The Fibrous Exterior Wall Assembly: Using Appropriate Technologies to Grow Component Materials for the Sustainable Wall

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INTRODUCTION

The work presented in this paper serves to augment the substantial literature regarding the use of biomass as a source of raw materials for building components [1][2]. The methodology employed involves both the empirical laboratory testing of original natural fiber reinforced concrete formulations and the design of a demonstration architectural project that utilizes the natural fiber composite in several distinct building components. The scope of the work intends to further both the experimental understanding of the behavior of biomaterial composites and the design opportunities that these materials embody.

The use of biologically derived material in components for buildings has been an ongoing project for many decades [3]. Much of the most interesting and wide-ranging work has occurred at research centers and universities in developing regions of the world. India and Latin America, and to a lesser extent Africa and Europe, 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. These regions believe that the enormous resource of biomass, as a source of inexpensive and easily produced raw material for building components, holds a great deal of promise in addressing these issues.

The potential for the use of biomass in building components has been investigated from many different angles. One primary path of research has been the potential for 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 aid in the working and casting of the matrix as well as increasing the overall toughness of the final material. The natural fibers are used because of their ease of processing and low cost. While many other issues contribute to their attractiveness as a raw material for building components, these two factors are the primary reasons that researchers and private entrepreneurs continue to work toward products derived of natural sources.

The work described here uses concrete as the matrix material for the biocomposite. Again, a great deal of work has been accomplished with regard to the use of natural fibers within a cemntitious matrix. However, there is a need for continued studies investigating natural fibers in concrete primarily because of the sheer number of different plant species that are potential donors of useful fibers. Also, there is a need for further research that better establishes the mechanical behavior and durability of these fibers within a concrete matrix.

Reinforced concrete dominates the construction industry in much of the developing world today. It is also a primary structural material, along with steel, in much of the developed 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 the 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 cast on site, especially in areas where the structural integrity is critical to the continued safe occupation of the buildings. Some practices have reduced the use of steel by increasing the overall mass of the final cast. However, this poses problems of an overabundance of mass for achieving acceptable levels of interior thermal comfort. In addition, this mass can be a critical factor in buildings that are unable to resist shear loads imposed during seismic events.

NATURAL FIBERS AND COMPOSITE MATERIALS: NATURAL POLYMER MATRICES

The focus of this research has been the determination of the suitability of a specific natural fiber as a source of structural reinforcement and volume filler within a concrete composite material for use in components for construction. The research also proposes the design of systems that utilize these materials as components in the exterior wall and structural frame. While composites have currently established a significant role within construction technologies, the possibility for the sustainable use of natural fibers for architectural applications has not been definitively established.

In addition to the use of concrete, improved natural and biodegradable polymers make it more possible for the sustainable manufacturing and recycling of these polymer composites strengthened with natural fibers. The use of these naturally derived polymers for the matrix lowers the cost and benefits the environment. In addition, innovative processing of the natural fibers themselves has made a wider array of fibers available for high quality composite inclusion. It is worthwhile describing these materials in some in some detail before the testing procedure and results are presented later in the paper.

While the physical properties of natural fibers have been relatively well established, there is a need for original research to be conducted in the behavior of composite systems utilizing natural fibers in concert with natural and synthetic matrix materials. By examining a number of properties, it may be demonstrated that natural fibers are appropriate materials to consider when seeking a fiber with a high strength-to-weight ratio. However, within the limited space of this paper, only a brief examination of properties is possible.

The table below lists the specific modulus for a number of natural fibers as well as glass fiber and demonstrates clearly that sisal, flax and hemp all possess reasonably good mechanical properties for use as structural reinforcement in a composite.

Fiber	Specific Gravity	Tensile Strength (MPa)	Modulus (GPa)	Specific Modulus (modulus/specific gravity)
Jute	1.3	393	55	42
Sisal	1.3	510	28	22
Flax	1.5	344	27	18
Sunhemp	1.07	389	35	33
Glass Fiber-E	2.5	3400	72	29

Figure 1. Selected Mechanical Properties of several widely available natural fibers

These mechanical properties, along with the comparatively low cost of natural fibers indicate good possibilities for their use in construction materials particularly as a component material in composites. Natural fibers have been utilized in a number of component parts from automobiles to a limited number of interior partition materials, however there is a need for further research regarding the beneficial properties of natural fibers for a wider range of building products. However, because of the variability of properties between individual species of plants contributing natural fibers, the formulation, design and making of exterior wall components and structural elements will necessitate testing to establish the viability of each material separately. This process could take many years of sustained research.

Type of natural matrix	Commercial sources
1. modified cellulose	Cellglass, Celluloseacetate, BIOCETA
2. modified starch	MATER BI, Novamont, SCONACELL A (BSL)
3. polyester	Hydroxy-functional polyesters, Polyhydroxybutyrat

Figure 2. Natural Matrix Types

In addition, it has been shown in several studies that the mechanical properties of natural fiber and matrix composites compare favorably with GFRP (glass fiber reinforced polymers) and other synthetic fiber and matrix composites. These naturally derived polymers offer the promise of low-cost, environmentally benign matrix materials for a wide range of composite materials. A short-list of commercially available natural polymers is given in Figure 2.

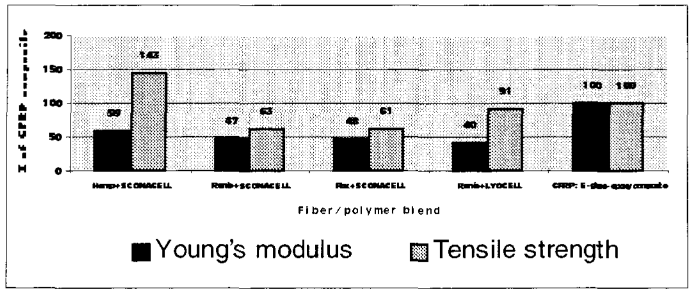
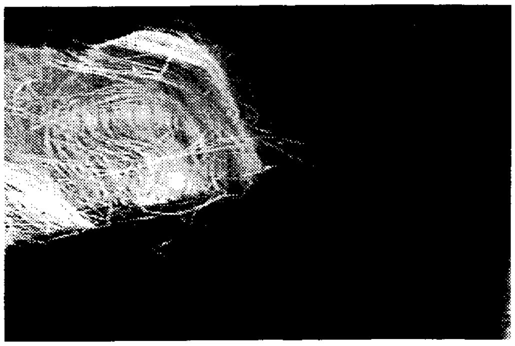


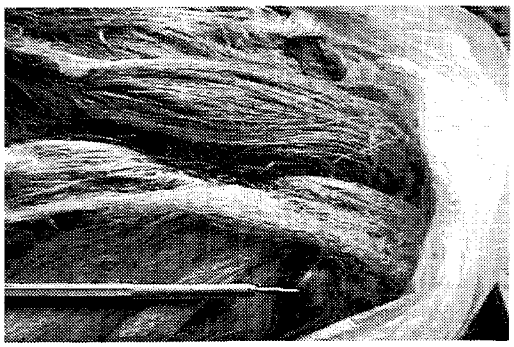
Figure 3. Comparison of Natural fiber reinforced composites and E-glass GFRP (Hermann et.al.)

While the mechanical properties of these natural fiber/natural polymer matrix composites vary widely with respect to the particular natural fiber, the inclusion morphology, the matrix properties and many other factors - several combinations begin to approach significant fractions of tensile and modulus of elasticity values of much more expensive and environmentally negative synthetic fiber composites (such as GFRPs and CFRPs) as illustrated in Figure 3. Further mechanical testing of a range of natural fiber and natural and biodegradable matrix components is a key missing aspect of research.

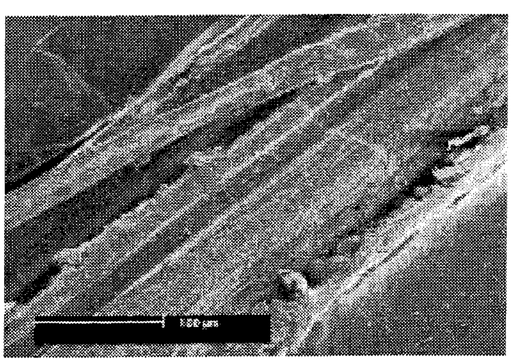
MATERIALS AND SPECIMEN PREPARATION: BRIEF HISTORY OF THE USE OF FLAX FIBERS

While the use of concrete as a primary building material throughout much of recorded history has been well-established and does not need further elaboration here, the use of natural fibers has a less well-documented past. It is worthwhile to briefly outline its use.





Flax has been used for a variety of products for roughly 10,000 years. This is a result of findings from evidence recovered from a number of archeological sites in the Near East. It is clear that from a very early date, a substantial amount of energy and attention was paid to cultivating the flax seed. 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.



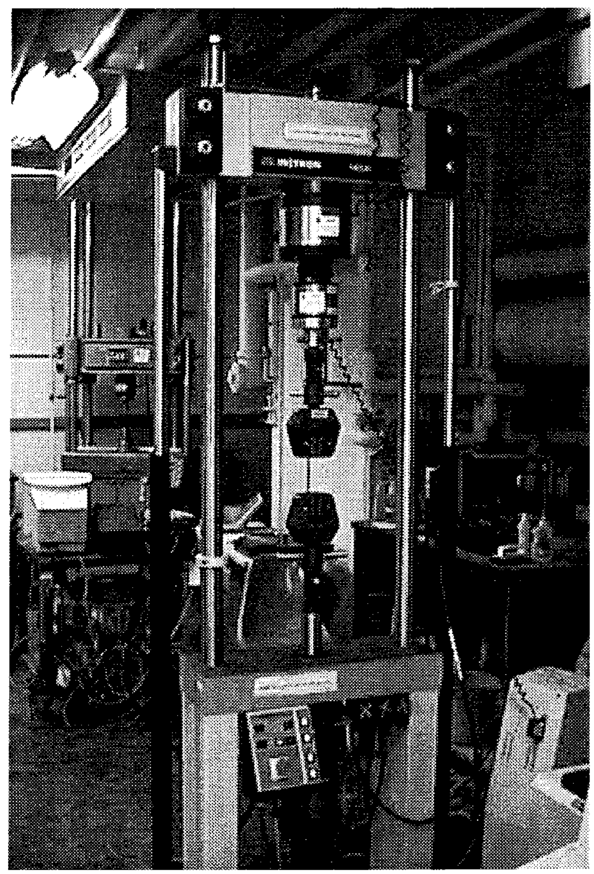
TEST PROCEDURE AND RESULTS: TOUGHNESS CHARACTERIZATION

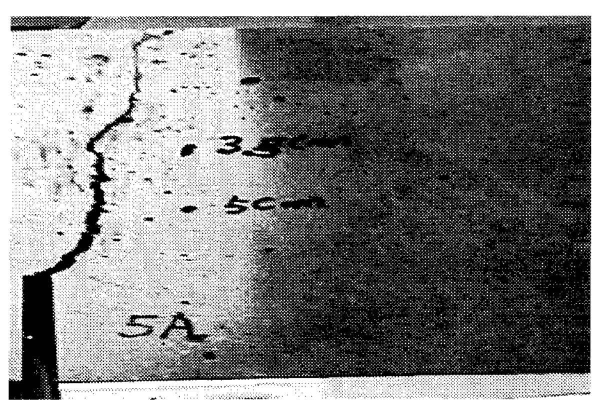
In light of the many natural fibers available around the world and given the rich history of the use of the flax fiber and its relatively robust nature, this research project chose to concentrate on the use of flax as a tensile reinforcement element and volume filler within the cementitious matrix composite material. Working with the MIT Department of Civil and Environmental Engineering, the US Department of Energy and the 3M Corporation, we decided on a series of mechanical tests that would best represent the mechanical properties of this NFRC. The tests conducted included:

1) tensile splitting test

2) axial compression test

3) 3-point bending test





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 size of the fibers ranged from 1-10cms. The mixing proportions and actual materials used were as follows:

Material	Mixing Proportion (%)	Description/ Manufacturer, origin	Note
1. Flax fiber (1cm+10cm)	5% (by volume)	Natural, unprocessed flax fiber	Specific gravity (0.45) of flax was roughly measured. 2.5% is 1cm flax and the other 2.5% is 10cm flax.
2. Sand	0.295	7030 sand UNIMIN, Industrial Quartz	(30% retained on 70mesh or Coarser) 1.0 surface profile as abrasive (MILS) Specific gravity: 2.6
3. Type 3 cement	0.369	7 day cure Portland Cement Dragon company	W/C is 0.5. The increase of W/C was caused by the difficulty of mixing (Workability problem). W/C=0.5 is also used in normal concrete mixing Specific gravity: 3.16.
4. Water	0.188	Tap	
5. Silica fume	0.138	Force 10.000 Grace company	High performance concrete admixture dry densified powder(microsilica) Specific gravity: 2.25
6. Superplasticizer	0.009	ADVA Flow Grace company	ASTM C 494, Type F, High range water-reducing admixture Specific gravity: 1.02

Figure 4. Materials and Mixing Ratio

The flax was included as part of the dry mix of the concrete thereby avoiding difficulties in the wetting of the fibers before mixing. The specimens tested were composed of flax fiber of various lengths randomly distributed within the concrete and additives mix. The lengths of fibers investigated were 1, 3, 5 and 10cm. The fibers were not treated. No aggregate was used because of the damaging effect these relatively large components would have on the flax fiber bundles and individual fibrils. In addition, the superplasticizer was kept at a minimum and used only to ease the mixing of the various components and casting. Several mixing proportions were attempted that failed due to the difficulty in working with the natural fiber. This is an issue that should be attended to in further research. The hydrophilic quality of most natural fibers makes it difficult to manipulate the bundles in an aqueous environment. Because of their substantial water absorption and rough surface the bundles tend to clump together posing problems with a homogeneous distribution in the concrete mix. The most successful mixing procedure was the following:

a) Dry mixing (S+C+S.F.): 5 min

b) Adding water(60%) (S+C+S.F.+W+ADVA): 3min

c) Adding Flax (40%) (S+C+S.F.+W+ADVA+Flax): 12min

d) Adding water (40%) (S+C+S.F.+W+ADVA+Flax): 3min

e) Adding flax (60%) (S+C+S.F.+W+ADVA+Flax): 12min

f) Total mixing (S+C+S.F.+W+ADVA+Flax): 3min

The tests listed above were most illuminating in terms of two separate values:

1) ultimate strength, and

2) toughness.

The ultimate strength is the easier value to define as it is simply the highest load carried by the specimen. As described by Barr [4] 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. The work presented in this paper adopted a set of recommendations, as stated in Barr [4], that prescribe several items worth mentioning here.

In Figure x one can see that the toughness, as measure by the area under the various displacement-load curves for the compression test 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.

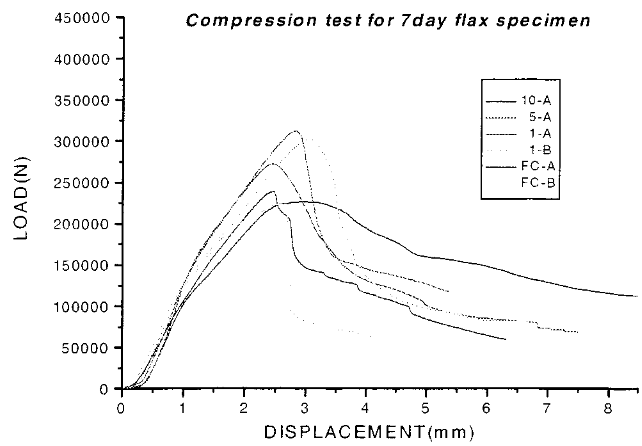


Figure 5

The bending test revealed a similar, yet less dramatic, result.

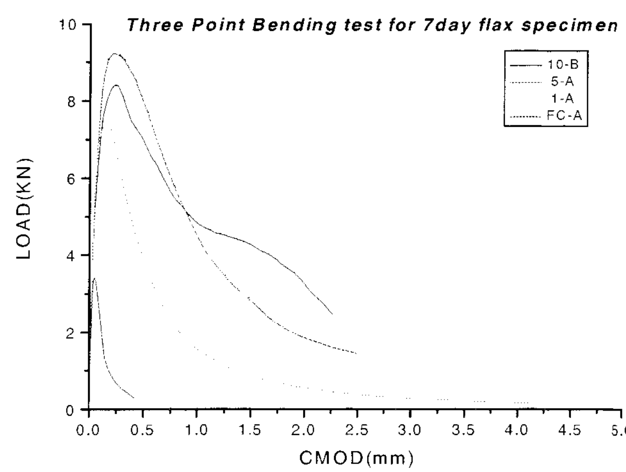


Figure 6

The bending test is a more complicated test and warrants certain descriptive detail at this point. First we decided to use a notched beam under 3-point bending instead of the more commonly used un-notched beam under 4-point bending. For brittle materials, such as concrete and mortars, the notched beam test clearly illustrates the mechanical behavior of the material at the initiation of the first crack [IMAGE 6]. Therefore, the notched beam test is a better test in which to evaluate the behavior of the composite as reinforced by fibers. The notched beam test is commonly used for the evaluation of the toughness due to the incorporation of fibers within the matrix. 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 directly from the test specimen. We decided to obtain a value from measuring the crack mouth opening displacement (CMOD) directly from the specimen. As in [4] we 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 [4].

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, see Figures 7 and 8.

SCANNING ELECTRON MICROSCOPE ANALYSIS

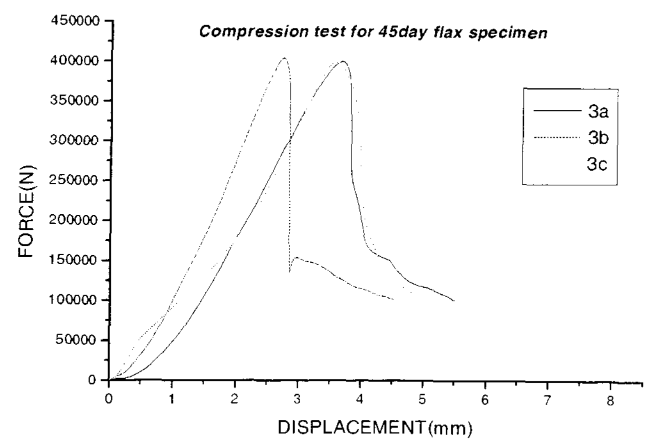
The distribution and characterization of the bundle fibers and the interfacial bond were investigated using a scanning electron microscope. Three important conclusions were reached by studying the microscopic character of the distribution and morphology of the fiber bundles within the cementitious matrix.

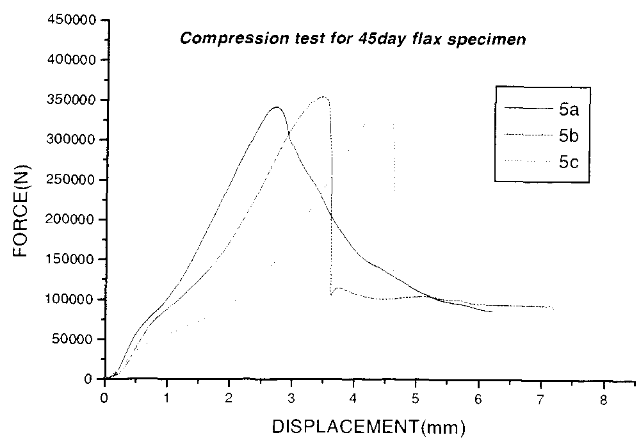
First, it is clear that the fiber bundles were left both intact as well as separated into individual fibrils during the manipulation of the fiber during casting and mixing. Both situations were found evenly distributed within the matrix.

Second, as a result of this ease of separation, cement paste was found to have infiltrated into the spaces in between fibers and bundles alike. No areas between individual fibers or fiber bundles were found void of cement paste.

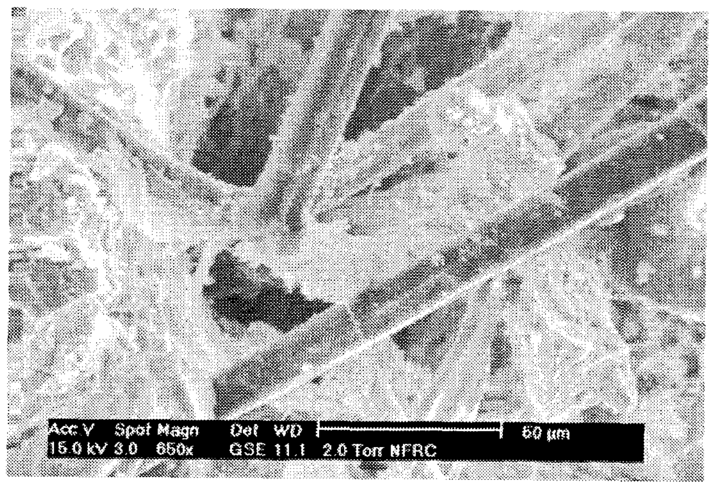
Third, from an initial examination, it seems clear that a variety of failure modes are operating in the failed specimens. Fiber rupture, debonding, friction and slippage all seem to have occurred in failed specimens, indicating that a substantial number of fibers are contributing to the augmentation of toughness.

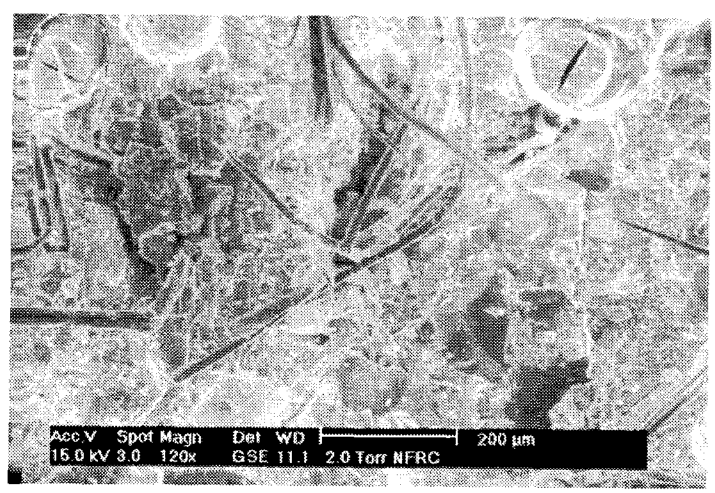
These conclusions are only preliminary and need to be substantiated by additional SEM analysis. Yet these preliminary results indicate that the conditions exist for good interfacial bond between the concrete matrix and the flax fibers.





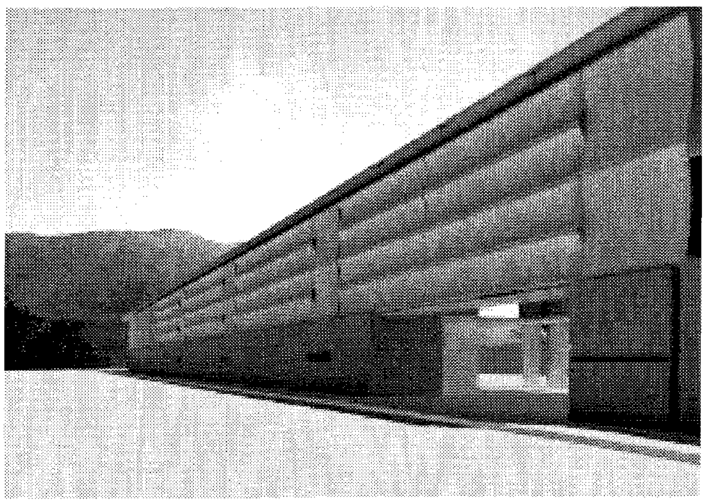
Figures 7, 8: 3cm and 5cm load tests

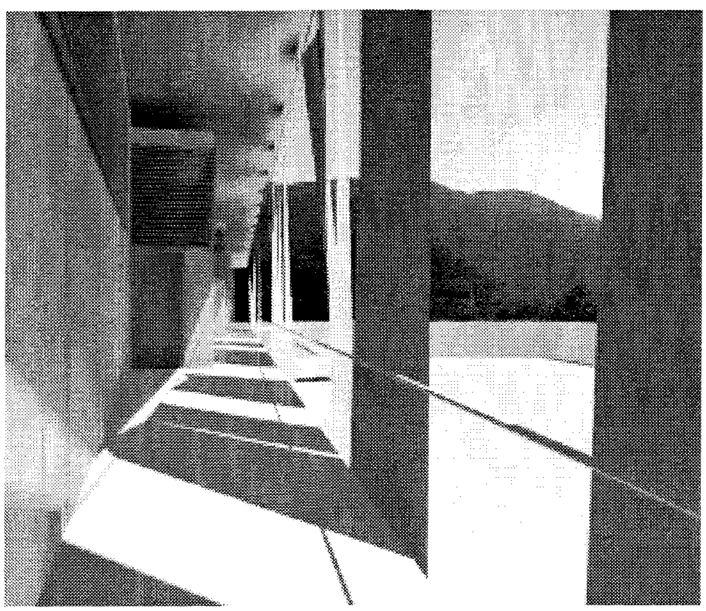




DEVELOPMENT WORK AND NATURAL FIBER PRODUCTS

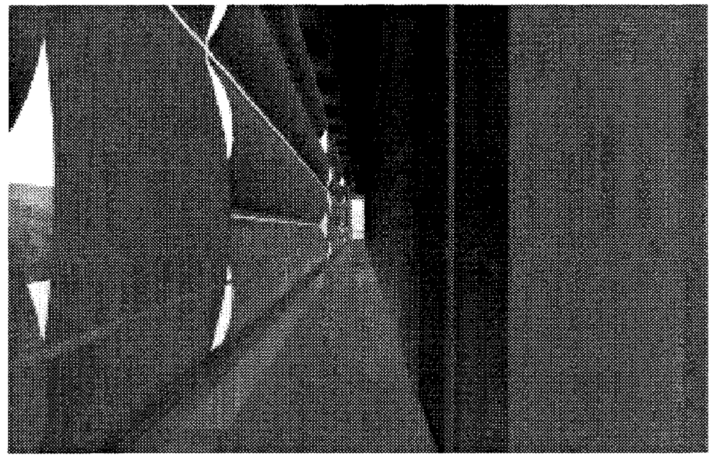
The brief presentation of these findings does not fully describe the substantial potential that we believe natural fiber reinforced composites have for the building industry, in particular in relation to new exterior wall systems and structural frame and bearing wall systems. As a way of investigating the structural properties inherent in flax reinforced concrete, as well as NFRCs in general, we decided to embark on the design of a small building that utilizes the material in a variety of morphologies. We have been engaged by the World Bank, Fundacomun of Venezuela and several municipalities in northern Venezuela to investigate these new materials for use in housing projects, community buildings and schools. Currently we have completed the conceptual design phase of a prototype school for a small city in northern Venezuela.

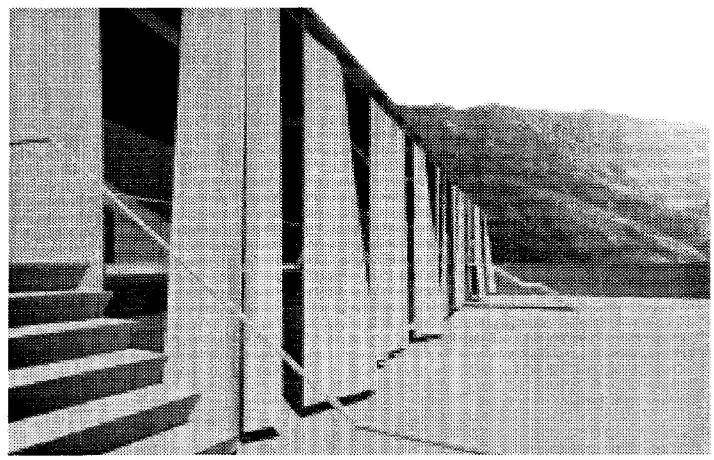


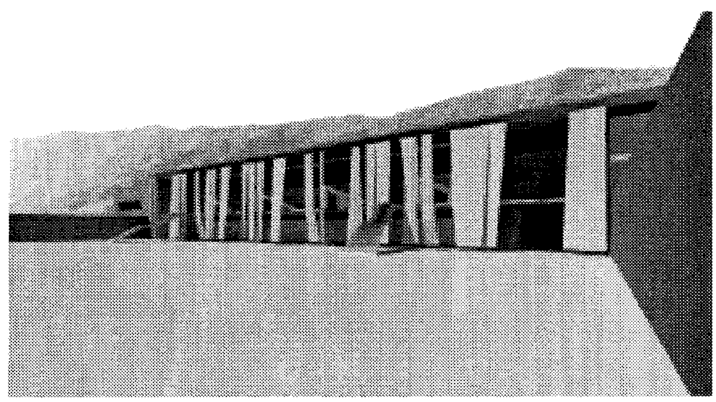


The school will contain 8 Classrooms, an Assembly Hall, a Reception, Office and Conference wing and an Outdoor Court. The prototype will utilize four separate types of natural fiber reinforced materials:

1. NFRC masonry units
2. NFRC precast conoid and other minimal surface shells
3. NFRC modular, interior lightweight partitions, and







4. NFRC cast-in place, "draped" sunscreen walls

The school is configured according to a traditional courtyard scheme in which the classroom wing forms one side of a protected court for the students. The bar of the school, containing the individual classrooms, is bracketed by circulation on both edges. This circulation is defined, on its outer edge by a series of panels of draped rigid NFRC panels. These panels are placed on the building first as a woven natural fiber curtain that is held along the top and pinned at the bottom. Once the weaving has been restrained, a layer of concrete is sprayed onto it using technology similar to that employed for «shotcrete». Once cured and rigid, the panels serve as exterior shading surfaces for the building.

The longitudinal classroom walls are composed of bearing walls of NFRC masonry units. Each block is a precast concrete unit reinforced with a natural fiber. The walls are placed as infill between the concrete frame of the building. It is assumed that the primary superstructure for the building is site cast steel-reinforced concrete.

The partition walls between classrooms are constructed using NFRC precast vertical plank. The precast morphology of these walls saves casting time on site as well as serving as a casting surface for the structural beams above.

Further research work is continuing to establish the precise dimensional parameters of the making of each of these types of NFRC building components. We are currently working toward writing structural guidelines for the use of NFRCs in buildings of this scale and larger.

APPLICATIONS

Composite materials are an ever-expanding realm for building systems research and product applications. Natural fibers in architectural applications take advantage of the particular properties of good strength to weight ratios, good availability, relative cost effectiveness, ease of processing, ease of recycling and good biodegradation properties. Particular fibers include the most widely available agriculturally important sources of cellulose and lignin. Sisal, straw, flax, hemp, jute, sunhemp and other tropical and temperate climate natural fibers are examples that have been shown to have good potential. Several studies have described and attempted prototypes leading to possible applications for a number of building components.

Applications for this research are intended to have an impact on advanced materials as well as low-cost systems for use in developing regions. Direct application to architectural components may yield the following:

- Light weight/ low embodied energy buildings: high strength to weight ratio and reduction of the energy of acquisition and processing of architectural materials.
- Fabric wall buildings: exploration of the use of woven technologies for the production of resilient composites.
- "Breathing" wall technology: textiles and composites in the use of exterior wall components that allow for natural ventilation.
- Natural fiber/Natural matrix composites: through agricultural sources, "growing" the primary raw materials for superstructural and exterior wall elements of buildings.
- International Urban Slum Upgrade Projects: cellulose fiber and cementitious panel technology for international development projects.

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 contribute generally to a positive potential as a reinforcing material in concrete. 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 3cm,

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 ranger 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 determined that certain specific steps needed to be taken during the mixing and casting process.

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