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Erosion control products from sugarcane bagasse

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**EROSION CONTROL PRODUCTS FROM
SUGARCANE BAGASSE**

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science in Engineering Science

in

The Interdepartmental Program in Engineering Science

by
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ABSTRACT

The erosion control industry uses different types of geosynthetics in order to mitigate the negative impact that erosion has on the environment. One of the most rapidly growing segments within this industry is the natural mats and blankets market. With new environmental regulations and enforcement, the demand for these natural products has considerably increased because of their biodegradability, good moisture retention, low cost and environmentally friendly image.

The goal of this present work was to develop a continuous manufacturing process for sugarcane bagasse mats, which could be implemented in the local sugar mills and could provide an economic benefit to both sugarcane industry and road construction industry.

To provide the market with a good and competitive product, several designs were tested at Audubon Sugar Institute, St. Gabriel, Louisiana. Using a simple prototype device 1.2 m x 2.4 m sugarcane bagasse mats were produced.

Different chemical and mechanical treatments were applied to determine which one will yield the most appropriate bagasse fibers for mat formation. Thermo-gravimetric analysis was used to compare the effect on bagasse fibers of two chemical treatments: sodium carbonate and sodium hydroxide. Two experimental plots were tested to examine the grass penetration capability of the bagasse mats.

The bagasse mats were tested for thickness, weight, strength, water absorption and smolder resistance according to the American Society for Testing and Materials (ASTM) methods, and following the guidelines of the Erosion Control Technology Council (ECTC)

CHAPTER 1. INTRODUCTION

1.1. Geosynthetics Overview

According to the American Society for Testing and Materials (ASTM), a *geosynthetic* has been defined as “a planar product manufactured from polymeric material used with soil, rock, earth or other geotechnical engineering related material, as an integral part of a man-made project, structure or system” [2]. The transportation industry is currently using different types of geosynthetics like geotextiles, geogrids, geomembranes, erosion control mats and blankets, geosynthetic clay liners, geocomposite drainage materials and geonets. Five of the most important functions performed by geosynthetics are filtration, fluid transmission, separation, reinforcement and environmental protection. In the future, the demand for the use of geosynthetics, especially the natural mats and blankets for erosion control, will increase with stricter environmental regulations and enforcement [3].

The erosion control industry has been created due to the increase in the magnitude of uncontrolled soil movement by water and wind. This problem is often overlooked by those unfamiliar with the impact of erosion. As a single example, the sediments account for more than two-thirds of all pollutants entering U.S. waterways. Annual outlays in the U.S. for mitigation of erosion and sedimentation are estimated at 13 billion dollars. The erosion control industry includes a diversity of professions and specialists like hydro-seeders, mats and blanket manufacturers, consulting engineers, landscapers and even earth moving contractors. One of the most rapidly growing segments within this industry has been the erosion control mats and blankets market. Rolled erosion control products were first used in the form of jute nettings imported from Asia, but they evolved quickly to include geosynthetic products [17]. As the rate of soil erosion increases, so is the demand for mats and blankets [18]. Erosion control blankets

are effective for soil stabilization on steep to moderate slopes, new landscaped areas and ditches that are to be planted or seeded. Desirable attributes include:

- Increasing water infiltration into soil
- Moderating soil temperature
- Promoting seed germination by reducing soil moisture loss
- Protecting the mix from being eroded during heavy rainfall or wind, – (when used with a seed mix)
- And most important, reducing soil erosion [17].

Emphasis is placed on the production of natural fiber products such as wood, straw and coconut because of their biodegradability, moisture-holding ability and environmental friendly image. A suitable natural fiber available for Louisiana is the sugarcane bagasse, a waste product for most of the sugarcane mills. Erosion control blankets can be produced in local sugar mills and provide an economic benefit to the transportation, construction and sugarcane industries [28].

1.2. Research Objectives

For the sugarcane mats to be introduced as a viable product on the erosion control market, a continuous manufacturing process is necessary. The aim of this study is to test several devices, and to decide on the easiest and most economical process of manufacturing erosion control mats, to provide the industry with a natural, effective and competitive product for soil erosion control. Another aim is to compare different types of mats formed by using different types of treated fibers, and to identify the most inexpensive and effective treatment for sugarcane bagasse fibers.

CHAPTER 2. LITERATURE REVIEW

2.1. Soil Erosion

Soil erosion has long-term effects on soil productivity and sustainable agriculture. It is most prevalent in tropical and semi-tropical areas, and leads to environmental damage through sedimentation, pollution and increasing flooding. Due to this process, the soil may lose 75-80% of its carbon content and reduce considerably its quality [18]. Soil erosion is a two-phase process. First, individual soil particles are detached from the soil mass and transported by erosive agents (water and wind), and second, the depositing occurs. One of the most important erosive agents is the rain splash. Exposure to intense rainstorms weakens the soil considerably. The factors that influence the rate of erosion may be considered under three classifications: energy, resistance and protection. The energy group refers to the potential ability of rainfall, runoff and wind to cause erosion. The resistance group includes the erodibility of the soil, which depends on its mechanical and chemical properties. The protection group focuses on factors relating to the plant cover. By intercepting rainfall and reducing the velocity of runoff and wind, plant cover can protect the soil from erosion [18].

2.2. Geosynthetics for Erosion Control

Erosion is a natural process that cannot be prevented, but it can be reduced considerably. Among the strategies for soil conservation are covering the soil to protect it from rain splash impact, increasing the infiltration capacity of the soil in order to reduce the runoff and improving the stability of the soil. An important role in soil conservation is played by the use of geosynthetics. Artificial geoweb and geogrids designed to give permanent protection to a slope are buried to reinforce the soil. After the vegetation cover is established, the plant roots and the fibers will act together to increase the cohesion of the soil. The most effective in controlling soil

detachment by rain impact are the mats and blankets made from natural fibers. Because they are laid on top of the soil, they provide good surface cover, high water absorption and are able to intercept the splashed particles. In contrast, buried mats of artificial fibers do not efficiently control the splash process. Even so, despite the ability of natural fibers to hold water, no significant differences in runoff productions were observed in laboratory experiments between unprotected slopes and slopes protected by natural or artificial fibers. However, erosion resulting from the runoff was significantly lowered on the slopes protected with jute mats because of the higher roughness that reduced the velocity of the runoff. Although the mats of coir, wood-chips and artificial fibers are capable of reducing soil loss, they are less effective than the jute mats because they do not adhere to the soil surface as well [18].

2.3. Erosion Control Mats and Blankets Overview

There are many types of products available for erosion control. Selection is based on several factors, such as:

- Duration required for usage (long term or short term)
- Effectiveness (by comparison with other soil stabilizers)
- Cost of purchase, installation and maintenance
- Visual impact to the public
- Biodegradability [17]

According to the Erosion Control Technology Council (ECTC), erosion control mats and blankets have been grouped into two primary categories:

1. Temporary Degradable
2. Long-term Non-degradable

The range in diversity of these products will expand as new categories are introduced on the market. Also standard methods are being developed to test their performance. Temporary Degradable erosion control products are used to improve the establishment of vegetation. These products are used in places where vegetation alone is sufficient in providing site protection after the temporary products have been degraded. These products are being manufactured into rolls, named as Rolled Erosion Control Products (RECP). In this category four types are included:

- Temporary Degradable – an RECP composed of degradable materials, that reduces soil erosion and promotes vegetation growth
- Erosion Control Net (ECN) – a natural fiber woven net or a geosynthetic mesh used either as a component in the manufacture of RECPs, or separately, as a temporary degradable RECP to secure loose fiber mulches
- Open Weave Textile (OWT) – a temporary degradable RECP composed of processed natural or polymer yarns woven into a matrix
- Erosion Control Blanket (ECB) – a temporary degradable RECP composed of natural or polymer fibers bound together, (mechanically or chemically), to form a continuous matrix

Long-term Non-degradable erosion control products composed of non-degradable materials intended to supply erosion protection, increase vegetative growth and expand the erosion control performance limits of vegetation. Included in this category are two types:

1. Long-term Non-degradable – a RECP composed of non-degradable materials.
2. Turf Reinforcement Mat (TRM) – a Long-term Non-degradable RECP that is usually buried to add stability to the soil, composed from synthetic non-degradable filaments processed

into a three dimensional matrix. TRMs provide sufficient thickness and strength to permit soil retention and development of vegetation within the matrix [17].

According to the Blue Book of Building and Construction there are 13 companies in Louisiana marketing erosion control products [4]. Among them, Industrial Fabrics, Inc., Baton Rouge, LA, is providing a large variety of erosion control blankets, turf reinforcement mats and accessories. Two of the most effective products with a high demand on the market are the “Curlex” blankets manufactured by American Excelsior Company, Arlington, TX and the straw blankets manufactured by North American Green, Evansville, IN [23]. The Curlex blanket is fabricated from elongated randomly entangled fibers, usually referred to as “wood wool” or simply “excelsior”. The fibers are held together by polypropylene that forms a net on one or both sides of the blanket. This type of netting is photodegradable. The blanket-net assemblies are then suitably packaged in individual rolls to facilitate easy handling and transportation to the erosion control site. Here, the blankets are unrolled evenly and smoothly, without stretching the material, and then anchored to the ground using wood or steel staples [1, 24].



Fig. 1 – Curlex blanket manufactured by American Excelsior Co. (scale in inches)

Despite the erosion control effectiveness of these excelsior blanket-net assemblies and the other blankets formed using a similar pattern, erosion control blankets of this general type have a distinct disadvantage. The problem relates to the use of netting material fiber containment. Even

though the netting may be photodegradable, it may last long enough to present ecological problems. The net is capable of trapping birds and other small wildlife animals in their attempt to nest or inhabit in the erosion control blankets. Until the netting material photodegrades, it does present an impediment to normal activity. It would be a great advantage to provide an alternative to the netting material. In this case, the net could be replaced with a bonding agent that would hold the fibers together such as heat, glue or some other mechanical mean [24].

2.4. Texas Transportation Institute Testing

Due to the rapid development in the erosion control mats and blankets industry a variety of laboratory tests are now available. But tests such as tensile strength and heat resistance do not effectively describe the field performance. Observations carried out in lab and field testing showed great variations regarding the soil-blanket interaction and the vegetation response amongst the same type of material, but manufactured by different companies [26]. The researchers from Texas Transportation Institute (TTI) in collaboration with Texas Department of Transportation (TX DOT) developed a fair system of evaluation for the erosion control products based upon their field performance. Between 1990 and 1992 the Hydraulics and Erosion Control Laboratory facility in College Station, TX, was established. The facility is a nine-hectare site that includes clay and sand treatment plots, reservoirs, pumping stations, rainfall simulators and diverse equipment [26]. Tests like slope protection, germination response, moisture retention, light penetration, tenting and longevity are carried out here since 1991. Due to some constraints, like budget and weather related failures, an evaluation program of the TTI testing was conducted to reduce annual expenses of the facility. A new protocol was developed, other methods of testing were proposed and a new facility was constructed. This includes two greenhouses that

allow the vegetation to grow on a year-round basis, a slope protection facility with two runoff beds and a rainfall simulator [13].

TTI is working in collaboration with different state transportation departments for product testing and methodology improvement. To be approved by TTI, a material must demonstrate the ability to develop a vegetation cover that will reduce the sediment loss considerably compared to an unprotected surface [12, 13]. For slope protection testing, treatment and control clay and sand plots are used in 1:2 and 1:3 slope conditions. At the request of the manufacturer, the product can be tested on one or both slopes, but regardless of which slope will be tested, the tests will be performed on both types of soil. The sediment loss was evaluated for three different storm intensities. Sediment retention performance and vegetative density coverage data for each product were collected and analyzed with respect to the type of soil and slope condition. But with the new protocol, the sediment loss is now being measured independently of vegetation. This way the test is providing better data to measure the ability of the product to protect the soil surface. After each simulated rainfall period, the sediment and the water are collected and stored temporarily. After 24 hours of settling, the water is discarded and the remaining sediment and water are weighted. Then ten soil samples are collected, dried and weighted in order to calculate the sediment loss [13]. For the vegetation coverage, a standard seeding mixture is selected from the TX DOT Standard Specifications for Construction of Highways, Streets and Bridges (1993). The first step in the seeding procedure is mixing the seeds with fertilizer in a water slurry and then deposit them on the test bed. The mixtures are different for the two types of soil: clay and sand. The vegetation coverage data is analyzed by a video/image capture and an interactive color analysis process. The minimum performance standards for the erosion control mats and blankets are presented in Table 1. If the manufacturer requests for the product to be tested on a severe

slope, and meets TTI testing standards, it will also be included as a successful product for a slope less severe as 1:3. But if the product is evaluated only for a moderate slope, it will not be included in the approved list of products for severe slope [22].

Table 1 – Performance standards for erosion control mats and blankets [13, 22].

Vegetation Density		
Application	Cohesive Soils (Clay)	Non-cohesive Soils (Sand)
1:2, 1:3 or flatter	80%	70%
2:1 and 3:1	50%	50%
Sediment loss		
1:3 or flatter	0.34 kg/10 m ² (0.7 lbs/100 ft ²)	12.2 kg/10 m ² (25 lbs/100 ft ²)
1:2	0.34 kg/10 m ² (0.7 lbs/100 ft ²)	26.84 kg/10 m ² (55 lbs/100 ft ²)
2:1	3.58 kg/10 m ² (7.89 lbs/100 ft ²)	286.58 kg/10 m ² (631.8lbs/100 ft ²)
3:1	3.58 kg/10 m ² (7.89 lbs/100 ft ²)	128.96 kg/10 m ² (284.3 lbs/100 ft ²)

The products that meet these specifications are included in the TX DOT Annual List of Approved Materials, and can be used in the road and highway construction industry. The products that are tested and fail to meet these criteria can be re-submitted by the manufacturers for a second evaluation. However, TX DOT has reserved the right to refine the standards based on supplementary data collected from the research program [13, 27].

2.5. Development of Sugarcane Fiber Products for Erosion Control

Sugarcane is grown in twenty four Louisiana parishes and is processed in thirteen mills. In current production processes, cane is crushed to extract the juice. *Bagasse* (Fig. 2) is the “sugar technology term for the fibrous residue of sugarcane after the application of the extraction process” [30].



Fig. 2 – Mill run bagasse, South Louisiana Sugars Cooperative, 2005 (scale in inches)

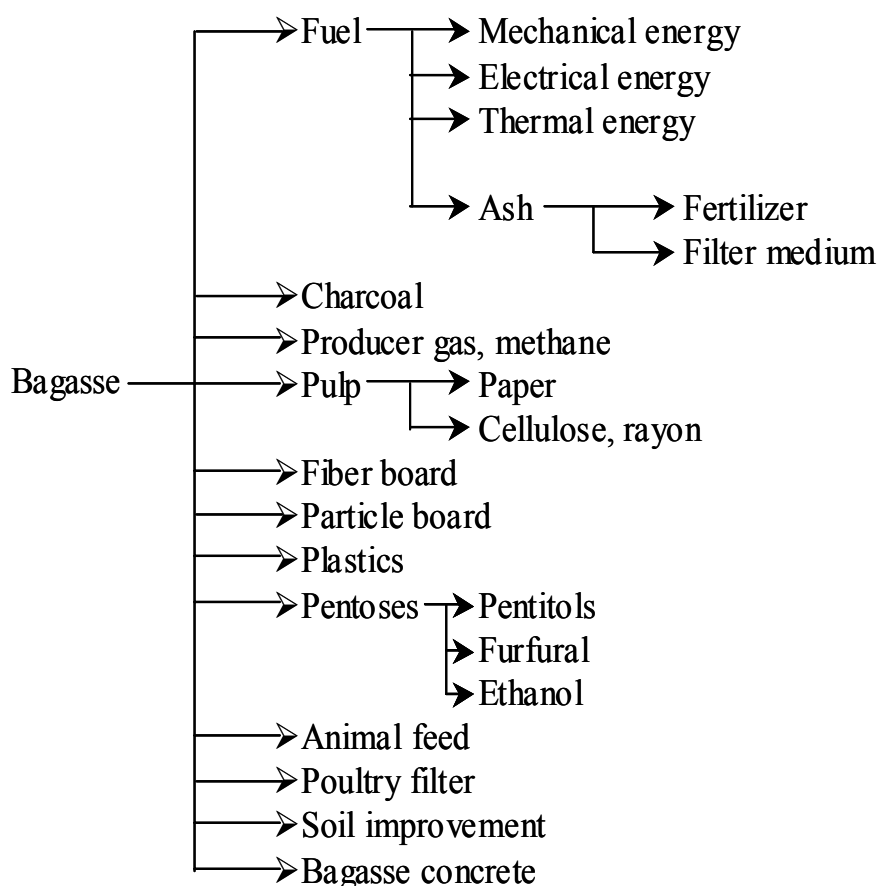


Fig. 3 – Utilization of bagasse [30]

Bagasse is an important material, suitable for many applications (Fig. 3) [30]. However, in the cane industry it is utilized as a source of energy generation by burning it in steam boilers. Where there is an efficient energy economy, a cane sugar factory produces excess bagasse [30].

This excess can be converted into valuable products, like paper and fiberboards or used as fuel or animal feed (Fig. 3). The composition of the bagasse and its characteristics vary widely:

1. water content: 45-55% (sometime higher)
2. fiber content: 53-40%
3. water soluble components: 2.5%
4. insoluble ash content: 1% up to higher value, depending on, for example, contamination of the cane by soil during harvest

The actual composition depends on various factors. These include: the sugarcane variety, soil conditions, agronomic techniques, climatic conditions as well as processing conditions [5, 30].

- **Fiber and Pith**

Bagasse fiber represents the water-insoluble material of the sugarcane. It is divided into two components with almost the same chemical composition, but with a different structure: “true fiber” and pith [30]. The true fibers are represented by the tough, hard-walled, cylindrical cells of the rind and vascular tissue. The soft, thin-walled, irregularly shaped parenchymatous cells of the inner stalks tissue represent the pith and they contain the majority of the sucrose [21, 31]. Both fibers and pith consist mainly of cellulose, pentosans and lignin (Table 2).

Table 2 – Chemical composition of bagasse [5]

Bagasse			
Characteristic	Whole	Fiber	Pith
α-Cellulose (%)	30-39	38-43	26-36
Pentosans (%)	24-30	27-32	28-33
Lignin (%)	1-22	20-23	18-22

Pentosans and lignin represent the encrusting materials that bound pith and fibers together in bundles [5].

- **Bagasse Handling and Storage**

Depending on the process plan of the factory and the fiber content of the sugarcane, surplus bagasse should be understood as the bagasse that exceeds the required mass for energy production used in cane processing. This surplus should not be confused with the temporary surplus which is stored for a short term to fill temporary gaps in bagasse production due to interruptions of cane supply or extraction plant stoppages. Surplus bagasse may be stored dry or wet, in bulk or baled, either as whole bagasse or depithed [30].

- **Bagasse Depithing**

Depithing is the operation of separating the fibrous portion of bagasse (the rind) from the non-fibrous portion (the pith). Usually bagasse has to be entirely depithed to improve pulping and pulp quality for uses in paper and paperboard production. About 30% of the whole bagasse is represented by pith [5, 16]. There are three methods for depithing:

1. Dry depithing
2. Moist depithing
3. Wet depithing

For the dry depithing the pith is removed by screening the bagasse. It is a simple and inexpensive method, but dry bagasse creates a lot of dust, which is injurious to humans when inhaled. Moist depithing is more suitable at the sugar factories. The bagasse that comes out of the milling plant has a moisture of about 50% and can be immediately sent to the depithing equipment. In wet depithing, bagasse is mixed with water in a vessel provided with a powerful agitator, to help remove the pith from the fibers. Wet depithing gives clear fibers deprived more or less of the entire pith, but this method requires large quantities of water [16].

- **The Benefits of Depithing**

Pith has undesirable properties especially in its low fiber length, which reduces the strength of the paper. Also because pith has high absorption properties any attempt in the chemical treatment of bagasse will result in high consumption of chemicals. If separated, pith can be used for burning fuel or animal feed, leaving the fibers to be used in paper and fiberboard manufacturing. The depithing process is reducing the weight of the bagasse therefore reducing the cost for the transportation [5, 16].

- **Delignification Process**

The amount of lignin that naturally occurs in sugarcane depends on the variety and age of the cane. The amount of sugars, lignin and lignin-like compounds increases as the plant advances in age. The result is a hardening of the fibers up to the time of tasseling, when the plant is considered fully mature. After the flowering stage, the sugarcane plant is predisposed to consume its stock of sucrose and lignin as a result of the physiological changes due to flowering. Because of the consumption of the organic compounds, the rind and thus the fiber bundles become softer and elastic [10].

Research at Louisiana State University (LSU) has been conducted to determine the feasibility of sugar cane fibers for textile and erosion control applications [9, 28]. The main interest of that work was in the rind fibers. The extraction of these fibers involved controlled removal of the encrusting materials, mainly lignin. In an earlier research study, sugarcane rind was subjected to delignification using sodium hydroxide (NaOH) and pressure. The amount of lignin removed from the vascular fiber bundles depended in generally on the severity of the extraction conditions. The highest alkaline concentration, at 1 atmosphere pressure, removed the

highest lignin quantity and for the atmospheric extraction, the longest treatment time had the same effect on lignin. Also the most severe conditions yielded the finest fiber bundles [7, 8].

In 1993, Louisiana Transportation Research Center (LTRC) and Louisiana Department of Transportation and Development (LA DOTD) funded a study to compare the erosion control properties of the following currently available natural fibers: wood (Curlex blanket, American Excelsior Company, TX), coconut and straw blankets (North American Green, IN) and a sugarcane product on a trial stage. Dr. John Collier, professor at Louisiana State University conducted the study (July 1st, 1993 – December 31st, 1995) [9]. Prior research involved the production and laboratory testing of sugarcane fiber mat. The rind portion of the sugarcane cane stalk was stripped from cane billets with a cane separator [8], and then treated with sodium hydroxide liquor under pressure and steam explosion. This process yielded fiber bundles appropriate for non-woven blanket formation. The chemically treated fiber bundles were then washed to remove excess sodium hydroxide and liberated lignin. The bundles were then suspended in water, deposited on a screen, de-watered and dried. The mat was produced in a piece of one square yard, because at that time a process for a continuous production was not yet available. The sugarcane fiber product was an entanglement of fibers with lignin content acting as a natural adhesive. The other natural products had polypropylene nets and stitches from even cotton or polyester. A variety of laboratory tests were conducted to describe product properties such as: weight, thickness, strength, water permittivity, water resistance, biodegradability, light penetration and flammability (Table 3). American Society for Testing and Materials (ASTM) and American Association of Textile Chemists and Colorists (AATCC) test methods were used to compare physical, mechanical and environmental properties among the different products [9].

Table 3 – Properties of natural fiber erosion control products [9]

Property; Test Method	Sugarcane (mean)	Wood (mean)	Coconut (mean)	Straw (mean)
Weight (g/m²) ASTM D 3776	416	487	247	209
Thickness (mm) ASTM D 1777	3.5	6.0	2.3	2.5
Strength (N) ASTM D 1682	9	43 (net)	109 (nets)	32 (net)
Water permittivity (s⁻¹) ASTM 4491	0.04	0.1	0.1	0.1
Water resistance (%) ASTM 42-1989	98	115	106	127
Biodegradability retained tensile strength (%) AATCC 30-1988	28	82 (net)	58 (nets)	96 (net)
Light penetration (%) Digital drape tester	37	63	50	58
Flammability (sec) ASTM D 1230	31	23	19	22

A commercial wood fiber blanket was used as a benchmark for evaluations because it was assumed that it possessed minimum product specification requirements for soil erosion control [9]. Sugar cane mat had a higher biodegradability rate, was intermediate in thickness and had a lower strength, light transmission and water penetration compared to the other products. In flammability tests, the sugarcane fiber mats burned more slowly than the commercial products and 70% of the specimen self-extinguished prior to burning the entire blanket length [9, 28]. Based on satisfactory laboratory results, a field test was designed to determine product performance in a natural environment. The test site was located in Baton Rouge, Louisiana, on Interstate 12 at Millerville Road. The field study was conducted between May-September 1995. A total of approximately 400 square yards of sugarcane, Excelsior wood, straw and coconut fiber

mats were tested. The sugarcane mat demonstrated comparable grass propagation and slope protection with the other products. The coconut mats shrank after the first rain, while even without stitching, the sugarcane mat maintained its integrity during heavy rains. However, because of their high opacity, both products had lower germination rates than straw and wood products.

The overall test performance was deemed to be in compliance with regulations required on Louisiana Department of Transportation and Development (LA DOTD) projects [9, 28].

CHAPTER 3. MATERIALS AND METHODS

3.1. Materials

- **Bagasse Preparation and Treatment**

Raw mill-run bagasse was obtained from Cinclare Sugar Mill, Brusly, LA, during two seasons: 2004 and 2005. The main treatment for the fibers was boiling with water and sodium carbonate for ninety minutes. Sodium carbonate in water dissociates according to Equations 1 and 2, providing alkaline medium during this treatment. This process frees the cellulose fibers by solubilizing most of the lignin and hemicellulose. Attempts to form mats from bagasse without any prior chemical treatment failed as the fibers were found to be too coarse, stiff and without cohesion once the mat was formed. Sodium carbonate (soda ash) was preferred to sodium hydroxide, because of its lower cost and less severe occupational hazard to human health. In a laboratory experiment, the solubility of pure lignin (Granit SA) in 1% sodium carbonate liquor was determined to be about 8.5 g/l. To decide which concentration of the Na_2CO_3 is more effective for the treatment, three experiments were conducted to compare different concentrations: 1%, 2.5% and 5% weight by volume (w/v). Also four different intervals were chosen: 25, 45, 60 and 90 minutes (Table 4). The final decision was for 90 minutes with concentration 2.5% because the treatment with this concentration of Na_2CO_3 had the highest average weight loss. Additionally, several other treatments were experimented: boiling the fibers with a lower concentration of soda ash and soaking the fibers with water and lime (CaCO_3). All those trials had a purpose in finding the most economical and efficient treatment for bagasse.

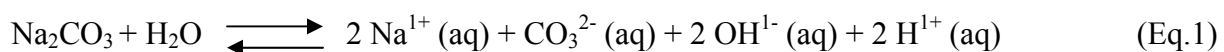


Table 4 – Bagasse samples treated with sodium carbonate at different concentrations

Sample No.	Soda Ash Conc. (%)	Time (minutes)	Sample Weight (g)		Weight Loss %DM Basis	Average
			Before Treatment	After Treatment		
1.	1%	20	3.1	2.58	17	20
2.	1%	45	3.1	2.47	20	
3.	1%	60	3.0	2.37	21	
4.	1%	90	3.1	2.42	22	
5.	2.5%	20	3.1	2.35	24	27
6.	2.5%	45	3.0	2.24	25	
7.	2.5%	60	3.1	2.22	28	
8.	2.5%	90	3.0	2.11	29	
9.	5%	20	3.5	2.89	17	16
10.	5%	45	3.3	2.49	24	
11.	5%	60	3.0	2.74	9	
12.	5%	90	3.5	3.05	13	

3.2. Experimental Methods

Five experiments were carried out at Audubon Sugar Institute (ASI), each of them representing the next step in the improvement of a continuous process for mat formation and fiber treatment.

3.2.1. The First Design

For the chemical treatment of the bagasse, a horizontal reactor heated with steam was used. The bagasse was boiled with water and sodium carbonate ($c = 2.5 \%$, w/ v). The reactor had an internal auger that rotated to assure good mixing of the bagasse with the water and the chemical. After boiling, the bagasse was ground using a grinder (Bauer Bros. Co. Springfield, OH), washed with water to remove the excess soda ash and liberated lignin, and stored into a tank. In the first experiment, a 0.3 m x 0.3 m rotary vacuum filter was used (Fig. 4). The vacuum filter was composed of a hollow drum rotating about a horizontal axis connected by two valves to a separation vessel under vacuum.

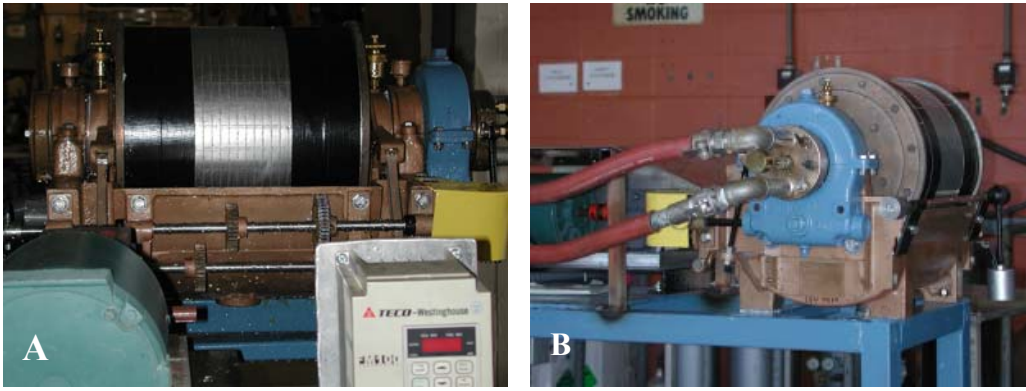


Fig. 4 – The vacuum filter (A – front view, the rotary drum; B – side view, the two valves)

The drum had attached a tank. The tank was connected with a peristaltic pump and the pump was connected with a second tank filled with water and fibers. The purpose of the pump was to assure a continuous feed of the vacuum filter. An agitator was used to mix the fibers and the water. As the water accumulated in the pressurized vessel, the cake built up, and then was collected with the help of a scraper. To test the vacuum filter, white cellulosic fibers (200 microns) from CreaFill Fibers Corp., Chestertown, MD, were used. The mats were formed more uniformly and continuously (Fig. 5A). Because bagasse has a heterogeneous composition and some of the bundles were relatively too heavy to be picked up by the vacuum, the result was a discontinuous mat of variable thickness. To obtain finer fibers, the bagasse was blended for one to two minutes. However, the blending process did not improve the mat formation (Fig.5B).

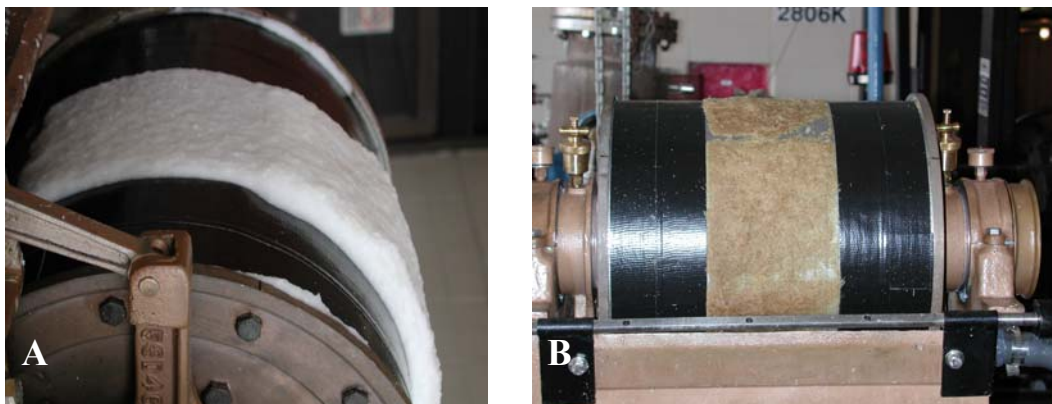


Fig. 5 – First design of mat formation (A – the cellululosic fiber mat; B – the bagasse mat)

The first experiment pointed out the need for depithing, because the pith made the mat too compact, like cardboard, and so impossible to use.

3.2.2. The Second Design

In the second experiment, the vacuum filter was transformed into a conveyor with the rotary drum serving as one of the two rollers. The conveyor belt was a vinyl coated polyester fabric with 1.5 mm mesh size, purchased from American Home & Habitat Inc., Squires, MO. Half of the belt was submerged into an aluminum tank containing water and fibers (Fig. 6A). As the belt rotated the mat was formed (Fig. 6B).

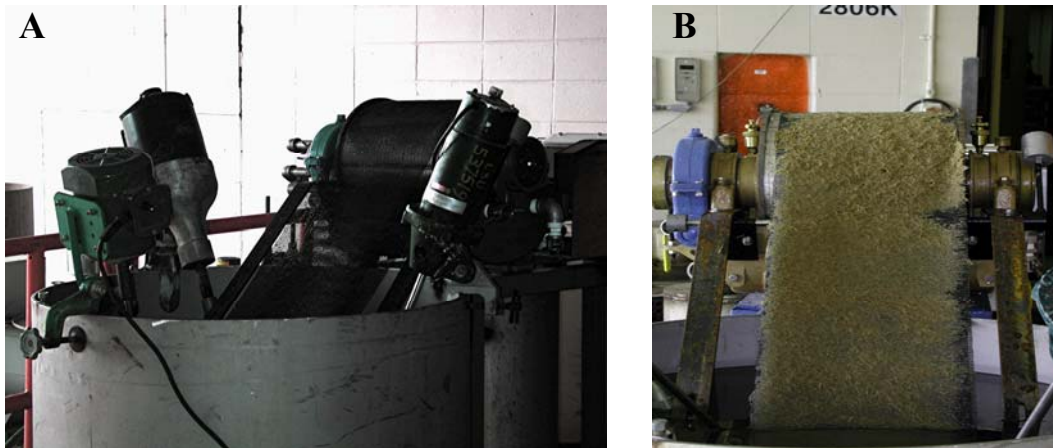


Fig. 6 – The second design (A – the belt submerged into the tank; B – mat formation)

Three mixers along with a bubbling air pipe were used to increase the mixing in the tank. Treated bagasse from the first trial was used, but this time the bagasse was subjected to wet depithing. To accomplish this, a small depither was built (Fig. 7). The main component of the depither was a perforated cylinder (with mesh size 3 mm) connected at the bottom with a peristaltic pump. The cylinder was fed with bagasse at the top and water was pumped through the bottom to wash the bagasse and remove the pith. Using this type of depither, the removal of pith from the total amount of bagasse tested was found to be 30%. After depithing, the fibers were also blended

and then added into the tank. The major inconvenience for this device was the fact that the fibers were accumulating inside the belt, making it difficult to spin (Fig. 8). Also, due to the high water content, the mat could not be detached from the belt without breaking it.



Fig. 7 – The wet cylindrical depither



Fig. 8 – Problems in the second design (the bagasse fibers trapped inside the belt)

3.2.3. The Third Design

In the next experiment the same conveyor was used, with some modifications to the process. This time a nozzle was used to deposit the fibers directly onto the belt. The tank from the previous design was removed, and a stainless steel nozzle was welded to the front part of the conveyor (Fig. 9A). The same type of fibers was used: treated with sodium carbonate, wet depithed and blended to reduce the size and make them softer.

To place the fibers on the belt two methods were used. First, the nozzle was connected with a peristaltic pump to help deliver the fibers onto the belt. Because the water flow was not constant due to the pump design, the mat was not forming uniformly (Fig. 9B). As an alternative to this experiment, the nozzle was connected to an elevated tank using a plastic hose. Gravity helped deposit the fibers at a constant pressure and flow. The peristaltic pump was used to assure a continuous process by recycling the water.



Fig. 9 – The third design (A – the nozzle; B – mat formation)

This change yielded some improvements to the uniformity of the mat (Fig. 10). However, this design had the most inconveniences. The fibers were getting stuck inside the hose that connected the nozzle to the tank, and stopping the flow, so the uniformity was again altered. Also, due to the high water content, the mat could not be easily scraped off the belt. One option to solve this problem was to mount a third roller on top of the drum to press the incoming mat, but this was insufficient to remove the water surplus, resulting in mat breakage. The first three designs described above had too many construction inconveniences that were affecting the mat formation.



Fig. 10 – Gravity helped for mat formation in the third design

3.2.4 The Fourth Design

A fourth design was built at ASI using a different approach of spreading the fibers directly onto the belt. The same conveyor with a third roller mounted on top of the drum was kept, but this time the fibers and the water were mixed in a rectangular aluminum tank (0.6 x 0.5 x 0.5 m). The tank was cut at the top of one side and a tray was attached (Fig. 11). The tray was laid directly on the belt. The tank was connected at the bottom with a water hose.

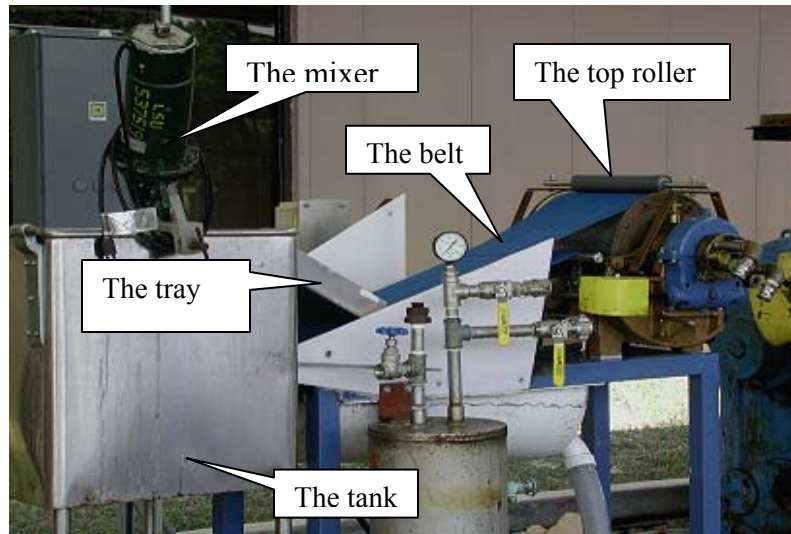


Fig. 11 – The fourth design, with the main components

As the level of water started rising, the flow was directed toward the opening and water along with fibers were discharged onto the plastic belt. This process proved to be continuous and required less maintenance. The same problem was encountered again after the mat was formed. It could not be scraped out of the belt because of the high water content. To improve this, a plastic support from the same material as the belt, was used in the process. The mat was formed and detached along with the supporting net (Fig. 12). It was let dry for a few hours, and scraped and rolled. All the bagasse used to test this design was previously dry depithed using a home-made shaker (mesh size = 0.4 mm) and treated with 2.5% Na_2CO_3 .



Fig. 12 – Mat detachment using a supporting plastic net

The dry depithing was easier to accomplish because it didn't require the use of water, and the time for depithing was considerably shorter. But sugarcane bagasse fibers do not have enough cohesion even after treatment, to allow the mat to be rolled. The mat was very brittle and could not be handled without breaking it. To improve the cohesion of the mat, the fibers were modified using the same blender as in the third design (Fig. 9). This action was splitting the big bundles and at the same time releasing the rest of the pith trapped among the fibers. The mats formed using these mechanically modified fibers were tested in a small experimental plot to observe their performance on grass penetration. The results were not satisfactory. Instead of growing through, the grass lifted the mat due to its light weight, and then died two weeks later from lack of sunlight.

A decision was made to combine the modified fibers with the original ones (3:1 ratio, original to modified fibers). We obtained 0.3 m x 2.4 m mats with good cohesion that were also tested for grass penetration in a second experimental plot. The results will be discussed in detail in Chapter 4, Testing Methods. As it was observed, almost all of the pith from the mixture was

lying at the bottom of the mat. The presence of the pith made the mats easy to detach from the supporting plastic net (Fig. 13).



Fig. 13 – Rolled sugarcane bagasse mat samples (scale in inches)

The alkali treatment was necessary for the bagasse fibers to increase their flexibility. The mechanical modification to the fibers contributed to the cohesion thus allows the mats to be rolled. Different treatments were tested to see if the chemical treatment could replace the mechanical action entirely, so only dry depithed bagasse was used with no other modification of the fibers. In the first trial, the water from the tank was replaced with lignin liquor obtained after boiling. Normally this liquor is discharged, but it was decided to recycle it to see if this would improve the cohesion of the fibers due to the presence of lignin, which acts as a natural adhesive. Unfortunately, the liquor added in the process made the mats too stiff to be rolled. In the second trial, the boiling step was eliminated, and the fibers were soaked with water and lime ($c = 0.4\%$ w/v) for three days. In the third trial, the fibers were boiled for one and a half hour using the same lime concentration 0.4% , and Na_2CO_3 0.4% was also added. The mats made with both types of treated fibers lacked cohesion therefore could not be rolled. The low concentration of sodium carbonate used in boiling and the lack of blended fibers from the mixture made the mats very brittle.

The process of boiling the fibers with 2.5% Na₂CO₃ was obviously necessary to soften the fibers and additional modification to the fibers was proven to be necessary to achieve good cohesion of the mats. The different treatments applied and the characterization of the bagasse mats produced are summarized in Table 5.

Table 5 – The four types of chemical treatments, and mat characterization

Treatment	Time	Composition	Mechanical Modification	Design	Characterization of the Bagasse Mats
1. Boiled with water and sodium carbonate; c = 2.5% (w/v)	90 min	With pith	Grinded and blended	No. 1	The presence of the pith made the mats too compact and too stiff, like a piece of cardboard.
		Wet depithed	Blended	No. 2 No. 3	The mats were still too compact due to the liberated lignin, but with a better cohesion.
		Dry depithed	Original	No. 4	The mats lacked cohesion and were very brittle and difficult to handle.
			Blended		Good cohesion, but due to its light weight the grass lifted the mat.
			Blended plus original		Mats produced had a very good cohesion and could be rolled easily.
			Original plus the liquid from the boiling		The liquid from the boiling process was kept, and then added back into the process, resulting in mats too stiff to be rolled.
		2. Soaked with water and lime; c = 0.4% (w/v)	3 days	Dry depithed	Original

(Table 5 continued)

3. Boiled with water, sodium carbonate and lime c = 0.4% (w/v)	90 min	Dry depithed	Original	No. 4	Adding sodium carbonate, only 0.4% did not improve the flexibility of the fibers. The mats lacked in cohesion and were very brittle.
4. Boiled with sodium carbonate c = 1% (w/v)	90 min	Dry depithed	Grinded plus original	No. 5	The combination of these two kinds of fibers yielded mats with a very good strength and cohesion.

3.2.5. The Fifth Design

A continuous manufacturing process of the bagasse mats was achieved in the fourth design. However, the dimensions of the product were limited, especially in the width that could not be more than 0.3 m. The scaled-up design constructed at ASI was able to produce 1.2 m wide mats with variable length, from 1.8 m to 3 m long. A schematic with the main components and dimensions of the mat formation prototype machine is shown in Fig. 14. The supporting frame that was built for the device held a 1.5 m conveyor, a rectangular aluminum tank (1) and two PVC rollers (2), that helped remove the excess water from the mat. A second tank (3) located beneath the conveyor, was used to collect and discharge the excess water (4). However, this water could be recycled back into the process. The conveyor was constructed with two rollers of different diameters welded onto the frame. The bigger roller (5-vulcanized rubber roller) was connected with a motor (6) to ensure the spinning of the belt (7). A second frame (8) was mounted perpendicular on the supporting frame, 0.3 m distance from the first smaller roller (9). This allowed the installation of the two PVC rollers that pressed the incoming mat to decrease the water content (Fig. 15).

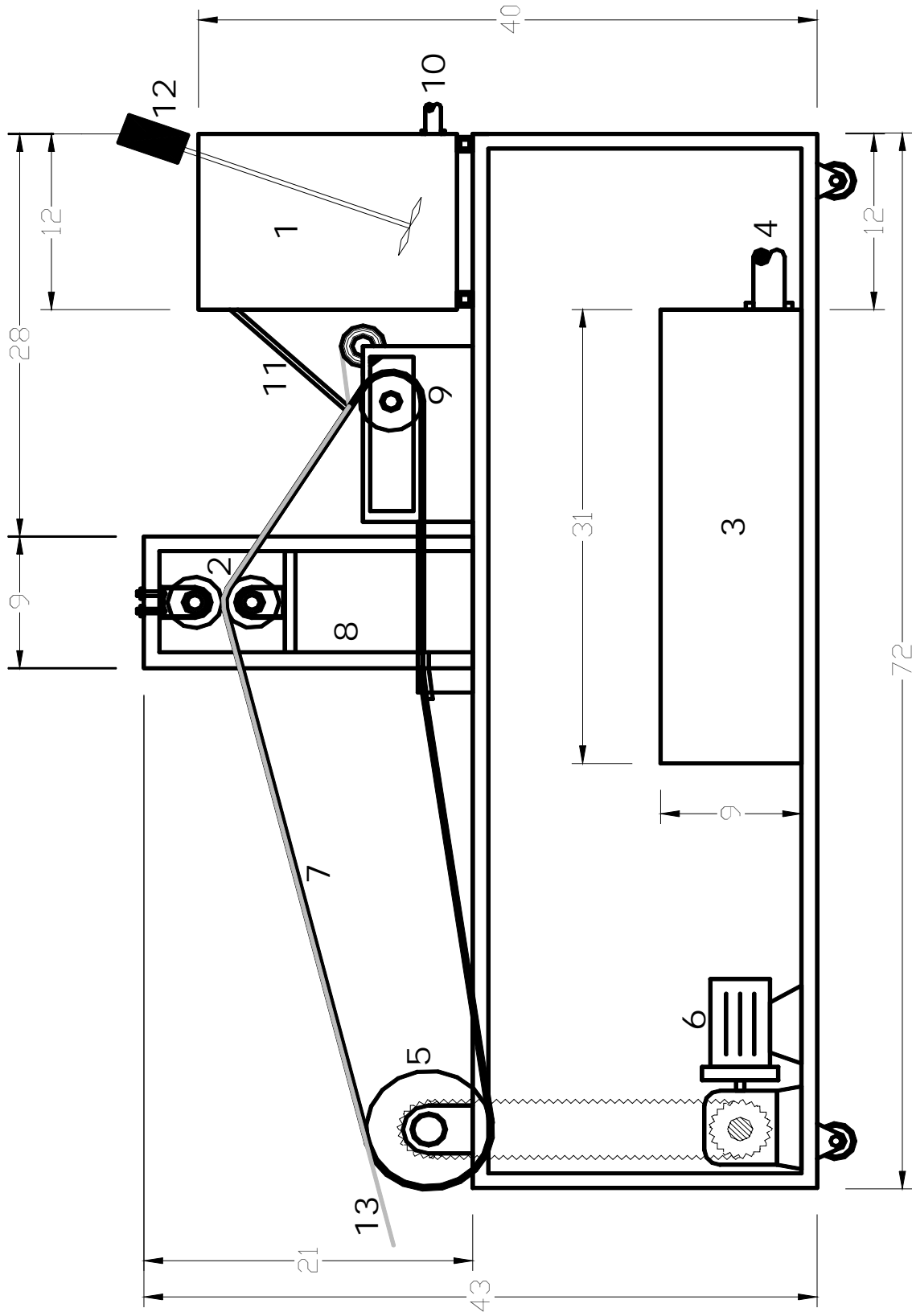


Fig. 14 – Schematic of the main components of the mat formation prototype machine

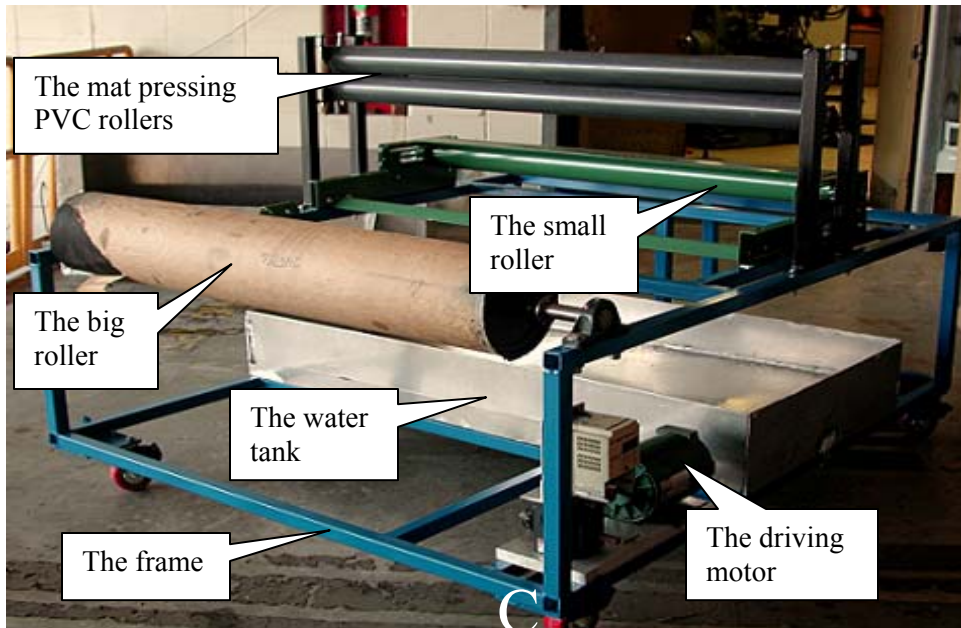


Fig. 15 – Mat formation prototype machine construction

The tank was connected with two hoses for the water supply (no.10 in Fig. 14). The aluminum tank (1.2 x 0.6 x 0.3 m) was cut on one side and a tray (no.11 in Fig. 14) was attached to allow the fibers to be discharged onto the belt. Four mixers (no.12 in Fig. 14) were mounted on top of the tank to promote good mixing of water and fibers. The fibers were added manually into the tank. The flow of the water and the speed of the belt were adjusted it time to obtain a uniform mat. A Sun-Mite infrared heater, Fostoria, OH, was used to dry the mats. The heater was placed on top of the belt to help remove the water surplus (Fig. 16).



Fig. 16 – The infrared heater placed above the belt

With this design, mats of 1.2 m width and 2.4 m length were produced. Because the heater action was not enough to dry the mats, they were detached from the conveyor using the same method as in the previous design. A supporting net (no.13 in Fig. 14) was rolled and placed beneath the tray on top of the belt. The mat was formed directly on the net and then pulled out and let dry (Fig.17).



Fig. 17 – The scaled-up design of mat formation

The operating parameters of the device are summarized in Table 6.

Table 6 – Operating parameters for the mat formation prototype machine

Parameter	Value
Tank volume	170 l
Belt length	3 m
Water flow	100 – 200 l/min
Time to form one 2.5 m long mat	~12 min
Belt speed	0.24 – 0.6 m/min
Mixers speed	400 rpm

Because the device demonstrated good performance, it was decided to eliminate any additional step in fiber modification with the exception of the alkali treatment. This was to see the effects on the mat quality. The sodium carbonate concentration was lowered from 2.5% to 1% to make the process as economical as possible. Whole bagasse was boiled in a kettle with soda ash for one and a half hour. Before placing it into the tank, the treated bagasse was run through a small

test sugar mill (Farrel Company, Ansonia, CT) to remove the excess liquid. The mats produced from the whole bagasse proved to have enough cohesion for rolling (Fig. 18), but very brittle, thus could not be handled without breaking them.



Fig. 18 – Partially rolled bagasse mats

To increase the strength it was decided that a mechanical modification to the fibers after the alkali treatment was mandatory. A 0.0005 m plate gap, 0.2 m diameter Bauer Bross single refiner was used. A single pass through the refiner resulted in the splitting of the big bundles and the releasing of the pith trapped amongst the fibers. The partially refined fibers were then re-mixed with the un-refined bagasse, and then used to form the mat (Fig.19). The parameters of the process are listed in Table 7.

Table 7 – Batch conditions for bagasse fiber preparation

Parameter	Value
Water	200 l
Na₂CO₃	2 kg
Raw bagasse for treatment	15 Kg
Time for treatment	90 min
Temperature	100 °C

The mats containing the refined fibers showed indeed an increased cohesion and strength, enough to be rolled and easily transported (Fig. 20).

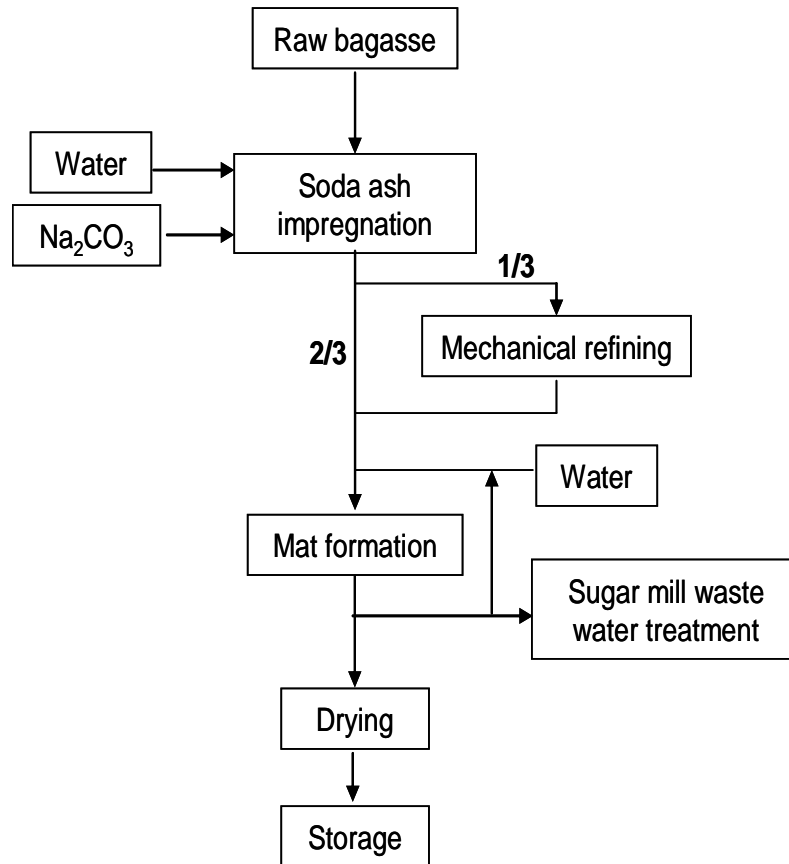


Fig. 19 – Block diagram for the manufacturing process



Fig. 20 – Rolled bagasse mats

To prepare the product to be officially tested at TTI, twenty mats 1.2 m x1.8 m were manufactured at ASI. For better storage and handling, it was decided not to roll them, but to keep them flat, one on top of another, to form a stack (Fig. 21). This way it would also be easier to transport and install them at the testing site.



Fig. 21 – Sugarcane bagasse mat storage

CHAPTER 4. TESTING METHODS

4.1. Physical Properties

The bagasse mats were tested for thickness, weight, strength, water absorption and smolder resistance according to the American Society for Testing and Materials (ASTM) methods, and following the guidelines of the Erosion Control Technology Council (ECTC) specified in Table 9. The specifications were compared (Tables 8 and 9) with those reported by the manufactures of four comparable commercial products.

Table 8 – Characteristics of the four commercial erosion mats (used for comparison with the bagasse product)

Product	Description	Manufacturer
S 150	Straw, double PP net	North American Green
C 125	Coconut, PP net	North American Green
Curlex I	Curled wood fibers, double PP net	American Excelsior Co.
Curlex-heavy duty	Curled wood fibers, double heavy duty PP net	American Excelsior Co.

Table 9 – Commercial erosion mats - product data sheet

Property	S150 ¹	C125 ¹	Curlex I ²	Curlex Heavy Duty ²	Bagasse Mats	Test Method
Thickness (mm)	8.13 ¹	8.91 ¹	9.14 ²	13.72 ²	7.5 – 10 ³	ASTM D 6525
Mass per unit area(g/m²)	257 ¹	271 ¹	407 ²	841 ²	550 – 850 ³	ASTM D 6475
Water absorption (%)	327 ¹	110 ¹	253 ²	194 ²	807 – 1090 ³	ECTC/ ASTM D 1117
Swell (%)	15 ¹	13 ¹	49 ²	48 ²	14 – 36 ³	ECTC procedure
Smolder resistance	YES ¹	YES ¹	NO ³	NO ³	NO ³	ECTC procedure
Tensile strength (kN/m)	2.27 ¹	3.12 ¹	1.4 ²	3.36 ²	0.10 ^{3*} 0.18 ^{3**}	ASTM D 5035

¹ - Product data sheet [19], ² - Product data sheet [1], ³ - Measured in this work

*- Samples orientated with most fibers perpendicular to the load direction

** - Samples orientated with most fibers parallel to the load direction

The thickness and the specific weight of the bagasse mats were comparable with those of the commercial products available. The swelling percentage of the bagasse mat was about the same as for the straw and coconut mats, and less than the wood product. The bagasse mat had relatively low smolder resistance. Unlike the straw and coconut mats that have wide spaces between fibers, the bagasse mat is very compact; the smoldering ring had a maximum of 102 mm compared with 15 mm for the Curlex products. The higher value of the tensile strength for the commercial products comes from the polypropylene (PP) net (single-sided or double-sided) embedded in the product. The tensile strength of the PP net alone isolated from a S150 sample was 0.18 kN/m or 80% of the reported value [19]. In the case of the bagasse mats, the strength was solely from fiber entanglement and adhesion. Because of how the wet-laid process was designed to form the bagasse mats, the fibers were oriented mostly perpendicular to the direction of belt movement, and the tensile strength was somewhat higher along the preferred orientation of the fibers. The PP net that holds the fibers together is described by the manufacturers as photodegradable, but it still can last long enough to present ecological problems. There have been reports of birds and other small wildlife animals trapped in the net in their attempt to nest in the erosion control blankets [24]. Obviously, PP nets could also be embedded in bagasse mats for higher strength, but their absence in the present process is considered to be an ecological advantage.

4.2. The First Experimental Plot

A small experimental plot was set up at ASI in order to test the grass penetration capability of the bagasse mats. Due to the lack of cohesion presented by the mats made using only original bagasse fibers, additional mechanical modification of the fibers was necessary. The blending action that was applied improved the mats cohesion considerably, by splitting the fibers and

releasing the rest of the pith trapped in between. A comparison of the two types of mats is illustrated in Figure 22.



Fig. 22 – Mat comparison (on the left: original fibers, on the right: blended fibers)
(scale in inches)

Both types of mats were manufactured using the fourth design. Due to the properties of the blended fibers that yielded a mat with better cohesion, this type of mat was chosen to be tested for grass penetration. The experimental plot (1.8 m x 0.6 m) was seeded with carpet grass and then covered with bagasse mats with a thickness of 3 mm (Fig. 23A). A small area (0.5 m x 0.3 m) was left uncovered and used as a control. The plot was watered twice a day for two weeks. At the end of this period a layer of 2.5 cm of grass was observed beneath the mats. Because the mats were very thin and had a light weight ($0.02 \text{ kg} / 0.09 \text{ m}^2$), instead of penetrating and growing through them, the grass lifted the mats (Fig. 23B). The good moisture retention provided by the mats enabled the grass to grow for two weeks. However, after three weeks the grass started to die due to the lack of sunlight. The process of blending the fibers had repercussions on the quality of the mats. The pith that was released acted as a strong binder and provided the mats with good cohesion, but at the same time made them too dense and compact for grass penetration (Fig. 23C). This experiment not only established the necessity for a mat composition improvement,

but also showed that bagasse mats can be characterized by good moisture retention which is a very important factor for seed germination.

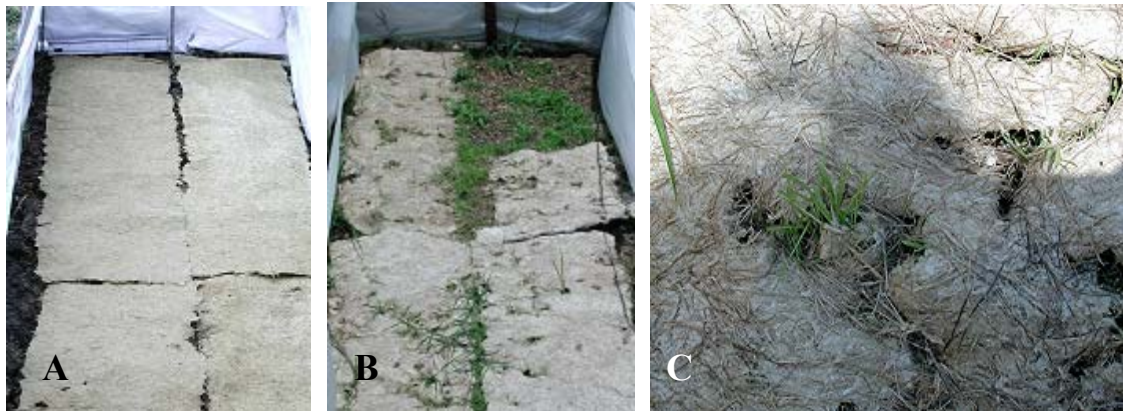


Fig. 23 – The first experimental plot (A – the first day after seeding; B – two weeks after seeding; C – detail of the mat).

4.3. The Second Experimental Plot

In the second experiment, two boxes with soil (0.45 m x 0.45 m) were seeded with carpet grass (Fig. 24). The first box was covered with a double-straw commercial blanket, S150 (North American Green, Evansville, IN) of 8 mm in thickness [18]. To eliminate the main inconvenience encountered in the first experiment, a mixture with blended and original fibers was prepared this time (3:1 ratio, original to blended fibers).



Fig. 24 – The second experimental plot comparison (A – the first day; B – after two weeks)

A mat of 7 mm in thickness was formed using the fourth design and the second box was covered with it. A small area (0.1 m x 0.1 m) was left uncovered and used as a control. The boxes were watered once a day for two weeks. It was observed that the grass grew in both boxes, but faster in the box covered with bagasse mat, even though the difference in thickness between the two mats was not significant (Fig. 24).

The two field experiments carried out at ASI demonstrated that bagasse mats are appropriate for good moisture retention and grass germination, two of the most important considerations in soil erosion control.

CHAPTER 5. FIBER CHARACTERIZATION

5.1. Origin and Storage

The bagasse used to test the scaled-up design was from 2005-2006 crop, and was brought from a Louisiana local sugar mill (Brusly, LA). The 600 pounds of bagasse had a moisture of 40%, and was stored outside in a trailer, uncovered to prevent rotting.

5.2. Macroscopic and Microscopic Characterization

The process of crushing cane in the mills causes the cane to break into small pieces. As a result, the bagasse has a heterogeneous composition from the very fine pith (0.6 mm), (Fig. 25) too short and long fiber bundles (1 cm – 9 cm), (Fig. 26).



Fig. 25 – Bagasse pith, macroscopic view (scale in inches)



Fig. 26 – Bagasse bundles, macroscopic view (scale in inches)

The pith is represented by the irregularly shaped and thin-walled parenchymatous cells of the inner stalk tissue, with a length of 0.1 mm – 0.3 mm (Fig. 27). The true fibers are represented by the hard-walled sclerenchyma cells of the rind, with a cylindrical shape and a length of 1.5 mm [21, 30]] (Fig. 28). Both types of cells are packed into vascular bundles, bound together by encrusting materials made up of mostly hemicellulose and lignin.



Fig. 27 – Pith cells viewed with SEM (scale 100 μ m)

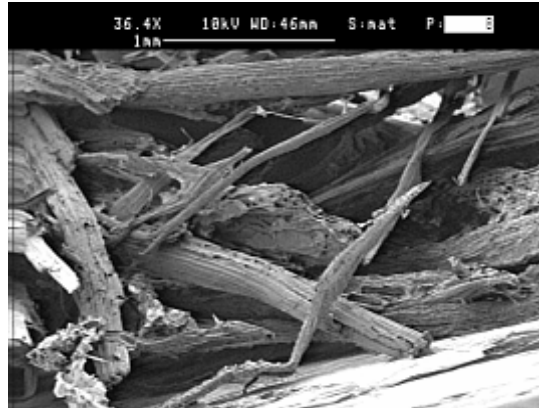


Fig. 28 – Vascular bundles of rind cells viewed with SEM (scale 1 mm)

The sample presented in Figures 27 and 28 was kept in a dessicator for twenty four hours, then cut in 1 cm x 1 cm and mounted on a circular plate. The specimen was then uniformly coated with gold in preparation for observation under the scanning electron microscope (SEM) [15].

The presence of lignin (18-20 %) in the bagasse [6] results in hardening the fibers, so lignin removal is an important step to yield soft and coarse fibers suitable for mat formation. Boiling the bagasse with sodium carbonate helps remove the hemicellulose and part of the lignin, thus making the fibers more flexible. Only some of the bundles are split in this process. To break the rest of the chunks, an additional mechanical treatment has to be applied. The presence of the bundles is a result of the shredding procedure therefore the additional mechanical treatment could be eliminated depending on the bagasse consistency as it leaves the mill. Figure 29 shows a comparison of the bagasse from a local sugar mill with two other types of bagasse from Texas and Florida.

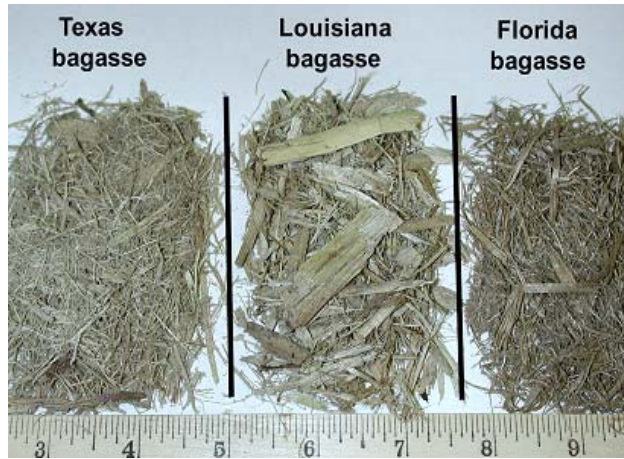


Fig. 29 – Comparison of three different types of shredded bagasse

Even though the samples may not be representative for all the mills, it is obvious that a shredding process that will yield a finer bagasse will help in eliminating any additional mechanical steps in fiber preparation, leaving only the chemical treatment.

During the mat formation, a separation process takes place between the pith and the large fibers. The mats tend to have a double-layer structure (Fig. 30), where most of the pith can be found at the bottom of the mats, while the larger fibers are on top. The pith contributes to the strength and the good cohesion of the mats and at the same time, allows an easy detachment of the mats from the supporting screen.

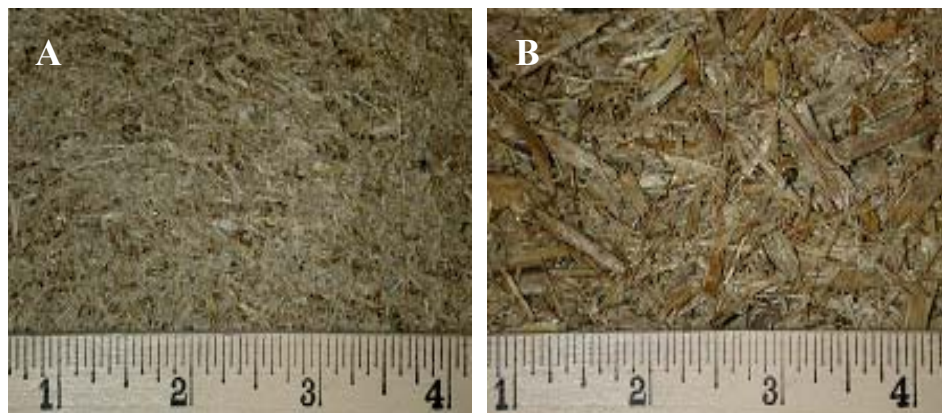


Fig. 30 – The double-layer structure of the mat (A – the bottom side with most of the pith; B – the top side composed mostly of coarse fibers) (scale in inches)

5.3. Thermo-Gravimetric Analysis

Thermo-gravimetric analysis (TGA) is a technique used to measure changes in the weight (mass), thermal decomposition and thermal stability of composite materials as a function of temperature and time [6]. Sugarcane raw bagasse contains on a dry basis about 32% - 48% cellulose, 27% - 32% hemicellulose and 18% - 26% lignin. Because the thermal behavior of such lignocellulosic materials is directly related to their chemical composition, this can be used to evaluate the content of bagasse fibers under different digestion conditions. The three main components of bagasse exhibit different thermal behaviors in terms of initial decomposition temperature, decomposition rate and residual weight [6].

The purpose of this analysis is to compare the effect of two chemical treatments sodium hydroxide (NaOH) and sodium carbonate (Na₂CO₃), on bagasse fibers. As a reference, relatively pure cellulose (Avicell, FMC BioPolymer), lignin (Granit, SA) and hemicellulose (oat spelt xylan from Sigma Chemical) were also analyzed.

5.3.1. Materials and Methods

Three types of treated bagasse were used. The first one was treated with 2N NaOH for one hour. The second and third samples were boiled with solution 1% and 2.5% Na₂CO₃ (w/v) for one and a half hour. The fourth sample used was untreated raw bagasse. All samples were ground with a Wiley Mill (Philadelphia) into powder using a 0.5 mm sieve, and were analyzed with a TGA/SDTA851° (Mettler Toledo Analytical, Switzerland). The weighing and sampling were automatically performed by the TGA instrument. The samples were heated from 40°C to 700°C at a heating rate of 10°C/min under nitrogen flow of 50 ml/min. The sample sizes ranged from 11 to 19 mg. The 700°C temperature was maintained for 10 minutes, and then the specimens were kept for another 10 minutes under air flow of 50 ml/min for ash recovery. The

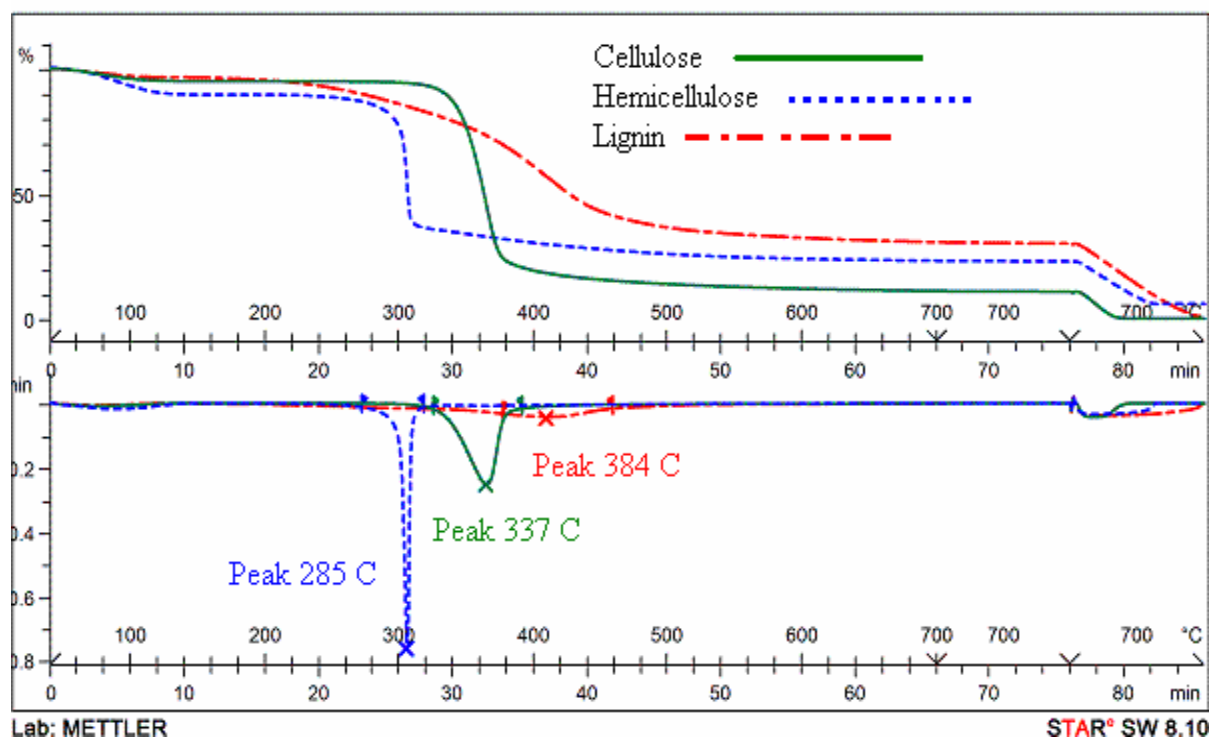
TGA data collected was analyzed for the onset and endset temperature of decomposition, peak rate of weight loss and residual weight (char and ash).

5.3.2. Results and Discussion

- **Thermo-Gravimetric Analysis of Pure Materials (Cellulose, Lignin and Hemicellulose)**

From all three components, the hemicellulose is less thermally stable with the onset of decomposition at 279°C, followed by lignin at 296°C and cellulose at 319°C. Lignin decomposition temperature is lower than that of cellulose, but depending on its sources, may be lower or higher than that of hemicellulose [6].

The derivative thermo-gravimetric (DTG) profiles obtained for the pure components (Graph 1) exhibit three peaks. Each peak corresponds to the temperature at which the maximum weight loss rate takes place: 285°C for hemicellulose, 337°C for cellulose and 384°C for lignin.

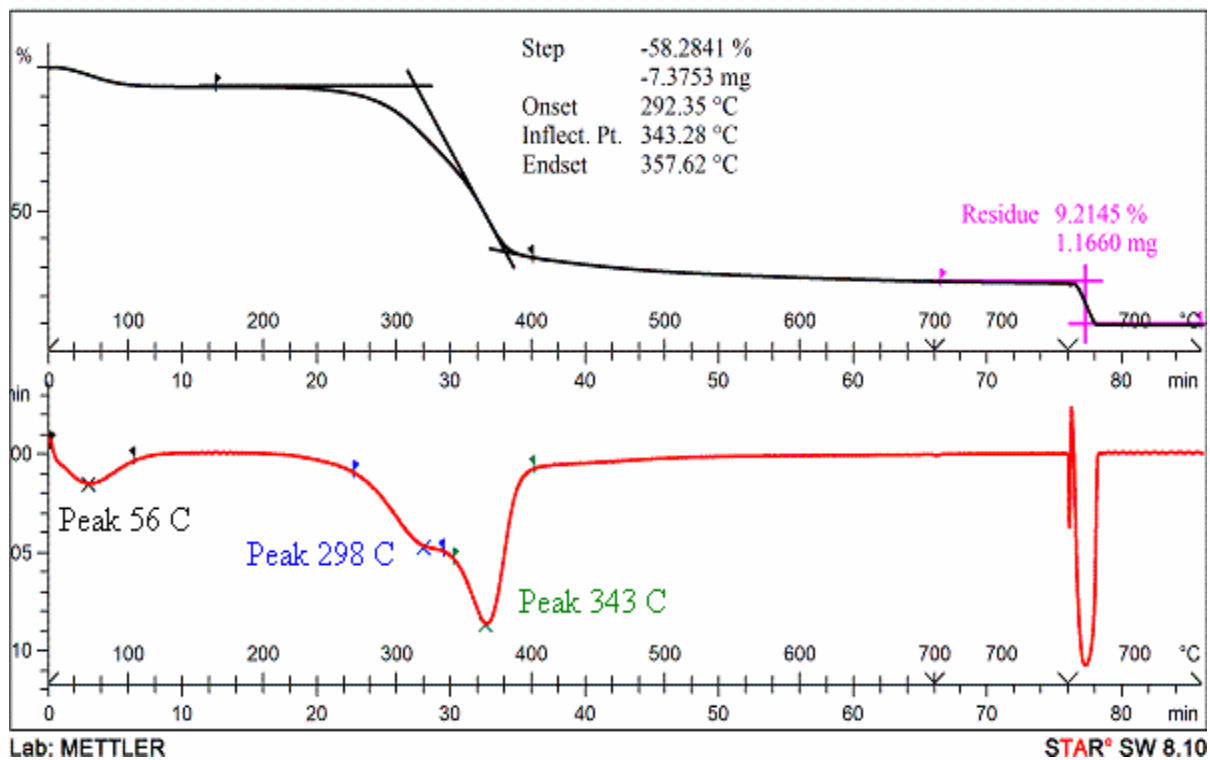


Graph 1 – Comparison of the TGA curves (top) and DTG curves (bottom) for pure compounds

The peak for lignin however, is not as distinct as for the other two, cellulose and hemicellulose. This is because lignin decomposes over a wider temperature range between 200°C and 500°C. The values found in this study are comparable with the values reported in the literature [14, 20, 25, 29].

- **Thermo-Gravimetric Analysis of Untreated Raw Bagasse**

As the temperature increases the bagasse is losing weight due to the chemical decomposition. In Graph 2 the TG curve of weight loss and the DTG curve of weight rate loss of untreated bagasse are plotted as a function of temperature and time. Using the advantage of the TGA software (Star^o Software) we can determine the onset and the endset temperatures of thermal decomposition by selecting a temperature region and drawing three tangent lines in the TG curve. The selected region has a starting point at 150°C and an ending point at 400°C.



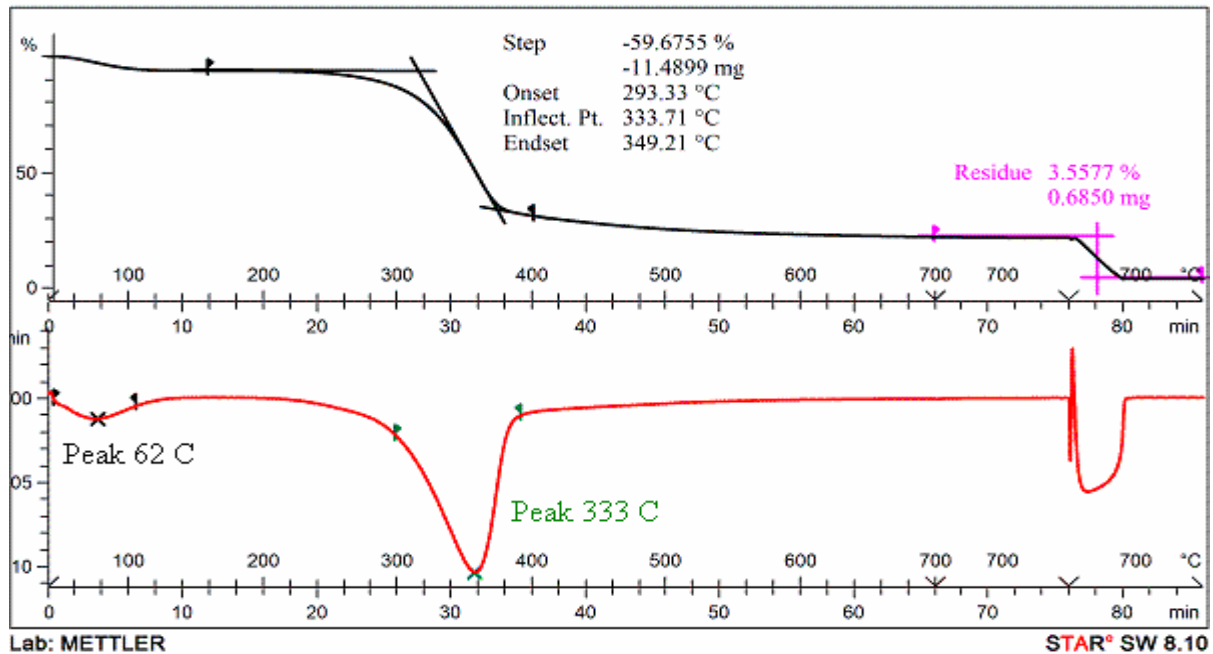
Graph 2 – TG and DTG curves for raw bagasse

This region was selected because at 150°C bagasse fibers have not yet begun to decompose, and after 400°C almost all the bagasse finished its thermal decomposition [6]. The intersection point for the first two tangents represents the onset decomposition temperature, which can be read at 292°C. The intersection point of the last two tangents represents the endset temperature, which can be read at 357°C.

The DTG curve obtained exhibits three peaks: the first one is due to the loss of moisture at 56°C, the second one is the result of hemicellulose decomposition at 298°C, and the third one is caused by the thermal degradation of the cellulose at 343°C.

- **Thermo-Gravimetric Analysis of the Bagasse Fibers Treated with 1% Na₂CO₃ (w/v)**

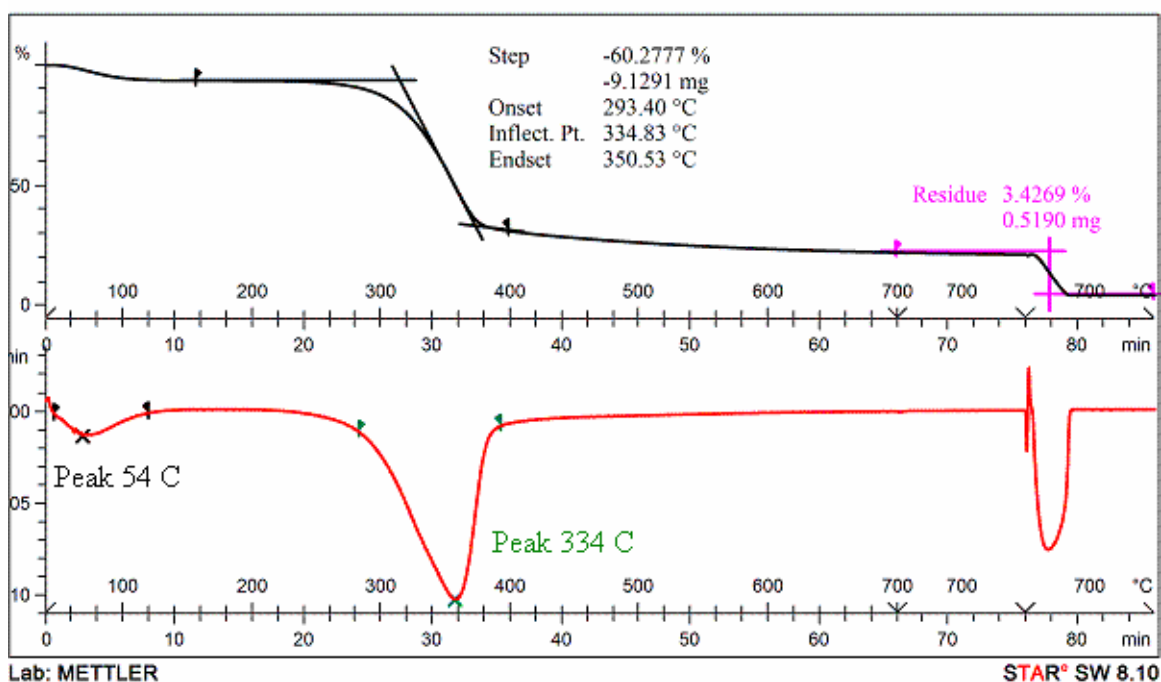
For the treated bagasse fibers the same procedure was used: a region between 150°C and 400°C was selected and three tangents were plotted. The onset value was 293°C and the endset was 349°C. Two peaks could be observed: one for moisture loss at 62°C and the second one at 333°C, the temperature for the highest weight loss rate of cellulose decomposition (Graph 3).



Graph 3 – TG and DTG curves for bagasse treated with 1% Na₂CO₃

- **Thermo-Gravimetric Analysis of the Bagasse Fibers Treated with 2.5% Na₂CO₃ (w/v)**

For this sample the onset value was 293°C, and the endset was 350°C. The first peak at 54°C corresponds to moisture loss, and the second at 334°C represents the temperature at which the highest weight loss rate for cellulose decomposition was achieved (Graph 4).



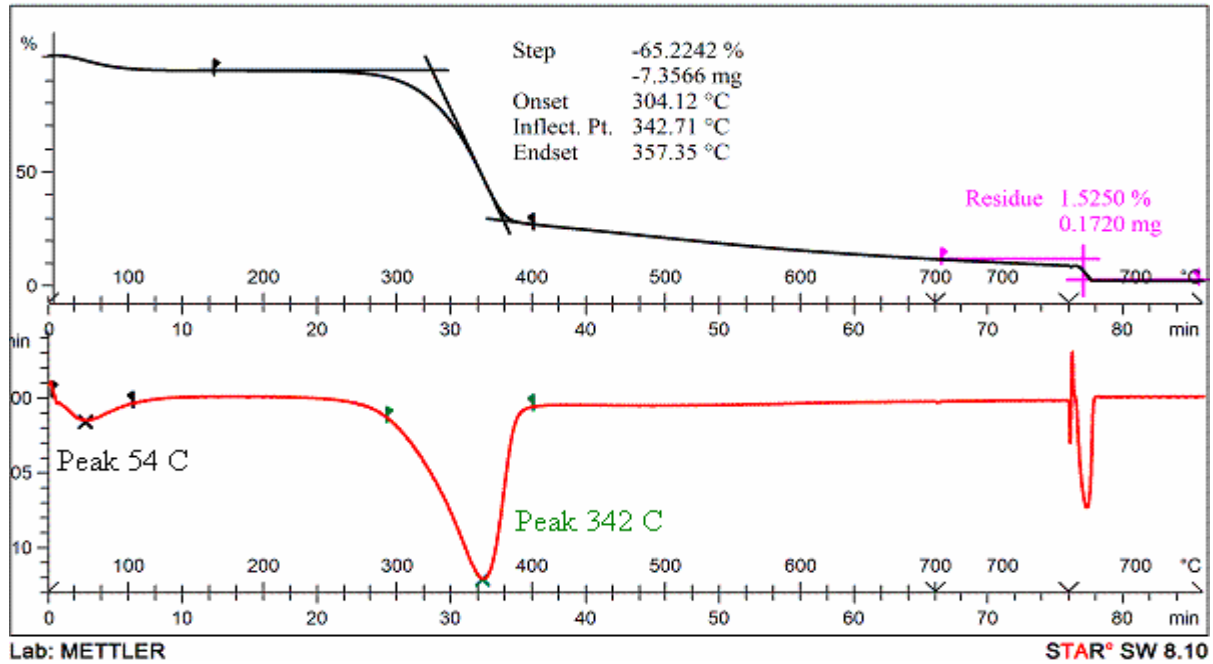
Graph 4 – TG and DTG curves for bagasse treated with 2.5% Na₂CO₃

- **Thermo-Gravimetric Analysis of the Bagasse Fibers Treated with 2N NaOH**

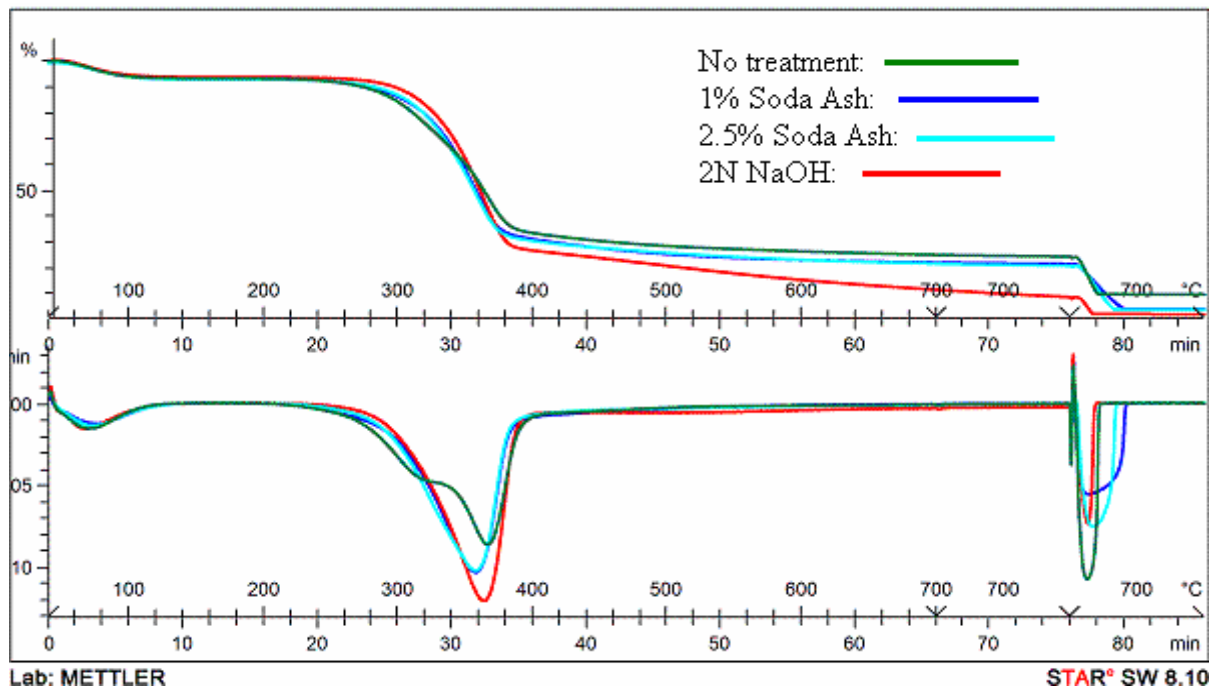
For this sample the onset temperature was 304°C and the endset was 357°C. The moisture peak was at 54°C and the second was at 342°C (Graph 5).

Graph 6 represents a comparison of the TG and DTG curves of raw bagasse with the three samples of treated bagasse. The missing peak for hemicellulose decomposition is evidence that both chemical treatments applied are removing part of it. Also, the rate of cellulose decomposition is increasing with the severity of the treatment condition. This may be related to

the fact that 2N NaOH will cause much more damage to the cellulose network by removing the encrusting materials than the mild treatment with Na₂CO₃.



Graph 5 – TG and DTG curves for bagasse treated with 2N NaOH.



Graph 6 – Comparison of the TG and DTG curves of the four types of treated bagasse

For the lignin decomposition, no apparent peak can be observed on either treated or untreated bagasse curves. The literature reports values up to 900°C [20, 25, 29] for lignin decomposition, but this may depend on the heating rate temperature applied, and also on the purity and source of the lignin. However, evidence that lignin removal took place in the alkali treatment is the high content of char exhibited by the untreated material compared with the treated one. This observation is consistent with reports [6, 20], and also with the char values for the pure compounds found in this work (Table 10). In addition, it can be observed that the onset decomposition temperature increases with a decrease in the lignin content of the samples, which corresponds to an increase of the cellulose content due to the lignin and hemicellulose partial removal [6] (Table 10).

Table 10 – The values of the onset, weight loss, char and ash for the pure components and for the three treated bagasse samples

	Onset Decomposition Temperature (°C)	Weight Loss at 400°C (%)	Char (%)	Ash (%)
Cellulose	319	78	11	0.5
Hemicellulose	279	63	24	7
Lignin	296	36	31	1.3
Untreated bagasse	282 - 291	58 - 60	28 - 30	13 - 16
Bagasse treated with 1% and 2.5% Na₂CO₃	292 - 294	64 - 66	20-23	3 - 6
Bagasse treated with 2N NaOH	304	67	11	1.5

In all the graphs that illustrate the DTG curves a peak appeared in the 700°C temperature region. These peaks are related to initial introduction of the air flow. That results in an apparent spike in the sample weight, but is not related to the actual weight of the material being tested.

5.3.3. Conclusions

The chemical treatment chose for the fibers, (boiling with sodium carbonate for one and a half hour), proved to be efficient in the partial removal of hemicellulose and lignin. Both of these components represent the encrusting materials that contribute to the stiffness of the fibers. This treatment yielded flexible fibers suitable for erosion control mat formation, and was preferred to sodium hydroxide because it is more economical and poses a less severe occupational hazard to human health than sodium hydroxide.

CHAPTER 6. DISCUSSIONS

6.1. Economic Advantages

Erosion control is a growing industry with different products varying in composition and structure [1]. Erosion control blankets for temporary soil protection during road construction and for levee and coastal erosion abatement range from \$0.4/m² for straw and wood based, to \$2/m² for polypropylene and up to \$3/m² for imported coconut fiber products. At 0.3 – 0.5 kg/m² this is equivalent to approximately \$0.8 to \$2/kg on a dry weight basis. Taking the estimate of \$0.8/kg for the potential bagasse based products, that indicates about \$0.4/kg bagasse at 50 percent moisture, making it a potentially attractive commercial product for the sugar industry. Louisiana distributors like Industrial Fabrics, Inc. (510 O’Neal Lane, Baton Rouge), are selling \$1 million to \$2 million worth of erosion control products per year to road building contractors for state highway projects. Calculating for only ten distributor companies in Louisiana, this would translate into a \$10 million to \$20 million in-state market. With an average price of \$0.5/m² (\$1.3/kg) that would represent a total annual in-state market of 800 to 1600 tons of erosion control fabrics.

With a 33% mat yield from bagasse, that would represent a requirement of 2,400 to 4,800 tons of bagasse having 50% moisture. It is estimated that a 6,000 t/d mill may produce some 2,000 t/d bagasse. At a conservative estimate of 10% “excess” bagasse or 200 t/d (the bagasse that is not required by the mill for steam and power generation), the total in-state erosion market might correspond to 12 to 24 days of operation of the 6000 t/d mill.

With no manufacturers for erosion control products in Louisiana, all the products have to come from out of state. With the simple process that has been developed at ASI, the sugar mills

can manufacture the erosion bagasse products themselves, with an advantage regarding the savings on the shipping cost for all Louisiana distributors.

6.2. Conclusions

This research work focused on the development of a continuous manufacturing process of sugarcane bagasse mats that will be used as erosion control products. With an increasing rate of erosion and stricter environmental regulations comes an increasing demand of the natural control products. The availability of the sugarcane bagasse and the simple treatment applied to the fibers assures a low cost on the market for this product along with its biodegradability.

The designs tested at ASI led to the construction of the final device for the mat formation, a prototype that allows the manufacturing of 1.2 m x 2.4 m bagasse mats.

Different chemical and mechanical treatments were applied to find the most efficient one that will yield fibers with the best properties to fit our purpose. The thermo-gravimetric analysis used to compare the effect on bagasse fibers of two chemical treatments: sodium carbonate and sodium hydroxide showed that both treatments are effective in partial removal of hemicellulose and lignin. The final decision was made for the sodium carbonate treatment because of its low cost and less severe occupational hazard posed to human health than sodium hydroxide. The mechanical modification of the fibers using a refiner was necessary to split the big bundles and release the pith trapped among the fibers. This had a result in increasing the cohesion of the bagasse mats. The two experimental plots conducted at ASI showed that the bagasse mats have a good moisture retention allowing grass penetration.

However, as future work and final approval for this product to be sold on the market, the bagasse mats need to be tested at Texas Transportation Institute. This will assure the eventual

customers that sugarcane bagasse mats are a reliable product and feasible for erosion control usage.

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VITA

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Irina graduated from Calistrat Hogaș High School from Piatra-Neamț in 1996. She attended Alexandru Ioan Cuza University, from Iași where in 2000 she obtained a Bachelor of Science degree in biology. After graduating she worked as a biology teacher at a middle school in Piatra-Neamț. In August 2004 Irina entered the Program of Engineering Science in Biological Engineering Department from Louisiana State University and she worked as a Graduate Assistant for Audubon Sugar Institute in St. Gabriel, Louisiana.