Flax fiber reinforced concrete – a natural fiber biocomposite for sustainable building materials

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Abstract

Fibers of many types, including some natural fibers, have been used widely for architectural applications in structural and non-structural assemblies. One important use of the mechanical properties of natural fibers is tensile reinforcing and volume filler within the matrix of a composite material; cementitious, polymeric, earthen or otherwise. While natural fibers offer a widely available and inexpensive source of mechanically useful cellulose, the full extent of the potential for architectural applications has not been adequately investigated. This paper presents the laboratory results of an optimized flax fiber reinforced concrete (FFRC). The mechanical results are intended as a demonstration of the use of natural fiber reinforced concretes (NFRCs) for buildings in developing regions with access to significant sources of cellulose fibers and small-scale industrial capacity to process them. Generally, the inclusion of natural fibers within a concrete matrix is intended to augment the energy absorption of the cured concrete. Specifically, an optimal ratio mix and fiber length of flax fibers in concrete was sought in obtaining the highest possible ultimate strength, toughness and crack management from the various samples. Results from mechanical laboratory testing yielded positive conclusions regarding the increased strength and toughness of the natural fiber-reinforced concrete. While strength was shown to increase with the inclusion of particular fiber lengths and decrease with others, results from the optimized formulation indicated the potential to substantially increase the flexural toughness of the concrete composite. A theoretical analysis confirmed the empirical results of an optimum length of 3cm for flax fiber in concrete. As a result, an increase in the shear strength of structural members composed of the flax fiber reinforced concrete offers strategies that may lead to substantial savings in construction materials, especially steel. For architectural applications, the results indicate good potential for a class of concrete biocomposites for use in a variety of building types in developing regions.
1 Introduction

The work presented in this paper serves to augment the substantial literature addressing the use of biomass as a source of raw materials for building components [1][2][3][4][5].

The use of biologically derived materials in components for buildings has been an ongoing project for many decades [3]. Much of the most promising and wide-ranging work has occurred at research centers and universities in developing regions of the world, primarily in collaboration with European universities. Researchers in India and Latin America, and to a lesser extent Africa, have led this work during periods of greatest sustained research interest and productivity. It stands to reason that the regions of the world most interested in this field are also those that have the capability to produce, in large enough quantities, the raw biomaterial. In addition, developing regions also continue to face substantial challenges in providing the necessary infrastructure and building stock to house growing urban populations.

Furthermore, recent research [6] has indicated the value of investigating techniques of technology transfer for development that take advantage of the embedded knowledge base of indigenous peoples. The use of natural materials, especially those derived of agricultural practices, brings with it the lessons of substantial experience with the materials at hand. This experience is often a valuable resource for evaluating what may be considered appropriate technologies in a particular area, given a particular culture.

![Fiber classification]

While the potential of biomass in building components has been investigated from many different angles, the primary path of research has been the use of fibers produced by plants for tensile reinforcing in earthen, cementitious and polymeric composites. These composites are generally low-strength materials in which the fiber reinforcing serves to increase the overall toughness of the final mix.

In addition, the availability of biomass for use in large scale industrial and energy production has been well documented. It has been estimated that 280 million tons of waste biomass is generated each year in the United States alone [7]. Specialty products have been formulated from materials derived of plant biomass such as starch-derived plastics, biopolymers for secondary oil-recovery, paper and fabric coatings, not to mention ethanol as a petroleum fuel substitute.
Figure 2: Current bio-based products

2 Mechanical properties of flax fiber reinforced concrete (FFRC)

Table 1 [1] lists various properties for a number of natural fibers as well as glass, aramide and carbon fibers. It is clear from the results for Young’s modulus that a number of natural fibers possess reasonably good mechanical properties for use as structural reinforcement in an architectural composite. It is also clear that natural fibers may not be used as a simple substitute for synthetic fibers because of their lesser tensile strengths. Note that flax rates highest among natural fibers in terms of tensile strength, a property critical to the behavior of a crack inhibitor in a cementitious composite.
Table 1: Various properties of selected natural and synthetic fibers

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Density (g/cm³)</th>
<th>Elongation (%)</th>
<th>Tensile strength (Mpa)</th>
<th>Young's Modulus (Gpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton</td>
<td>1.5-1.6</td>
<td>7.0-8.0</td>
<td>287-597</td>
<td>5.5-12.6</td>
</tr>
<tr>
<td>Jute</td>
<td>1.3</td>
<td>1.5-1.8</td>
<td>393-773</td>
<td>26.5</td>
</tr>
<tr>
<td>Flax</td>
<td>1.5</td>
<td>2.7-3.2</td>
<td><strong>345-1035</strong></td>
<td><strong>27.6</strong></td>
</tr>
<tr>
<td>Hemp</td>
<td>-</td>
<td>1.6</td>
<td>690</td>
<td>-</td>
</tr>
<tr>
<td>Ramie</td>
<td>-</td>
<td>3.6-3.8</td>
<td>400-938</td>
<td>61.4-128</td>
</tr>
<tr>
<td>Sisal</td>
<td>1.5</td>
<td>2.0-2.5</td>
<td>511-635</td>
<td>9.4-22.0</td>
</tr>
<tr>
<td>Coir</td>
<td>1.2</td>
<td>30.0</td>
<td>175</td>
<td>4.0-6.0</td>
</tr>
<tr>
<td>Viscose (cord)</td>
<td>-</td>
<td>11.4</td>
<td>593</td>
<td>11.0</td>
</tr>
<tr>
<td>Softwood</td>
<td>1.5</td>
<td>-</td>
<td>1000</td>
<td>40.0</td>
</tr>
<tr>
<td>E-glass</td>
<td>2.5</td>
<td>2.5</td>
<td>2000-3500</td>
<td>70.0</td>
</tr>
<tr>
<td>S-glass</td>
<td>2.5</td>
<td>2.8</td>
<td>4570</td>
<td>86.0</td>
</tr>
<tr>
<td>Aramide (normal)</td>
<td>1.4</td>
<td>3.3-3.7</td>
<td>3000-3150</td>
<td>63.0-67.0</td>
</tr>
<tr>
<td>Carbon (standard)</td>
<td>1.4</td>
<td>1.4-1.8</td>
<td>4000</td>
<td>230.0-240.0</td>
</tr>
</tbody>
</table>

These mechanical properties, along with relatively low cost and ease of handling indicate good possibilities for their use in composites. In terms of cost, flax fiber rates among the more expensive of the natural fibers, often exceeding that of e-glass. However, this fact alone should not affect consideration of the overall importance of the fiber as a tensile reinforcing agent. Natural fibers bring various positive attributes to the task of tensile reinforcing that stand to temper the economic costs associated.

1. Natural fibers are found globally and often commonly harvested as either a primary material or secondary by-product of well-established agricultural processes. Natural fibers from plant material are the primary source for new biocomposite material technologies.

2. Natural fibers, as the product of natural processes, are renewable [1] and often biodegradable. In addition, the environmental impact during seeding, growing and maturation of the plant is restricted to the soil in which it is planted.

3. Natural fibers fix and retain carbon. The CO₂ released during combustion or decomposition is returned to the environment from which it was originally fixed thereby contributing a net zero sum gain to the overall amount of carbon in the atmosphere [1][7].

4. Natural fibers are a group of materials with a long economic, technological and social history within developing and predominantly agricultural regions. This widespread familiarity in cultivation, harvesting, processing and...
manipulation of natural fibers is an important component in the formulation of viable sustainable production processes. Certain fibers have been in use for various products for thousands of years. Any development of contemporary technologies utilizing natural fibers can build upon this existing knowledge and vernacular expertise [6].

5. Natural fibers embody low levels of energy due to the low levels of processing required - relative to synthetic fibers. In addition, natural fibers are biodegradable and may therefore re-enter the organic material cycle through recycling [7].

6. Natural fibers are much less abrasive than synthetic fibers such as glass and carbon. This lower abrasiveness aids in the various processing steps [5].

7. Natural fibers possess generally high strength to weight ratios.

The most important negative characteristics, or more precisely counter-productive characteristics, should also be listed here before we introduce the specific characteristics of flax fibers.

1. Natural fibers are strongly hydrophilic. This property is primarily due to the bonding of hydrogen to the hydroxyl groups of the cellulose molecule. This is a problem in both polymer and cementitious matrices. Water absorption before, during and after casting and curing, may affect both the durability of the fibers [8] as well as the integrity of the interfacial bond between matrix and fiber.

2. Mechanical and physical properties of natural fibers vary widely between species and even among fiber bundles of the same species. Natural fibers are a complex mixture of cellulose, hemi-cellulose and lignin (among other materials) with variations in a wide range of properties important to their application in building components.

3. The cellulose molecule, the structural backbone of all plant fibers, is sensitive to attack in an alkaline environment. Careful consideration needs to be taken of the pH level of any matrix material [8][9][10][11].

Natural fibers consist of cellulose, hemi-cellulose, lignin, pectin, waxes and water soluble substances. Table 2 lists the component mean values of several natural fibers.

Table 2: Component content of selected natural fibers

<table>
<thead>
<tr>
<th></th>
<th>Cotton</th>
<th>Jute</th>
<th>Flax</th>
<th>Ramie</th>
<th>Sisal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose</td>
<td>82.7</td>
<td>64.4</td>
<td>64.1</td>
<td>68.6</td>
<td>65.8</td>
</tr>
<tr>
<td>Hemi-cellulose</td>
<td>5.7</td>
<td>12.0</td>
<td>16.7</td>
<td>13.1</td>
<td>12.0</td>
</tr>
<tr>
<td>Pectin</td>
<td>5.7</td>
<td>0.2</td>
<td>1.8</td>
<td>1.9</td>
<td>0.8</td>
</tr>
<tr>
<td>Lignin</td>
<td>11.8</td>
<td>1.0</td>
<td>2.0</td>
<td>0.6</td>
<td>9.9</td>
</tr>
<tr>
<td>Water soluble</td>
<td>1.0</td>
<td>1.1</td>
<td>3.9</td>
<td>5.5</td>
<td>1.2</td>
</tr>
<tr>
<td>Wax</td>
<td>0.6</td>
<td>0.5</td>
<td>1.5</td>
<td>0.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Cellulose can perform the structural function of the plant because it is a linear condensation polymer of anhydroglucose units. The degree of polymerization (Table 3) is an important aspect of the morphology of cellulose in the fiber. The level of polymerization determines the supramolecular structure of the fiber. In
addition, this supramolecular structure determines most mechanical and physical properties of the fiber itself [1].

<table>
<thead>
<tr>
<th>Fiber</th>
<th>P₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton</td>
<td>7000</td>
</tr>
<tr>
<td>Flax</td>
<td>8000</td>
</tr>
<tr>
<td>Ramie</td>
<td>6500</td>
</tr>
</tbody>
</table>

2.1 Concrete and flax fiber

Reinforced concrete dominates the construction industry in much of the developing world today. It is a primary structural material, along with steel, throughout the world. This relatively simple composite serves as the predominate material for the superstructure and, to a lesser extent, the exterior envelope of a variety of buildings of all types and scales. Reinforced concrete is particularly prevalent in developing regions for a number of reasons; the most common being the relative low-cost of the constituent materials as well as the availability of low-skilled, inexpensive labor. However, the reinforcing steel of the composite is often a relatively expensive component. While the amount of steel used within reinforced concrete is relatively small in weight and volume, its high expense contributes substantially to the overall cost of the composite. This is a major concern with regard to the quality of concrete delivered and ultimately formed on site - especially in areas where the resistance to dynamic loading from earthquakes is critical to the safe occupation of the buildings. Substandard contracting practices have reduced the use of steel by increasing the overall mass of the final cast. While this may be sufficient for uniaxial loading of certain members, it is a dangerous practice when applied to members in flexure. The substitution, or partial substitution, of steel in reinforced concrete is an important way to offer low-cost alternative methods for achieving flexural integrity in structural members.

Flax has been used for a variety of products for roughly 10,000 years [12]. Evidence of the use of flax for food as well as textiles has been recovered from a number of archeological sites dating back to the time of the earliest agricultural settlements in the Near East. It is clear that, from a very early date, substantial energy and attention was devoted to the cultivation of the flax plant. This crop was one of the earliest sources of a variety of important products, including linseed oil, linen fiber for fabrics and food grain. Linum usitatissimum, the most important and useful of flax varieties, found its way around the Near East and is determined to have been an important crop throughout Mesopotamia and Egypt. The crop then spread to the Middle East, Europe and eventually to the Americas.

Flax is a temperate bast plant currently cultivated in Europe, North and South America and China. The useful fiber is produced within the stem of the plant and separated mechanically using a variety of techniques. Fibers acquired for this study ranged between 10 and 17 cm. Flax fiber is composed of fiber bundles of approximately 100 micrometers in diameter. Each fiber bundle contains
between 20 and 50 fibrils of 20 micrometers in diameter each. The fibril is more or less cylindrical in section with a very fine lumen and relatively thick cell walls. Historically, retting – a process of rotting the stems and running them through compressive rollers - has been the method of choice [13] for removing fiber from the stem.

Several researchers [1][12] have identified flax, along with hemp, kenaf, jute and coir, as holding great promise for use in composites for construction materials and other applications.

Figure 3: Flax fiber

Figure 4: SEM image of flax fibril

In order to establish a set of data that would be most useful in determining the general mechanical properties and eventually the structural capacity of the FFRC, the following tests were conducted:

1) tensile splitting test: 10 x 20cm cylinder
2) uniaxial compression test: 10 x 20cm cylinder
3) 3-point bending test: 100 x 100 x 350mm beam

Some details regarding the choice and use of the tests are given below. These tests were considered to be the minimum number required to establish the overall mechanical properties of the material. For all tests the mixing proportion of the various materials was held constant while the length of the fibers tested were 1, 3, 5, 7.5 and 10cms. The mixing proportions and actual materials used are as follows:
Table 4: FFRC mixture ratio

<table>
<thead>
<tr>
<th>Material</th>
<th>Mix Proportion (%)</th>
<th>Description/Manufacturer, origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Flax fiber (Flax)</td>
<td>5% (by volume)</td>
<td>Natural, unprocessed flax fiber bundles</td>
</tr>
<tr>
<td>2. Sand (S)</td>
<td>0.295</td>
<td>7030 sand UNIMIN, Industrial Quartz</td>
</tr>
<tr>
<td>3. Type 3 cement (C)</td>
<td>0.369</td>
<td>7, 14 and 28 day cure Portland Cement Dragon Company</td>
</tr>
<tr>
<td>4. Water (W)</td>
<td>0.188</td>
<td>Tap water</td>
</tr>
<tr>
<td>5. Silica fume (SF)</td>
<td>0.138</td>
<td>Force 10,000 Grace Company</td>
</tr>
<tr>
<td>6. Superplasticizer (ADVA)</td>
<td>0.009</td>
<td>ADVA Flow Grace Company</td>
</tr>
</tbody>
</table>

While there is substantial evidence that various treatments of the fibers may increase their longevity in the concrete matrix as well as contribute to an incremental increase in tensile strength [14][15][16][17], the study chose not to use any treatments and incur the associated costs in production. Also, no aggregate was used because of the damaging effect these relatively large elements would have on the flax fiber bundles and individual fibrils. These aggregates would hinder the random and uniform distribution of fibers in the concrete mix [5]. Because of their substantial water absorption and rough surface the bundles tend to clump together posing some problems with achieving homogeneous distribution in the concrete mix. The superplasticizer minimizes this issue. Silica fume was used based on studies that have identified pozzolans as substantially contributing to reduced moisture sensitivity of cellulose fiber reinforced cement composites [8][9][10][11]. In addition to these properties, the silica was used to provide a denser filling between all hydration particles and the natural fiber [18]. The most successful mixing procedure was the following:

a) Dry mixing (S+C+SF): 5 min
b) Adding water (60%) (S+C+SF+W+ADVA): 3min
c) Adding Flax (40%) (S+C+SF+W+ADVA+Flax): 12min
d) Adding water (40%) (S+C+SF+W+ADVA+Flax): 3min
e) Adding flax (60%) (S+C+SF+W+ADVA+Flax): 12min
f) Total mixing (S+C+SF+W+ADVA+Flax): 3min

The tests listed above were most illuminating in terms of two separate values:
1) ultimate strength, and
2) toughness.

By characterizing these two values a useful understanding of the energy absorption of the material was possible. Also, Hannant and Piggott [19][20] stress the importance of evaluating the contribution of the fiber and matrix separately. The ultimate strength is the easier value to define as it is simply the highest load carried by the specimen, whether in compression, bending or tensile
splitting. The value of toughness, while empirically derived in a more complex way, is an increasingly important property for fiber-reinforced composites. Recently a good deal of work has been accomplished toward the establishment of guidelines for the measuring and quantification of toughness [21][22][23][24][25]. As described by Barr [21] toughness can be defined as the energy absorption capacity of the material as determined by the area under the load-displacement curve as obtained by experimental measurement. This is also the definition given under ASTM C 1018, 3. Terminology, 3.1.5. While this definition is not in dispute, the method of obtaining a valid set of data for establishing a value for toughness has been in debate for several years.

Figures 5A & B: Graphical results of load testing
In Figure 5A one can see that the toughness, as measured by the area under the displacement-load curve indicates that there is little benefit in the inclusion of 1 and 5cm (1-A, 1-B, 5-A) flax fibers in comparison with the unreinforced samples (FC-A, FC-B). Even though there is an increase in the ultimate load for these samples, the failure mechanisms for all of these specimens was relatively catastrophic (that is, the drop off from the yield load is steep). However, the 10cm fiber inclusion specimen demonstrates a dramatically better response to its yield load, resisting a significant fraction of the yield load through a much greater displacement and therefore having a significantly larger toughness value.

At failure, the maximum bending stress is considered to be the flexural strength of the material [26]. The notched beam test is commonly used for the evaluation of the toughness due to the incorporation of fibers within a brittle matrix. For the incorporation of natural fibers within a cement matrix the notched beam loaded in 3-point bending is particularly useful for assessing the actual behavior of the fiber bundles. In addition, due to the overestimation of the net deflection of the loaded specimen from measurements obtained through the load frame, it was decided to measure deflection, with respect to its neutral axis, directly from the test specimen. We also obtained values for deflection from measuring the crack mouth opening displacement (CMOD) directly from the specimen.

Using the CMOD has certain advantages over a measure of the deflection of the specimen; CMOD is easier to measure than deflection, it is a direct measure of the displacement across the crack opening, and the increase in CMOD is much larger than deflection therefore making it more sensitive to the failure mechanism. As in [21] we also determined the toughness through a measurement of the net central displacement as stipulated in ASTM C 1018. For further discussion on the advantages of a CMOD measurement scenario and the
overall advantages of evaluating toughness using notched specimens see Barr [21].

After reviewing the results of these and other tests, a further series of loading was carried out to determine a clearer conclusion regarding the optimal length of flax fiber in concrete. From these tests it was determined that a length of 3cm was the experimentally derived optimal length.

3 Scanning electron microscope analysis

The distribution and characterization of the fiber bundles and the interfacial bond at the fracture surface (FS) were investigated using a scanning electron microscope. The SEM methods used an unpolished specimen as the primary method [27] for analyzing the character of bonding between fiber and matrix at the FS. Three general conclusions were reached by studying the microscopic character of the distribution and morphology of the fiber bundles within the cementitious matrix at the FS.

First, it is clear that the fiber bundles were found to be both intact and separated into individual fibrils in the hydrated and cured concrete. There was no clear preponderance of one condition over another and both situations were found evenly distributed within the matrix, as far as could be examined. It is important to note that fiber bundles were found intact in the matrix because the existence of fiber bundles aids in the dissipation of imperfections in individual fibrils. This dissipation can be multiplied by the number of bundles and may substantially contribute to the overall strength of the fiber reinforcement [20].

Second, as a result of the relative ease of separation into fibrils during casting, there was a concern that cement paste may not penetrate into the spaces between bundles and fibrils. However, it was found without exception, that cement paste had infiltrated into these spaces and had fully surrounded both fibers and fiber bundles. No areas between individual fibers or fiber bundles were found void of cement paste. In addition, many fibers that were left exposed at the fracture surface showed surfaces covered with cement paste. There is evidence from the images of the formation of large crystals of portlandite in the transition zone interior. The high porosity of the natural fibers induces the formation of these crystals as described by Savastano [28].

Third, from this initial examination of at least 36 tested specimens, it seems clear that a variety of failure modes are contributing to the fracture mechanism of the composite. Fiber rupture, debonding, friction, slippage and pull-out all seem to have occurred in failed specimens, indicating that a substantial number of fibers, in a variety of failure modes, are contributing to the augmentation of toughness through tensile reinforcement at crack formation and propagation.

These conclusions are only preliminary and need to be substantiated by additional SEM analysis. Yet these preliminary results do indicate that there is evidence for good interfacial bond between the concrete matrix and the untreated flax fibers.

In Figures 7A through F, various interfacial bond conditions may be seen. SEM images A, B, C, E, and F all show good interaction between hydrated
concrete and the surface of the flax fibers, bundles and fibrils alike. In addition, the random distribution of fibers is clearly visible in images C and F. Image A shows a fiber bundle separated as it emerges from the matrix. In addition, the fibers are all seen to be closely bonded to the matrix as well as retaining areas of cement paste on their surfaces even after pull-out from the matrix, see Images E and F. It is also clear in images B and E, that calcium-silicate-hydrates are adhered to the fiber surfaces. Image D shows an area along the fracture surface in which imperfect distribution of fibers has resulted in some minor clumping of fibers in the matrix. A more detailed examination of failed samples is necessary to establish the amount of clumping that is occurring in the cured specimens. However, the images show that the cement and flax fibers are clearly establishing a working mechanical interfacial bond.

Figures 7A, B, C, D, E, F: SEM images of fracture surface (FS)
4 Conclusions

This paper presents the result of the formulation, mixing procedure, casting and load testing of flax fiber reinforced concrete. From previous research, the results for NFRCs are promising. The results of testing flax fiber in concrete indicates good potential for architectural applications. Results of the testing and SEM analysis indicate that:

1. flax fiber contributes well to both the strength and toughness of concrete,
2. flax fiber in concrete is optimized at a length of around 3 cm,
3. a positive inclusion morphology of the fibers in concrete is possible with the proper mixing protocol,
4. flax fibers contribute to the augmentation of the mechanical properties of the concrete composite through a complex range of fiber/matrix failure mechanisms,
5. flax fiber reinforced concrete approaches to within reasonable expectations of overall strength and toughness for a viable structural material for buildings of short to moderate spans.

However, flax fibers demonstrate the usual negative characteristics of most natural fibers. One of the most important is that natural fibers are relatively difficult to handle as part of any wet process such as the casting of concrete into molds and forms. The rough surface of the fibers and their varying lengths and grades leads to the fibers forming unmanageable clumps when handling. Also natural fibers are highly hydrophilic and this leads to difficulty including well-distributed volumes of fiber within the matrix of the composite for which water is a major ingredient. In this study it was found that the handling of the fibers simply required a certain experience that, once acquired, determined that certain specific steps needed to be taken during the mixing and casting process.

5 References


