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# Flexural Characteristics of Coir Fiber Reinforced Cementitious Composites

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**Abstract:** This study has examined the flexural properties of natural and chemically modified coir fiber reinforced cementitious composites (CFRCC). Coir fibers of two different average lengths were used, and the longer coir fibers were also treated with a 1 % NaOH solution for comparison. The fibers were combined with cementitious materials and chemical agents (dispersant, defoamer or wetting agent) to form CFRCC. The flexural properties of the composites, including elastic stress, flexural strength, toughness and toughness index, were measured. The effects of fiber treatments, addition of chemical agents and accelerated ageing of composites on the composites' flexural properties were examined. The results showed that the CFRCC samples were 5-12 % lighter than the conventional mortar, and that the addition of coir fibers improved the flexural strength of the CFRCC materials. Toughness and toughness index, which were associated with the work of fracture, were increased more than ten times. For the alkalized long coir fiber composites, a higher immediate and long-term toughness index was achieved. SEM microstructure images revealed improved physicochemical bonding in the treated CFRCC.

**Keywords:** Coir fibers, Mechanical properties, Fracture toughness, Cement, Surface treatments

## Introduction

Coir fiber is abundant in many Asian countries such as India, Philippines, Indonesia, Sri Lanka, Malaysia and Thailand. Global annual production of coir has been around 330,000 tonnes in the last few years [1]. While coir fiber is cheap (174 US$/tonne for mattress fiber in 2004), it is also strong and durable [1], making it suitable for use in the cementitious matrix for high performance structural elements [2-5].

Flexural properties are very important for construction materials, especially when their intended applications are in areas such as country road or pavement. There are various advantages of using natural fibers as reinforcement, e.g. improved bending strength, post-crack load bearing capacity and much higher energy absorption. Coir fiber was claimed to be better than other fibers in fiber-reinforced cementitious composites [6,7]. Table 1 shows the flexural strength results of various coir fiber-reinforced cementitious composites (CFRCC) [3,4,6-9]. A good flexural strength was achieved in Aggarwal's research [3]. The shortcomings of those experiments are the need for a very high percentage of fiber content and an appropriate casting pressure. The higher the percentage of fiber in the composites, the more difficult the mixing and casting procedures become. Maintaining a certain pressure is also difficult when casting components of a complex structure.

Chemical modification of the matrix and fibers may be one of the approaches for improving the flexural properties of CFRCC. Limitation in performance of coir-based fiber composites can be greatly improved through chemical modification techniques [10]. The modification can be on either the coir fibers or the matrix. Coir has a low cellulose content (36-43 %), a high lignin content (41-45 %) and a high microfibrillar angle [7]. Morphological studies of coir fibers show that the fiber is roughly circular in cross section with

**Table 1.** Flexural strength results of CFRCC reported in the literature

| Fiber length (mm) | Fiber content (%) | Water/ cement | Sample age (Days) | Sample size (mm) | Flexural strength (MPa) | Chemical agent | Casting pressure (MPa) | Ref. |
|---|---|---|---|---|---|---|---|---|
| 38 | V[a]: ~5 | 0.25 | 8 | 13 × 100 × 380 | ~5.50 | Rapidard 60 cc/kg | 3.10 | [8] |
| 30 | W[b]: 15 | 0.40 | 11 | 100 × 100 × 300 | ~10.70 | / | 3.00 | [3] |
| 15 | V: ~1 | 0.65 | 28 | 100 × 100 × 600 | ~2.30 | / | / | [7] |
| 9 | V: 4.5 | 0.40 | N/A | 50 × 50 × 300 | 1.76 | / | / | [4] |
| 30 | V: ~0.5 | 0.40 | 28 | 100 × 100 × 400 | ~5.70 | Lignosulphonic acid-polyol 2.5~3.0 cc/kg (Water reduce) | / | [9] |
| 10~20 | W: 3 | 0.35 | 28 | 8 × 76 × 242 | 6.26 | / | / | [6] |

a: percentage by volume, b: percentage by weight.

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an outer sheath of lignin. Removal of this surface layer of lignin usually results in a better and more stable fiber/matrix bond [11]. Also, though all natural fibers are hydrophilic in nature, coir fibers are not completely oil-free [8]. The presence of a small amount of oily layer around each fiber was found to adversely affect the bond strength between the fiber and the cement paste. Coir fibers with NaOH alkalization treatment have been reported in composite applications [6,11]. Adding dispersant and defoaming agents to fiber reinforced concretes (FRC) has been reported to improve fiber distribution, hence achieving a better bond between fiber and matrix [12]. The propose of these treatments is to seek an economic and convenient way for CFRCC casting. However, the respective effects of dispersant or defoaming agent and wetting agents on CFRCC properties have not yet been thoroughly examined.

In this paper, the dispersant agent and defoamer were used to modify coir fiber surface, improve the fiber distribution and promote better mixing. A wetting agent was applied to increase the water absorption of coir fiber surface and a superplasticizer was used to achieve a suitable workability of fresh mortar composite. The performance of CFRCC was evaluated against conventional mortar. To demonstrate the different reinforcing effects of various fibers more clearly, two different fiber lengths (2 cm and 4 cm, average length) and two types of coir fibers (untreated and 1 % NaOH treated) were investigated in this study. The flexural elastic stress, flexural strength, elastic limit toughness (1D), 15.5D toughness, toughness indices (I30) and flexural ductility properties of CFRCC composites were examined.

## Experimental

### Materials

The Australian Cement Ltd. supplied the cement, and Fibretex Pty Ltd. in Australia supplied the coir mat. Munzing Chemie GMBH Company in Germany supplied the Agitan® P800 ($SiO_2$, non-ionic fatty derivates, and modified fatty acid ester), and Dow Chemical Company in Australia provided the Methocel® A15LV (Methyl cellulose). The ViscoCrete 5-500 (polymer-based ultra high range superplasticizer) was provided by Sika Australia and the Albatex® FFC (silicone oil-poly, dimethylsiloxane) was supplied by Ciba Specialty Chemicals Pty Ltd., Australia. Sodium hydroxide dry powder (500 g bag) was supplied as general laboratory reagent. The local washed granitic sand was supplied by a local pre-mixed concrete company as normal building materials.

### Fiber and Composite Preparations

Coir fibers were extracted from the random coir mat by a mini carding machine and the loose fibers were then divided into two batches. One batch was soaked for 48 hours in 1 % NaOH solution in a water bath where the temperature was about 20 °C. Then the treated fibers were rinsed several times before being dried in an oven for 10 hours at 80 °C. The colour change of coir fibers from dark brown to light yellow was observed during experiment due to removal of lignin and surface oil. The other batch was also dried in the oven under the same condition before use. The fibers were manually trimmed into two different length groups, with an average length of 2 cm and 4 cm respectively. The experimental design is shown in Table 2. An explicit nomenclature system for the samples is used in this paper for clarity. For example, M-TLDD02 means the sample was treated by NaOH, reinforced with long fiber (40 mm), dispersant and deformer were applied, and mixed with 0.2 % wetting agent. Any item absent from the composite was replaced by "/".

Mortar was mixed in a laboratory mixer at a constant speed of 30 rpm, with a cement:sand:water:superplasticizer ratio of 1:3:0.43:0.01 by weight. After mixing for 5 minutes, fibers were slowly put into the running mixer, to make sure the fibers were distributed well in the matrix. Following that, the wetting agent was sprayed on the mix before the dispersant

**Table 2.** Composites mixture design

| Composite reference No. | Group | NaOH treated | Fiber length (mm) | Dispersant A15LV (%) | Defoamer P800 (%) | Wetting agent FFC (%) |
|---|---|---|---|---|---|---|
| R0 | | / | / | / | / | / |
| M-/LDD02 | 1 | / | 40 | 0.6 | 0.3 | 0.2 |
| M-/LD/03 | 1 | / | 40 | 0.6 | / | 0.3 |
| M-/L//02 | 1 | / | 40 | / | / | 0.2 |
| M-TLDD02 | 2 | Yes | 40 | 0.6 | 0.3 | 0.2 |
| M-TLD/03 | 2 | Yes | 40 | 0.6 | / | 0.3 |
| M-TL//02 | 2 | Yes | 40 | / | / | 0.2 |
| M-/SDD02 | 3 | / | 20 | 0.6 | 0.3 | 0.2 |
| M-/SD/03 | 3 | / | 20 | 0.6 | / | 0.3 |
| M-/S//02 | 3 | / | 20 | / | / | 0.2 |

Note: All percentages in this table are determined by weight of ingredients, except for the percentage of ViscoCrete 5-500, which is calculated by the weight of cement. All samples except the R0 samples had ViscoCrete 5-500 (/cement) = 1 % and fiber content = 1.5 %.

and defoamer (powder) were poured into the mixer. After mixing a further 5 minutes, the composites were poured into steel moulds (100 × 100 × 350 mm), then vibrated on a vibration table (100 Hz, driven by LG IC5 series) until dense air bubbles stopped coming to the surface (approximately 3-5 minutes).

After casting, the composites were allowed to settle inside the covered moulds at a room temperature of 24 °C for 24 hours. The hardened samples were then removed from the moulds and cut into 50 × 50 × 175 mm specimens with a construction diamond saw. The outside of the cut specimens was sprayed with the DAVCO® masonry waterproofer to prevent water absorption during the curing period. The specimens were batched and cured in a water tank at the same temperature for 26 days. For the accelerated ageing samples, the modified MacVicara's accelerated ageing method [13] was used in the final two days of the curing period. The procedure for accelerated ageing was: taking the specimens out of the water tank, air dry, then freezing them at −10 °C for 24 hours, followed by thawing the specimens at 24 °C for 2 hours and baking in a forced draft oven at 90 °C for 22 hours. This is still one of the most convenient methods to simulate the ageing effect at present. After curing, all specimens were conditioned at room temperature until the testing date (28 days).

### Measurements

The coir fiber properties were measured on a single fibre analyser (SIFAN) from BSC Electronic Pty Ltd., Australia, which can scan each fiber for diameter along the fiber length, followed by a fiber tensile test.

Four point bending tests on beam specimens at a span of 150 mm were carried out on a LLOYD tensile machine at a constant loading rate of 1 mm/min. The bending load, flexural strength, and net deflection over time were recorded.

SEM micrographs of untreated fibers, treated fibers and CFRCC composites were taken using a scanning electron microscope (LEO 1530). This was to reveal the interfacial morphology formed during hydration of cement paste and the fracture status of the composites. Prior to SEM observation, the samples were coated with gold using the BAL-TEC SCD050 plasma sputter coater.

The flexural toughness and flexural toughness indices (I30) of the CFRCC specimens were calculated according to the ASTM 1018. Each test result represents the average of 4 individual tests. Since the surface of the specimen can not be perfectly flat, there was excessive initial displacement before load was actually applied on the specimen. The amount of displacement, which was defined as the interval from the beginning of the test until the point at which linear load increase was observed, was not used in the calculations of the mechanical properties.

Moisture content of coir fibers was measured in two different humidity environments. One batch of fibers was conditioned at 20 ± 2 °C and 65 ± 2 % humidity for 24 hours. After measuring the fiber weight ($w_1$), the batch was oven dried at 105 °C oven for 2 hours after which the dry weight ($w_0$) was measured. The standard moisture content $M$ was calculated using equation (1). The other batch of fibers was put in a steel frame above the water in a large container and then the container was sealed. It was reopened after one week; the weight ($w_1'$) of fibers under 100 % humidity was measured and the dry weight ($w_0'$) was measured as stated above for calculation purposes. The water absorption ratio ($M'$) under 100 % humidity was calculated using equation (2).

$$M = \frac{w_1 - w_0}{w_0} \times 100\% \quad (1)$$

$$M' = \frac{w_1' - w_0'}{w_0'} \times 100\% \quad (2)$$

The density of each CFRCC group sample was determined by averaging the results of ten 28-day open air cured specimens. These specimens would be quite similar to those materials used in real life construction environments.

## Results and Discussion

### Properties of Untreated and Alkalized Fibers

Some physical and mechanical properties of untreated and treated coir fibers are shown in Table 3.

The moisture content and water adsorption results suggest that some waxy substance of the fiber had been removed by the alkaline treatment in 1 % NaOH solution, resulting in a higher moisture content and water absorption ratio for the treated fibers. The tensile strength of treated fiber is weaker because of the removal of lignin.

### General Behaviour of CFRCC

Compared with the plain mortar, the addition of coir fiber in the cementitious composite significantly improved the flexural strength, toughness index and ductility as shown in Figure 1. For easy observation, the starting points for the 28 days CFRCC and the aged CFRCC have been offset by 1

**Table 3.** Typical properties of coir fiber

| | Untreated coir fiber | Treated coir fiber |
|---|---|---|
| Diameter ($\mu$m) | 270 ± 73 | 263 ± 69 |
| Tensile strength (MPa) | 142 ± 36 | 110 ± 22 |
| Elastic modulus (GPa) | 2.0 ± 0.3 | 1.8 ± 0.2 |
| Elongation at break (%) | 24 ± 10 | 27 ± 12 |
| Moisture content (20 °C) (%) | 10 | 15 |
| Water absorption ratio (100 % humidity) (%) | 24 | 32 |

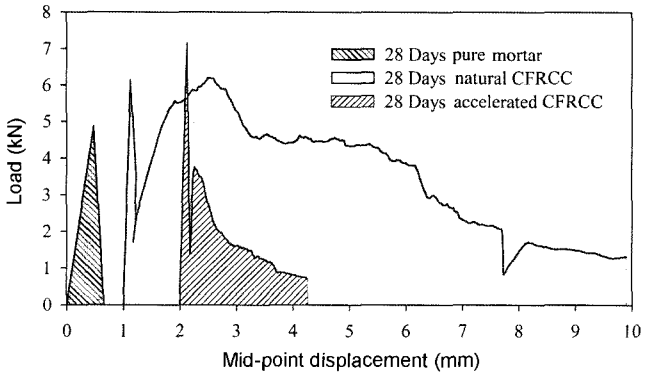


**Figure 1.** Compression-deflection curves of plain mortar (reference specimen), 28 days water cured and accelerated ageing specimens.

and 2 mm respectively in Figure 1. Water cured CFRCC had a much stronger capacity to withstand the load and crack than pure mortar. After ageing, the CFRCC had an increased flexural strength but the ductility was poorer than that of normal cured samples. This probably means that over time, the CFRCC will become stiffer and more brittle, which will weaken their energy absorbability. However the performance of the aged CFRCC was still better than normal mortar.

## Flexural Properties of Water-cured Composites

The flexural properties of water cured CFRCC specimens are shown in Table 4. The specific density of CFRCC samples was 5-12 % lighter than the control sample R0 (conventional mortar). This is largely due to the low fiber density and the air carried into the samples as a result of fiber addition. Flexural strength increased by up to 12 % for the short untreated fiber composites (M-/S//02) compared to the reference plain mortar, the toughness (15.5D), toughness index (I30) and ductility of the CFRCC increased by 340-940 %, 615-1680 %, 860-1280 % respectively. Because the LLOYD tensile machine was set to stop recording data at a certain load (10 % of the maximum load), the water cured and aged specimens still held a load of 0.8 and 1.5 kN (Figure 1) respectively when the test stoped. The real whole fracture energy absorbability of CFRCC samples should be greater than the results represented here. This property is very important to a structural component as it could support the structure longer and carry a greater load before total failure.

Three groups of composites were examined (Table 2) in this study. Group 1 was long untreated coir FRCC (M-/LDD02, M-/LD/03 and M-/L//02); group 2 was long treated fiber composite (M-TLDD02, M-TLD/03 and M-TL//02) and group 3 samples were reinforced with short untreated fibers (M-/SDD02, M-/SD/03 and M-/S//02). As shown in Figure 2, groups 2 and 3 have very similar trends in flexural strength and toughness index. As for the flexural strength of CFRCC, when comparing M-/L//02 to M-/LDD02, M-TL//02 to M-TLDD02 and M-/S//02 to M-/SDD02, it was found

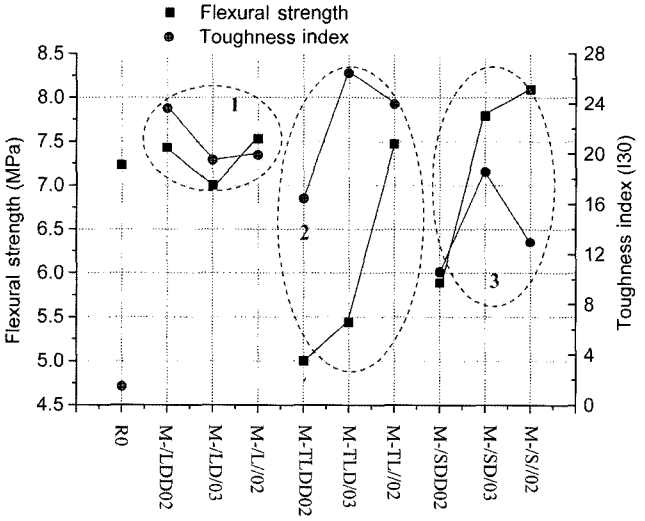


**Figure 2.** The flexural strength and toughness index (I30) of water cured CFRCC samples.

**Table 4.** Properties of 28 days aged specimens and changes (±%) compared to the control (R0)

| Sample ref. | Specific density (± %) | Flexural strength (MPa ± %) | | Toughness (15.5D) (kJ/m$^2$ ± %) | | Toughness index (I30 ± %) | | Flexural ductility (mm ± %) | |
|---|---|---|---|---|---|---|---|---|---|
| R0 | 0 | 7.23 | 0 | 0.75 | 0 | 1.48 | 0 | 0.65 | 0 |
| M-/LDD02 | −8.33 | 7.43 | 3 | 4.45 | 493 | 23.64 | 1497 | 8.94 | 1275 |
| M-/LD/03 | −9.58 | 7.00 | −3 | 6.48 | 764 | 19.51 | 1218 | 8.92 | 1272 |
| M-/L//02 | −4.58 | 7.53 | 4 | 6.33 | 744 | 19.91 | 1245 | 8.73 | 1243 |
| M-TLDD02 | −10.42 | 5.00 | −31 | 6.72 | 796 | 16.43 | 1010 | 8.99 | 1283 |
| M-TLD/03 | −12.08 | 5.44 | −25 | 3.73 | 397 | 26.44 | 1686 | 8.45 | 1200 |
| M-TL//02 | −8.75 | 7.47 | 3 | 7.81 | 941 | 23.97 | 1520 | 8.36 | 1186 |
| M-/SDD02 | −7.92 | 5.89 | −19 | 3.28 | 337 | 10.58 | 615 | 6.26 | 863 |
| M-/SD/03 | −9.58 | 7.79 | 8 | 4.26 | 468 | 18.57 | 1155 | 7.88 | 1112 |
| M-/S//02 | −8.33 | 8.09 | 12 | 6.96 | 828 | 12.98 | 777 | 6.88 | 958 |

that the absence of chemical agent (dispersant agent and defoamer) was good for the flexural property in all three sample groups. With the toughness index property of FRCC, when 0.1 % difference of wetting agent content in the composites was omitted, dispersant agent itself worked well in groups 2 and 3. If the dispersant was combined with the defoamer, more positive results were achieved in group 1 than the other two groups.

Comparing the flexural strength in group 1 to that in group 3 in Figure 2, it can be seen that some short fiber (2 cm) CFRCCs show better flexural strength than the long fibre (4 mm) CFRCCs. This may suggest that the long fiber is neither well dispersed nor straightened.

The mechanism of toughness improvement in the fiber reinforced composites is mainly related to the fiber bridging effect. It is already well known that during the debonding between matrix and fiber, the fiber either eventually fractures, or is subsequently pulled out of the matrix. There are two components of additional work coming from fiber bridging. One is the pull-out work, which is important for brittle fibers. The other is the plastic deformation that precedes fiber fracture; it is the main contributor to the added fracture toughness when the fiber is ductile. Therefore, the interface bonding is a crucial factor to determine the pull-out resistance. The stronger the bonding, the better is the toughness. However, the flexural strength is governed by the mechanical properties of fiber and matrix such as Young's modulus and tensile strength of fiber and matrix including fiber volume fraction.

Even though the chemical reaction between dispersant agent, defoamer and cementitious material inside the composites is still not very clear, the experimental results indicated that both dispersant agent and defoamer had a weakening effect on the cementitious matrix. So the flexural strength of M-/L//02, M-TL//02 and M-/S//02 was better than the other two samples within the group. But the dispersant agent and defoamer helped fibers to distribute and bond better in the composites, so the toughness index trends were totally different. The chemical agents seemed to improve the toughness properties of CFRCC more than its flexural strength.

The main component of dispersant agent (Methocel A15LV) is methyl cellulose, that of defoamer (Agitan P800) is $SiO_2$, because the wetting agent (Albatex FFC) works stably under the strong alkalized environment and the superplasticizer (Sika ViscoCrete 5-500) is added for improved workability with a fresh mortar composite, they will not be analysed separately in this paper. From the introduction of chemical modifications of acetylation reaction with accessible hydroxyl groups on the cell wall polymers [10], the reaction between coir fiber and methyl cellulose is shown in Figure 3.

The first functional group from the reaction would make single coir fibers repel each other which would produce more uniform distribution within the matrix during mixing, and also enhance the interface bonding between fiber surface and matrix paste. However the second functional group from

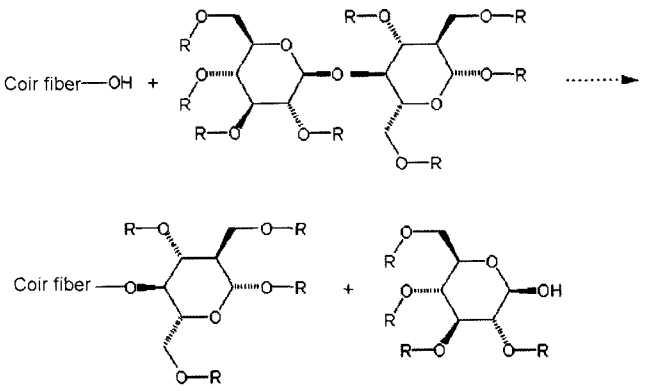


**Figure 3.** Chemical reaction scheme between coir fiber and methyl cellulose.

the reaction may weaken the structure of cement matrix which could be noticed from the experimental results. The flexural strength and toughness index properties of group 1 were more stable with different percentages of dispersant agent, defoamer and wetting agent than groups 2 and 3. This is because long untreated fibers need these agents during the composite mixing procedure while the alkalized or short fibers could be mixed more easily with matrix without the use of these agents. Higher bending properties were achieved in groups 2 and 3 as the dispersant agent and defoamer contents were reduced.

In groups 2 and 3, the flexural properties were sensitive to the dispersant agent and defoamer, and the variation within a group was quite large. Under the same dispersant agent and defoamer percentage conditions, short coir fiber with FFC wetting agent achieved the highest flexural strength (M-/S// 02). However, the treated fiber with wetting agent gained the best toughness index (M-TLD/03). It is apparent from the overall mechanical test results, for the composites, that the maximum flexural strength and maximum toughness (and also toughness index) cannot be achieved simultaneously. Composites must be designed to suit their intended applications with desired mechanical properties [14].

## Flexural Properties of Composites after Accelerated Ageing

As shown in Table 5 below, the maximum flexural strength of the 28 day aged CFRCC increased by up to 25 % on short untreated fiber composites (M-/LDD02). The toughness (15.5D), toughness index (I30) and ductility were increased by as much as 375 %, 400 %, and 1740 % respectively.

The flexural strength of aged CFRCC in Table 5 shows that untreated long fiber composites were more able to sustain the load over a long period. However the treated long fiber reinforced composites had a relatively high toughness and toughness index among the three groups. Aged FRCC samples with alkalization treated fiber composites absorbed more energy than untreated fiber composites during flexural

**Table 5.** Properties of 28 days accelerated aged specimens and changes (±%) compared to the control (R0)

| Sample ref. | Flexural strength (MPa ± %) | | Toughness (15.5D) (kJ/m$^2$ ± %) | | Toughness index (I30 ± %) | | Flexural ductility (mm ± %) | |
|---|---|---|---|---|---|---|---|---|
| R0 | 8.81 | 0 | 0.65 | 0 | 2.25 | 0 | 0.32 | 0 |
| M-/LDD02 | 11.03 | 25 | 1.61 | 148 | 1.77 | −21 | 1.01 | 216 |
| M-/LD/03 | 9.46 | 7 | 1.22 | 88 | 3.05 | 36 | 0.93 | 191 |
| M-/L//02 | 10.60 | 20 | 1.31 | 102 | 1.90 | −16 | 1.05 | 228 |
| M-TLDD02 | 6.23 | −29 | 3.09 | 375 | 11.42 | 408 | 5.89 | 1741 |
| M-TLD/03 | 9.21 | 5 | 1.91 | 194 | 4.48 | 99 | 2.39 | 647 |
| M-TL//02 | 7.68 | −13 | 2.34 | 260 | 7.86 | 249 | 3.91 | 1122 |
| M-/SDD02 | 7.28 | −17 | 1.84 | 183 | 6.89 | 206 | 3.08 | 863 |
| M-/SD/03 | 9.36 | 6 | 1.97 | 203 | 5.98 | 166 | 2.42 | 656 |
| M-/S//02 | 10.37 | 18 | 1.96 | 202 | 7.05 | 213 | 2.16 | 575 |

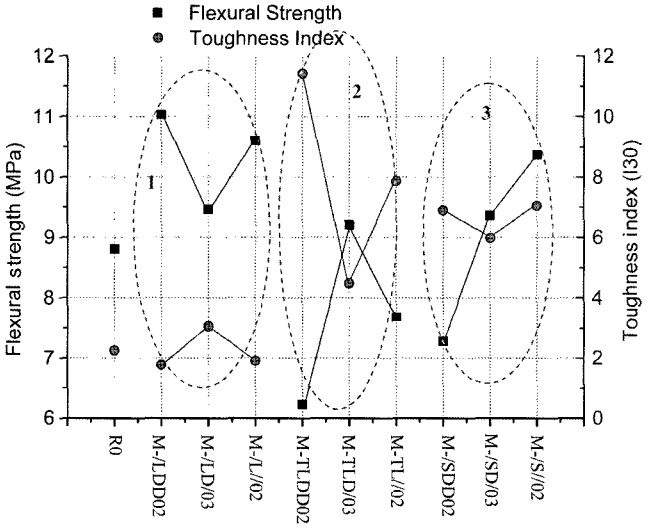


**Figure 4.** The flexural strength and toughness index (I30) of accelerated aged CFRCC samples.

failure.

For the flexural strength property of aged CFRCC samples, the presence of dispersant agent and defoamer gave an optimistic result in M-/LDD02; however dispersant agent itself worked well with wetting agent in M-TLD/03 and M-/SD/03. Without chemical agents (dispersant agent and defoamer), sample M-/S//02 produced the best overall results among the short (2 cm) fiber reinforced composites. Figure 4 shows that single dispersant agent with FFC did have some advantages in the toughness index of M-/LD/03; however, wetting agent and defoamer together were contributing factors to achieve the I30 of M-TLDD02. This is because the modified fibers bonded with cementitious matrix better than untreated fibers in the longer term. Results from group 2 are better than that from the other two groups. Also as stated above, though the defoamer will weaken the matrix inner-structure, it will improve the bonding strength between fiber and matrix, which leads to a tougher composite.

Comparing samples M-/LDD02 to M-/S//02 within three groups, untreated long fiber composites were more stable in either flexural strength or toughness index than treated or short fiber composites. Fiber treatment affected the flexural strength performance of the aged CFRCC, untreated fiber composites had a generally higher flexural strength value than treated fiber composite; however treated long fiber and short fiber composites had a better toughness index performance than untreated long fiber samples. Long fiber composite M-/LDD02 had the highest aged flexural strength and the treated fiber composite M4 had the best toughness index value after ageing. The reasons for these experimental results are mainly due to the chemical reactions between the different functional groups of chemical agents, fiber, and cement paste. The accelerated ageing and long term curing further complicated these reactions.

Therefore, the chemical agents may not be necessary ingredients as can be seen from Table 4 and Figure 4. However, in the accelerated ageing CFRCC they do have some positive effects on the flexural strength of the untreated CFRCC in the long fibre (40 mm) case and also on the toughness of all samples. It suggests again that composites should be designed with desired mechanical properties for intended applications.

### Flexural Ductility of Different Cured Composites

In the ductility property of CFRCC (as shown in Figure 5), group 1 exhibited a great variation between water cured and accelerated ageing specimens; among these three groups, group 2 had the best ductility property regardless of whether it was a normal or aged specimen. Another point to be noted is the trend of CFRCC specimens' ductility within one group. The trends of normal samples and aged samples in group 1 were slightly different; in group 3 they remained dissimilar; however in group 2, they stayed the same. This meant that the fiber treatment with chemical agent was effective and the performance may improve over time. The treated samples resulted in higher ductility for both curing methods; in

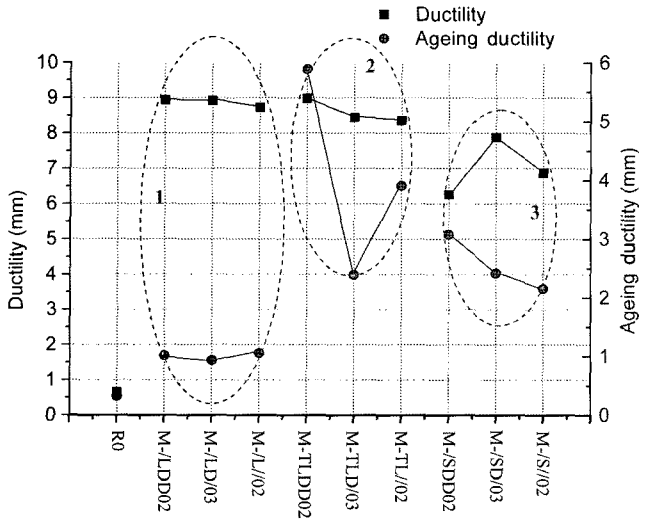


**Figure 5.** The flexural ductility of CFRCC samples.

untreated fiber samples, the 2 cm one was better than the 4 cm one in terms of improving composite ductility.

## Fiber Microstructure Study

Crystal growth on the fiber surface from 28-day aged specimens, as shown in Figures 6 and 7, indicates the presence of thin crystal of portlandite (Calcium Hydroxide or CaOH), and the development of porous gel. A part of this gel is conjectured to be a product of the reaction of lignin (oxidation of end groups) or the remaining phenol or tannin in the fiber surface and the hydroxyl group of the cement matrix [4]. The image of treated fiber surface supports this assumption. The magnified structure of pores, tyloses, and waxy cuticle can be seen on the outer surface layer of untreated fiber in Figure 6(b). After alkalization treatment, shown in Figures 7 (a) and (b), with some of the lignin removed from the outer layer, dense CH (Calcium Hydroxide) at fiber interface and porous layer of CSH (Calcium silicate hydrates) gel lay parallel at the interface. Thicker crystal formation appeared in the treated fiber outer layer which meant that the fiber could bond better with the cementitious hydration products.

The protrusions on untreated fibres in Figure 8(a) can offer extra anchoring points such that the fiber can withstand stresses from the matrix better (mechanical bonding). Removing these protrusions (Figure 8(b)) resulted in less mechanical bonding in

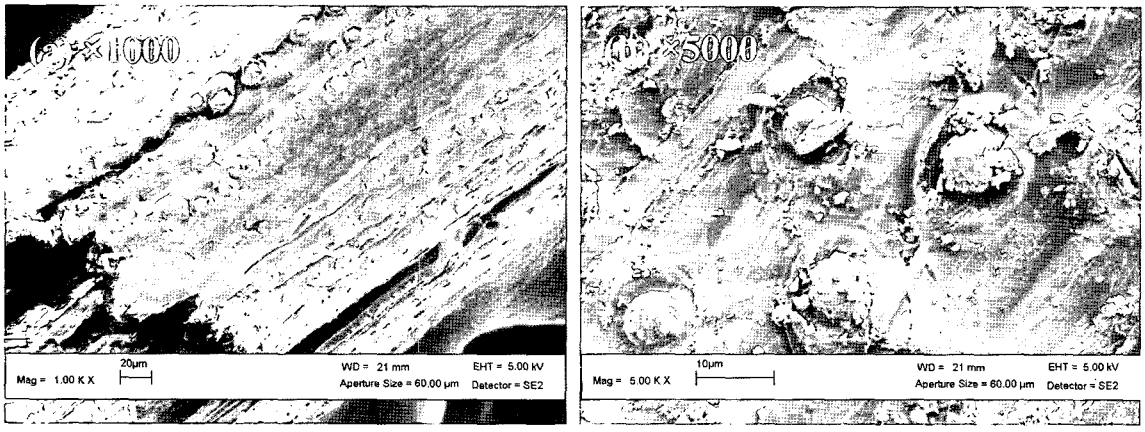


**Figure 6.** SEM photographs of untreated fiber after failure at different magnifications.

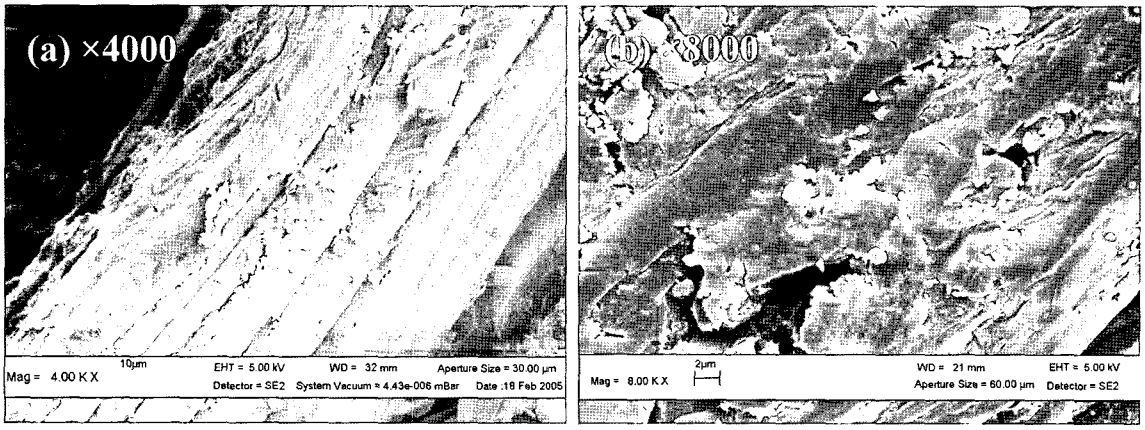


**Figure 7.** SEM photographs of treated fiber after failure at different magnifications.

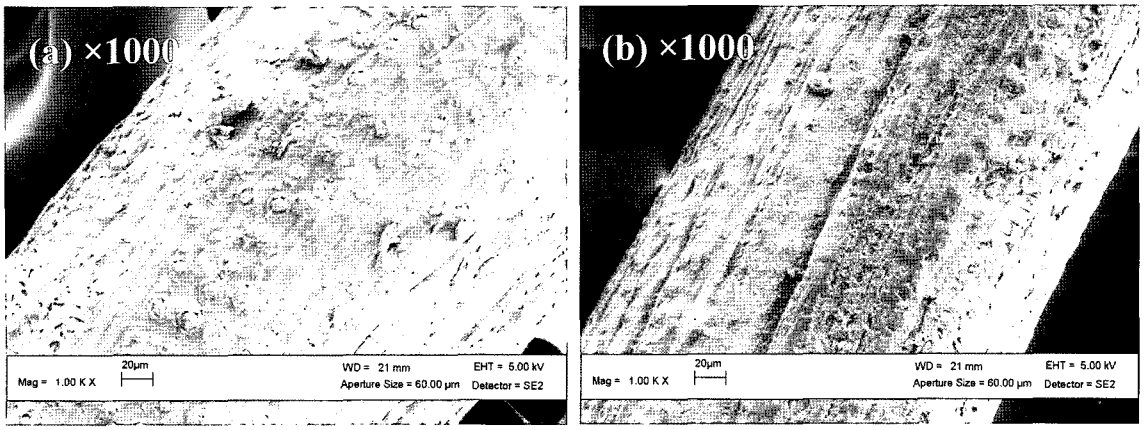


**Figure 8.** Surface morphology of untreated and treated fibers.

composites which leads to a certain drop in composite performance. The composites aged for a longer period had more hydration products in fiber/matrix interface. The improved quality of hydration products (physicochemical bonding) in fiber/matrix interface provided extra benefit for over-all performance especially in the long term. This is why the ageing treated CFRCC specimens had superior ductility over untreated CFRCC.

## Conclusion

In this study, untreated and alkalized coir fibers have been used in cementitious composites as reinforcement materials. The effects of adding fibers to cement matrix, on the composite performance were investigated empirically. This study has confirmed that coir fiber reinforced cementitious composites (CFRCC) have better flexural strength, higher energy absorbing ability and ductility, and lighter than conventional cementitious materials. Good results are achieved with the addition of a low percentage of coir fiber and chemical agents in cementitious matrix.

Within the naturally cured samples, flexural strength increased by up to 12 % for short untreated fiber composites. The toughness (15.5D), toughness index (I30) and ductility of CFRCC were increased by 340-940 %, 615-1680 %, 860-1280 % respectively. Within the accelerated ageing samples, the toughness (15.5D), toughness index (I30) and ductility of CFRCC were increased by as much as 375 %, 400 %, and 1740 % respectively.

With the accelerated ageing procedure, alkalized fibers improved toughness index of composites and alkalized fibers worked very well with the chemical agents and the performance of composites made from treated fibers decayed little over time. The microstructure studies revealed that the alkaline treated CFRCC have a good physicochemical bonding which accounts for its superior properties. The untreated fiber composites showed a large difference in their ductility property compared to the naturally cured samples, which meant their properties would probably deteriorate over time.

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