffness of this type of composite can only be varied by changing the fiber volume fraction and fiber aspect ratio, given the same fiber and matrix material. Fiber aspect ratio (l/d) plays a significant role in the performance of randomly distributed fiber composites, but has also been shown to have only a negligible effect on composite strength and stiffness in

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0958-9465/$ - see front matter
doi:10.1016/j.cemconcomp.2005.08.004

unidirectional aligned discontinuous fiber composites subjected to off-axis stresses. Thus, by using aligned pulp fiber sheets, the relatively short length of the pulp fibers is less important in determining composite properties. Lastly, another possible benefit of using pulp fiber sheet reinforcement is that the reinforcement can be placed only where needed. That is, the pulp fiber reinforcement could be located near the base of a concrete section to provide additional flexural capacity, tensile strength, and toughness. Located near the surface of the section, the fiber reinforcement might provide additional resistance to surface cracking, which may result from over-finishing, shrinkage, salt crystallization, or cyclic freezing and thawing, for example.

The objective of this research is to assess the performance of aligned pulp fiber sheets used to reinforce mortar. Aligned fiber sheets were prepared with varying thicknesses (or basis weights), perforations, and fiber treatments. Fiber treatments include the addition of fly ash and Kymene as well as refinement (beating) of the pulp fibers. The mechanical performance of the composites prepared with one, two, and three layers of fiber sheets is assessed by center-point bending tests, and failure is characterized by stereomicroscopy.

2. Experimental study

2.1. Materials

Composite beams were made with a water-to-cement ratio of 0.50 and a sand-to-cement ratio of 1.0 using commercially available ASTM Type I portland cement, deionized water (resistivity = 18.2 MΩ m), and natural siliceous sand (fineness modulus = 1.80), obtained from Brown Brothers Quarry in Junction City, Georgia. Oxide analysis and Bogue potential composition for the cement are listed in Table 1.

Aligned fiber sheets were prepared from Slash pine (softwood) bleached kraft pulp fibers using a dynamic sheet former. A dynamic sheet former prepares uniform fiber sheets by spraying a pulp suspension inside a rotating drum. Water is drained from the sheet by centrifugal force. Fiber alignment can be controlled by varying the rotational velocity of the drum. Fiber sheet basis weight (thickness) was varied by using different concentrations of pulp slurry.

Table 1
Oxide analysis and Bogue potential composition of ASTM Type I portland cement

Oxide	Percent by mass
SiO_2	20.17
Al_2O_3	5.34
Fe_2O_3	3.85
CaO	63.93
MgO	0.91
Na_2O	0.05
K_2O	0.35
SO_3	4.00
Loss on ignition	0.80
Insoluble residue	0.05
C_3S	54.16
C_2S	16.97
C_3A	7.64
C_4AF	11.70

The fibers were obtained from Buckeye Technologies in Plant City, Florida. The primary experimental fiber sheet matrix is found in Table 2. The wet-strength chemical, Kymene (polyamide epichlorohydrin resin), used in some samples, was produced by Hercules Incorporated in Wilmington, Delaware. Fiber sheet basis weights investigated were 15, 30, 60, and 90 g/m^2. Basis weight is a measure of the fiber sheet mass/surface area. Increases in basis weight indicate thicker and stiffer fiber sheets. Approximate fiber sheet thicknesses were 100, 165, 260, and 350 μm, respectively. In addition, if the pulp fibers were distributed throughout the mortar samples, the equivalent fiber volume fractions of these basis weights would be 0.0394%, 0.0787%, 0.1575%, and 0.2362%, respectively.

Perforated fiber sheets were prepared with round perforations. By partially filling the plastic forming wire, placed inside the dynamic sheet former barrel, with hot-melt resin, perforated sheets were formed by blocking the accumulation of fibers on the resin. Two sizes of perforations were manufactured as illustrated in Fig. 1. The diameter of the small and large perforations was approximately 5 mm and 7.5 mm, respectively. Additionally, the total fiber sheet surface area available for matrix bonding remained constant for the small and large perforated fiber sheets. A separate experimental study matrix was developed for the perforated fiber sheets and is given in Table 3.

Table 2
Fiber sheet sample matrix

Group number	Basis weight (g/m^2)	Fly ash addition (percent by fiber mass)	Kymene addition (percent by fiber mass)	Corn starch addition (percent by fiber mass)	Beaten
1	30	100	0.5	1	No
2	30	100	0.5	1	Yes
3	30	200	0.5	1	Yes
4	30	0	0.5	0	Yes
5	30	100	0	1	Yes
6	15	100	0.5	1	Yes
7	60	100	0.5	1	Yes
8	90	100	0.5	1	Yes

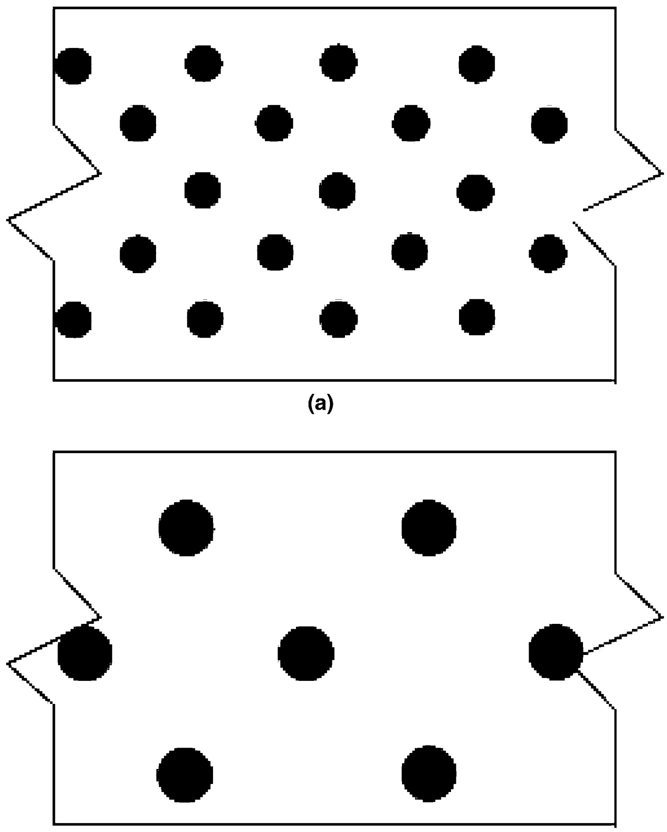


Fig. 1. Aligned perforated fiber sheets: (a) small perforations and (b) large perforations.

2.2. Sample preparation

Mortars were prepared by mixing the cement and sand for 3 min at 60 rpm in a 1.5 L capacity Hobart mixer. Subsequently, the water was slowly added and mixing continued at 60 rpm for another 5 min.

Depending on the fiber sheet depth, a predetermined mass of mortar was initially added to the mold and vibrated to level the mortar surface. The fiber sheet was then placed in the mold and lightly tamped to remove trapped air voids beneath the fiber sheet. Then, the remaining mortar was slowly added to the mold, taking care to keep the fiber sheet plane. For the samples with multiple fiber sheet addition, a thin layer of mortar was spread between the fiber sheets to ensure bonding between the sheets. Distributed fiber mortar composites were prepared similar to [3]. For the distributed fiber composites, the sand was mixed with the cement in a separate Hobart mixer for 5 min and added to the pulp fiber slurry.

Flexure specimens were cast in $2.54 \times 2.54 \times 30.5$ cm ($1 \times 1 \times 12$ in.) brass molds and were placed in a curing box at 22 ± 2 °C and $90 \pm 5\%$ RH. After 24 h, the samples were demolded, cut with a masonry saw to a 10.2 cm (4 in.) length, and placed in a limewater curing tank at 18 ± 2 °C until testing commenced.

2.3. Mechanical test methods

The $2.54 \times 2.54 \times 10.2$ cm ($1 \times 1 \times 4$ in.) samples were tested in center-point bending with a span of 7.6 cm (3 in.). The span-to depth ratio of 3 was chosen to comply with ASTM C 348-97 and C 293-94 [4,5]. Tests were performed in triplicate using a 100 kN (22 kip) screw driven test frame (Satec model 22EMF) with a cross-head displacement of 0.1 mm/min. The testing setup can be seen in Fig. 2. The deflection was captured using an electronic deflectometer (Epsilon model 3540-012M-ST), placed under the center point of the beam. The test was controlled using the deflection system to better capture the post-cracking behavior of the beams.

Toughness is defined as the post-cracking toughness or the area under the load–deflection curve beyond first cracking. For all the specimens tested, post-cracking softening was observed. Thus, peak strength is equal to the first crack strength (Fig. 3) and will be referred to as flexural strength.

3. Results and discussion

In this research, the performance of aligned pulp fiber sheets as reinforcement for mortar was assessed. Results, presented in Sections 3.1–3.3, will describe the proof of concept, variations in fiber sheet properties, and variations in composite properties. As a proof of concept, mortars containing equivalent fiber volume fractions of randomly distributed fibers were compared to those with aligned fiber

Table 3
Aligned perforated fiber sheet experimental study matrix

Group number	Basis weight (g/m^2)	Fly ash addition (percent by fiber mass)	Kymene addition (percent by fiber mass)	Corn starch addition (percent by fiber mass)	Beaten	Size of perforation
1	30	0	0.5	1	No	None
2	30	0	0.5	1	No	Small
3	30	0	0.5	1	No	Large
4	30	0	0.5	1	Yes	None
5	30	0	0.5	1	Yes	Small
6	30	0	0.5	1	Yes	Large
7	60	0	0.5	1	Yes	None
8	60	0	0.5	1	Yes	Small
9	60	0	0.5	1	Yes	Large

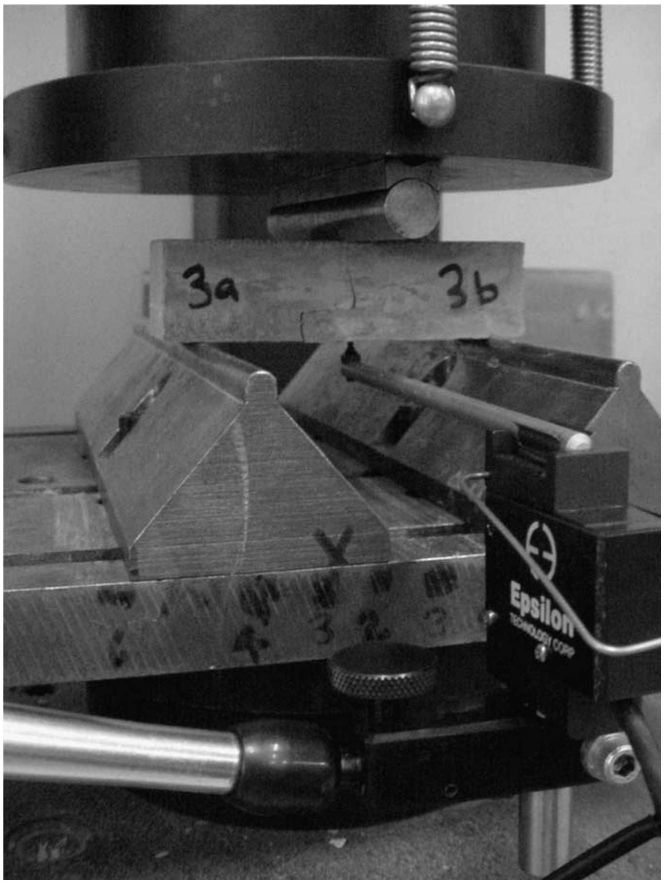


Fig. 2. Flexural testing setup.

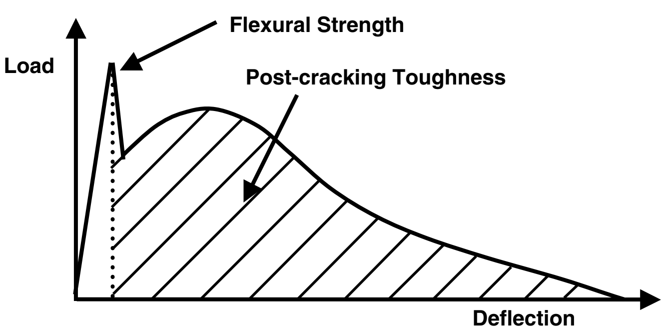


Fig. 3. Definition of flexural strength and post-cracking toughness.

sheets. Additionally, fiber sheet orientation was varied to assess the effect of fiber alignment and to ensure that the fiber sheets were prepared in such a way as to produce sufficient fiber alignment. Fiber sheet variations included the addition of the wet strength additive Kymene and fly ash. Furthermore, fibrillated fibers were compared to unbeaten fibers. Also, fiber sheets were prepared with perforations in an effort to improve the stress transfer through the fiber sheet. Finally, composite properties were assessed by varying the fiber sheet basis weight and layering of the fiber sheets. The fiber sheets were also placed at different depths through the cross-section to optimize fiber sheet location.

3.1. Proof of concept

3.1.1. Aligned fiber sheets versus randomly distributed fibers

Previous research by Mu and Meyer [6] has shown that fiber meshes of AR-glass, PVA, and polypropylene were more effective than their respective equivalent volumes of randomly distributed fibers at improving flexural strength and toughness of composite members. These results would be expected according to laminated plate theory. In the face of an oncoming crack, more oriented fibers are able to bridge the crack than if the fibers were randomly distributed. In that case, only a small number of fibers are able to bridge the crack. Furthermore, of those fibers bridging the crack, not all fibers will be oriented at 0° relative to the stress direction. As discussed previously, as the fiber orientation is increased from 0°, reductions in composite strength and stiffness occur [1,2]. From laminated plate theory, this is expected considering that the fibers carry the stress across a crack. Thus, additional fibers in the direction of the principle stress will yield greater composite strength and stiffness. Since randomly distributed fiber composites contain fibers throughout their sections (i.e., in regions experiencing tension or compression, in flexure), it can be expected composite strength and stiffness will increase by concentrating the fibers in regions expected to experience tension.

In this research, four fiber sheet thicknesses were investigated, ranging from 15 to 90 g/m^2. These thicknesses correlate to distributed fiber volume fractions ranging from 0.0394% to 0.2362%. Typical load–deflection curves for each composite type are illustrated in Fig. 4. As seen in Fig. 5, aligned fiber sheet composites showed increases in flexural strength with 15 and 30 g/m^2 sheets of 12.5% and 31.4%, respectively, as compared to distributed fiber composites. On the other hand, the distributed fiber composites exhibited improvements of 8.6% and 16.3% in flexural strengths at fiber sheet equivalents of 60 and 90 g/m^2, respectively. Furthermore, as the fiber content increased

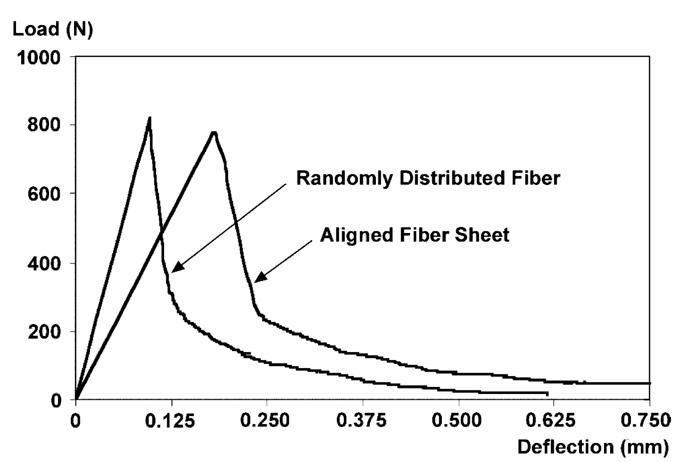


Fig. 4. Typical load–deflection curves of randomly distributed fiber composites and fiber sheet composites.

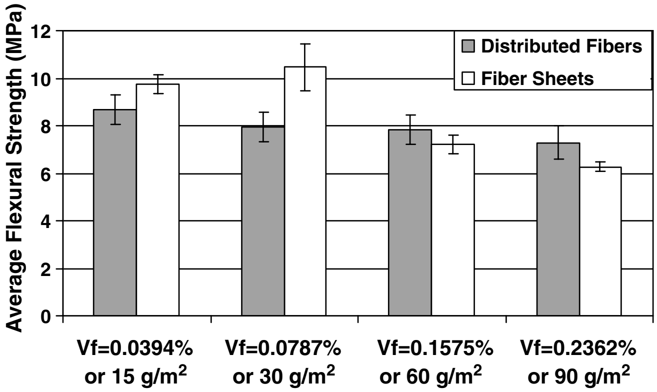


Fig. 5. Effect of aligned fiber sheets on flexural strength at 28 days.

beyond 30 g/m^2, the flexural strength of the fiber sheet composites tended to decrease. However, the distributed fiber composite flexural strength did not appear to vary significantly over the range of fiber contents investigated. This suggests that with increased fiber sheet thicknesses, stress transfer efficiency decreases, possibly due to an increasing propensity for debonding within the thicker fiber sheets.

Toughness increases with increasing fiber contents, as expected, for both aligned fiber composites and distributed fiber composites (Fig. 6). Non-reinforced mortars bars, in comparison, have effectively no post-cracking toughness. The toughness of the fiber sheet composites was 72.9–125.8% greater than the distributed fiber composites for the fiber sheet thicknesses investigated. As expected, the use of aligned fiber sheets when compared to equivalent distributed fibers shows tremendous benefits in terms of increasing the post-cracking toughness of the composite beams due to an increase in aligned fibers in the tension zone of the beam able to bridge a crack and improving the stress transfer across the crack.

3.1.2. Effect of fiber sheet orientation

To assess the effect of fiber alignment on the properties of the composite, fiber sheets were oriented along the beam at 0° and 90° relative to the long direction of the composite. The 0° composite, then, would be constructed to align the length of the fibers with the length of the specimen and the largest stresses induced in the specimen during loading. Thus, it is expected from lamination theory that the 0° composite will exhibit greater strength and toughness than the 90° composite [1,2].

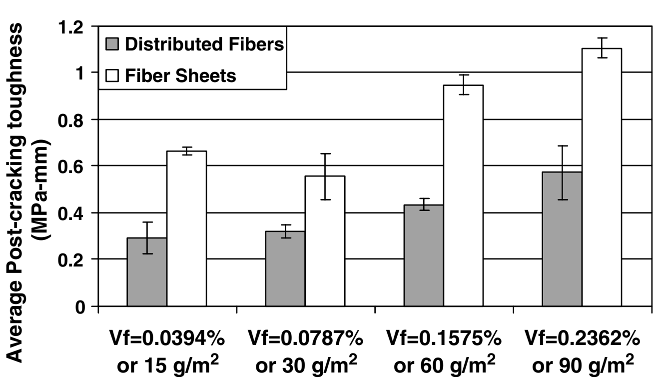


Fig. 6. Effect of aligned fiber sheets on post-cracking toughness at 28 days.

This concept has been well-established by research. For example, Mashima et al. [7] and Xu and Hannant [8,9] have shown that the flexural strength of polypropylene network composites significantly decreased as the primary fiber angle was incrementally increased from 0° to 90° relative to the length of the composite beam. Additionally, Mu and Meyer [6] produced similar results for flexural strength and toughness of AR-glass, PVA, and polypropylene fiber mesh composites as the primary fiber angle was increased.

In the current research, as anticipated, the 0° fiber sheet composites exhibited greater strength and significantly greater toughness values as compared to the 90° fiber sheet composites, as shown in Figs. 7 and 8. These results validate that the fiber sheets are produced in a way that results

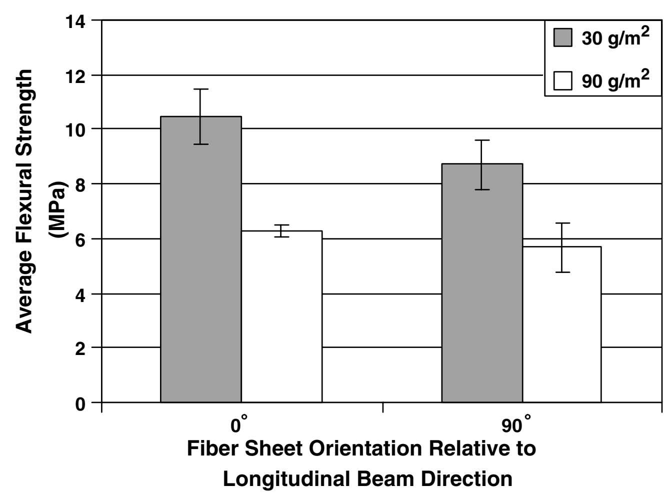


Fig. 7. Effect of fiber sheet orientation on flexural strength at 28 days.

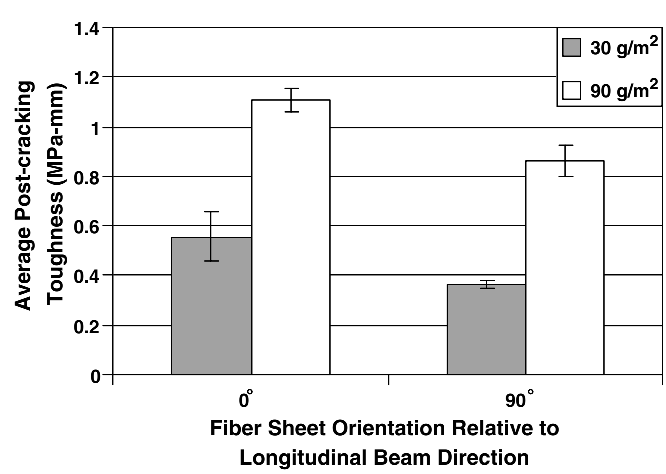
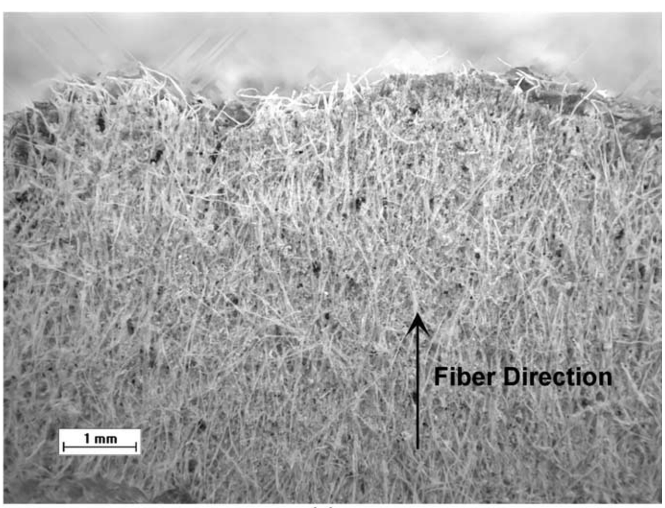


Fig. 8. Effect of fiber sheet orientation on post-cracking toughness at 28 days.

in significant fiber orientation. Furthermore, stereomicroscope images with of fracture surfaces with fiber sheets aligned at 0° and 90° are shown in Fig. 9. These images indicate fiber orientation was achieved during in the sheets during composite preparation. This improved behavior is due to improved crack arrestment and bridging by fibers oriented along the length of the beam. For applications where a load may be distributed along any direction, the use of layered fiber sheets at varying orientations may be appropriate.

3.1.3. Effect of fiber sheet location

In order to optimize the placement of the fiber sheets, the effect of the fiber sheet location was investigated. When placed within the bottom half of the beam (tension half), the fiber sheet had a negligible effect on flexural strength as seen in Fig. 10. In the compression half of the beam, the flexural strength tended to increase as the fiber sheet was placed further from the neutral axis.



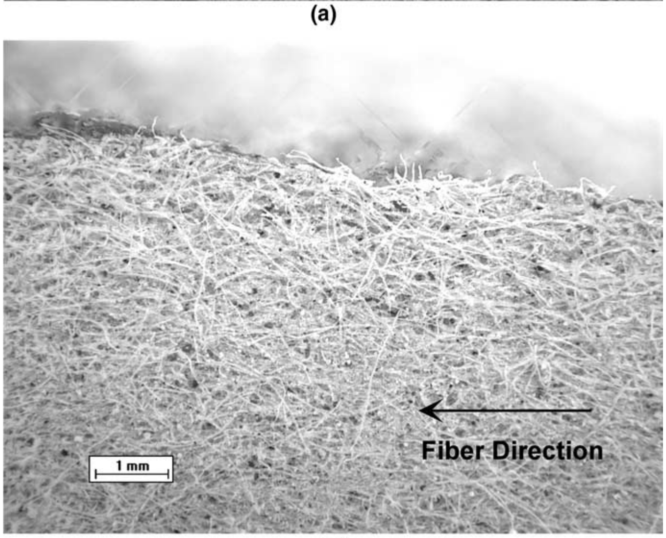


Fig. 9. Stereomicroscope fracture surface images: (a) fiber sheet at 0° and (b) fiber sheet at 90°.

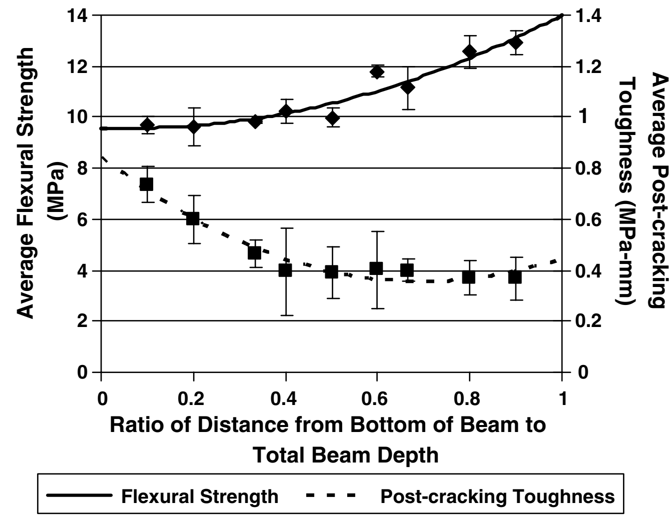


Fig. 10. Effect of fiber sheet depth on flexural strength and post-cracking toughness at 28 days.

Post-cracking toughness results (Fig. 10) appeared to exhibit an opposite trend. Below the composite neutral axis, composite toughness increased. As the fiber sheet was placed further from the neutral axis (towards the bottom of the beam), the composite toughness increased as well. Above the neutral axis, the placement of the fiber sheet had a negligible effect on post-cracking toughness. These results appear to be acceptable since the largest flexural stresses are found farthest from the neutral axis. Thus, as the fiber sheet is placed towards the bottom of the beam, the fibers are able to transfer the large stresses upon cracking, while minimizing crack width and subsequent failure. On the other hand, the fiber sheet, when placed above the neutral axis, does not have any effect on toughness when in compression. This is regardless of the fiber sheet location within the compression zone.

3.2. Fiber sheet properties

3.2.1. Effect of Kymene

During production, some fiber sheets were treated with the wet strength additive Kymene (polyamide-epichlorohydrin resin). Kymene resin forms a crosslinked insoluble network around and through fiber contacts. Upon rewetting, the network formed by the resin minimizes fiber separation during tensile loading. Thus, the fiber sheet maintains a portion of its original dry strength.

Results show negligible changes in flexural strength with Kymene addition (Fig. 11), although toughness values were slightly increased by its use. Kymene treatment facilitates with the handling and lay up of the fiber sheet composites, but does not appear to significantly impact mechanical behavior.

3.2.2. Effect of fly ash

Previous research by this team [10,11] has shown that the addition of fly ash to pulp fibers could improve their

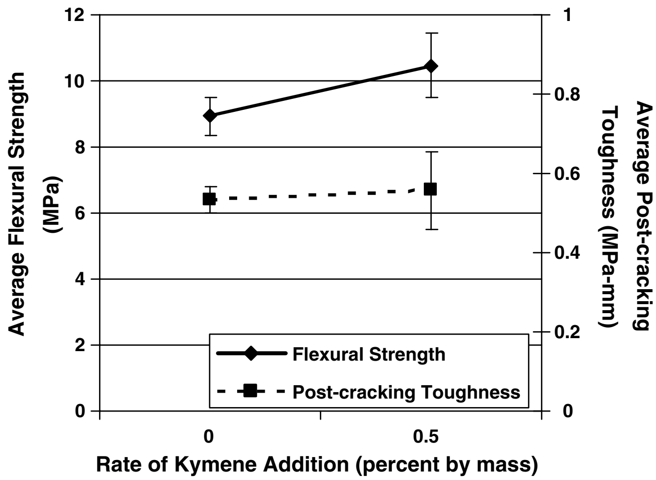


Fig. 11. Effect of Kymene addition on flexural strength and post-cracking toughness at 28 days.

dispersion in cement-based matrices. Additionally, the presence of fly ash is thought to possibly improve the fiber-matrix bonding via pozzolanic reactions forming C–S–H from reaction with CH which may be larger and present at greater amounts at the interface. Thus, the matrix for fiber sheet production (Table 1) includes variations in the amount of fly ash used in the fiber sheets.

Mechanical testing (Fig. 12) shows, however, that the rate of fly ash addition to the fiber sheets (i.e., 100% vs. 200% by mass) had no significant effect on the performance of the fiber sheet composite strength and toughness. Further, sheets containing no fly ash performed similarly to those containing fly ash. Because the flexure test on aligned fiber sheets does depend upon stress transfer between the matrix and the sheet, it is proposed that the use of fly ash, therefore, has no measurable effect on the fiber sheet-to-matrix bonding within the range of parameters investigated here.

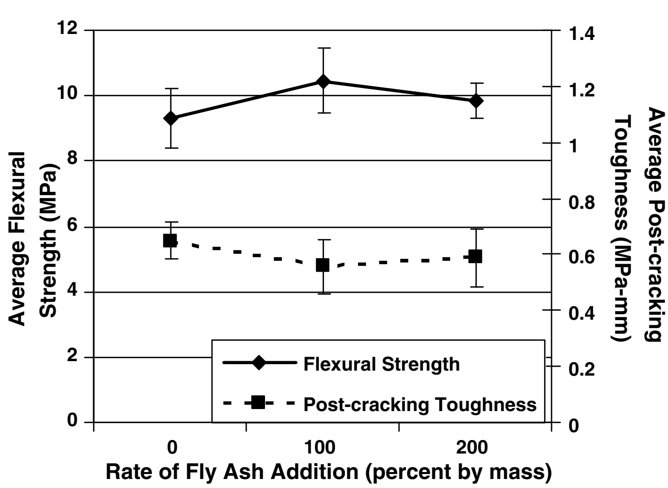


Fig. 12. Effect of fly ash addition on flexural strength and post-cracking toughness at 28 days.

3.2.3. Effect of beating

Refinement or beating of the pulp fibers fibrillates the fiber surface layers [12–14]. The outermost later, S1, may become damaged by beating, causing microfibrils, normally aligned within the layer to extend from the fiber, thereby increasing the fiber surface area. In addition to increasing the fiber surface area, beating may also decrease the average fiber length—a competing effect. Beaten fibers also tend to be more conformable than unbeaten fibers, and this change in fiber stiffness may affect the behavior of the composite. It has been shown, for example, by [3,11,13], that composites reinforced with randomly distributed unbeaten fibers exhibit increased flexural peak strength and post-cracking toughness, as compared to beaten fibers. It is believed that the increased fiber–cement bonding of beaten fibers decreases the fiber pull-out length, thus decreasing the energy dissipation during composite failure.

Similar to distributed fiber composites, results for fiber sheet composites, show that while beating of fibers appears to have a negligible effect on flexural strength (Fig. 13), the toughness of the composites (Fig. 14) decreased by 17.2% as compared to unbeaten fiber sheet composites. This decrease in toughness may be the result of changes in the fiber sheet properties with beating and changes in fiber sheet-matrix bonding. For the fiber sheets, beating tends to decrease the thickness of the fiber sheet from approximately 165–125 μm. Since beaten fibers tend to be flat and conformable, the fiber density increases as the sheet thickness decreases, as compared to unbeaten fiber sheets. Observation and comparison by stereomicroscopy indicated that the alignment of the fibers within the fiber sheets was not altered by beating, as compared to unbeaten fibers. Thus, it is expected that penetration of cement hydration products into the fiber sheet may be minimized, due to the increased sheet density. It is also possible that additional bleed water may become trapped beneath the fiber sheet during casting, creating a region of higher water-to-cement ratio and higher porosity.

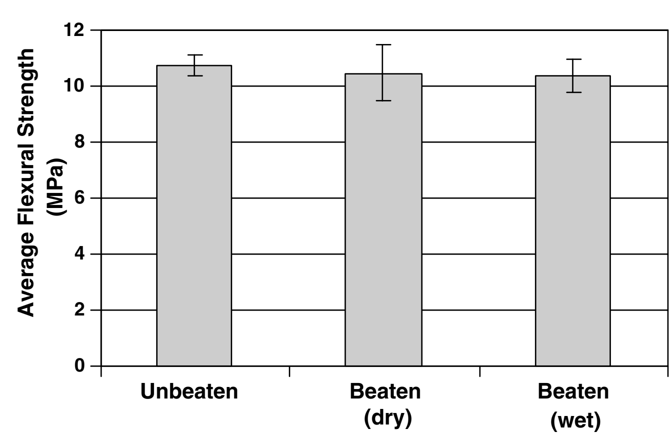


Fig. 13. Effect of fiber beating on flexural strength of 30 g/m^2 fiber sheet at 28 days.

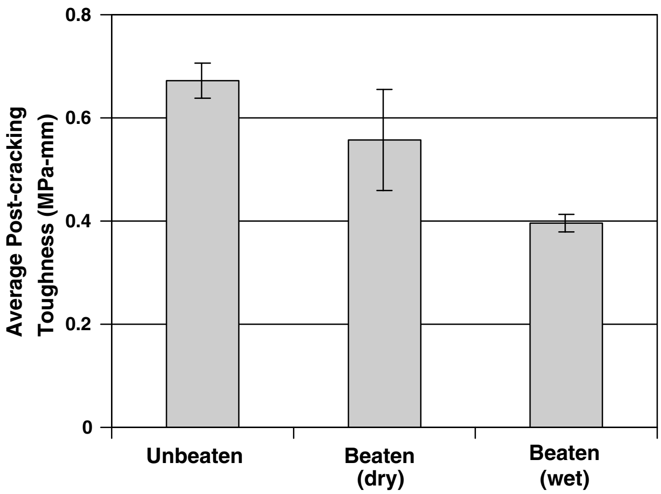


Fig. 14. Effect of fiber beating on post-cracking toughness of 30 g/m^2 fiber sheet at 28 days.

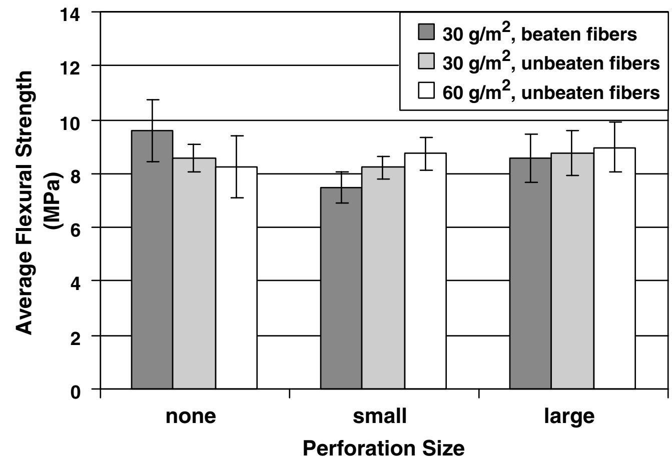


Fig. 15. Effect of perforation size on flexural strength at 28 days.

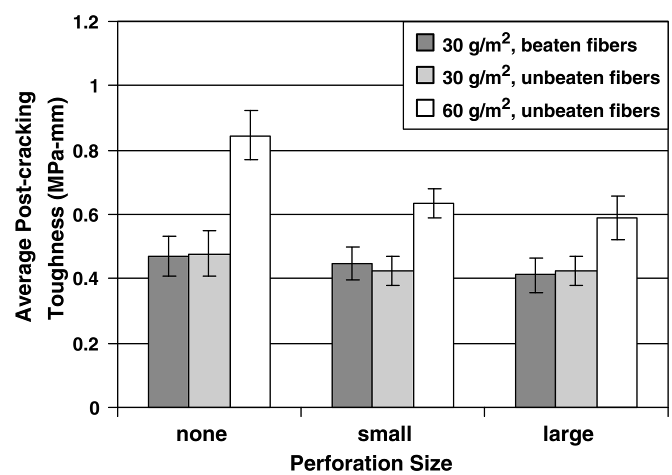


Fig. 16. Effect of perforation size on post-cracking toughness at 28 days.

To additionally evaluate the influence of fiber sheet-mortar bonding, beaten fiber sheets were soaked for 2 h prior to casting. Originally, fiber sheets were placed in fresh mortar in a dry state. In this state, it is thought that beaten fiber microfibrils may not completely extend from the fiber. Thus, the beaten fiber sheets were soaked to increase the fiber sheet-mortar bonding. Results shown in Fig. 13 indicate that the toughness of soaked beaten fiber sheet composites decreased by 28.7% and 41.0% compared to the beaten (placed dry) and unbeaten fiber sheet composites, respectively. This seems to verify that soaking of the beaten fiber sheets does increase fiber sheet-mortar bonding by allowing fiber microfibrils to extend and bond to the matrix.

However, increasing the fiber sheet-mortar bond by fiber microfibril extension does not appear to affect the flexural strength of the composites. Thus, it is proposed that, unlike distributed fiber composites [3,11,13], fiber sheet-matrix bonding does not influence the flexural strength of composite beams. However, as the fiber sheet-matrix bonding increases, the post-cracking toughness of the composite significantly decreases.

3.2.4. Effect of perforation size

Fiber sheets were also prepared with two sizes of perforation in an effort to assess if the stress transfer through the fiber sheet could be improved as well as minimizing the tendency for delamination through the fiber sheet during mechanical testing. As seen in Fig. 15, the effect of fiber sheet perforation size on flexural strength appears negligible within the range of sizes investigated.

As for post-cracking toughness, it appears that as the perforation size is increased, there is no apparent change in toughness for the 30 g/m^2 fiber sheets as seen in Fig. 16. However, for the 60 g/m^2 fiber sheet, toughness decreased by 25.2% and 30.4% when small and large perforated sheets were used, respectively, compared to the non-perforated fiber sheet composite. The difference in toughness between the large and small perforations is negligible, possibly due to a constant fiber sheet surface area available for bonding. Thus, the mechanical performance of perforated fiber sheets does not appear to warrant the additional cost and energy associated with the production of perforated sheets.

Regardless of the perforation size, the composite flexural strength, Fig. 17, appears to be independent of the fiber sheet basis weight. This result is contrary to the trend for the non-perforated sheets (Section 3.3.1). However, the discrepancy is most likely due to effect of the perforations controlling the fiber sheet-matrix stress transfer more effectively than non-perforated sheets.

On the other hand, as the fiber sheet basis weight was increased from 30 to 60 g/m^2, the post-cracking toughness increased by 30.4% and 38.7% (Fig. 18) for fiber sheets with small and large perforations, respectively. Additionally, there is no significant difference between the small and large perforation size with either fiber sheet basis weight. This seems to indicate that the perforation size has little effect on post-cracking toughness. For comparison, the

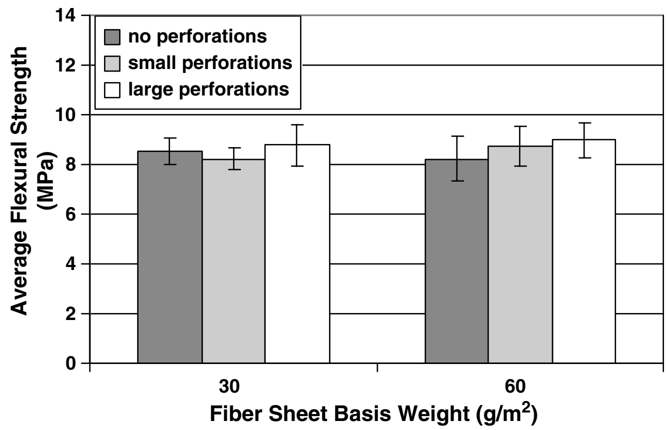


Fig. 17. Effect of perforated unbeaten fiber sheet basis weight on flexural strength at 28 days.

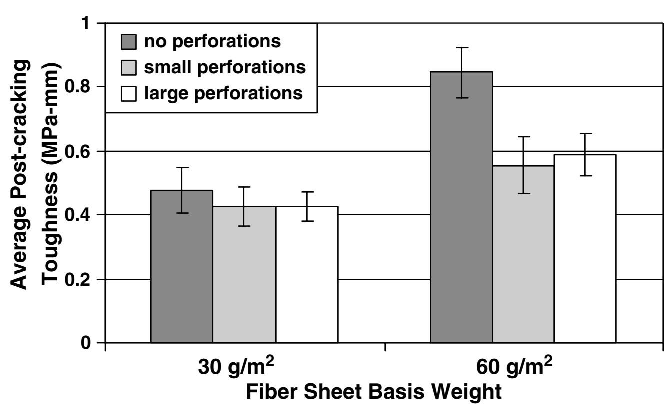


Fig. 18. Effect of perforated unbeaten fiber sheet basis weight on post-cracking toughness at 28 days.

fiber sheet composite without perforations exhibited a 77.0% increase in post-cracking toughness when the fiber sheet basis weight was increased. Though the effect of perforating the fiber sheets was not significant for the 30 g/m^2 fiber sheet, there was a significant effect for the 60 g/m^2 fiber sheet. That is, the 60 g/m^2 fiber sheet composite without perforations exhibited a 30.4–34.5% improved post-cracking toughness, compared to the 60 g/m^2 perforated fiber sheet composites.

3.3. Composite properties

3.3.1. Effect of fiber sheet basis weight

Results in Fig. 19 indicate that as the basis weight of the fiber sheet increases from 15 to 90 g/m^2, the flexural strength generally decreases. However, with increasing fiber sheet basis weight within this range, the post-cracking toughness generally increases. It is thought that by increasing the thickness of the fiber sheet, the propagation of cracking through the composite beam is changed by deflecting the advancing crack through the fiber sheet. By increasing the thickness of the fiber sheet, the fiber sheet is better able to deflect the crack tip and improve the

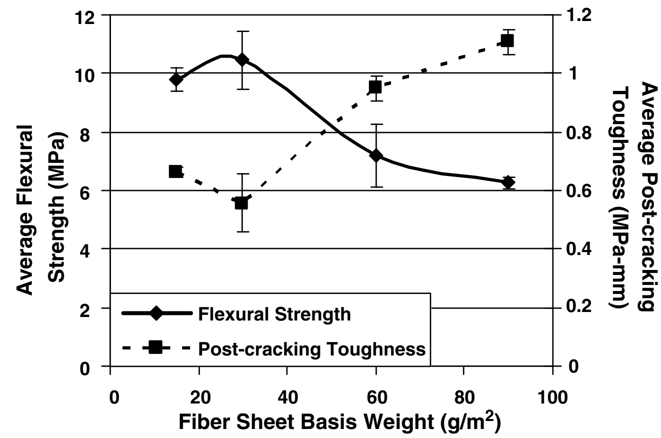


Fig. 19. Effect of fiber sheet thickness on flexural strength and post-cracking toughness at 28 days.

post-cracking ductility of the composite. Photographs showing typical failure patterns for each of the fiber sheet thicknesses investigated can be seen in Fig. 20. As the fiber sheet basis weight was increased, the length of the delamination crack also increased. This deflection may also lead to delamination within the fiber sheet for the thicker fiber sheets as seen in Fig. 21. However, this delamination may result in lower strength due to inefficient stress transfer between the mortar and fiber sheet.

3.3.2. Effect of layering fiber sheets

In addition to reinforcement with single fiber sheets, reinforcement with multiple fiber sheets was investigated. Two separate cases were examined: (1) comparing the effect of multiple fiber sheet reinforcement, while increasing the total basis weight and (2) comparing the effect of multiple fiber sheet reinforcement, while maintaining a constant total basis weight.

Fig. 22 shows the effect of using 1, 2, and 3–30 g/m^2 fiber sheets, where the total fiber basis weight of the composite increases with the number of fiber sheets used as reinforcement. This strategy did not produce any noticeable differences in flexural strength. However, a pronounced effect was observed for toughness. Increasing the number of fiber sheets significantly improved the toughness of the composite member by 13.7% and 78.1% for the 2 and 3 layer composites, respectively, as compared to the single layer composite. Similar trends in flexural strength and toughness were obtained by Mansur and Aziz [15] using layers of bamboo mesh and by Mu and Meyer [6] using AR-glass mesh layers. It is possible that multiple sheets are more effective than a single sheet at slowing crack propagation by bridging the oncoming crack at multiple locations. It is also intuitive that as the amount of fiber reinforcement increases, toughness increases.

Separately, the effect of layering fiber sheets while maintaining the total basis weight constant (i.e., comparing 2–15 g/m^2 sheets versus 1–30 g/m^2 sheet) was also evaluated. Results shown in Fig. 23 indicate that the use of multiple fiber sheets of lower basis weights produced higher strength

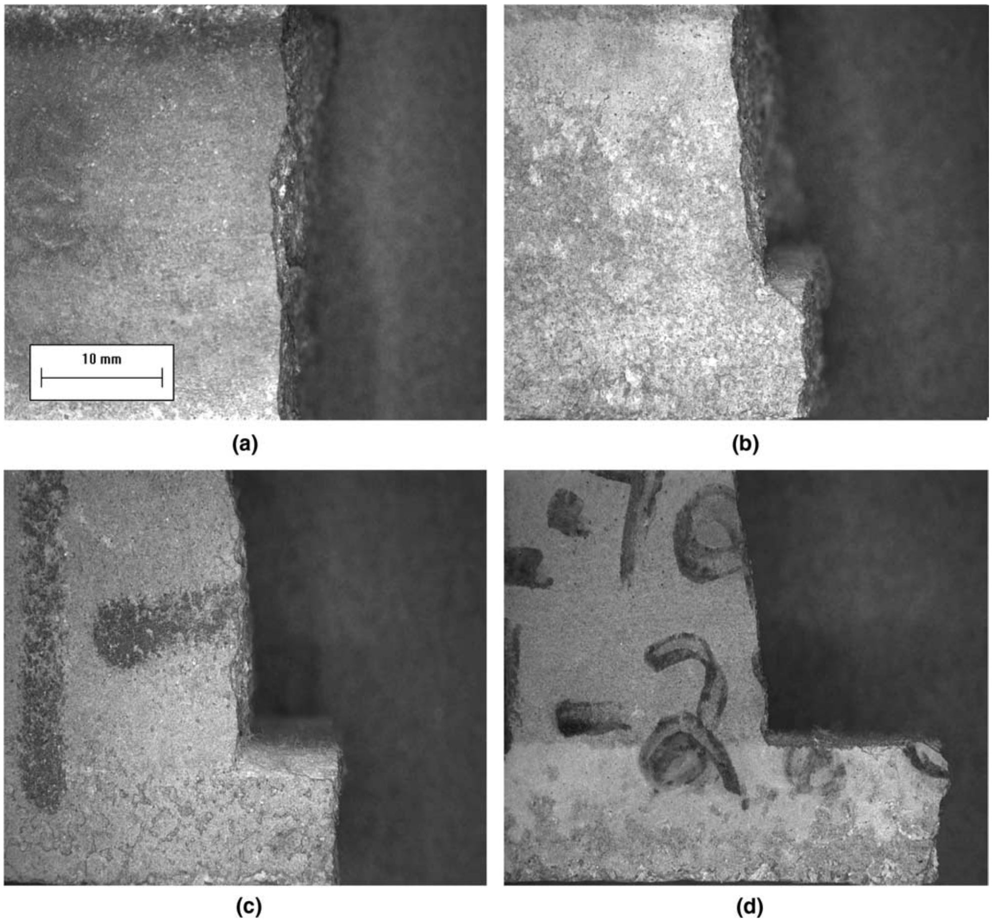


Fig. 20. Effect of fiber sheet basis weight on crack tip deflection (flexure beam side profile). *Note*: Cracking initiated on the tension side of the beam (bottom of images) due to loading of the beam (top of images): (a) 15 g/m^2, (b) 30 g/m^2, (c) 60 g/m^2 and (d) 90 g/m^2.

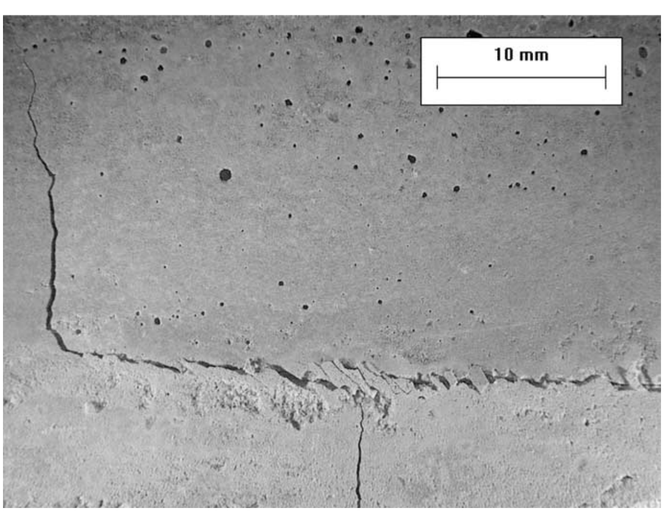


Fig. 21. Delamination along fiber sheet.

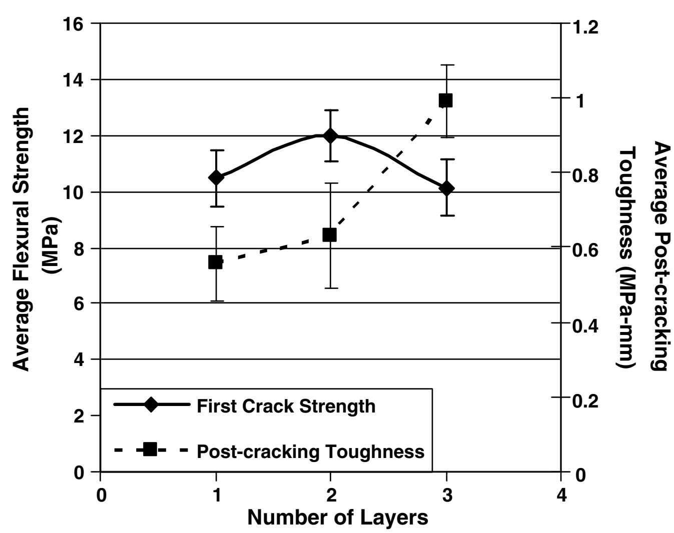


Fig. 22. Effect of 30 g/m^2 fiber sheet layering (total basis weight changing) on flexural strength and post-cracking toughness at 28 days.

composites than composites with a single equivalent higher basis weight fiber sheet. Increases in strength ranged from 9.4% to 66.2%. On the other hand, composites reinforced with multiple fiber sheets exhibited 10.5–50.0% lower toughness, Fig. 24, than a single fiber sheet composite. This may be due to increased fiber-mortar bonding of multiple fiber sheets (due to increased available surface area) leading to improved strength but lower toughness compared to a thicker single fiber sheet. Furthermore, it can be thought that a single higher basis weight fiber sheet is more effective

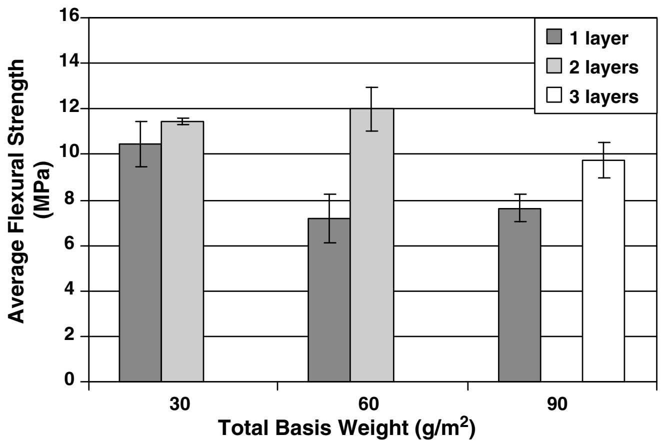


Fig. 23. Effect of fiber sheet layering (total basis weight remaining constant) on flexural strength at 28 days.

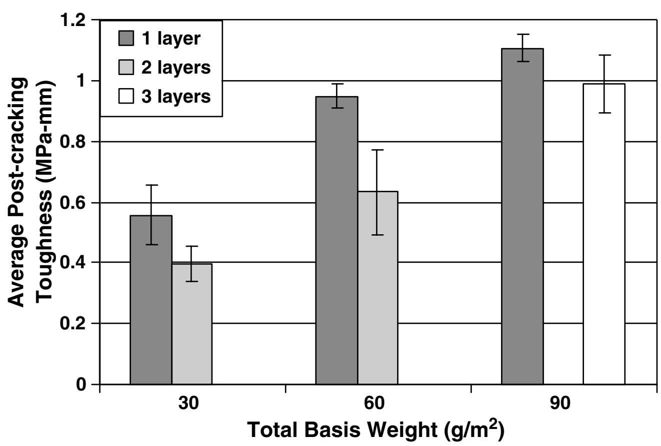


Fig. 24. Effect of fiber sheet layering (total basis weight remaining constant) on post-cracking toughness at 28 days.

in deflecting cracking in the mortar matrix than multiple fiber sheets, but less effective in transferring stress through the composite.

4. Conclusions

In this research, the use of aligned pulp fiber sheets to reinforce mortars was investigated. Fiber sheet properties examined included the addition of Kymene, fly ash, and the effect of fiber sheet perforations and fiber beating. The effect of fiber sheet basis weight (thickness), layering of sheets, and sheet location were also investigated for their effect of composite performance. Stereomicroscopy observation of fracture surfaces was done to verify the mechanical testing results. From testing and microstructural characterization, these conclusions may be drawn:

- Comparing reinforcement with aligned fiber sheets to equivalent volumes of randomly distributed fibers, flexural testing showed that the fiber sheet composites possess significantly greater toughness than the distributed fiber composites.
- Fiber sheets were produced in a way that results in sufficient fiber orientation. Composites with fiber sheets aligned at 0° relative to the longitudinal beam length exhibited significantly improved flexural strength and post-cracking toughness.
- The influence of Kymene and fly ash addition appeared to produce no measurable effects on flexural strength or post-cracking toughness. However, Kymene did facilitate the placement of fiber sheets by improving the wet strength of the fiber sheets.
- Beating or refinement of fibers creates a thinner and denser fiber sheet. This effect had no observable effect on flexural strength, but toughness was significantly decreased if beaten fibers were used.
- Perforation of fibers sheets, with either small or large round holes, appears to interfere with the toughening mechanism afforded by the reinforcement.
- Reinforcement with multiple layers of the same basis weight was found to increase toughness, as the number of layers increased. However, there was little effect on flexural strength.
- Where the total basis weight for reinforcement was kept constant, but the number of layers varies, flexural testing showed that as the number of layers increased, flexural strength increased and toughness decreased.
- Thus for improving toughness, it appears that the amount of fiber reinforcement overall in the composites is a more important factor than the number of layers, whereas reinforcement with multiple layers may have a positive effect on flexural strength.

Acknowledgements

The authors would like to acknowledge the National Science Foundation (CMS-0122068), the Institute of Paper Science and Technology (IPST)/Georgia Tech seed grant program, and IPST PATHWAYS program for their financial support. Shaobo Pan from IPST is acknowledged for his technical assistance. Buckeye Technologies is thanked for providing the softwood fibers used in this study.

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