FINAL REPORT

DEVELOPMENT OF DURABLE WATER-REPELLENT JUTE GEOTEXTILES WITH NATURAL ECO-FRIENDLY ADDITIVE FOR APPLICATION IN EROSION CONTROL IN RIVER BANKS AND OTHER APPROPRIATE END USES

(MM IV Projects 12 and 13)

Debasis Roy, Principle investigator
Basudam Adhikari, Co-Principle Investigator
Ramkrishna Sen, Co-Principle Investigator

sponsored by

National Jute Board
Ministry of Textiles
Government of India
3A Park Plaza, 71 Park Street
Kolkata 700016

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Department of Civil Engineering
Indian Institute of Technology
Kharagpur 721302

EXECUTIVE SUMMARY

Free hydroxyl groups of the cellulose chains within jute fibers and fabric tend to attract water molecules in moist environment causing the fibers to swell and causing the cellulose chains undergo hydrolytic and oxidative degradation instigated by factors such as enzymatic activities of microbes present in the environment, acidity, alkalinity, salinity or UV irradiation. Because of their relative lack of degradation resistance lignocellulosic fibers such as jute find limited use in the manufacture of industrial textiles, e.g., geotextiles.

In this research a chemical process has been developed for treating jute fibers and fabric using an alkaline water-based emulsion of neem oil and plant based phenolic resin to enhance their short-term tensile strength and degradation resistance without potential toxic leachate generation. The process is inexpensive and not energy intensive and uses generic, non hazardous and non toxic reagents derived by and large from plant biomass. The treatment involves part transesterification of cellulose hydroxyl groups of fibers and fabric with neem oil and blocking of hydroxyl groups with phenolic resin via hydrogen bond formation. Yarns were spun manually and mechanically from treated jute fibers. Fabrics were also woven in a commercial jute mill from the treated fibers to establish the industrial adaptability of the process. Additionally, treatment was applied on geotextiles manufactured from untreated jute fibers available in the market for similar end use. The treatment did not adversely affect flexibility and filtration properties of the fabrics.

The treatment caused the short term fiber tensile strength to increase by 75 % for jute, the water absorption to decrease from 255 % to 79 % (in terms of dry fiber weight) for jute. Treated jute fibers retained, on an average, 80 % of their initial tensile strengths after 120-d biodegradation. The corresponding tensile strength retention for untreated jute fibers were only 10 %. After 120-day immersion into a 3 % saline environment, NO-resol treated jute fibers retained 72 % of their initial tensile strengths, while untreated jute fibers retained only 6 %. Further the treated fibers and fabric manufactured from them were found to be stable upon being exposed to pH ranging between 4 and 9.

The estimated field half-lives for the fabric manufactured from treated fiber, woven jute fabric procured from a jute mill treated with the chemical process developed in this project under microbial action, 1584 and 1080 days, respectively, exceeded the corresponding estimate for untreated woven jute fabric (between 240 and 384 days) considerably. The estimated field half-lives for fabric prepared from treated fibers was 1115 days and that for treated fabric was 881 days in an installation directly exposed to sunlight and periodic drying and wetting compared to only 294 days estimated for untreated fabric. Similarly, the estimated field half-lives for the fabric manufactured from treated fiber, woven jute fabric procured from a jute mill treated with the chemical process developed in this project for underwater installations with 3 % salinity exposure, 887 and 1060 days, respectively, are also very large compared to only 41 days estimated for untreated woven jute fabric.

The treatment costs for either fabric or fiber level treatment to be consistently in INR 17 to INR 19 range per square meter of 700 g/m^2 woven jute fabric. It should be noted that the costs are likely to come down further in larger scale manufacturing. The cost of bitumen treatment – the alternative treatment approach being used to manufacture degradation-resistant jute geotextiles – of around INR 35 per square meter of 700 g/m^2 woven jute fabric, it appears that the treatment process developed in this research is relatively inexpensive.

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The Project Team

Debasis Roy, Principal Investigator
Basudam Adhikari, Co-Principal Investigator
Ramkrishna Sen, Co-Principal Investigator
Prosenjit Saha, Project scholar
Suvendu Manna, Project scholar
Satyagopal Shee, Junior Project Assistant
Samir Mazumdar, Project Assistant

LIST OF SYMBOLS AND ABBRIVIATION

LCFs	:	Lignocellulosic fibers
TD4	:	*Tossa daisee* jute of grade 4
UV	:	Ultraviolet radiation
TS	:	Tensile strength
EB	:	Elongation at break (%)
WA	:	Water absorption
EMC	:	Equillibrium moisture content
CL	:	95 % confidence level
VO	:	Vegetable oil
CNSL	:	Cashew nut shell liquid
PR	:	Phenolic resin comprised of formaldehyde, resorcinol, CNSL and plant tannin
SDS	:	Sodium dodecyl sulphate
NO	:	Neem Oil
FTIR	:	Fouir-transform infrared spectroscopy
MSBT	:	Modified soil burial test
ppm	:	Parts per million
AAW	:	Artificial accelerated weathering
FLMY	:	Machine spun yarn from fiber treated in laboratory
FLHY	:	Handspun yarn from fiber treated in laboratory
UUHY	:	Untreated handspun yarn
FLMG	:	Machine made geotextiles from fibers treated in laboratory
UUMG1	:	Untreated-machine made geotextiles (control for FLMG)
FIMG	:	Machine made geotextiles from fibers treated in industry
TIMG	:	Machine made geotextiles treated in industry
UUMG2	:	Untreated-machine made geotextiles (control for FIMG, TIMG)
MD	:	Machine direction
CD	:	Cross machine direction

1. OBJECTIVES OF THE PROJECT

Free hydroxyl groups of the cellulose chains within jute fibers and fabric tend to attract water molecules in moist environment causing the fibers to swell and causing the cellulose chains undergo hydrolytic and oxidative degradation instigated by factors such as enzymatic activities of microbes present in the environment, acidity, alkalinity, salinity or UV irradiation. Because of their relative lack of degradation resistance lignocellulosic fibers such as jute find limited use in the manufacture of industrial textiles, e.g., geotextiles.

A range of chemical treatments, quoting and blending strategies have been developed for enhancing tensile strength, hydrophobicity and degradation resistance of jute and other lignocellulosic fibers and fabrics manufactured from them. But many of the treatment processes use expensive and hazardous chemicals and turn the treated fabric into a potential source of toxic leachates. Complex process design and extensive energy requirements also pose additional problems in using some these processes. Long term effectiveness of these treatments in preventing chemical, biological, or physical degradations and potential toxicity of the degradation products have also not been assessed systematically.

So, there is a need for a process for treating jute fibers and fabrics for manufacturing degradation resistant geotextiles and a reasonably precise estimate of the long-term tensile strength of the products. Additionally, the process should be economical adaptable in an industry engaged in manufacturing technical textiles. The process should by and large be based on the use of inexpensive, eco-friendly possibly plant-based reagents so that potential degradation products are not harmful to the environment. Based on this scope the objectives of the present research were set up as follows:

- Identification of suitable eco friendly polymers and natural additives to modify jute geotextiles for enhancing its durability and strength
- Accelerated laboratory testing for assessing the resistance of treated jute fibers and fabric against biological, chemical and UV and moisture related degradations
- Assessing adaptability of the treatment process in existing industrial set ups
- Final report submission and recommendations

2. LITERATURE REVIEW

In recent years natural fibers such as sisal (Sarsby, 2007), palm (Bhattacharyya et al. 2009), bagasse (Dinu and Saska, 2007), flax (Rawal and Anandjiwala, 2007), hemp (English, 1995), jute (Ranganathan, 1994) and coir (Subaida et al., 2008) have been used for manufacturing geotextiles because they are inexpensive, renewable agricultural commodities unlike their manmade, petroleum-based alternatives. Geotextiles based on jute fibers have a number of additional application-specific advantages. For instance, swelling and water absorption of jute fibers lead to reduction in runoff energy and improvement in filtration characteristics of the fabric to provide better stability in an erosion control application. Further, they also prevent extreme variations in soil moisture and temperature (Sutherland and Ziegler, 2007).

Despite their relative advantages, geotextiles based on natural fibers find limited use in many engineering projects because of biological, chemical and physical degradations. Consequently, they are mainly used to support vegetation growth, which, in turn, imparts mechanical resistance of soils against erosion and sliding. The hydroxyl groups and ester bonds of natural fibers, e.g., jute are susceptible to hydrolysis and oxidation often initiated by biological and chemical actions and UV irradiation. Although hemicelluloses are the main contributor to hydrophilicity of jute, cellulose and lignin may also cause the fibers to absorb water and swell. This, in turn, lets water and hydrolytic or oxidative agents find an entry into the interior of the fiber matrix accelerating their swelling and eventual disintegration.

A range of chemical treatments, quoting and blending strategies have been developed for enhancing tensile strength, hydrophobicity and degradation resistance of jute and other lignocellulosic fibers and fabrics manufactured from them. For instance, defibrillation instigated by alkali treatment (mercerization) has been found to increase fiber surface area (Bledzki et al., 1996) and removal of amorphous materials, the presence of which prevents optimal load path development and tensile strength mobilization (Le Troedec et al., 2008). Graft copolymerization (Montazer and Saheli 2008), acrylatization (Vasoya et al. 2008), etherification (Rahman et al. 1996), acetylation (Andersson and Tillman 1989) or coating with precondensate of cashew nut shell liquid formaldehyde (Mitra et al. 1998) have been found to increase hydrophobicity of jute fibers. Biodegradation resistance and mechanical strength on the other hand has been increased by photografting or graft copolymerization under UV radiation (Hassan et al. 2005, Hassan et al. 2003, Hassan et al. 2002, Uddin et al. 1996). Attempts have been made to enhance the resistance of jute geotextiles against biological degradation by coating them with bitumen (Dutta, 2007; Sanyal and Chakraborty, 1994) or antimicrobial benzothiazole chemicals (Sinha and Chakraborty, 2004). Geotextiles have also been manufactured from jute fibers blended with synthetic fibers (Rawal and Sawaswat, 2011; Basu et al., 2009) for durability enhancement. However, biodegradation of untreated fibers within such geotextiles is likely to lead to disintegration of fabric structure.

Many of the treatment processes discussed above use expensive and hazardous chemicals and turn the treated fabric into a potential source of toxic leachates (Basu et al., 2009). Details of

the efficacy and limitation of different jute treatment process were presented in Table 1. Complex process design and extensive energy requirements pose additional problems in using some these processes. Long term effectiveness of these treatments in preventing chemical, biological, or physical degradations and potential toxicity of the degradation products have also not been assessed systematically. For instance, in one of the river bank stabilization projects described by Dutta (2007) and Sanyal and Chakraborty (1994), bitumen coated jute geotextiles were found to lose as much as 70 % of their initial tensile strength within two years of installation. Bitumen coating also adversely affects the flexibility, porometry and drapability of geotextiles. Relative economy of the processes discussed in the preceding and their impact on mechanical behavior and spinability of jute fibers, and their adaptability to the industrial processes prevalent in Indian jute mills have also not been established.

Table 1. Efficacy and limitation of previous jute treatment processes

Treatment	Treatment efficacy	Remarks
Acetic anhydride (Abdul and Ismail, 2001)	• 8 % higher tensile strength • 30 % lower water absorption • Retained 80 % tensile strength after 140-d biodegradation	• Use of hazardous chemicals • Expensive process • Untreatable crystalline cellulose
Oleoyl chloride, pyridine, dichloro-methane (Corrales et al., 2007)	• "Reduced" water absorption • "Decreased" biodegradation susceptibility	• Use of hazardous chemicals • Expensive process • Lower thermal stability
Acrylamide (Hassan et al., 2002)	• 20 % higher tensile strength • "Reduced" water absorption • Retained 66 % tensile strength after 112-d biodegradation	• Use of hazardous chemicals and organic solvent • Expensive process • Energy intensive
Acrylic acid (Patel and Parsania, 2010)	• 42 % higher tensile strength	• Use of hazardous chemicals and organic solvent • Expensive process • Energy intensive
Butyl acrylate/ sodium silicate (Sahoo et al., 2005)	• "Remarkably reduced" water absorption • 46 % weight loss after 1-y biodegradation	• Use of hazardous chemicals and organic solvent • Expensive process • Energy intensive
MAPP, toluene (Mohanty et al., 2004)	• 72 % higher flexural strength • 61 % lower water absorption	• Use of hazardous chemicals • Expensive process • Energy intensive
MA, BCFA / jute fabric 9Vasoy et al., 2008)	• 24 % higher tensile strength • 32 % lower water absorption	• Use of hazardous chemicals • Expensive process • Energy intensive
Enzyme mix, cellulase (Zedorecki and Flodin, 1985)	• 18 % *lower* tensile strength	• Use of hazardous chemicals and organic solvent • Expensive process • Long treatment time • Hydrolyses crystalline cellulose

Table 1. Efficacy and limitation of previous jute treatment processes…

Treatment	Treatment efficacy	Remarks
PF resin (Mitra et al., 1998)	• 83 % higher tensile strength • 50 % lower water absorption	• Use of hazardous chemicals and organic solvent • Expensive process • Long treatment time • Hydrolyses crystalline cellulose
Lignin modified resol (Sarkar and Adhikari, 2001)	• Little increase in tensile strength • "Reduced" water absorption	• Use of hazardous chemicals and organic solvent • Expensive process • Long treatment time
Bitumen (Sanyal and Chakraborty, 1992; Dutta, 2007)	• Decrease in tensile strength • "Reduced" water absorption	• Use of non-renewable chemicals • Affects flexibility, filtration and drapability of textiles • Less biodegradation but looses up to 70 % of tensile strength within 2 years of field use • Generate toxic leachate
Benzothiazole Chemicals (Sinha and Chakraborty, 2004)	• Little *decrease* in tensile strength • Retained 96 % of tensile strength after 21-d compost burial *without* replenishing nutrients	• Use of hazardous and toxic chemicals • No adverse impact on permeability and drapability • Generate toxic leachate
Vegetable oil - phenolic resin (Saha et al. 2012, this research)	• 80 % higher tensile strength • 62 % lower water absorption • Treated products are stable in pH between 4 and 9 and salinity of typical sea water (12.4 ppt) • 60 % retention of tensile strength 4 % weight loss after 120-d compost burial with nutrient replenishment	• Mainly based on the use of plant based chemicals • Inexpensive process • Lower treatment time • No detectable leachate toxicity • No adverse impact on permeability and drapability

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3. SUMMARY OF LITERATURE REVIEW

Jute geotextiles have a number of additional application-specific advantages. For instance, swelling and water absorption of jute fibers lead to reduction in runoff energy and improvement in filtration characteristics of the fabric to provide better stability in an erosion control application. Further, they also prevent extreme variations in soil moisture and temperature. Despite their relative advantages, geotextiles based on natural fibers find limited use in many engineering projects because of biological, chemical and physical degradations. Consequently, they are mainly used to support vegetation growth, which, in turn, imparts mechanical resistance of soils against erosion and sliding.

Review of literature indicated that degradation resistance of jute fibers, yarns or fabric could be enhanced by modifying the hydroxyl groups within the cellulose chains of jute fibers and coating the fibers with hydrophobic and degradation-resistant, cross-linkable, non-leachable resin. A range of chemical treatments, coating and blending strategies have been developed for enhancing tensile strength, hydrophobicity and degradation resistance of jute and other lignocellulosic fibers and fabrics manufactured from them. But many of these processes use expensive or hazardous chemicals and turn the treated fabric into a potential source of toxic leachates. Complex process design and extensive energy requirements also pose additional problems in using some these processes. Long term effectiveness of these treatments in preventing chemical, biological, or physical degradations and potential toxicity of the degradation products has also not been studied. Their relative economy, impact on mechanical behavior and spinability of fibers, and adaptability in jute textile manufacturing industry are also not established. Thus there appears to be need for an alternative process based on economical, eco-friendly non leachable reagents to impart hydrophobicity, which can be easily adapted in jute textile manufacturing industry.

4. THE NEED ASSESSMENT AND MARKET SURVEY REPORT

The Need Assessment and Market Survey were carried out by IIT, Kharagpur in collaboration with Roots & Yards, Kolkata. Details on the methodology adopted in this assessment are provided in Appendix 1. The annual demand for jute geotextiles for erosion control application in India has been estimated in this assessment to be INR 3.18 crore in 2012-13. Similarly the estimated global market size for JGT was INR 38 crore for erosion control application in 2012-13. In comparison, the corresponding estimates obtained by others for the Indian market were found to vary between INR 3.3 crore and INR 4.5 crore and those for the global market size ranged between INR 38 crore and INR 65 crore.

5. METHODOLOGY OF RESEARCH AND DEVELOPMENT ACTIVITIES

This research involved:

- Treatment of jute fibers, yarns and fabrics with reagents prepared by combining a variety of vegetable oils (e.g., neem oil and rice bran oil), fatty acid distillates and phenolic resins (e.g., extract of *Diospyros cordifolia* plant, resorcinol, plant tannin, cashew nut shell liquid) with known anti microbial characteristics in various proportions.
- Optimization of reagent compositions and reaction conditions (pH, temperature and duration) were optimized for short-term tensile strength and biodegradation resistance of treated products.

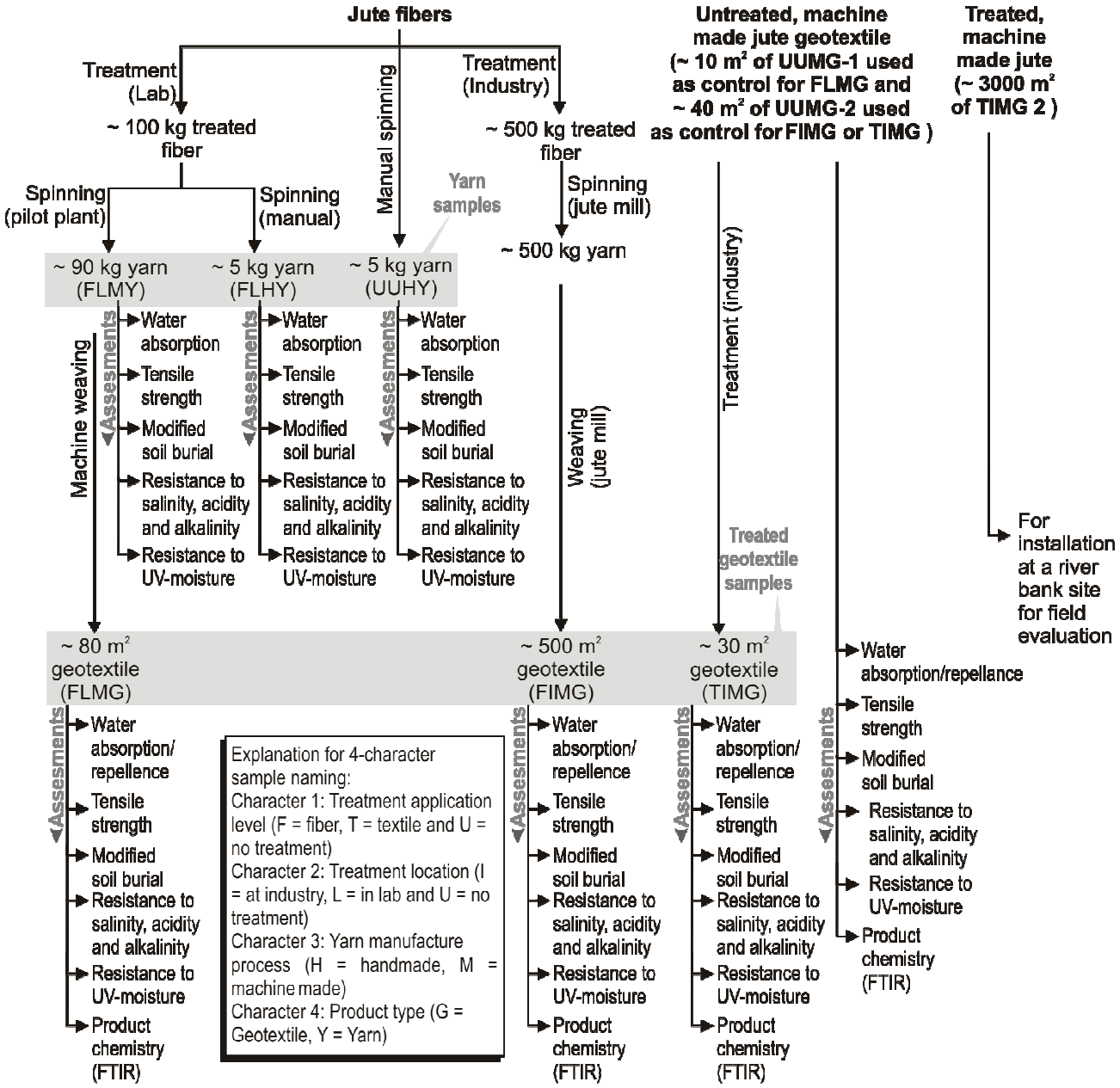

Figure 1. Methodology

- Use of the optimized process to treat fibers and fabrics
- Fabric making from treated jute

- Testing treated and untreated fiber and fabric samples for assessing treatment efficacy (resistance of treated products against degradation due to moisture or wetting, pH, salinity, UV exposure and biodegradation)
- Analysis of test results
- Organization of workshops technology transfer.
- Schematic outline of these activities are presented in Figure 1.

6. DETAILED REPORT ON RESEARCH AND DEVELOPMENT ACTIVITIES

6.1. Materials

This study pertains to the treatment of jute (*Corchorus olitorius*) fibers. Sodium hydroxide (NaOH) pellets, resorcinol, formaldehyde, commercially available neem oil (NO), cashew nut shell liquid (CNSL) and commercial grade condensed black wattle plant tannin were used to treat the fibers and fabric as discussed below.

6.2. Chemical Modification

Review of literature indicated that degradation resistance of jute fibers, yarns or fabric could be enhanced by modifying the hydroxyl groups within the cellulose chains of jute fibers and coating the fibers with hydrophobic and degradation-resistant, cross-linkable, non-leachable resin. To this end, jute fibers, yarns and fabrics were treated with reagents prepared by combining a variety of vegetable oils (e.g., neem oil and rice bran oil), fatty acid distillates and phenolic resins (e.g., extract of *Diospyros cordifolia* plant, resorcinol, plant tannin, cashew nut shell liquid) with known anti microbial characteristics. Reagent compositions and reaction conditions (pH, temperature and duration) were optimized for short-term tensile strength and biodegradation resistance of treated products.

The exercise led to the following definition of the optimized process (Figure 2):

- Dipping of Jute fibers or commercially available jute fabric were dipped for 24-h within an aqueous emulsion prepared from sodium hydroxide, plant tannin, cashew nut shell liquid, resorcinol, neem oil and formaldehyde in 1:10:8:2:6:4 proportion by weight with pH of 8

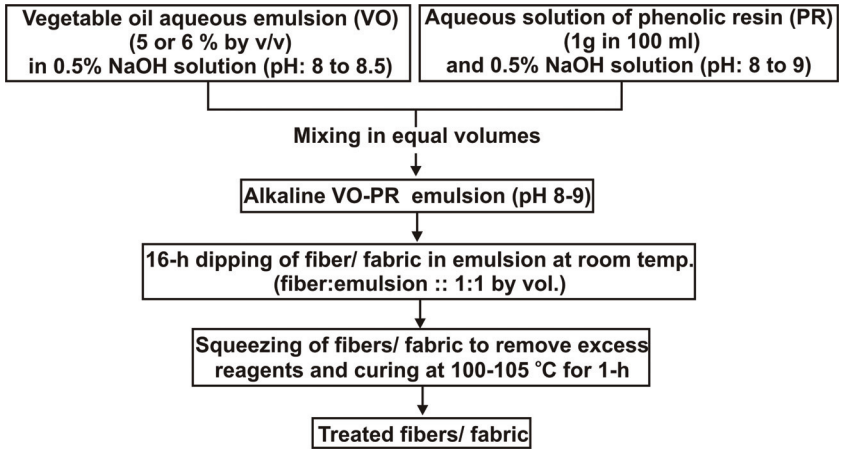

Figure 2. Process outlines

- Squeezing the recovered the fibers / fabric mechanically to recover unused reagents and expelled amorphous matter, e.g., lignin, hemicelluloses and waxes
- Curing the fibers / fabric in a convection oven at 105 ± 5 ° C for 1 h.

6.3. Yarn Manufacture from Treated Fibers

To adapt the laboratory based chemical treatment process for jute fibers to industrial scale, large amount of jute fibers were treated in laboratory (Figure 3) and in the industrial set up (Figure 4) of KETex Pvt. Ltd. near Kharagpur. Minor difficulties were encountered in applying the chemical reagents uniformly on the fibers, which affected the spinability of the treated fibers slightly affected. The problem has since been sorted out by (a) reducing reagent concentration, (b) controlled spraying of measured quantity of the reagent (Figure 3a) and (c) squeezed after spraying (Figure 3b). These modifications appear to have led to the lowering of treatment cost and an improved quality of treated fiber. The treated fibers were characterized in terms of their mechanical strength and resistance against biodegradation. Manual and machine manufacturing of yarn was attempted using 10 kg and 120 kg of treated fibers, respectively.

Yarn could be handspun with treated jute fiber without the necessity of any softening, moisture conditioning or batching oil application (Figure 5). Yarn (9 to 10 count) could also be spun at the pilot plant operated by Indian Jute Industries' Research Association (IJIRA) in Kolkata. The machinery and processes in this case were very similar to the carding, 3-stage drawing, and spinning activities of yarn manufacture in Indian jute mills. Figure 6 illustrates the carding (sliver making) and drawing activities of the treated fibers at the IJIRA pilot plant.

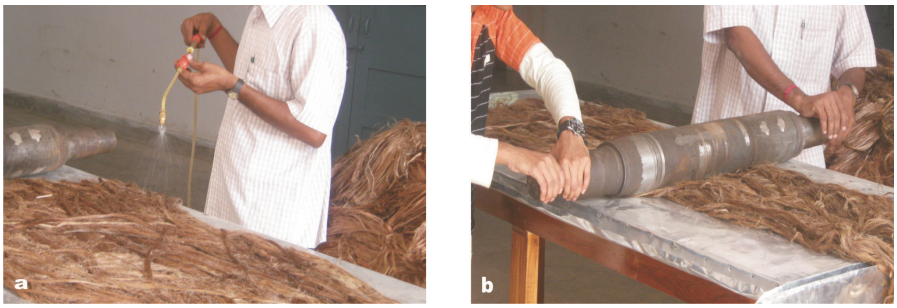

Figure 3. Treatment of jute fibers in laboratory

Figure 4. Treatment of jute fibers in KETex

It was observed that the fibers were suitable for carding and drawing without the necessity of moisture conditioning and batching oil application. However, spinning of fibers necessitated (a) raising the gravimetric moisture content to 30 % and (b) minor modifications of spinning machinery (essentially increasing the gage length of feed to cylinder and cylinder to doper, and incorporating an additional scraper during spinning to overcome lapping of the treated fibers). Since the treated fibers were more hydrophobic than untreated fibers, moisture conditioning could be done after application a relatively minor amount of jute batching oil: 1 % of dry weight of treated fibers was needed in this case as opposed to 3 % normally required in yarn making in a jute mill. Figure 7 illustrates the quality of handmade and machine made yarns obtained in this evaluation. These yarns were assessed for their mechanical strength and resistance against biodegradation.

Figure 5. Hand spinning of yarn with treated fibers

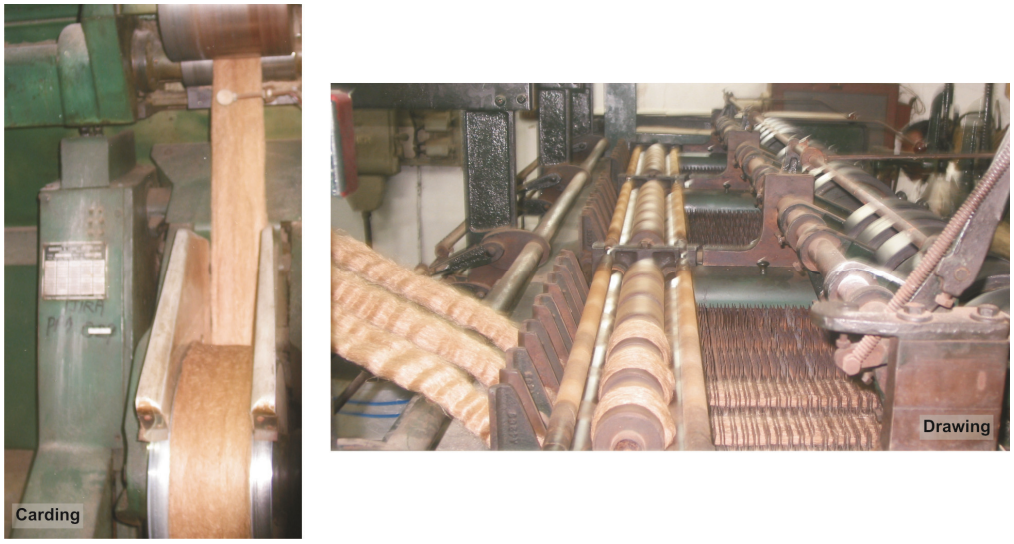

Figure 6. Carding and drawing of treated fibers IJIRA

7. RESULTS OF RESEARCH AND DEVELOPMENT

Increase of tensile strength, hydrobhobicity and degradation resistance of the yarn manufactured from treated fibers were investigated and reported in the following sections.

7.1. Fourier transform infrared Spectroscopy (FTIR)

Chemical changes were investigated by studying FTIR spectrogram of untreated and treated yarns (Figure 8). The peak spectral response at around 1740 cm^{-1} representing C=O stretching vibration for acetyl ester and carbonyl aldehyde groups of hemicellulose and lignin

disappeared following alkali treatment (highlighted region, Figures 8) possibly because of substantial removal of hemicellulose and lignin.

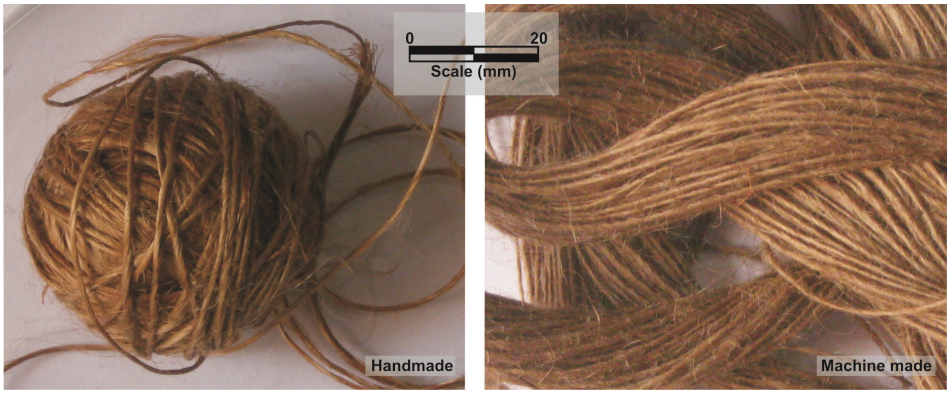

Figure 7. Hand and machine made yarns

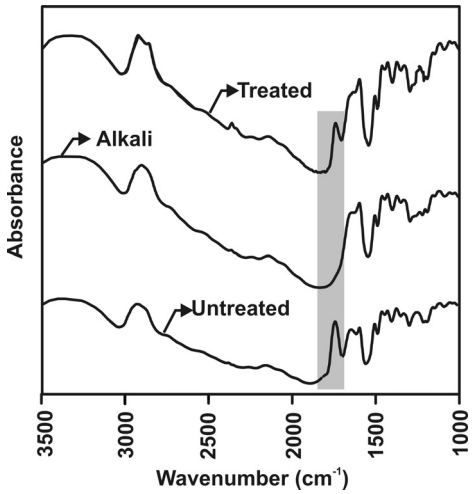

Figure 8. FTIR spectrogram

Reappearance of the peak following the treatment could be because of new ester bond formation (transesterification) between the hydroxyl groups in LCFs and vegetable oil triglycerides as illustrated in Figure 9.

7.2. Tensile Strength and Hydrophobicity

Tensile strengths were found to increase by 43 % and 33 %, respectively, for handmade (FLHY: explanation of four-letter sample designations can be found in Figure 1) and machine made yarns (FLMY) spun from treated jute fibers compared to handmade yarn (UUHY) spun from untreated jute fibers (Table 2). These increases were less remarkable than the increases observed for fibers following chemical treatment. For instance, for FLMY the tensile strength increased by only 33 %, whereas jute fibers exhibited 75 % increase in tensile strength after chemical treatment. Considering the tensile strength of yarn made from short fibers, e.g., jute is expected to be a strong positive function of frictional interlocking between individual fibers, treatment-related fiber surface smoothening appears to be the explanation for this relative lack of efficacy.

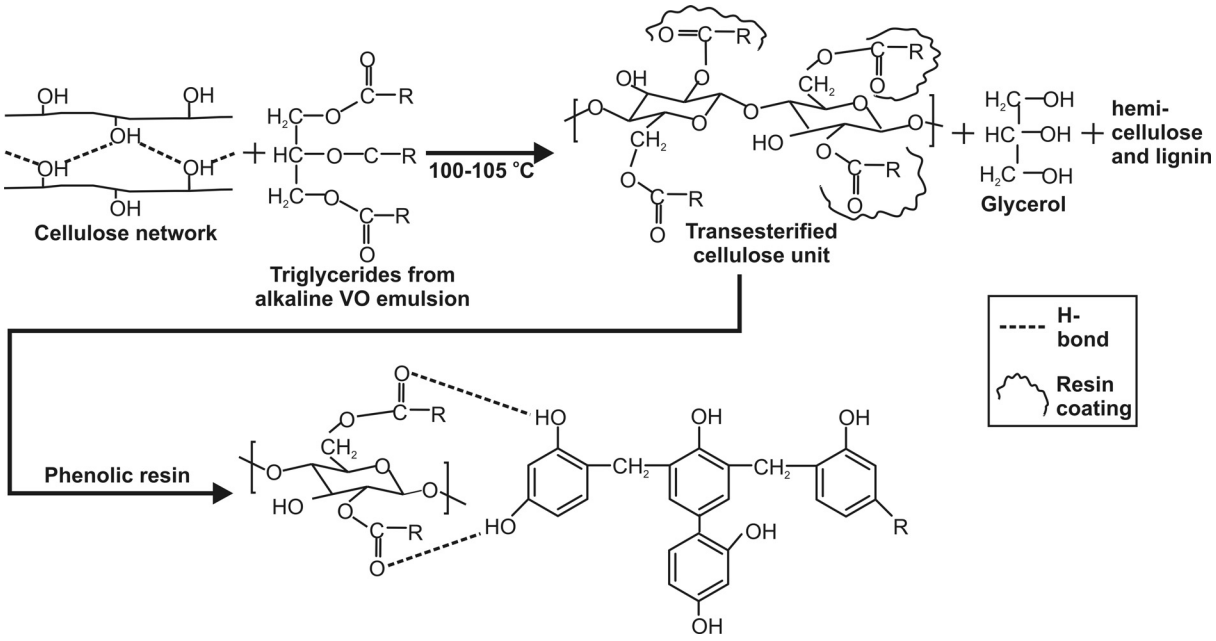

Figure 9. Reaction mechanism of the treatment

Similarly water absorption and equilibrium moisture content (EMC) were reduced remarkably for the yarns spun from treated fibers. However, in this case the proportional reductions were similar to those observed for fibers following the treatment. The results also indicate that the handmade yarns were marginally stronger and absorbed less moisture compared to the machine made sample. Since the twist (number of turns per unit length) in the handmade yarn is remarkably larger compared to the machine made sample, the short fiber interlocking in FLHY is expected to be greater causing the sample to develop greater tensile strength and water repellency.

Table 2: Properties of jute yarn

Yarn	Tensile strength (MPa)	Elongation at break (%)	Water absorption (%)	EMC (%)
UUHY	105	0.60	170±30	12
FLMY	140	0.70	80±20	7
FLHY	150	0.65	75±28	5

7.3. Biodegradation Resistance

FLMY and FLHY samples were found to retain 60 % and 62 % of their initial tensile strengths, respectively, while UUHY retained only 12 % of its initial tensile strength after 90-day in soil burial test (Figure 10) demonstrating remarkably higher biodegradation resistance for yarns manufactured with treated fibers. Notably, the tensile strength retention observed in this case is smaller than the corresponding retention for treated and untreated fibers. This can also be explained by progressive loss of friction lock with the degradation of individual short fibers, with which the yarns were manufactured. Better tensile strength retention in the handmade yarn can be explained by its better short fiber interlocking.

7.4. Salinity Related Degradation

FLMY and FLHY samples were found to retain 61 % and 74 % of their initial tensile strengths, respectively, while UUHY retained only 5 % of its initial tensile strength after 90-d immersion in 3 % aqueous solution of NaCl (Figure 11) demonstrating remarkably higher

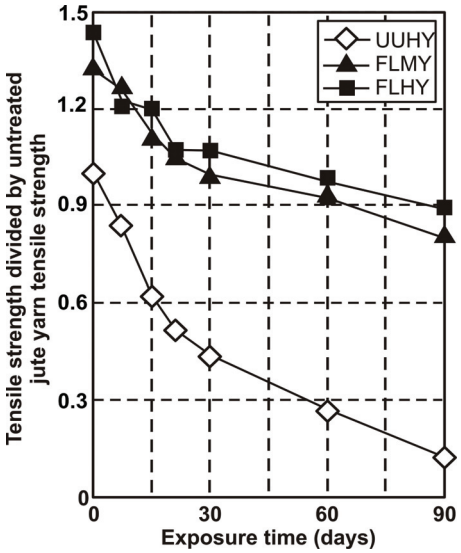

Figure 10. Yarn biodegradation resistance

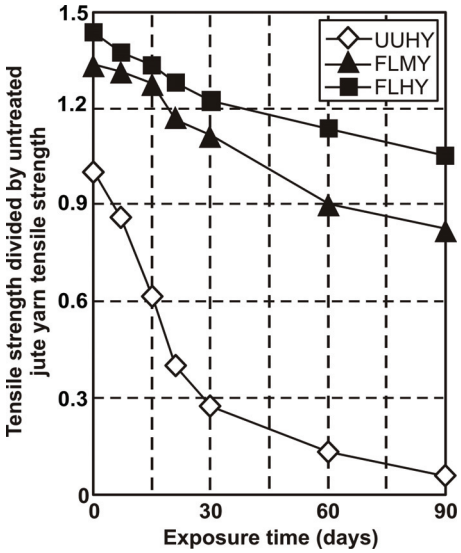

Figure 11. Yarn stability in saline solution

resistance for yarns manufactured with treated fibers. As in soil burial, the tensile strength retention observed in this case is smaller than the corresponding retention for treated and untreated fibers. Interpolation of these data indicates little degradation susceptibility of treated products for salinity level of 2 % or lower.

7.5. Acidity or Alkalinity Related Degradation

Average tensile strength retentions for handmade and machine made yarns (FLHY and FLMY) manufactured from treated fibers were about 70 %, 80 %, and 58 % of their initial tensile strength in the solutions of pH 4, 7 and 9, respectively. Correspondingly, UUHY retained only 7 %, 25 %, and 5 % of its initial tensile strength (Figure 12). The results also indicate that the handmade yarn retained somewhat greater proportions of tensile strength compared to the machine made sample. Additionally, yarns manufactured from treated fiber exhibited greater susceptibility to degradation under elevated acidic and alkaline conditions than under neutral conditions. As demonstrated earlier, treated fibers contained fatty acid ester bonds. Since ester bonds are known for their susceptibility to hydrolysis under elevated acidic and alkaline conditions, the yarns manufactured from treated jute retained smaller proportion of tensile strength in acidic and alkaline conditions.

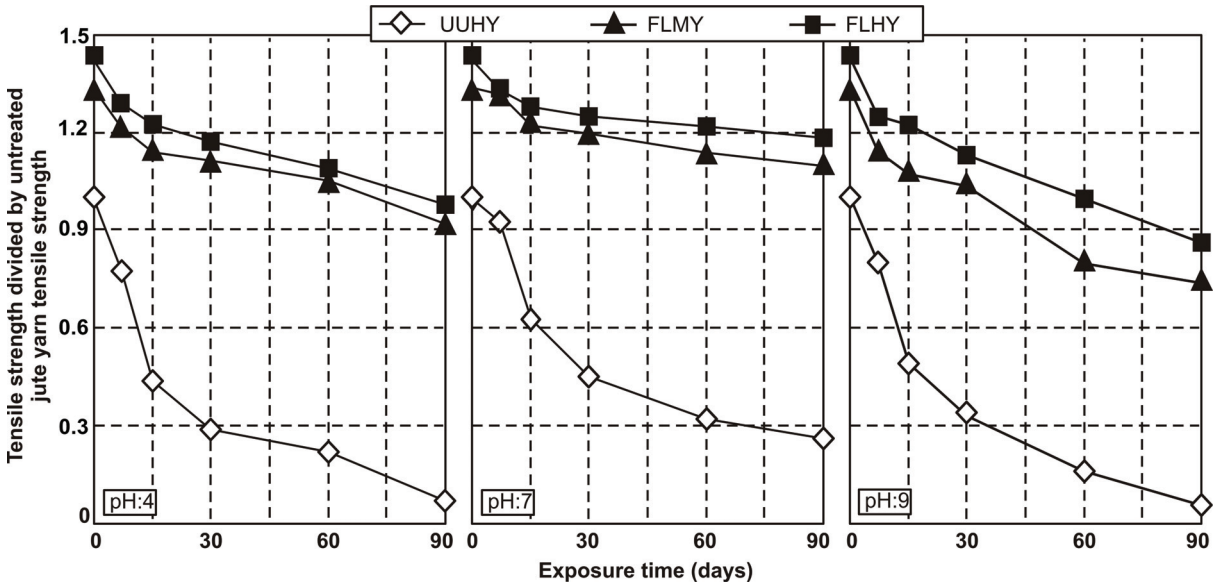

Figure 12. Resistance of yarns against acidity and alkalinity

8. PRODUCT/PROCESS STANDARDIZATION

Review of literature indicated that degradation resistance of jute fibers, yarns or fabric could be enhanced by modifying the hydroxyl groups within the cellulose chains of jute fibers and coating the fibers with hydrophobic and degradation-resistant, cross-linkable, non-leachable resin. To this end, jute fibers, yarns and fabrics were treated with reagents prepared by combining a variety of vegetable oils (e.g., neem oil and rice bran oil), fatty acid distillates and phenolic resins (e.g., extract of *Diospyros cordifolia* plant, resorcinol, plant tannin, cashew nut shell liquid) with known anti microbial characteristics. Reagent compositions and reaction conditions (pH, temperature and duration) were optimized for short-term tensile strength and biodegradation resistance of treated products.

The exercise led to the following definition of the optimized process:

- Dipping of Jute fibers or commercially available jute fabric were dipped for 24-h within an aqueous emulsion prepared from sodium hydroxide, plant tannin, cashew nut shell liquid, resorcinol, neem oil and formaldehyde in 1:10:8:2:6:4 proportion by weight with pH of 8
- Squeezing the recovered the fibers / fabric mechanically to recover unused reagents and expelled amorphous matter, e.g., lignin, hemicelluloses and waxes
- Curing the fibers / fabric in a convection oven at 105 ± 5 ° C for 1 h.

9. REPORT ON PILOT SCALE / BULK SCALE TRIALS AND DISSEMINATION WORKSHOPS

9.1. Pilot scale trail 1

About 80 m^2 jute geotextiles (FLMG) was manufactured by weaving yarns in a pilot plant of IJIRA, Kolkata, India equipped with jute mill machinery. Similarly, around 500 m^2 of FIMG fabric was manufactured at Kamarhatty jute mill in India (Figure 13). Tensile strength and other physico-chemical properties of jute geotextiles were evaluated both for treated and untreated jute geotextiles.

Figure 13. Weaving of FIMG at Kamarhatty Jute Mill

9.1.1. *Manufacturers' Feedback*

Yarn (9 to 10 count) could also be spun at the pilot plant operated by Indian Jute Industries' Research Association (IJIRA) in Kolkata. The machinery and processes in this case were very similar to the carding, 3-stage drawing, and spinning activities of yarn manufacture in Indian jute mills. It was observed that the fibers were suitable for carding and drawing without the necessity of moisture conditioning and batching oil application. However, spinning of fibers necessitated (a) raising the gravimetric moisture content to 30 % and (b) minor modifications of spinning machinery (essentially increasing the gage length of feed to cylinder and cylinder to doper, and incorporating an additional scraper during spinning to overcome lapping of the treated fibers). Since the treated fibers were more hydrophobic than untreated fibers, moisture conditioning could be done after application a relatively minor amount of jute batching oil: 1 % of dry weight of treated fibers was needed in this case as opposed to 3 % normally required in yarn making in a jute mill.

For the trial of the spinning process 400 m^2 of geotextile has been manufactured within the commercial set-up of machinery present at Kamarhatty Company Ltd., Kolkata in February 2011. Approximately 500 m^2 geotextile (680 gsm, 12 lb/14400yard warp yarn and 23 lb/14400yard weft yarn) could be manufactured with the fibers treated with the technology developed in this project for possible field trial. Following feedback was obtained from Kamarhatty Co. Ltd. from the manufacturing process:

- During processing, one of the steps of carding has been avoided before spinning to maintain the regularity and uniformity of the yarn

- Avoiding one of the carding steps affected the quality ratio (QR) of the yarn. The QR for yarn after spinning was marginally low for warp and weft direction
- The application of JBO or any other batching oil could be avoided for treated fibers, as the fibers were already treated with vegetable oil
- No particular problem was encountered during weaving.

Further optimization of the spinning process is considered necessary before the viability of manufacturing geotextiles with treated yarn at an existing jute mill can be assessed. Kamarhatty authorities opined that they could optimize their spinning process and machinery if approximately 2.5 t of treated jute fibers were available. However, NJB considered it more practicable to apply the treatment on commercially available woven jute fabric if the degradation resistance of treated fabric obtained in this manner is comparable to those manufactured from treated jute fibers. Consequently, degradation resistance was assessed for woven jute fabric manufactured from treated jute fiber and commercially available jute fabric treated with the chemical process developed in this project as discussed later.

9.2. Pilot scale trail 2

Similar chemical treatment was applied on commercially available jute geotextiles in an industrial set-up of Textile manufacturing unit KE Technical Textiles Pvt. Ltd. (KETex) near Kharagpur. Approximately 30 m^2 of raw jute woven fabric (700 g/m^2, thickness: 1.63 mm) supplied to us were treated with the mixture of a resin (1.25 %) and vegetable oil in alkaline medium by dipping for 16 h in chemical vats. After that the water based resin was soaked and excess resin was squeezed out. Then jute geotextiles was passed through a vertical oven maintaining a temperature of the oven at 110° C for 20 min. The speed of fabric movement was 1.49 m/min. The pressure of squeezing was 3.5 kg/cm^2. The entire work was done in an industrial set-up of KETex on June 27, 2011 (Figure 14).

9.3. Characterization of the geotextiles manufactured in pilot scale trials

Untreated and chemically treated geotextiles (UUMG, FLMG, TIMG, and FIMG) were characterized for their degradation resistance and the results were discussed in the following subsections. The specifications of the geotextiles are shown in Table 3.

9.3.1. Tensile Strength

The cross machine direction tensile strengths for TIMG was about 10 % higher compared to UUMG2 samples (control of TIMG) (Table 4). The increase was less remarkable than the corresponding increases for jute fibers (75 %) and yarns (33 %, for FLMY). The loss of efficacy is explained by loss of short fiber interlock within the fabric because of removal of alkali hydrolysable fiber constituents, e.g., hemicelluloses and lignin, during NPRA treatment of jute fabric.

Figure 14. Industrial treatment of Jute geotextiles at KETex

Table 3. Geotextiles specifications

Parameters	UUMG	FIMG	TIMG	Standard
Area density (g/m2)	700	690	620	ASTM D5261-10
Tensile strength (kN/m)	22	19	25	ASTM D751-06
Thickness (mm)	1.4	1.3	1.4	ASTM D5199-10
Yarn linear density (ktex)	0.68[a], 0.99[b]	0.46[a], 0.46[b]	0.68[a], 0.99[b]	ASTM D861-07
Fabric mesh (threads/mm)	5.5[a], 3.9[b]	7.1[a], 3.9[b]	5.5[a], 3.9[b]	IS1963-81
Weave pattern	1 up 1 down	1 up 2 down	1 up 1 down	-
O_{95} (mm)	235	255	245	ASTM D4751-04
Permittivity (cm/sec)	0.083	0.09	0.083	ASTM D4491-99
Water repellence (%)	0	90	90	IS390-1975

[a] Machine direction
[b] Cross machine direction

Table 4. Short-term tensile strength and elongation at break of geotextiles

Sample	Tensile strength (kN/m) ± CL		Elongation at break (%) ± CL		Water absorption (%)	EMC (%)
	MD	CD	MD	CD		
UUMG1	17±3	19±2	09±2	12±3	250±17	16±07
FLMG	18±3	16±2	12±2	10±4	87±12	10±05
UUMG2	22±6	21±5	11±1	08±2	270±35	19±06
TIMG	25±4	23±3	13±4	09±2	120±30	13±03
FIMG	19±2	21±3	12±5	09±3	90±22	09±05

Similarly water absorption and equilibrium moisture content (EMC) reduced remarkably for the FLMG, FIMG, and TIMG. The proportional reductions in this case, were similar to those observed for jute fibers following NPRA treatment. The results also indicate that the geotextiles fabricated from treated fibers (FLMG and FIMG) exhibited marginally less water and moisture affinity compared to a similar product obtained after fabric level treatment (TIMG). Since the application of treatment on fabric prevents the reagents to penetrate into the fiber surface, the efficacy of chemical treatment for TIMG is expected to be less.

9.3.2. *Biodegradation Resistance*

FLMG samples retained about 53 % of their initial narrow strip tensile strengths while UUMG1 (control for FLMG) retained only 11 % (Figure 15) after 90-d MSBT. Similarly, TIMG and FIMG samples retained 37 % and 48 % of their initial narrow strip tensile strengths, respectively, while tensile strength for UUMG2 could not be measured beyond 90 days of exposure because of complete disintegration (Figure 16). More pronounced effect of

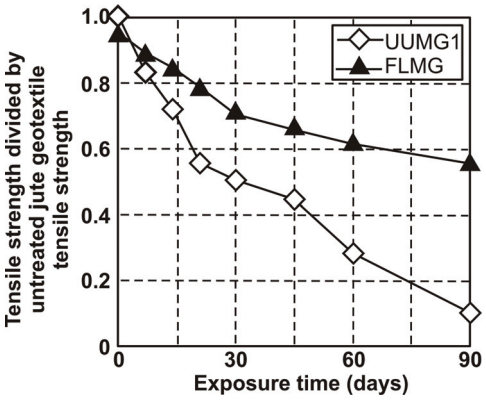

Figure 15. Resistance to biodegradation jute geotextiles treated at laboratory scale

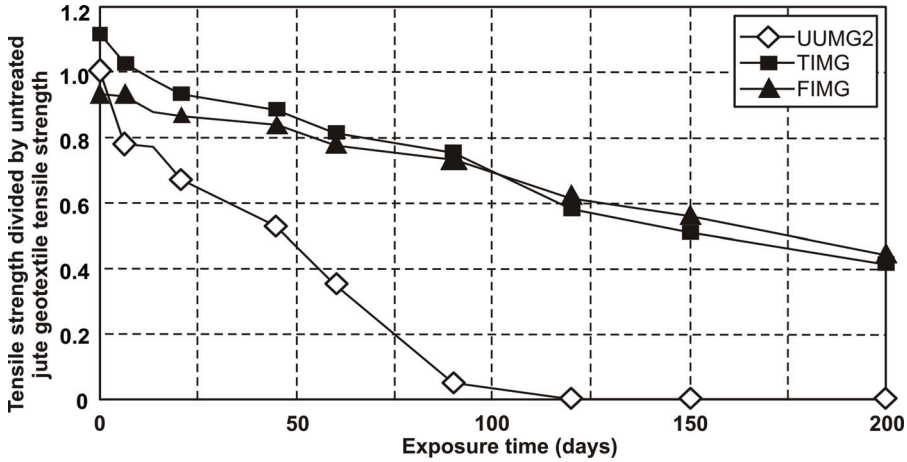

Figure 16. Resistance to biodegradation jute geotextiles treated at industrial scale

biodegradation on UUMG2 is apparent from the photographs presented in Figure 17. It also appears from the figure that biodegradation affected the TIMG sample more remarkably than FIMG. These results demonstrate a remarkably higher biodegradation resistance for jute geotextile fabricated from treated fibers. Notably, the tensile strength retention observed in this case is smaller than the corresponding retention for treated and untreated fibers. This can

also explained by better effectiveness of chemical reaction for processes when applied on treated fibers compared to that applied on fabric level.

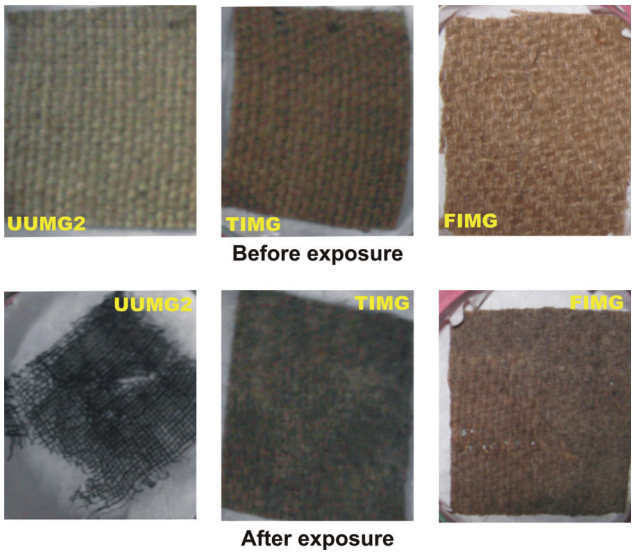

Figure 17. Photographs of jute geotextiles before and after 200 days soil burial test

9.3.3. Salinity Related Degradation

FLMG samples retained about 65 % of their initial narrow strip tensile strength after remaining immersed in 3 % NaCl aqueous solution for 90 days (Figure 18). A similar untreated fabric, UUMG1, retained only 28 % of its initial strength after an identical exposure. In comparison, TIMG and FIMG samples retained 64 % and 82 % of their initial narrow strip tensile strengths, respectively, after remaining immersed in 3 % NaCl aqueous solution for 120 days (Figure 19). A similar untreated fabric, UUMG2, retained only 17 % of its initial strength after an identical exposure.

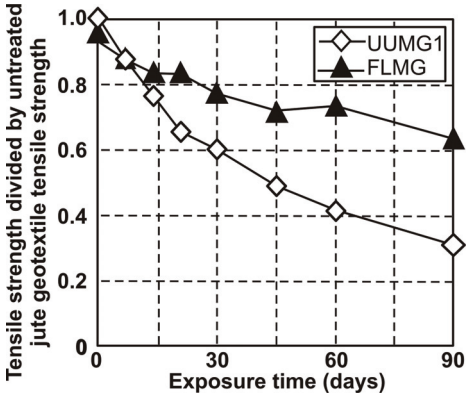

Figure 18. Salinity-related tensile strength degradation of FLMG and UUMG1

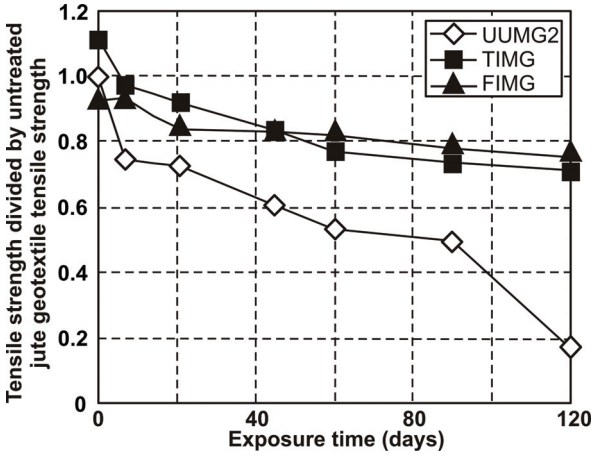

Figure 19. Salinity-related tensile strength degradation of FIMG, TIMG and UUMG2

9.3.4. *Acidity and Alkalinity Related Degradation*

Tensile strength retentions for FLMG were 53 %, 46 % and 33 % of their initial narrow strip tensile strength upon being immersed in aqueous solutions with pH 4, 7 and 9, respectively for 90 days. Samples of a similar untreated fabric, UUMG1, retained only 12 %, 22 %, and 5 % of their initial narrow strip tensile strength (Figure 20). In comparison, TIMG, and FIMG

samples retained more than 60 % of their initial narrow strip tensile strengths upon being immersed in aqueous solutions with pH between 4 and 9 for 120 days.

Samples of an untreated fabric, UUMG2, retained only 15 % after an identical exposure (Figure 21). The results also indicate that the geotextiles fabricated from treated fiber exhibited greater susceptibility to degradation under alkaline conditions (greater than pH 9) and under acidic conditions (less than pH 3).

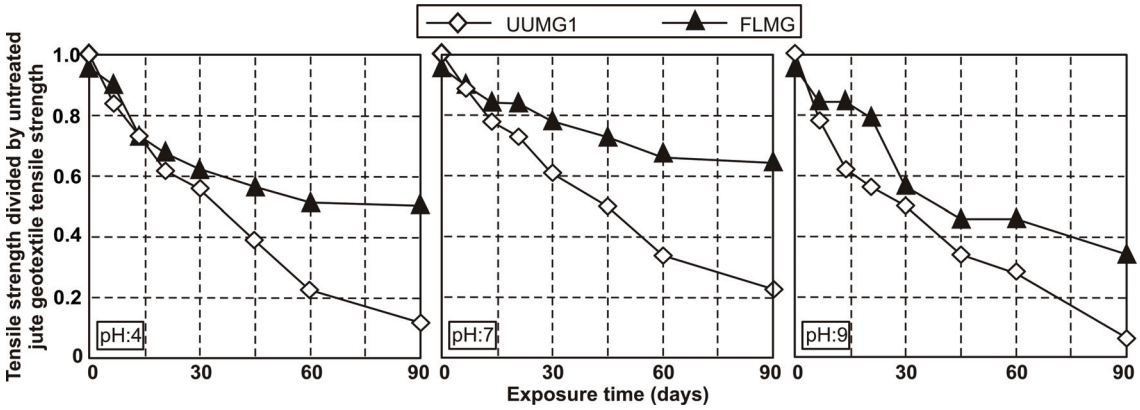

Figure 20. Resistance of laboratory treated jute geotextiles to acidity and alkalinity

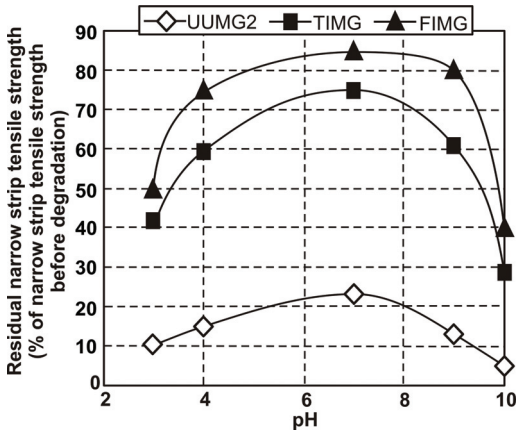

Figure 21. Tensile strength retention of industrially treated geotextiles as function of pH

9.3.5. *UV and Moisture Related Degradation*

After 500-h AAW, FLMG samples retained 65 % of its initial narrow strip tensile strengths, respectively (Figure 22). In comparison, samples of a similar untreated fabric, UUMG1, correspondingly retained only 22 %. Similarly, TIMG and FIMG samples were found to retain 75 % and 80 % of their initial narrow strip tensile strengths (Figure 23). Samples of a similar untreated fabric, UUMG2, correspondingly retained only 33 %. Discoloration effect was also found to more remarkable for UUMG2 compared to that of FIMG and TIMG after AAW (Figure 24) possibly because of delignification.

9.3.6. *Leachates Study*

The treated and untreated fabrics were further characterized for potential toxicity of degradation products. Result showed that the concentration of the toxic chemicals within the

post-degradation leachates were lower than the permissible limit (Table 5). Further details of the tests can be found in Saha et al. (2012), a copy of which can be found in Appendix 2.

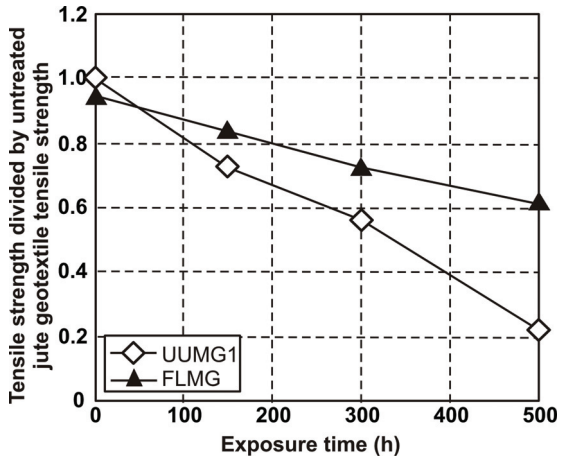

Figure 22. AAW-induced tensile strength degradation of UUMG1 and FLMG

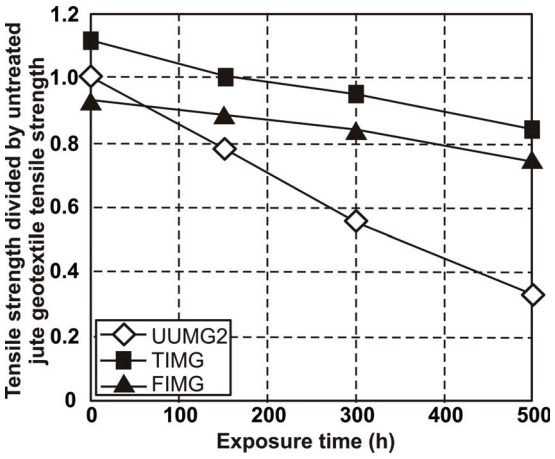

Figure 23. AAW-induced tensile strength degradation of UUMG2, TIMG and FIMG

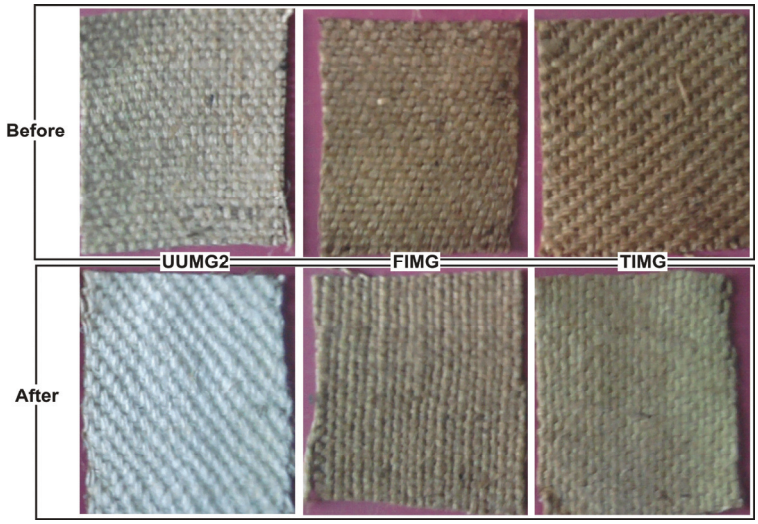

Figure 24. Appearance of jute geotextiles before and after 500-h AAW

Table 5. Leachate characterization

Source	FIMG		TIMG	
	Formaldehyde(1)	Tannin(1)	Formaldehyde(1)	Tannin(1)
Soil burial	0.02	0.1	0.01	0.1
Salinity	0.02	0.1	0.02	0.2
At pH 3, 7 and 10	0.01, 0.01, 0.01	0.7, 0.2, 0.5	0.01, 0.02, 0.01	0.5, 0.3, 0.8
AAW	0.02	0.1	0.02	0.2

Note. 1. Allowable limits in surface and groundwater: 0.05 mg/L (detection limit: 0.01 mg/L) for formaldehyde and 6 mg/L (detection limit: 0.01 mg/L) for tannin

9.3.7. *Service Life Estimation*

For this present investigation up three types of samples were used. Untreated B-twill jute geotextiles (800 g/m^2) sample was obtained from Indian Jute Industries' Research Association (IJIRA), Kolkata. This untreated sample was chemically treated with the process developed at IIT, Kharagpur. Details of the chemical treatment process have been provided

elsewhere. The untreated and treated geotextiles designated as UUMG1, FLMG, UUMG2, and FIMG were characterized for their susceptibilities to physical, chemical and biological degradation. Another B-twill geotextile (700 g/m^2), designated TIMG, manufactured by blending approximately 15 % raw jute fibers with 85 % TD4 grade jute fiber treated with IIT Kharagpur chemical treatment process was also similarly characterized.

Three types of geotextiles samples (untreated, treated and geotextiles manufactured with treated fibers from JGN project) were exposed in the weather chamber (SUNTEST XXL/XXL, ATLAS), and recovered after different time duration to evaluate the residual mechanical strength, and water repellency. Specimens were exposed for 150, 300 and 500-h duration under artificial weathering cycles using Xenon Arc light UV source in the wavelength between 300 and 400 nm with 66 KJ/m^2/h irradiation (AAW). The exposure is coupled with repetitive cycles comprised of 90 minutes of drying in at 65 ± 5° C sample temperature and 50 ± 5 % relative humidity and 30 minutes of water spraying. The loss of tensile strength after 150, 300, and 500 hour of exposures was assessed according to ASTM D-4595 (2005) for narrow strip geotextile samples.

Following Koerner et al. (2005), the estimate was scaled with the ratio of total AAW UV irradiation to the yearly UV irradiation of eastern India obtained from Wypych (2008) to obtain the field half-life. The time needed for 50 % loss of tensile strength found in the laboratory – the sample half life – and the service life estimated from laboratory half life are listed in Table 6. The water absorption of all the samples was found to increase with exposure time during the accelerated physical weathering tests.

Half-life for geotextile samples (UUMG1, FLMG, UUMG2, FIMG, and TIMG) was estimated by fitting the AAW data to $Y = A + bt$, where Y is the narrow strip tensile strength at time t (days) and A and b are constants, and estimating the time of exposure for 50 % degradation of the initial narrow strip tensile strength, the so-called half-life, from the best-fit relationship. Subsequently the estimate was scaled with the ratio of total AAW UV irradiation to the yearly UV irradiation of eastern India obtained from to obtain the field half-life Koernar et al, 2005; Wypych, 2008). These results together with the correlation coefficients presented in Table 4 indicate field half-lives for UUMG1, FLMG, UUMG2, FIMG and TIMG geotextiles to be 294, 619, 330, 1115 and 881 days, respectively, for installations under direct sunlight.

Half-life for geotextile samples (UUMG1, FLMG, UUMG2, FIMG, and TIMG) was also estimated by fitting the data obtained from 3 % salinity exposure to $Y = A + b\log t$, where Y is the narrow strip tensile strength at time t (days) and A and b are constants, and estimating the half-life from the best-fit relationship. In this case, the laboratory estimates are expected to be similar to those representing field conditions although field salinity is likely to be significantly smaller than the 3 % salinity used in the laboratory while testing and vary seasonally.

Table 6. Half-life of jute geotextiles

Sample	Test	Y (kN/m), A, b, r^2	Expected half-life (d)	
			Lab	Field
UUMG1	AAW	9, 18, –3.1×10–2, 0.98	14	294
	Soil burial	–	30	240
FLMG	AAW	9, 17, –1.2×10–2, 0.99	30	619
	Soil burial	–	98	784
	3 % Salinity	9, 1.19, –0.20, 1.00	887	887
UUMG2	AAW	11, 21, –2.9×10–2, 0.99	15	330
	Soil burial	–	48	384
	3 % Salinity	11, 1.23, –0.38, 0.98	41	41
TIMG	AAW	12, 24, –1.2×10–2, 0.99	41	881
	Soil burial	–	135	1080
	3 % Salinity	12, 1.10, –0.18, 0.99	1060	1060
FIMG	AAW	10, 20, –7.9×10–3, 0.99	53	1115
	Soil burial	–	198	1584

Consequently, the laboratory estimates are likely to be conservative. These results together with the correlation coefficients presented in Table 6 led to field half-life estimates of 41, 887, 1060 days, respectively, for UUMG2, FLMG, and TIMG geotextiles installed under water with 3 % salinity. Extrapolated tensile strength retention of untreated and treated geotextiles at different years is presented in Table 7.

Table 7. Estimates of retained tensile strength (kN/m)

Sample	Test	Initial strength	After being in service for (years)				
			1	2	3	4	5
UUMG	AAW	22.0	7.7	ND	ND	ND	ND
	Soil burial		1.1	ND	ND	ND	ND
FIMG	AAW	19.0	18.2	15.5	12.4	9.3	6.5
	Soil burial		16.2	14.3	11.4	8.6	5.7
TIMG	AAW	25.0	21.3	18.1	14.2	10.6	7.4
	Soil burial		22.5	19.0	16.8	11.3	6.3

Laboratory observations indicate that for treated samples the rate of deterioration of narrow width tensile strength beyond half life is substantially slower than that of raw sample. Consequently, the service life for treated samples is expected to be higher than that estimated above. On the other hand, the half-life estimates obtained by extrapolating laboratory observations, during field installations, the fabric is expected to be exposed to an environment with fluctuating water levels, seasonally variable microbial actions and exposures to sunlight and activities of burrowing animals. Therefore the performance of geotextiles in typical field environment needs to be evaluated to verify the estimate. It is understood that such verification has been planned with TIMG-2.

Regardless, the extrapolated half-lives of treated samples – an approximate measure of the service life of these fabrics – were found to be in the range between about 1100 and 1600 days. These estimates are several times longer than service lives of untreated jute geotextiles of 1.5 to 10 months found in the literature.

9.4. Bulk scale trial

An industrial treatment has been done to treat 3000 meters of jute geotextiles (700 GSM, thickness: 1.63 mm) provided by NJB, Kolkata. The treatment was done by dipping the Geotextiles in vegetable Oil-phenolic resin (solid content 1%) for 24 h. Subsequently the geotextiles was squeezed and dried in a vertical oven at 110° C for 20 min. The entire work was done in an industrial plant of KETex between March 7 and 11, 2013 (Figure 25). The treated fabric is ready to be installed in a river bank for erosion control.

Figure 25. Industrial treatment of 3000 meters jute geotextiles

9.5. Dissemination Workshops

A workshop was organized for the evaluation of projects funded by JMDC on December 21, 2009 at Indian Institute of Technology, Kharagpur to provide an update to the stakeholders (representatives of industrial organizations, marketing agencies, and research and development organizations) on the status of technology development. Thirty one participants from different governmental agencies, jute mills and companies were participated in this workshop. The details of the participants were given in Appendix 3.

A second workshop was organized at the Kolkata Center of IIT Kharagpur on April 19, 2012 in Salt Lake City, Kolkata to apprise the stakeholders on process details and initiate possible technology transfer. Forty two participants from different governmental agencies, jute mills and companies were participated in this workshop. The details of the participants were given in the appendix 3.

9.5.1. *Workshop Interactions*

The issues relevant to the jute geotextile project raised by the stakeholders present in the workshop and the responses of the project team follow:

a) Determination of additional cost factor for compliance of OHSA & ASTM standards.

- The process developed is OHSA and ASTM compliant.

b) Examining comparative suitability of treatment at the fiber/yarn/fabric stage.
   - Technically a part of the treatment needs to be applied in the fiber stage for maximum effectiveness. The treatment can be applied to the fiber/yarn/fabric stage (see section B).

c) Confirmation regarding full/partial elimination of jute batching oil and the resultant reduction in cost.
   - It appears that jute batching oil can be eliminated fully.

d) Confirmation regarding requirement of special machinery for the treatment. If so, the cost involvement.
   - A dipping tank, squeezer, and an oven capable of heating the treated fabric to 105 °C.

e) Confirmation regarding improvement of physical characteristic regarding spinability, tensile strength etc.
   - Physical characteristics of treated jute fibers have been extensively studied as outlined in this report. As advised by the project reviewers, the focus was shifted from fiber-level treatment followed by spinning and weaving of geotextiles to treating commercially available woven jute fabrics. As a result, the issue of spinability does not arise. However, feedback from the jute mill, where jute fibers treated with the process developed in this project were spun into yarns and woven thereafter into a fabric, indicated that with minor modifications of existing sinning machinery the treated fibers can possibly be accommodated in the manufacturing process of the mill.

f) Quantification of water-repellence and durability in different water-ambience (saline/sweet/turbid).
   - Treated fibers and yarns manufactured from treated fibers were evaluated for their resistance to chemical (pH and salinity), physical (UV) and biological degradations extensively outlined in this report.

g) Availability of the developed fabric for pilot study. Dissemination of technology to selected jute mills for production. Physical demonstration of the process technology
   - Two pilot studies have been done for treatment of the industrial fabric.

h) Comparative analysis of properties vis-à-vis man-made geotextiles and conventional JGT
   - Comparative analysis of the properties of fibers and yarn tensile strength is complete.

9.5.2. *Industrial Interests*

Representatives of jute mills participating in the workshops organized by IIT Kharagpur to disseminate the information regarding technology development related to this research project evinced keen interest in adopting the technology. More details on these workshops are provided in Appendix 3. Their essential enquiry revolved about need for capital expense and process equipment.

They were informed that the technology is ready to be transferred on non-exclusive basis and details such as process equipment particulars can be provided on a case-by-case basis. A number of other organizations in the small-scale and medium-scale sectors have also shown interest in manufacturing jute-based products using the treatment technology developed at IIT Kharagpur. Specifics of these interests are summarized in Table 8.

Table 8. Name and contact detail of the NGO and company

Organization	Description of the organization	Contact
KE Technical Textiles Pvt. Ltd, Rupnarayanpur, Jakpur, Kharagpur 721301	Industrial manufacturers of technical textiles. Intends to manufacture geotextiles	Mr. Sukumar Roy 03222291521, skr@ketex.com
Roots & Yards 79/1/A AK Mukherjee Road, Kolkata 700090	Hand spinning of yarns and manufacturer of jute-based products, e.g., carpets and drapery. Intends to manufacture yarns and weave them into fabrics	Mr. Atis Chandra 09836002746
Chaplin Club, Trilochonpur, Medinipur, WB 721101	Hand spinning of yarns and manufacturer of jute-based products, e.g., carpets and drapery. Intends to manufacture yarns and weave them into fabrics	Mr. Sanjoy Karak or Mr. Rabindra Pandit 03222239950

10. COST ANALYSIS / COST EFFECTIVENESS STUDY REPORT

Actual treatment costs incurred during trial manufacturing of jute geotextiles is summarized in Table 9. The results indicate the treatment costs to be consistently in INR 17 to INR 19 range per square meter of 700 g/m^2 woven jute fabric. It should be noted that the costs are likely to come down further in larger scale manufacturing. Considering the cost of bitumen treatment – the alternative treatment approach being used to manufacture degradation-resistant jute geotextiles – of around INR 35 per square meter of 700 g/m^2 woven jute fabric, it appears that the treatment process developed in this research is relatively inexpensive. Further cost comparison of jute-based and other industrial textiles reported by Saha et al. (2012), Appendix 2, also establishes relative economy of geotextiles treated with the process developed in this research.

Table 9. Treatment costs in INR/ m^2 of different geotextile (700 g/m^2)

Geotextile sample	Reagent	Capital	Water	Manpower	Energy / operation / logistics	Total Cost (INR)
FLMG (2011 costs)	7.20	3.20	0.03	2.2	5.6	18.23
FIMG (2011 costs)	7.00	2.70	0.03	1.8	5.5	17.03
TIMG (2013 costs)	7.80	3.00	0.01	1.13	7.1	19.04

Details of the cost calculation (for TIMG) have been provided in Table 10. It should be noted that the machinery used during these treatments was not optimized for the treatment process. Consequently the treatment cost is expected to be smaller than those indicated in Tables 9 and 10 once manufacturing begins at a facility optimized for the process.

Table 10. Details of the cost calculation

Items	Details	Cost (INR/m^2)
Reagents (resorcinol, formaldehyde, CNSL, tannin and Neem oil)	1 l reagent mixture is needed to treat 1 m^2 of geotextiles. Cost of the mixture is INR7.8 per l.	7.8
Infrastructure (vat, stirrer)	–	3.0
Water	2 l water is needed to treat 1 m^2 of geotextiles. Cost of the water is 0.01 per lit (Kumar, 2003)	0.02
Man power	Man power cost for per h fabric treatment is INR 68. Within an hour 60 m^2 fabric can be treated using KETex facility.	1.13
Energy / operation / logistics	Electricity cost is INR 0.88/ m^2 fabric treatment, gas flow cost is INR6.22/ m^2 fabric treatment	7.1
	Total cost	**19.04**

11. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

11.1. Summary and Conclusions

In this research a chemical treatment process has been developed using an alkaline water-based emulsion of vegetable oil and plant based phenolic resin for enhancing tensile strength, hydrophobicity of LCFs to make them more resistant against biological, chemical, and UV-related degradations. The process is mainly based on the use of inexpensive, non-hazardous and non-toxic chemicals and adapted in existing industrial plants. The treatment was applied to jute fibers leading to a demonstrable increase in their tensile strength, hydrophobicity and resistance against biological, chemical, and UV-related degradations without affecting their flexibility. These improvements appeared to be due to the removal of amorphous fiber constituents (cellulose and lignin) known to prevent optimal load transfer, chemical modification (transesterification) and blocking (attachment of phenolic compounds via H-bonding) of some of the hydroxyl groups of fiber cellulose and changed crystallinity. Industrial fabrics were manufactured from treated jute fibers at an existing jute mill although the attempt indicated that the spinning and weaving processes optimized for untreated jute fibers would require modification before using the fibers treated with the process developed in this research. The treatment was also applied on a commercially available jute-based industrial textile leading to improvements in degradation resistance and long term tensile strength although the improvements in this instance were somewhat less remarkable compared to the fabric manufactured from treated fibers. Indian Patent application has been filled by joint ownership of IIT Kharagpur and NJB, Kolkata for patenting the technology (Patent application No- 1263/KOL/2009, dated 4th November, 2009).

The major findings from the industrial manufacture of woven fabric with jute fabric treated with the process developed in this research, treatment application on woven jute fabric procured from a jute mill and laboratory scale assessments of the treated products were:

- The treatment caused the short term fiber tensile strength to increase by 75 %, the water absorption to decrease from 255 % to 79 % (in terms of dry fiber weight) for jute.
- The treated fibers could be spun into yarn in existing machinery facilities in jute mills, however, the spinning process needs optimization to overcome the fibers lapping during spinning process.
- Jute fibers treated with the chemical process developed in this research in an industrial setup were manually and mechanically spun into yarns.
- The short term tensile strengths of handmade and machine made yarns were found exceed the corresponding values for yarns manufactured from untreated fibers by 43 % and 33 %, respectively.
- Several trials were done for treatment and manufacture of jute geotextiles in the industries
- Degradation resistance of the fabric manufactured from treated jute fibers in UV-moisture were somewhat larger than that of the woven jute fabric treated with the process

developed in this project. For instance, the estimated field half-life of the FIMG sample (fabric manufactured from treated jute fibers) was 1584 days, while that for TIMG sample (woven jute fabric treated with the process developed in this project) was 1080 days. Correspondingly the half-lives for UUMG2, FLMG, and TIMG geotextiles to be 41, 887, 1060 days, respectively, for installations under immersion within water containing 3 % saline.

- The performance of geotextiles in typical field environment needs to be evaluated to verify the estimate. It is understood that such verification has been planned with TIMG-2
- The treatment process developed in this research is relatively inexpensive than the alternative bitumen treatment approach.
- The leachates collected from fiber or geotextile degradation medium were tested for presence of potential toxic chemicals and found that the concentrations of toxic elements in leachate were within the maximum allowable limit for ground and surface water.

11.2. Recommendations

Jute-based industrial textiles can be prepared from treated fibers in the existing jute mills by minor changing in the spinning and weaving processes. The treatment also can be applied on the commercially available jute-based industrial textile leading to improvements in degradation resistance and long term tensile strength although the improvements in this instance were somewhat less remarkable compared to the fabric manufactured from treated fibers. Regardless since it was apparent that the fabric level treatment process is more feasible in being adapted at an existing jute mills, the fabric level treatment is recommended at the present time.

The treated fabrics should be installed in full-scale river bank erosion control projects for assessing the service life estimates and obtaining feedback from potential users. If the performance of the treated products is found satisfactory and a favorable feedback is obtained from potential users based on these performance studies setting of a dedicated geotextiles manufacturing facility optimized to accommodate the more effective fiber level treatment may be considered feasible.

11.3. Acknowledgements

The project team wants to acknowledge the critical reviews, suggestions, facilitation and encouragements of the officials and consultants of NJB, Kolkata. The help received from Mr. S.K. Roy, MD, KETex Technical textiles Pvt. Ltd. at various stages of the project work is also appreciated. Critical help was also received from Mr. Sushant Agarwal, MD, Kamarhatty Group, Mr. D.N. Singha of Kamarhatty Jute Mill and Mr. B.M. Thakkar of Budge Budge Jute Mill, for which the project team is grateful. The project team also wants to acknowledge the help and technical input received from Gloster and Ludlow jute mills during the execution of the project.

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Appendix 1

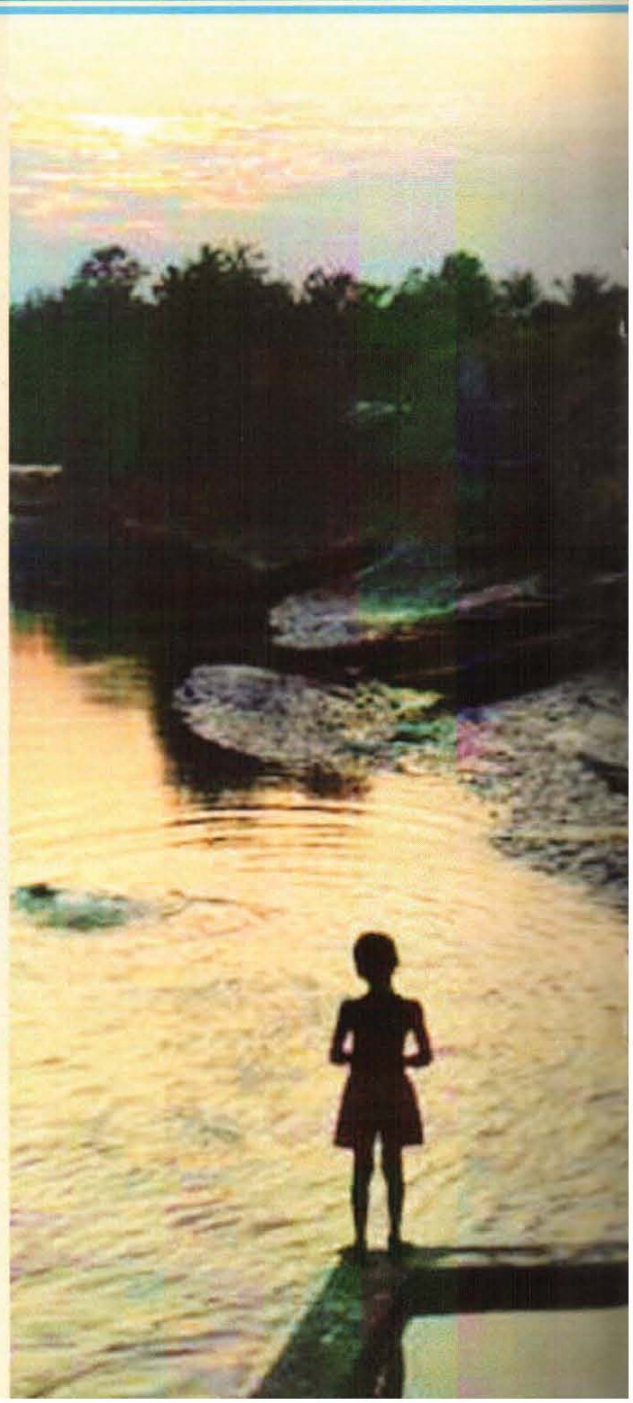
Need Assessment and Market Demand Survey

Need Assessment and Market Survey for Jute-geotextiles in Riverbank Erosion Control Applications

Prepared by:
Debasis Roy
Prosenjit Saha
Atish Ch. Chanda

For:
National Jute Board (NJB)
Ministry of Textiles, Govt. of India

Correspondence may be made to:
Debasis Roy
Associate Professor
Department of Civil Engineering
Indian Institute of Technology,
Kharagpur. 721302
WB, India
debasis@civil.iitkgp.ernet.in
Tel. +91 3222 283456
Fax: +91 3222 282254



1. Executive Summary

River bank erosion is one of the major application areas for geotextiles. Geotextiles is a special kind of technical textiles made with synthetic and natural fibers. The contribution of synthetic fibers is predominant for manufacturing geotextiles due to its high strength and durability. Use of natural fibers has been increasing for past few years. Natural fibers are environmental friendly, economic (prices are not affected with the global petroleum market unlike synthetic counterpart), hydrophilic (allow the growth of vegetable and plants in installation sites). However, lower durability of natural fibers is the major disadvantage which restricts its use as geotextiles in river bank erosion control. Considering this problem, a funded research project from National Jute Board (NJB, India) was undertaken by the Department of Civil Engineering, IIT Kharagpur to manufacture durable geotextiles with natural fibers such as jute. The main objective of this project was to develop a chemical method to enhance the durability of JGT and to replace the existing method of improving JGT durability with bitumen coating, as bitumen is not eco-friendly and its price is affected by the instability of global market price of petroleum. The market need and demand assessment of JGT in river bank erosion control has been presented in this report as it was one of the sun-objective of the assigned research project.

A methodology based on the estimation of potential and typical application area where JGT can be installed has been adopted to forecast the market of JGT. Length of the available river dikes was estimated for the several countries. These countries were chosen to illustrate the representative market analysis for the categories of high income countries. After estimating the total dike length of representative countries, the length of river dike where the synthetic geotextiles could be used for erosion control was calculated based on the available data sources. Thereafter the % of length where synthetic geotextiles can be replaced with JGT was forecasted. The details of the data sources and methodology are given in this report. After that we compared the numbers obtained from our methodology with available numbers obtained from several recognized sources and found that the numbers were well comparable. The report estimates the global market for JGT for the year 2012-13 will be INR 27 crores.

20 July 2011

Debasis Roy
Department of Civil Engineering
IIT Kharagpur

Prosenjit Saha
Materials Science Centre
IIT Kharagpur

Atish Ch. Chanda
Roots & Yards
Kolkata

Need Assessment and Market Survey for Jute-geotextiles in Riverbank Erosion Control Applications

Table of Contents

1. Introduction

"The technical textiles industry is expected to register a growth of 11% per annum till 2012-13 and is likely to grow at 6-8% per annum till 2020 without any policy interventions. However, if government interventions take place in the form of regulatory push, the growth of technical textiles industry can be estimated at 12-15% per annum till 2020." Said Rita Menon, Secretary, Ministry of Textiles, Government of India, speaking at, "Techtex India Summit 2011" organised by Confederation of Indian Industry.

In technical textiles, natural geotextile is a prominent contestant in the geotextile subject. Natural textiles include sisal, coir, bamboo, jute and other bast and lignocellulosic fibers.

This report consists of the facts and figures of the market potential, i.e. expected demand figures and need assessment of jute geotextiles (JGT) with the treated jute fibers, treatment technology developed by IIT, Kharagpur and its application to prevent soil erosion in the river embankments and vulnerable ground slopes.

The marketing of JGT is very limited so far but scope of exploration is immense. To find potentials of that area, a market survey (sample survey method) and need assessment has been conducted in order to assess the need of JGT for control of soil erosion in different areas.

Certain synthetic geotextile materials are imported in India and are used routinely by irrigation and Public Works Departments of various state governments for soil erosion control and embankments and for other applications. The use of synthetic geotextiles and synthetic-natural geotextiles for erosion control is likely to increase in the future with stricter environmental regulations and enforcement.

Jute Geotextiles (JGT) is therefore likely to enter as an environmentally safer substitute over polymer based geotextiles. Here JGT may be used as an alternative and better substitution with proper design and "state of the art" product for soil erosion control and embankment. IIT, Kharagpur has developed a JGT which is technically advanced and ensures the long term support to the soil erosion.

The survey within the scope of Need Assessment and Market Survey encompasses the various areas of geotextile applications in the civil engineering sector with an emphasis on "Soil Erosion Control" because the product developed by IIT is exclusively for soil erosion control. The methodology of the survey and need assessment has properly been furnished. There are feedbacks from the suppliers' end, there are projected investment plans of the multinational companies in technical textile, feedback from the public sector has been taken, and there are detailed study of flood prone river banks and coastal areas across the world. Therefore the report is a compilation of various facets of study to assess the need of JGT in the Erosion Control and Embankment chapter.

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2. Existing Applications of JGT

- **Slope stabilization**

Slope stabilization envisages strengthening a soil body threatened with distress. JGT, when inserted within an embankment in appropriate layers, can prevent rotational slides. As a basal reinforcement, JGT curbs the settlement of an embankment or any fill. The principal cause of lateral dispersion of any fill, besides its low shear strength, is intrusion of water into the fill body. Drainage of water can be facilitated by insertion of the right type of JGT at appropriate levels within the fill.

- **As Separator to improve roadway performance**

The performance of roadways constructed on soft soils can be improved using jute geotextiles. Jute fabric when used as separator prevents the penetration of subgrade material into voids of granular base course. Jute geotextile was tried in several trials as a separator between subgrade and sub base layers. Results showed negligible settlements of the pavement after six months under traffic and no signs of surface distress observed in the treated test section.

- **Surficial soil erosion control**

Erosion of top soil either on a flat ground or on a slope can be effectively prevented by open weave JGT. Three dimensional construction of open weave JGT helps reduce the velocity of surface runoff by interposing successive micro barriers to the direction of flow and entrap the soil particles dissociated by the kinetic energy of rain drops. It has also been reported that JGT may add micronutrients to the soil on which it is laid and do not draw upon nitrogenous reserves on bio-degradation. Moreover JGT residue is beneficial as it helps enhance the hydraulic conductivity of soil.

- **Protection of river and canal banks**

Bitumen treated woven JGT has performed satisfactorily in controlling erosion of river and canal banks in different trials. Woven JGT can serve as a better and cost effective substitute of the conventional granular filter. Availability of granular aggregates often poses difficulty, apart from the difficulties encountered in exercising quality control. A layer of woven JGT treated with a suitable water repellant additive may replace the layers of granular aggregates. An armour layer over the fabric is however necessary to prevent the fabric displacement and its exposure to weather. Here IIT's technology should bring the appropriate solution to this sector.

3. Prospective Applications of Jute Geotextiles

Bitumen-treated woven JGT has performed satisfactorily in controlling erosion of river and canal banks. Woven JGT can serve as a better and cost-effective substitute of the conventional granular filter. Availability of granular aggregates often poses difficulty, apart from the difficulties encountered in exercising quality control. A layer of woven JGT treated with a suitable water-repellant additive may replace the layers of granular aggregates. An armour layer over the fabric is however necessary to prevent the fabric displacement and its exposure to weather. Bitumen however is not the ideal material for coating JGT as bitumen makes

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the fabric rigid and less drapeable. Search is on for a better additive that can retard degradation of JGT even after its continuous exposure to water; but we may have to rely on bitumen as a water-repellant additive till such time a more suitable alternative is found and successfully tried. Incidentally bitumen and jute have excellent thermal compatibility. IIT Kharagpur has been entrusted with this project by NJB under Jute Technology Mission, India. Let us hope technology developed by IIT Kharagpur will serve the purpose.

- **Approach to Control Bank Erosion**

Soil erosion by water and wind is responsible for about 56 percent and 28 percent respectively of world-wide land degradation. The US Army Corp of Engineers has estimated that in the USA alone the damage caused by soil erosion costs at least $200 million annually.

A soil erosion nuisance can become a serious landslide problem causing damage to property and loss of life. The solution is the provision of an erosion control systems by applications of geotextiles. IIT, Kharagpur suggests that the treated JGT can be of suitable use for the soil erosion control at lower price. The figure 1 shows how the JGT is installed for embankment management.

The approach to control bank erosion is to ensure 'sand tightness' and permittivity to prevent differential over pressure developing across the fabric. At the same time, it requires to be ensured that JGT should

possess sufficient strength to withstand installation stresses (Survivability of JGT) and retain the design strength up to at least 4 years for tidal rivers with two-way flows and 2 years for one-way rivers. Use of woven JGT in controlling riverbank erosion is recommended as an eco-friendly substitute of the conventional granular filter comprising graded boulders and ballasts of stone, laterite or similar materials of the desired specific gravity. JGT, while ensuring sand tightness under different types of extraneous hydraulic and mechanical loads, facilitates dissipation of the over pressure created as a result of intrusion of water into the bank soil due to rise of water level usually during the high tides in a tidal river and in unidirectional rivers during the rains. This is essentially a function of filtration ("sand tightness"). Lateral dispersion of water is also facilitated by JGT (drainage). Erosion is controlled as migration of the bank soil is substantively prevented and the entrained water within it is effectively release. JGT laid over the prepared bank soil requires to be ballasted by a layer of armour stones to prevent its direct exposure to weather. It is strongly advised by the engineers that seeds of local deep-rooted vegetation/grass should be spread after laying of the fabric. On degradation of JGT vegetation will take over, cling to the bank soil and dissipate energy of current and waves to a good extent. This is a bio-engineering approach that is being increasingly favoured in developed countries. JGT on its degradation will nourish the bank soil and improve its hydraulic conductivity, fostering quick growth of vegetation under normal situation. Care is to be taken to ensure that porometric features and tensile strength of the fabric are not adversely affected due to treatment. IIT, Kharagpur has invented a technology towards development of pretreated and post treated JGT which ensures the best solutions for erosion control.

Slope protection

A soil erosion nuisance can become a serious landslide problem causing damage to property and loss of life. The probable technical solution for soil erosion has been worked out by IIT, Kharagpur with treated JGT in two typical eroded sites in Contai and Panskura in West Bengal as shown in figure 1a and 1b.

Figure 1a
Soil erosion control trial
with treated JGT in Contai

Figure 1b
Soil erosion control trial
with treated JGT in Panskura

4. Process Flow

The Process Flow is drawn hereunder in Figure 2. The Process is shown in the fibers and in the fabric levels in Figure 3 & 4.

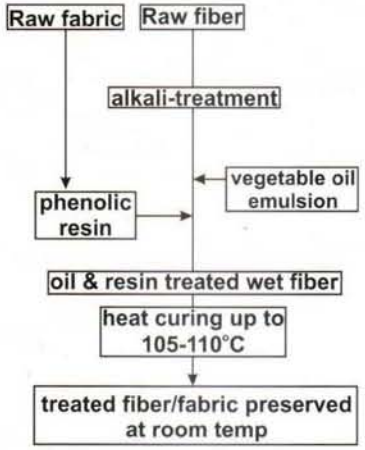


Figure 2. Process flow chart

Figure 3. Product photograph

Figure 4. Fiber treatment process and manufacturing of geotextiles within an industrial set up

5. Treatment

The details of the treatment and treatment cost are given as follows in Table no.1. The advantage of the treatment is also given in the following section.

Advantages of the treatment

- This treatment can replace the use of JBO
- Initial strength of the fibers increase up to 80 % than that of raw fibers after treatment
- Fibers become resistant to biological, physical and chemical degradation
- Durability of the treated fibers enhanced up to 70 % with respect to raw fibers
- Life expectancy of the fibers expected to be increased up to 2.5 times after treatment
- Process is suitable in existing industrial set up

Table 1. Estimated cost in INR/ sqm of geotextile (700 gsm)

Item	Cost
Treatment cost	
Sodium Hydroxide	1.50
Resorcinol	2.00
Tannin	1.50
Formaldehyde	1.00
CNSL	1.00
Vegetable oil	2.00
Reagent cost	9.00
Capital cost	2.00
Manpower	3.00
Logistics and other running cost @ 30 %	3.00
Total	17.00
Bitumen treatment cost estimate: 35/- (700 gsm)	

- This process can be adopted in industrial, semi-industrial or even in rural sector manufacturing unit
- The treatment can also be applicable on woven JGT, however the treatment cost will be a bit higher and the efficacy would be lower as indicated from the laboratory based results of IIT Kharagpur.

Need Assessment and Market Survey for Jute-geotextiles in Riverbank Erosion Control Applications

6. Properties and physical features of the JGT developed by IIT, Kharagpur

The Civil Engineering Department of IIT, Kharagpur has developed technology of JGT which is having several reasons to give the required solutions to soil erosion control.

The jute mills (the producers of the JGT) may use their own existing plant and machineries to manufacture the treated JGT. The treatment may be done at the fiber level before spinning or after the JGT is woven. However, IIT suggests the treatment process should be carried out at the fiber level in order to minimize the cost of JGT. If the treatment is done at the fiber level, use of batch oil (JBO) is limited for spinning. Heat is required for curing of the treated fibers. Since additional cost is negligible for treatment of fibers, it is expected that the technology will be highly accepted by the users. The specifications of the treated fabrics have been shown in Table 2.

Table 2 Specifications of JGT

Type of fabric	Weight (gsm)	Width (cm)	Threads		Thickness (mm)	Quality ratio = Tensile strength of yarn/count of the yarn x100	Tensile strength (KN/m		Water absorption capacity (%)	Indicative price (Rs/m^2)	Application areas
			MD	CD			MD	CD			
B-Twill woven[1]	650	40	10	10	0.5	0.55 (wd), 0.50 (wed)	20	18	80	18-20	River embankment
B-Twill woven[2]	680	42	11	12	0.45	0.65 (wd), 0.55 (wed)	21	20	70	18-20	do

[1] manufactured in IJIRA, Kolkata, [2] made in Kamarhati Co. Ltd, Kolkata , wd: wrap direction, wed: weft-direction

The civil engineering department of IIT, Kharagpur would like to see the application of that technology in the manufacturing of the JGT in the mills and the diversified sectors of JDPs. IIT shall transfer the technical document to the interested takers. The technical document will help the users to market the product globally. It is expected that industries will develop a proper process flow within the existing set up with all necessary technical inputs. The process demonstration may be provided by the IIT, Kharagpur to the interested takers only after technology is transferred.

7. Potential takers of the technology and the possible suppliers of JGT

After survey and conducting correspondences in the mills and companies who are engaged in JGT manufacturing in a controlled and systematic fashion the four mills hereunder is the "avant guard" of all. A few exporters were interacted however those exporters are only converter of the JGT which is actually manufactured by the four mills. This study had shown that 2-3 % is allocated for the JGT for domestic and export sales in all 4 mills. However there is ample scope within the mill setup to increase the

production upto 10% without any modifications in the infrastructure and machineries. At least 10 major jute mills have been interacted but informations from the 4 mills are reported to be closest to the total sales figure of JGT from India. There are some other diversified sectors and exporters who export JGT and composites are not taken in this report because no valid quantified data were available. The present volume of business of the potential takers is shown in Table 3 below.

Table 3 Potential manufacturer of JGT in India

Company	Turnover	Period	Present business of JGT %	Value (from export and domestic sales)
1. Gloster Jute Mills Ltd	72.05	2010-11	3%	1.44
2.Birla Corporation Ltd	180	2010-11	4%	7.2
3. Kamarhatty Co. Ltd	40	2010-11	2%	0.80
4. Ludlow Jute Ltd	36	2010-11	2%	0.36

(Source: http://www.moneycontrol.com/financials and personal interactions with the companies)

As per the assessment these four mills might look for the technology developed by IIT after required trials in their mills. These four jute mills may come to the supply chain in different soil erosion control projects run by central and state governments.

IJMA has been trying to involve the member mills for the marketing and promotion of JGT in a serious and effective way. IJMA is doing an evaluation of a proposal of marketing of JGT is a large scale in the public and private sectors. The proposal is suggested by the National Jute Board and a draft of marketing plan has been prepared. After the evaluation the interested mills may sit together to find mutually the marketing scope of JGT and may engage marketing agency to explore the scope of the JGT. As per Indian Jute Mills' Association, the net worth of sale of JGT shall not exceed more than 3% of the total sales of jute products in the mill level.

According to the survey done by Roots & Yards it seems that Rs 36 lakh worth of JGT business was achieved during 2010-11 financial year with the 5 mills.

8. Market and marketability of jute geotextile

USA remains the most important market for geotextiles, Asia has become comparable, followed by Europe and South America. In all these markets it is important to look at the specifics of demand in particular national markets, barriers and distribution. It is important to undertake detailed market research covering more markets than in the past.

All the materials stand to benefit from growth in the markets for erosion control products. Polypropylene stands to benefit the most and it is likely to be PP from India or China as much as if not more than from USA. Natural materials are increasingly preferred wherever they can meet needs as much as synthetics. Then there is competition between natural materials where they can be substituted for one another and the competition takes the form of price.

Jute, on one level, is in competition with other materials: with synthetics and other natural materials. But on another level depends on its unique characteristics and how far these are translated into products. There is a limited range of existing products that is well known in most markets.

Detailed market research in national markets has identified development potential for existing JGTs and the needs that jute can contribute to meeting. The producers who are the JGT products should then be assisted in meeting required standards.

The size of markets has been studied wider than in the past and it included North America, Europe, Asia, Australia, and parts of South America and Africa.

Domestic demand for technical textiles has been increasing and there is substantial opportunity for investments in this sector. Ministry of Textiles, Government of India estimates an annual growth rate of 12% for geotextiles and is project a market size of Rs 1150 crore for the year 2020.

9. Need Assessment

The global market demand of geotextiles was estimated and reported by several studies. However in this present study a new approach has been adopted to quantify the market size of geotextiles. The details of the methodology are described in two segments in this report. In first part the market size of overall geotextiles is estimated whereas in second part the market size of jute geotextiles (JGT) for application in river bank erosion control is forecasted by extrapolating the demand of geotextiles obtained in first part.

10. Methodology

10.1 Part I: Market assessment for geotextiles

The estimated demands for JGT summarized in Table 4 were obtained proceeding as follows. The estimated market demand of geosynthetics for the Indian (Ministry of Textiles 2006, and telephonic enquiry of IIT Kharagpur) and US (Freedonia Group, Inc., 2007) were first scaled according to the size of the construction markets in 55 jurisdictions estimated from annual reports on the construction industry prepared by Business Monitor International (2008) and Crosthwaite and Connaughton (2008) considering the US demand for geosynthetics to represent mature (high and middle income) markets and the Indian demand to represent emerging (low income) markets. The countries treated as emerging markets are indicated in Table 4 using italics. Where information was available from Business Monitor International (2008) as well as Crosthwaite and Connaughton (2008), the average of the two

estimates was assumed to represent the size of the construction industry.

Finally, in 2008 the demand for JGT was estimated considering that the share of JGT is about 2 % in terms of tonnage of geotextile demand (Chand 2008) that translates into 1 % in terms of dollar cost based on the data presented by Shepley et al. 2002 and those obtained by IIT Kharagpur based on enquiries from Indian manufacturers. The corresponding estimate for 2012 was obtained based on the assumption that JGT would have a market share of 5 % in terms of dollar cost in 2012 of the geotextiles, geogrid and geonet market. For JGT demand estimation it was further assumed that the demand of geotextiles and that of geotextiles, geogrids and geonets will remain unchanged at 24 % and 33 %, respectively, of the overall demand for geosynthetics – shares estimated by Koerner (2005) for 2003 international market. Region wise distribution of the demand is indicated in Figure 5.

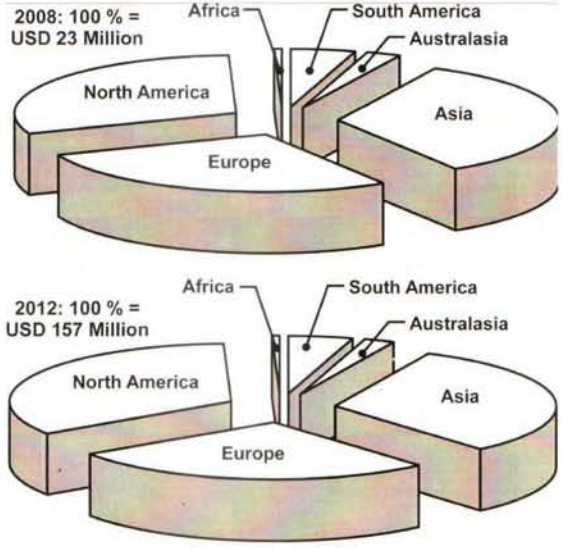


Figure 5. Regional demand estimates for JGT

There is a considerable uncertainty and subjectivity in the estimated and projected demands for JGT presented in Table 4. These are highlighted in the following:

The estimates for the size of construction markets for a few countries varied by as much as 200 % depending on the source of information utilized in this assessment. The Indian and US markets were subjectively considered to be representative of typical emerging and mature markets, respectively.

The classification of emerging and mature markets was based on the perceived state of the construction industry in a country and could be considered subjective.

Table 4. Country wise potential market size of geotextiles

Country	Construction market size (Billion USD)		Estimated demands (Million USD)			
			Geosynthetics		Geotextile, geogrid and geonet	
	2008	2012	2008	2012	2008	2012
Argentina	24	31	43	53	14	18
Australia	89	102	161	174	54	58
Baharin	1	1	1	1	0	0
Belgium	14	15	26	25	9	8
Brazil	118	126	212	214	71	71
Bulgaria	2	3	4	6	1	2
Canada	130	200	234	342	78	114
Chile	15	17	27	29	9	10
China	438	603	811	826	270	275
Czech Rep.	15	21	27	36	9	12
Denmark	8	8	14	14	5	5
Egypt	5	9	9	12	3	4
Estonia	1	2	3	3	1	1
Finland	7	7	13	13	4	4
France	286	325	514	556	171	185
Germany	220	247	396	421	132	140
Greece	30	40	53	68	18	23
Hong Kong	5	5	9	9	3	3
Hungary	5	8	9	13	3	4
India	91	180	169	247	56	82
Indonesia	39	44	72	61	24	20
Iran	22	26	40	45	13	15
Ireland	7	7	13	13	4	4
Italy	119	128	215	218	72	73
Japan	522	554	939	946	313	315
Kuwait	2	2	3	4	1	1
Latvia	2	3	3	4	1	1
Libya	2	2	3	4	1	1
Malaysia	4	7	8	10	3	3
Mexico	67	77	121	132	40	44
The Netherlands	25	26	44	44	15	15
Nigeria	3	6	6	8	2	3
Norway	10	10	18	18	6	6

to be continued...

Country	Construction market size (Billion USD)		Estimated demands (Million USD)			
			Geosynthetics		Geotextile, geogrid and geonet	
	2008	2012	2008	2012	2008	2012
Oman	2	3	3	4	1	1
Peru	9	13	16	22	5	7
Qatar	4	9	7	15	2	5
Romania	13	19	23	32	8	11
Russia	39	63	70	107	23	36
Saudi Arabia	21	26	37	44	12	15
Singapore	5	6	10	11	3	4
S. Africa	8	10	14	17	5	6
South Korea	88	98	159	167	53	56
Spain	86	92	155	157	52	52
Sweden	13	13	23	23	8	8
Taiwan	6	7	11	12	4	4
Thailand	7	8	13	11	4	4
UAE	15	22	27	38	9	13
UK	156	178	281	304	94	101
US	1160	1452	2088	2480	696	827
Venezuela	14	22	26	37	9	12
Vietnam	8	10	14	14	5	5
Others	772	869	1431	1190	477	397

The projected demand for geosynthetics does not consider the cost escalation because of the steep increase in the prices of petrochemicals and other inputs.

The impact of recent, sharp input cost escalation on the forecast of the size of construction industry is unknown.

Although a partial switch from petrochemical based geosynthetics to natural fiber based products is expected because of the sharp increases in petrochemical costs the international market is enduring in recent years, the assumption that JGT market share will rise to about 5 % of the geotextiles, geogrid and geonet market is also subjective.

10.2 Part II: Market Assessment for Jute Geotextiles (JGT)

The market size for JGT for erosion control was obtained as follows. The estimated market demand of geotextiles only for erosion control application for low/medium income countries has been calculated by considering the market share of the countries such as India and Bangladesh and the estimated JGT market for high income countries has been calculated with respect to USA and Canada. For each case the total length of flood prone river dikes in both coastal and non-coastal areas was calculated as per the

information obtained from elsewhere. (http://www.banglapedia.org/httpdocs/HT/R_0207.HTM, Central Water Commission, India, Draft recommendation for a National Levee Safety Program, Jan 15, 2009) Then the total length was estimated considering the length of right bank and left bank of river side as shown in column 3 of Table 5. The percentage of potential embankment length out of total length was estimated as per report. (http://www.banglapedia.org/httpdocs/E_0049.HTME, Draft recommendation for a National Levee Safety Program, Jan 15, 2009, www.textileworld.com/Articles/2011/January/Jan_Feb_issue/Geotextiles.html). Percentage of length out of total embankment length has been estimated as 25 % (Ghoshal and Som, 1993) and the potentially JGT requirement out of the length for geotextiles was considered as 10 % (Chand, 2008).

From Table 5, it is seen that the total length of 199 Km will be available for JGT application in river bank erosion control. That length of JGT will be needed for at least 5 years of recurring periods. The recurring periods of the natural calamities has been estimated as 5 years, based on the report of Centre for Research on the Epidemiology and Disasters, 2004. The height for the river bank slope was estimated as 4 - 5 meters and the slope was considered as 2:1. That entails the width of geotextiles would be 16 meter, hence the total need of JGT for India would be 31, 84,104 m2. IIT, Kharagpur considered the rate of per m2 of JGT as INR.50. The total JGT market for India will be 15, 920, 5200 for 5 year span, which indicates the market for JGT per year in India will be INR 3.18 crore for the year 2012-13. Similarly the market for Bangladesh, USA and Canada was estimated based on the above principle (column 6, Table 5).

The most potential areas considered as having emerging markets for JGT all over the World are Pacific Asia, USA, Japan, Europe, Canada, Australia, South Africa and South America (source: http://www.the-infoshop.com/report/fd90373-eosynthetics.html). Region wise global market share of JGT is presented in column 2 of Table 6. Overall world geotextiles market potential was estimated from the annual reports on the construction industry prepared by Business Monitor International (2008), The US market for technical textiles, 2002, report from David Rigby Associates (2008), (www.textileworld.com/Articles/2011/January/Jan_Feb_issue/Geotextiles.html) and Crosthwaite and Connaughton (2008) considering the US demand for geotextils in column 4 of Table 6. Following this the market for rest of the countries and rest of the world was calculated and presented in Table 6. The same ratio as India and Bangladesh was applied for low-middle income countries and the ratio of USA-Canada was applied for other higher income countries.

During the selection of the rest of the world the regions with the rainfall less than 500 mm were not considered for the market estimation of the JGT.

Table 5. Estimated market for jute geotextiles in river bank erosion control (2012-13)

Country	Flood prone river length (km)	Estimated repairable length of river dikes (km)	Geotextiles needed (km)[1]	JGT market (Sqm)[2]	Market (crore INR)
India	24122	7960[3]	1990	3184104	3.18
Bangladesh	11307	7462[3]	1865	1492524	1.50
USA	92339	16621[4]	4155	6648400	6.64
Canada	9233	1662[4]	415	664840	0.66

[1] considering that 25 % of the repairable length can be captured by geotextiles [2] Length of geotextiles needed × 0.1 × 1000 × 16 [3] estimates 33 % of the length of flood prone river [4] estimates 9 % of the length of flood prone river

Hence the annual demand for jute geotextiles for erosion control application in India has been estimated INR 3.18 crore in the year 2012-13. Similarly the market for global JGT was estimated as INR 27 crore for erosion control application for the year 2012-13 (Table 6).

The estimated numbers for India and for the World were in good agreement with the numbers predicted by the Ministry of Textiles, 2010 and David Rigby Associates.

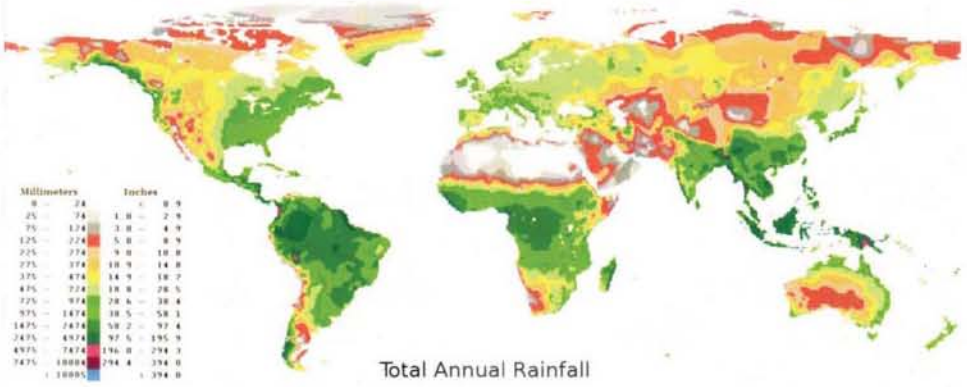
The estimate is marginally high for IIT's method that of the estimate by David Rigby Associates for global market. However, it indicates the significant accuracy of the method adopted by present survey (Table 6).

Table 6. Global Market estimate for JGT for erosion control applications

Area	% Market share	Geotex market (INR Crore)	JGT market (INR Crore) @10% in 2012-13	Actual market surveyed by IIT KGP in 2012-13
Asia Pacific	41	155.8	15.58	10 crore
USA	24	91.2	9.12	7 crore
Canada	2.4	9.12	0.912	0.70
S America	6	22.8	2.28	2
Japan	10	38	3.38	3
Europe	11.6	44.08	4.408	3
Australia	2	7.6	0.76	0.60
Africa	1	3.8	0.38	0.30
Rest of world	2	7.6	0.76	0.50
Total INR (2012-13)	100	380	38.00	27.00

Referring a study (EM-DAT THE OFDA/CRED International Disaster Database) it is seen that India and East Asian countries observe maximum number of floods during 30 years (from 1974-2003). It is seen in the report that India, China and South East Asia suffered flood more than 60 times. Therefore it could be assumed that Indian market is quite good for soil erosion control. JGT gives the best solutions to erosion control, so a quantitative figure can be drawn on the basis of the report.

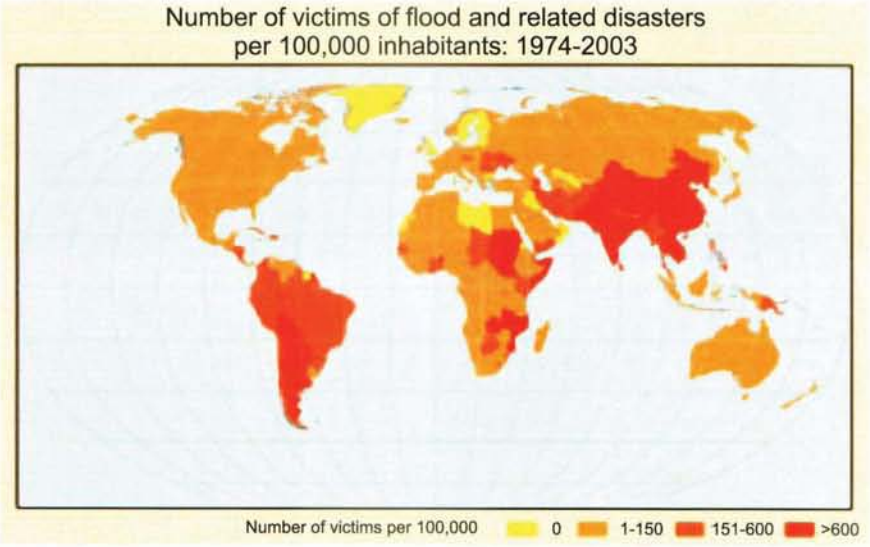
The global climate maps presented here are based on data for mean monthly values of temperature, precipitation and cloudiness prepared in 1991 by R. Leemans and W. Cramer and published by the International Institute for Applied Systems Analysis (IIASA). The IIASA data correspond to an imaginary "net" covering the Earth's surface with a mesh size of 0.5 degrees. This is equivalent to about 60 km - an area of about 3,600 sq. km - at the equator.

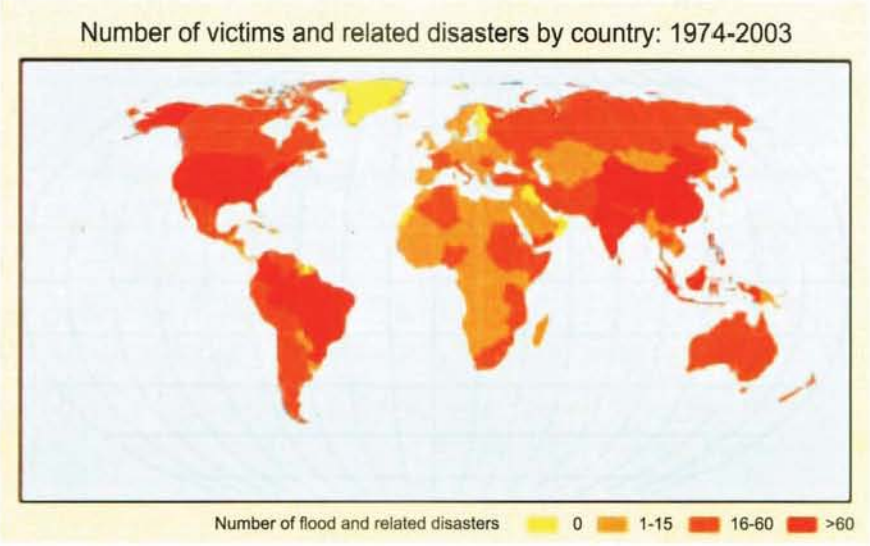


Total Annual Rainfall

Source: Global Climate Maps. http://www.climate-charts.com/World-Climate-Maps.html

To achieve the estimate for River Bank Erosion Control, IIT, Kharagpur has studied World Climate and 30 years of Natural Disasters 1974-2003. This study helped IIT to anchor the arithmetic calculation.





Source: Thirty Years of Natural Disasters 1974-2003: The Numbers. D. Guha-Sapir, D. Hargitt, P. Hoyois. Centre for Research on the Epidemiology of Disasters. UCL PressesUniversitaires de Louvain.

Need Assessment and Market Survey for Jute-geotextiles in Riverbank Erosion Control Applications

A report says that after the break out of Tsunami in India about 1,24,000 million geotextiles were required.

On the basis of several studies and following a scientific methodology, IIT Kharagpur established an estimated market size foe JGT and figured out a report in the following table no. 7.

Table 7. Estimated market for jute geotextiles in erosion control application

Market demand	Organization	Estimates crore (INR) 2012-13
India	Technopak, Ministry of Textile, India, estimate 2010	4.50
	Dornier study	3.30
	IIT Kharagpur estimates market only for River Bank Erosion Control	**3.18**
World	David Rigby Associates	38.00
	IJSG, Dhaka estimate	45.00
	Elwood Consultant	65.00
	IIT Kharagpur estimates market only for River Bank Erosion Control	**27.00**

11. A Survey Report of the Public Sectors

A sample survey was carried out in the Pubic Departments. The concerned departments had shown their interests to try the IIT developed treated JGT at fields. The few feedbacks from the departments are given in Table 8.

Table 8. Survey in the Public Sectors

Name	Dept.	Feedback analysis
1. A. D Sarangi, Sup Eng (Civil)	MORT, Govt. of India	Though Indian Road Congress has no typical guideline for application of JGT but it can be used for soil erosion stabilization. There is fund for trials but the JGT supplier has to implement the project. Rs 40 lakh can be spent in trials. Scope of work area: Tindharia to Darjeeling Road, NH 55. Area 43.5 km. Demo of the implementation can be arranged.
2. Partha Pratim Nath	SERP (Sundarban Embankment Reconstruction Project), I and W Department, Govt. of WB	Geosynthetics were implemented after Aila. JGT has a scope for further reconstruction programme. Rs 5032 crore worth of embankment project in 778 kilometers is under process with geosynthetics. A technical committee looks after the embankment requirement. Therefore treated JGT can come as an alternat ive in the embankment projects in the Sundarbans and other coastal areas in India.
3. R K Ghosh	Chief Eng, CPWD, Govt. of India	JGT can only be used in embankment and slope stabilization for its unique properties.
4. Secretary Zilla Parishad	Zilla Parishad, Howrah, Govt of WB	Howrah Zilla Parishad shows willingness for the trial of JGT in the PMGSY schemes. River banks across Rupnarayan in Shyampur block are vulnerable for floods.

Need Assessment and Market Survey for Jute-geotextiles in Riverbank Erosion Control Applications

12. Conclusions

As per the Federation of Indian Chambers of Commerce and Industry, geotextiles consumption is likely to grow at a rate of over 15-20 per cent per annum in India. The demand for geotextiles is expected to grow at the rate of 12 per cent by 2013.

An industry report has stated that demand for geosynthetics is projected to increase 12.3 per cent a year to 100 million square metres by 2013, up from just 56 million square metres in 2008, with transportation being its biggest market. Demand of geotextiles in embankments and erosion control are likely to come with priority after the Tsunami and multiple cyclones in the coastal India. The domestic demand is likely to grow at much faster pace and here JGT will see right opportunity to fulfill the demand. The information was obtained from the source, "Indian Minister Predicts Growth in Technical Textiles" by Devraj Parthasarathi, (NWI, November 2009).

The Need Assessment and Market Survey were carried out by IIT, Kharagpur collaborated with Roots & Yards. The methodology of the entire work has been discussed in the Market Assessment for JGT Part II. It was a scientific and an innovative study from different angles. The sample survey in the public and private sectors gave some believable data. The assumptions on the basis of mathematics and logical reasoning were anchored by several references from different sources. Thus it was a logical combination of different tools to achieve desirable results in the report of the survey.

This trend of combining materials, i.e. Jute and PP based Geotextiles is expected to continue and the barriers between synthetic and natural fibre geotextiles will be less rigid. The initiation of such research towards combined geotextiles might be a good attempt towards the solution of river bank erosions in a much effective way.

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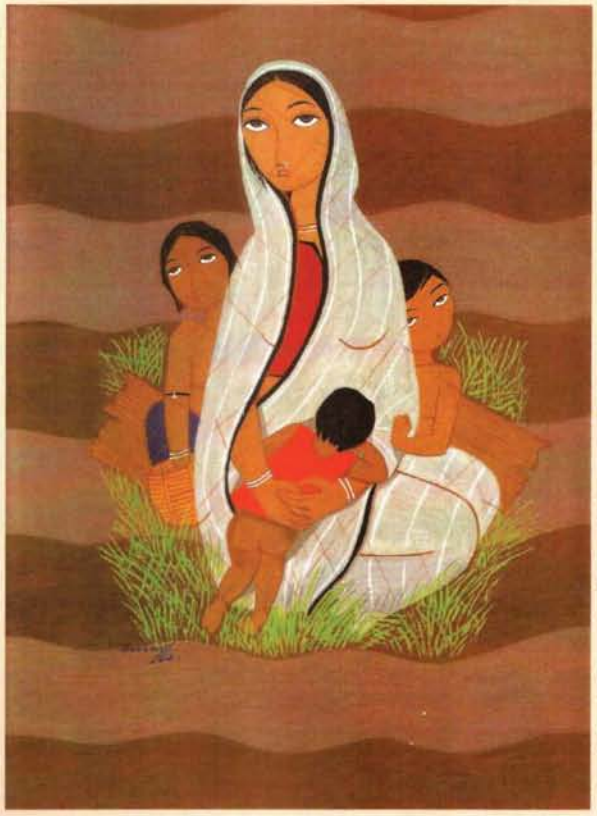

Painting by Surayia Rahman, Bangladesh - *The Flood*. April 29, 2010.

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6. S. Shee, Project Assistant, IIT, Kharagpur
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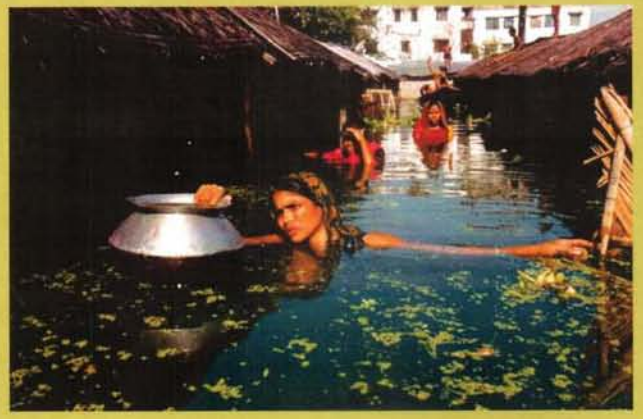

Indian Institute of Technology
Dept. of Civil Engineering
Kharagpur 721302, WB, India

Appendix 2

Research papers

Carbohydrate Polymers 87 (2012) 1628–1636

Contents lists available at SciVerse ScienceDirect

Carbohydrate Polymers

journal homepage: www.elsevier.com/locate/carbpol

Durability of lignocellulosic fibers treated with vegetable oil–phenolic resin

Prosenjit Saha[a], Suvendu Manna[a], Ramkrishna Sen[b], Debasis Roy[c,*], Basudam Adhikari[a]

[a] Materials Science Centre, Indian Institute of Technology, Kharagpur, West Bengal 721302, India
[b] Department of Biotechnology, Indian Institute of Technology, Kharagpur, West Bengal 721302, India
[c] Department of Civil Engineering, Indian Institute of Technology, Kharagpur, West Bengal 721302, India

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ABSTRACT

Jute and sisal fibers were treated with an aqueous emulsion of neem oil and phenolic resin at elevated temperature for enhancing their tensile strength, hydrophobicity and resistance against biological and chemical degradations. The process was found to lead to the transesterification of cellulose chain hydroxyl groups and increased crystallinity. Treatment efficacy was evaluated by characterizing fibers by exposing them to biological and chemical degradations. The results indicate that the short-term tensile strength increased by 61–75% following treatment. After biodegradation, treated fibers were found to retain 63–70% of their initial tensile strength, while untreated fibers retained 28–32%. Treated fibers retained 52–60% of tensile strength after 90-day exposure to 3% salinity and 48–55% of tensile strength after similar exposure to pH between 3 and 10. For untreated fibers the corresponding figures were 9–13% and 10–12% respectively.

1. Introduction

The major impediments in high performance industrial applications of lignocellulosic fibers (LCFs) are that they are mechanically weak and are highly susceptible to chemical and biological degradations vis-à-vis many man-made fibers. LCFs are composites of cellulose, hemicelluose and lignin with small amounts of pectin and other chemical constituents. Crystalline cellulose mainly imparts mechanical strength and ductility to the LCFs. Hemicellulose molecules are attached to crystalline cellulose through hydrogen bonding forming an amorphous matrix (Jayaraman, 2003). Although lignin and pectin enhance primary dimensional stability of the LCFs, they are brittle and often prevent efficient transfer of mechanical load. The free hydroxyl and other oxygen-containing groups of the LCFs exhibit a tendency to attract water molecules through hydrogen-bond formation causing the fibers to swell. As a result, the cellulose molecules are exposed to microbial attacks, which degrade the cellulose and cause strength loss. Exposure to chemical environment similarly results in loss of tensile strength because of hydrolysis, oxidation or dehydration reactions. Thus, one of the possible strategies to minimize microbial degradation and increase long term mechanical strength would be to make the LCFs less hydrophilic by blocking the free hydroxyl groups.

Chemical modification of hydroxyl groups of LCFs by graft copolymerization with methyl methacrylate, saturated fatty acid, subtilisin Carlsberg solvent and silane coupling (Montazer & Salehi, 2008; Pickering, Abdalla, McDonald, & Franich, 2003; Vaca-García, Thiebaud, Borredon, & Gozzelino, 1998; Zhang & Fan, 2010) have also been reported to enhance hydrophobicity and mechanical strength. Resistance of LCFs against biodegradation could be increased by UV acrylamide photografting or boric acid or acetic anhydride treatment (Hassan, Islam, & Khan, 2002; Lyon et al., 2007; Teramoto, Urata, Ozawa, & Shibata, 2004). Transesterification of LCF hydroxyl groups with *n*-butylacrylate and pyridine led to the development of a greater resistance against biological and chemical degradations (Samal, Acharya, Mohanty, & Ray, 2001). Hydrophilicity of LCFs has been reduced by applying natural rubber (Jacob, Varughese, & Thomas, 2005), phenolic resin (Medeiros de, Agnelli, Joseph, Carvalho, & Mattoso, 2005), fatty acid derivative such as oleoyl chloride (Corrales et al., 2007), and pentafluorobenzoyl chloride (Cunha et al., 2007) on fiber surface. Similar application of vegetable oil and phenolic cross-linking agents reportedly increased the mechanical strength of LCFs and dimensional stability of LCF-based particle boards (Wang, Wasylciw, & Guoliang, 2007). Surface application of chitosan (Lim & Hudson, 2004), and neem (*Azadirachta indica*) seed extract with cross linking agents on cotton–polyester fabric (Joshi, Ali, & Rajendran, 2007) has led to an enhanced resistance against microbial degradation. Enhancement of hydrophobicity, durability and tensile strength of LCFs in all the reported literature was based on the chemical modification such as coating with phenolic resin, grafting with methyl methacrylate, esterification and transesterification with synthetic or toxic chemicals.

In this study an alternative, non-hazardous and inexpensive process has been developed for treating LCFs to enhance

* Corresponding author. Tel.: +91 3222 283456; fax: +91 3222 282254.
E-mail address: debasis@civil.iitkgp.ernet.in (D. Roy).

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their hydrophobicity, mechanical strength and resistance against biological and chemical degradations using a water-based emulsion of vegetable oil and phenolic resin (resol). As demonstrated later, vegetable oil treatment transesterified the fibers, while application of plant-based resol coated the fiber surface and increased process efficacy. It should be noted that the fatty acid triglycerides present in vegetable oil utilized here for durability enhancement are completely different from those in the process based on neem seed extracts described by others. Further, vegetable oils have not been used in a chemical process involving solvent-free transesterification of LCFs as has been accomplished in this research.

2. Experimental

2.1. Materials and chemicals

This study pertains to the treatment of jute (*Corchorus olitorius*) and sisal (*Agave sisalana*) fibers. Sodium hydroxide (NaOH) pellets (assay > 97%), resorcinol (assay > 99%), formaldehyde (37%), commercially available 40% oil extracted from neem seed (*A. indica*) and kernel, Neem oil (NO) or 20% rice bran oil (RBO) extracted from inner husk of rice (*Oryza sativa*), cashew nut shell liquid (CNSL) and commercial grade condensed black wattle plant tannin were used to treat the fibers as discussed below.

2.2. Chemical treatment

The LCFs washed with distilled water were oven dried at $85 \pm 2\,^{\circ}C$ until obtaining a constant weight. These fibers were dipped in 0.5% (w/v) NaOH solution for 24 h at $30 \pm 2\,^{\circ}C$ according to the procedure described earlier by our group (Saha et al., 2010). The alkali-treated fibers were then cooled, washed and neutralized at pH 7 ± 0.5 with distilled water.

A mixture of phenolic compounds was prepared by mixing resorcinol, CNSL and condensed tannin proportioned 1:4:5 by weight. Base catalyzed phenol–formaldehyde resin (resol type) was prepared following Singh and Gupta (2005) by mixing the above phenolic composition with formaldehyde in 1:1.3 ratio (by weight) at $28 \pm 2\,^{\circ}C$. Solid content of this resol was adjusted to $1 \pm 0.2\%$ (w/v). The diluted resol resin was found to be stable up to 12 h without any agglomeration. An aqueous emulsion was prepared by mechanically mixing 4–7% (by volume) of NO or RBO and 0.01% (by weight) of sodium dodecyl sulfate (SDS) surfactant. Stability of this emulsion was also evaluated via emulsification index (Kodali, Das, & Sen, 2009) and found to be satisfactory. The vegetable oil emulsion was mixed with the resin solution in 1:1 proportion (by volume) to get a final reagent within 12 h from resin preparation. Amount of vegetable oil in the final reagent was 2–3.5% (by weight) and subsequently the solid content of the resol was $0.5 \pm 0.1\%$ (by weight). The final reagent was found to be stable for several days. Finally the reagent mixture was sprayed over the alkali-treated fibers maintaining a fiber to liquid ratio of 2:1 (by weight). Subsequently, the fibers were mechanically squeezed to recover excess reagent. Finally, the fibers were cured in an air circulating oven at $105 \pm 5\,C$ for 1 h.

2.3. Testing and characterization

Untreated and treated fibers were characterized for their mechanical strength and flexibility, hydrophilicity, surface characteristics, chemical composition, crystallinity, and susceptibility to biological and chemical degradations as described below.

2.3.1. Mechanical strength and flexibility

Single fibers were manually separated from fiber bundles for assessing their uniaxial tensile strength. To ensure fiber separation and measure fiber diameter Leica DMLM microscope (at 10×) was used. For tensile strength measurement of each fiber, a maximum load of 100 N with the crosshead speed of 3 mm/min was applied and a gage length of 25 mm was maintained. Tensile strength of 50 fiber samples was measured following ASTM D 3822-01 (ASTM, 2001) using Hounsfield H10KS universal testing machine maintaining 25 ± 2 mm gage length and 3 mm/min crosshead speed. For each batch tested, the average and standard deviation of these measurements were used as the estimates of the uniaxial tensile strength and its variability, respectively.

2.3.2. Hydrophilicity estimation

Steady state water absorption, equilibrium moisture content (EMC), and contact angle were measured to estimate the hydrophilicity of LCFs before and after treatment. These parameters were determined on triplicate samples of bundle of 10 fibers and the average is reported in this study.

The steady state water absorption was obtained after immersing oven dry LCF specimens in distilled water at $30 \pm 2\,^{\circ}C$ following Alvarez and Vázquez (2006). A portion of the specimens was taken out from the distilled water bath after fixed time periods. It was carefully wiped with an absorbent paper to remove surface water and weighed to determine the steady state water absorption. The exercise was continued for longer immersion periods until obtaining a constant value of water absorption.

The EMC was determined according to ASTM D 4442-07 (ASTM, 2007). Before testing, the LCF specimens were oven dried until obtaining a constant weight.

A fiber bundle washed with ethyl alcohol was placed on a glass slide and a drop (1–2 μl) of Millipore water was carefully placed on the fiber bundle using a micro syringe. The contact angle between the drop and the fiber bundle was estimated at $30 \pm 2\,^{\circ}C$ from digital photographs following Alix et al. (2009).

To evaluate the swelling property and the effect of charge density on the hydrophilicity of LCFs, apparent zeta potential (ζ) was measured using Zetasizer ZS90, Malvern Instrument System at $30 \pm 2\,^{\circ}C$ following Pothan, Simon, Spange, and Thomas (2006). For this, samples were prepared by manually cutting LCFs maintaining 1–2 mm length, dispersing 10 ± 2 mg of the LCF sample in 1×10^{-3} M NaCl solution and sonicating the liquid for 15 min. Zeta potential was determined for 5 fiber powder samples and their average is reported in this study.

2.3.3. Surface characteristic

Surface characteristic of the LCF specimens was investigated through scanning electron and atomic force microscopy.

LCF powder samples for scanning electron microscopy (SEM) were prepared by washing LCFs with ethyl alcohol and manually cutting 5 ± 1 mm long pieces of LCFs. 1–2 mg of sample was coated with a thin layer of gold by a plasma sputtering apparatus and examined with TESCAN $VEGA_{LSV}$ scanning electron microscope operated in the high vacuum mode with secondary electron detector and with accelerating voltage between 5 and 10 kV.

The surface topography of LCF samples was examined with Nanonics Multiview 1000 atomic force microscope at $70 \pm 5\%$ relative humidity and at $30 \pm 2\,^{\circ}C$ following Pietak, Korte, Tan, Downard, and Striger (2007). The microscope was equipped with a silicon nitride tip and was operated in the contact mode. LCFs, prewashed with ethyl alcohol, were cut into 1–2 mm long pieces and 2 ± 0.5 mg of these pieces was dispersed in 50 ml distilled water by sonicating the liquid for 30 min. About 1.5 μl of the suspension was extracted with a micro tip and placed on a glass slide for examination with the microscope.

Table 1
Mechanical properties and hydrophilicity of untreated and treated fibers.

Fibers	Treatment	Water absorption (wt% increase) ± COV[a]					EMC[b] (wt%)	TS[c] ± COV[a]	EB (%)[d] ± COV[a]
		6 h	12 h	24 h	48 h	72 h			
Jute	Untreated	186 ± 23	216 ± 20	256 ± 23	252 ± 21	255 ± 18	14 ± 06	370 ± 68	1.4 ± 0.48
	Resin	130 ± 30	103 ± 21	106 ± 17	98 ± 10	95 ± 07	09 ± 02	518 ± 55	1.2 ± 0.30
	6% NO	127 ± 12	141 ± 14	145 ± 05	147 ± 10	146 ± 15	11 ± 04	594 ± 84	1.5 ± 0.52
	5% RBO	105 ± 19	128 ± 12	131 ± 09	133 ± 12	134 ± 06	10 ± 04	528 ± 68	1.6 ± 0.22
	NO–resin	62 ± 09	76 ± 10	78 ± 10	78 ± 12	79 ± 16	07 ± 02	648 ± 94	1.5 ± 0.46
	RBO–resin	82 ± 11	101 ± 13	103 ± 07	102 ± 03	103 ± 04	9 ± 02	606 ± 70	1.5 ± 0.15
Sisal	Untreated	156 ± 17	176 ± 12	182 ± 13	186 ± 9	185 ± 11	12 ± 03	471 ± 49	1.5 ± 0.26
	Resin	120 ± 14	111 ± 16	102 ± 19	101 ± 03	98 ± 13	07 ± 02	564 ± 72	1.3 ± 0.34
	5% NO	90 ± 11	103 ± 12	113 ± 08	112 ± 16	115 ± 13	06 ± 03	796 ± 91	1.7 ± 0.56
	5% RBO	130 ± 08	127 ± 17	136 ± 15	135 ± 11	135 ± 10	10 ± 02	752 ± 64	1.6 ± 0.35
	NO–resin	56 ± 09	63 ± 08	62 ± 11	61 ± 10	62 ± 08	05 ± 02	759 ± 78	1.5 ± 0.33
	RBO–resin	70 ± 21	77 ± 13	75 ± 06	78 ± 07	78 ± 06	08 ± 01	708 ± 58	1.4 ± 0.24

[a] COV: standard deviation/mean, was calculated based on 50 observations.
[b] Equilibrium moisture content expressed in wt% increase.
[c] TS: tensile strength in MPa unit.
[d] EB: elongation at break.

2.3.4. Fourier transform infrared (FTIR) spectroscopy

Changes in fiber chemistry were assessed from FTIR spectra of LCFs obtained using a Thermo Nicolet, Nexus 870 spectrophotometer operated at 35 ± 2 °C. Samples for FTIR spectroscopy were prepared by cutting LCFs, pre-washed with ethyl alcohol, into powder form and oven drying them at 105 ± 2 °C for 1 h. The spectra were recorded for wave numbers ranging between 4000 cm^{-1} and 400 cm^{-1} using 32 scans for each sample comprised of 10 ± 2 mg of LCFs mixed with 100 ± 10 mg of potassium bromide (KBr) pellets.

2.3.5. Quantitative elemental analysis

Elemental analysis was carried out to investigate the chemical changes of LCFs after chemical modification. The mass percentages of carbon, hydrogen, oxygen and nitrogen of LCFs were analyzed following the method described elsewhere (Phan et al., 2006). LCFs, pre-washed with ethyl alcohol, were cut into small pieces and 3 ± 0.5 mg of them was tested with EURO EA Elemental Analyzer in triplicate.

2.3.6. X-ray diffraction (XRD)

RIGAKU X-ray diffractometer (ULTIMA III) operated at room temperature was used to characterize the crystallinity of LCFs as changes in crystallinity partly affect the tensile strength and hydrophilicity of the fibers. LCFs were cut into 5 ± 1 mm long pieces, 1 ± 0.5 g of which was subjected to XRD. The diffractogram was obtained using Cu-Kα radiation source for 2θ range between 10° and 50° and at a scanning speed of 2° min^{-1}. According to Buschle-Diller and Zeronian (1992), the degree of crystallinity is given by the equation, $Cr = (I_{22.5} - I_{18.5})/I_{22.5}$, where $I_{22.5}$ and $I_{18.5}$ are the intensities at 2θ values of 22.5° and 18.5°, respectively.

2.3.7. Durability assessment

Resistance to biodegradation of LCFs was assessed from soil burial test by exposing LCFs to a composting environment. The susceptibility to chemical degradation was evaluated by exposing LCFs to elevated (3% by weight) saline solutions and alkaline–acidic pH conditions.

The compost for soil burial tests was prepared by mixing organic (black) garden soil, sand and cow dung in 2:1:1 ratio (by weight) as specified in BIS (BIS, 1992). The compost was changed once every seven days for simulating the fiber degradation in an open environment. Further, the fibers were exposed to biodegradation up to 90 days instead of the 21 days duration specified by BIS. Three specimens of LCF bundle were tested for each category. The ratio of LCF fiber bundles to soil was kept 1:100 (by weight) as suggested by other researchers (Di Franco, Cyras, Busalmen, Ruseckaite, & Vàzquez, 2004). Soil pH was maintained within 6 and 7 by adding dilute hydrochloric acid or dilute sodium hydroxide as needed and the moisture content of the soil was kept at 65 ± 5% over the entire duration of biodegradation. The compost-LCF system was kept in a vented glass enclosure, which, in turn, was stored within an incubator at 35 ± 5 °C and 85 ± 5% relative humidity during the test. Fiber samples were periodically recovered, washed and tested for tensile strength.

The chemical stability of LCFs was investigated by immersing them within an aqueous solution of 3% sodium chloride (by weight) and aqueous solutions of hydrochloric acid and sodium hydroxide with pH ranging between 3 and 10 for 90 days duration. These tests were conducted at 35 ± 5 °C maintaining fiber to liquid ratio as 1:100. LCF specimens were periodically recovered, oven-dried and tested for tensile strength.

3. Results and discussions

3.1. Tensile strength and elongation at break

Maximum increase in uniaxial tensile strength of jute and sisal fibers was observed when they were treated with 5–6% of NO or RBO in the absence of phenolic resin. Upon treatment with NO the tensile strength was found to increase by 69%, while for the RBO treatment the increase was 60% (Table 1). For treatment with phenolic resin without vegetable oil, on the other hand, uniaxial tensile strength increased up to 40% and 20%, respectively, for jute and sisal fibers when the fibers were treated with a resin with 1% solid content. Tensile strength was found to increase up to 75% and 64% when jute fibers were treated with NO and RBO, respectively, in the presence of resin emulsion. For sisal fibers, corresponding increases were 61% % and 50%, respectively.

The covariance (standard deviation divided by sample mean) of tensile strength and elongation at break for vegetable oil–phenolic resin treated LCFs was found to be less compared to corresponding values of untreated fibers (Table 1). This demonstrates a reasonable repeatability of treatment outcome.

Treatment of LCFs with phenolic resin led to a reduction in the elongation at break for the LCF specimens. Other treatments resulted in marginal increase in this parameter. Enhancement of uniaxial tensile strength and marginal reduction of brittleness of vegetable oil–resin treated LCFs shows that the effectiveness of this treatment is more than that of others.

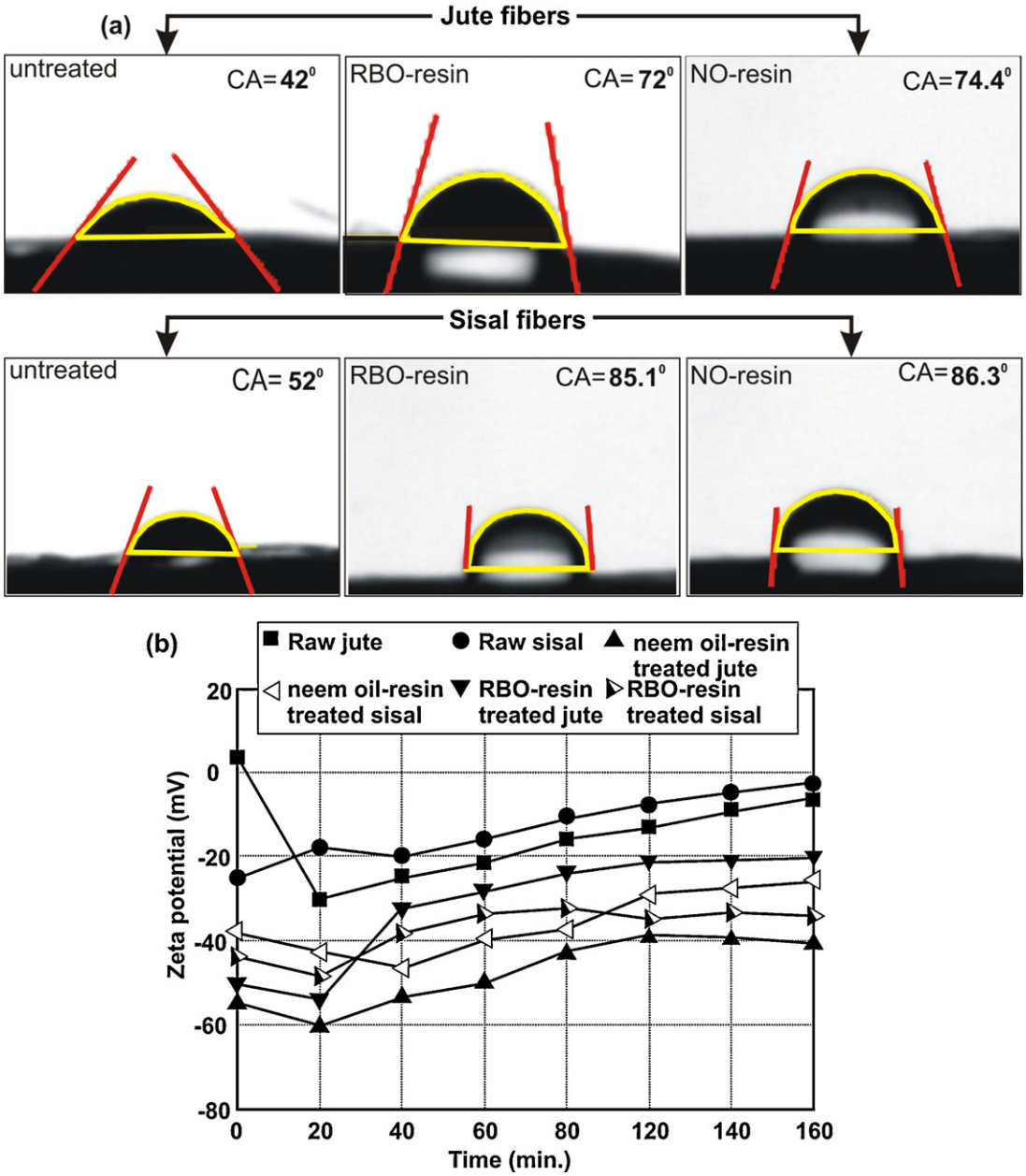

Fig. 1. (a) Measured contact angle (CA) values for untreated and treated LCFs (RBO: rice bran oil and NO: neem oil); (b) variation of Zeta potential (ζ) of untreated and treated LCFs with time.

3.2. Hydrophilicity

Water absorption and EMC of the treated LCFs with vegetable oil only, phenolic resin only and combination of oil and resin were measured and the results have been presented again in Table 1. It was observed that the hydrophilicity for the combined treatment with vegetable oil (NO and RBO) and resin was reduced to the maximum extent. NO–phenolic resin treatment was found to reduce water absorption on an average from 255% to 79% for jute fibers and 185–62% for sisal fibers. While the contact angles for untreated jute and sisal fibers were found to be 42° and 52°, respectively. The corresponding values following NO–resin treatment were 74.4° and 86.3° and RBO–resin treatment were 72° and 85.1° (Fig. 1a).

The covariance of water absorption and EMC for vegetable oil–phenolic resin treated LCFs was found to be less compared to corresponding values of untreated fibers demonstrating a reasonable repeatability of treatment efficacy.

Continuous reduction of the ζ-potential with time for untreated LCFs was observed as shown in Fig. 1b. In comparison, for treated LCFs the ζ-potential was found to decrease up to about 60 min and remained relatively unchanged thereafter, also shown in Fig. 1b. It has been suggested by others (Bismarck, Springer, Mohanty, Hinrichsen, & Khan, 2000) that such reductions in ζ-potential is due to moisture absorption and consequent swelling of dissociable groups, e.g., uronic acid in hemicelluloses, other weaker acids in lignin and free hydroxyl groups in cellulose, and removal of water soluble constituents such as hemicelluloses and pectin. Thus the results obtained in this research appears to indicate that while untreated LCFs continued to swell over the 160 min exposure to NaCl solution, treated LCFs did not swell appreciably beyond the initial 60 min of exposure. For treated fibers the water soluble constituents and lignin were substantially removed and dissociable groups were partially blocked by vegetable oil treatment leading to a reduction in swelling tendencies.

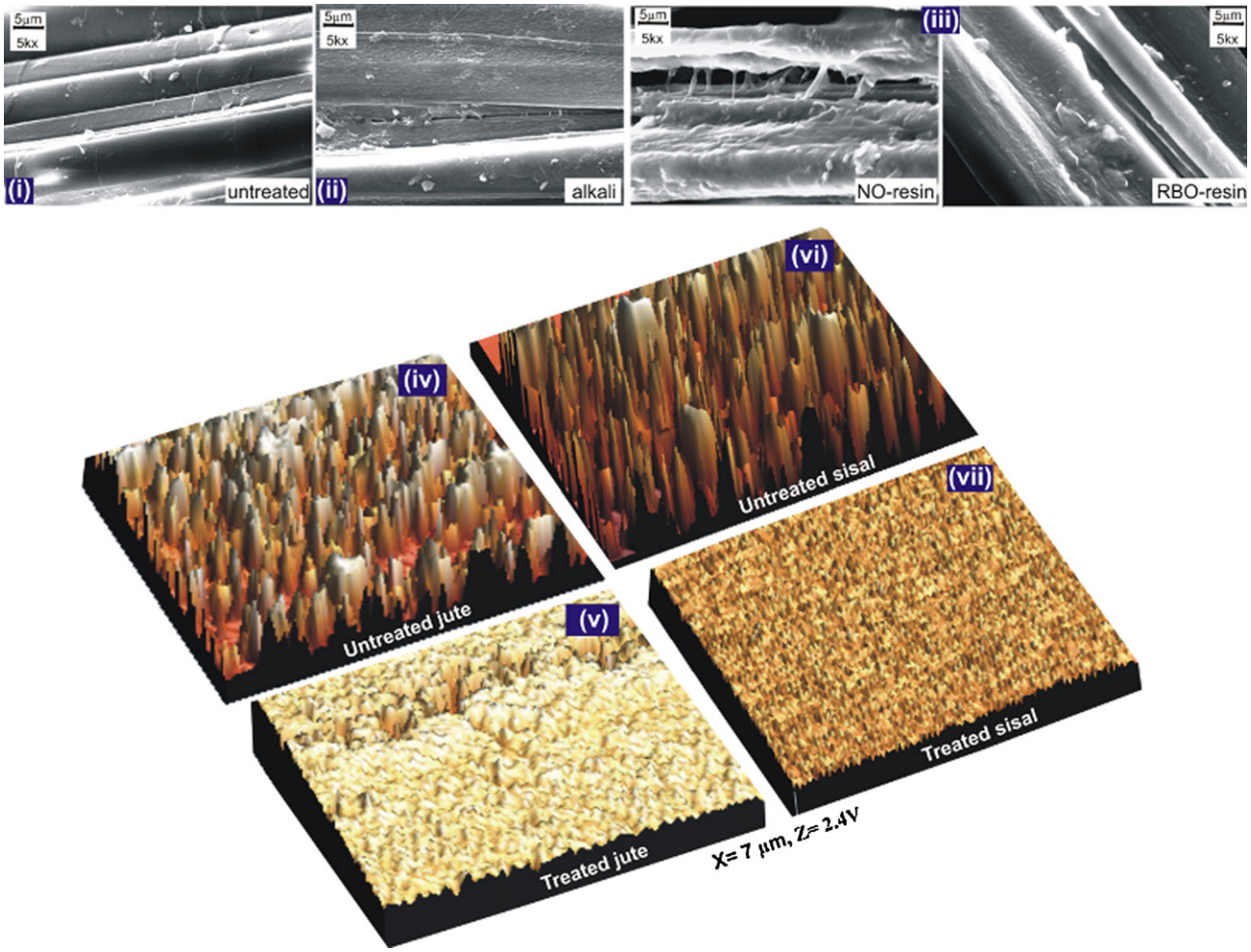

Fig. 2. SEM and AFM photomicrographs of untreated and treated LCFs. (i) untreated jute fibers, (ii) alkali treated jute fibers, (iii) neem oil (NO)–resin and rice bran oil (RBO)–resin treated jute fibers, in AFM topographic images, (iv) untreated jute, (v) neem oil–resin treated jute fibers, (vi) untreated sisal, and (vii) neem oil–resin treated sisal fibers.

From water absorption, EMC, contact angle and ζ-potential measurements it can be inferred that chemical treatments led to a reduction of hydrophilicity of LCFs and the maximum reduction of hydrophilicity was achieved with NO–resin treatment only.

3.3. Surface morphology

SEM photomicrographs of untreated and alkali-treated jute fibers, Fig. 2(i) and (ii), indicate that the surface roughness has increased and the fiber cross sectional area has become smaller following alkali treatment. The observed changes in the surface morphology and fiber cross section appears to be due to the partial removal of surface impurities, non-cellulosic materials, inorganic substances and waxes and fiber separation following alkali treatment. Vegetable oil–resin treatment was found to lead to the development of a smoother surface (Fig. 2(iii)). Surface smoothing in morphology for sisal fibers were also same as jute fibers (figures not given). Smoothening of surfaces of sisal fibers has been reported by Megiatto, Hoareau, Gardrat, Frollini, and Castellan (2007) after modification with furfuryl alcohol and polyfurfuryl alcohol. AFM topographic images, shown in Fig. 2(vi) and (vii), of jute and sisal fibers show similar smoothening in surface morphology following alkali and NO–resin treatment.

3.4. FTIR spectroscopy

Since the peak in the 3200–3450 cm^{-1} region in FTIR spectra of LCFs is often deemed to represent the OH stretching vibration of cellulose molecules or N–H stretching (Tornc et al., 2007), weakening of the intensity of the peak in this region following vegetable oil-resin treatment provides evidence of chemical alteration of some of the hydroxyl groups (Fig. 3). The corresponding reduction of intensity for resin-only and vegetable oil-only treatments was found to be less significant indicating relative inefficiencies of these treatments in hydroxyl group blocking.

The peaks in the FTIR spectra in the 1734 cm^{-1} region for untreated jute fibers and that in the 1650 cm^{-1} region for untreated sisal fibers representing C=O stretching vibration for aryl ester of hemicellulose and lignin (Frisoni et al., 2001; Navarro et al., 2003) were found to disappear following alkali treatment indicating substantial removal of hemicellulose and lignin in the process (Abraham et al., 2011). Surface roughening due to removal of hemicellulose and lignin of LCFs was observed from photomicrographs obtained from SEM and AFM after alkali treatment. Reappearance of the peak following vegetable oil–resin treatment could be interpreted as indicators of a new ester bond formation due to transesterification of the hydroxyl groups in LCFs with triglycerides in vegetable oil. Similarly, the peaks in the 1230–1250 cm^{-1} and 1150–1160 cm^{-1} regions for both jute and

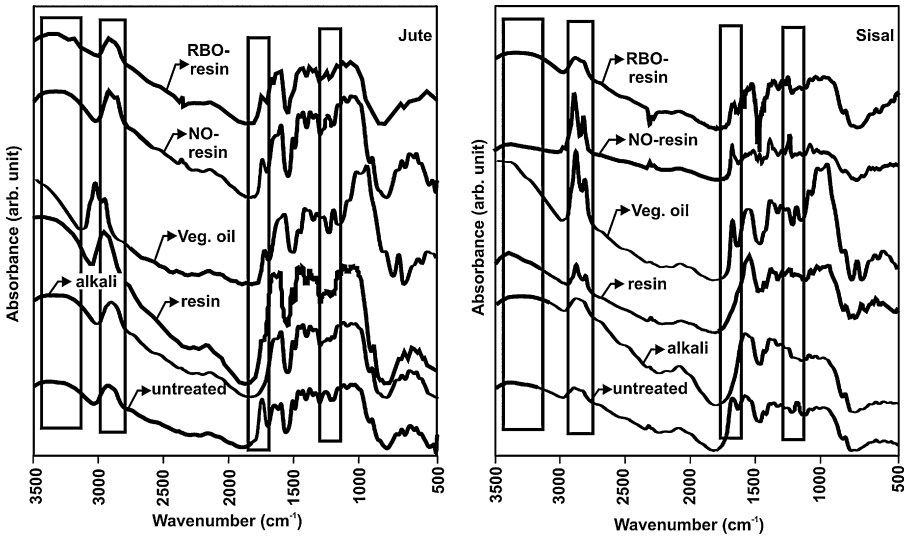

Fig. 3. FTIR spectra of LCFs (RBO: rice bran oil and NO: neem oil).

sisal fibers correspond to glycosidic C–O–C and C–O stretching of ester groups of lignin and hemicellulose (Peng et al., 2011; Bessadok et al., 2009) disappear after alkali treatment and reappear following vegetable oil-resin treatment. This observation also indicates transesterification of hydroxyl groups in LCFs.

FTIR response in the 2800–2950 cm^{-1} region representing C–H stretching vibration of LCFs (Ibrahim, Dufresne, Zawaway, & Agblevor, 2010) was found not to amplify or de-amplify significantly following alkali treatment. The response becomes more intense following vegetable oil and resin treatment due to the attachment of long aliphatic chain of vegetable oil triglyceride to cellulose (Pasquini, Belgacem, Gandini, & Curvelo, 2006) after transesterification.

The FTIR spectra of LCFs treated with vegetable oil only also indicate similar chemical transformation. In contrast, for the LCFs treated with phenolic resin only no transesterification could be inferred from FTIR spectroscopy. However, the FTIR response in the 2800–2950 cm^{-1} region was found to intensify in the resin-only treatment because of attachment of polymeric side chain of phenolic resin to the LCF cellulose.

3.5. Elemental analysis

The results of elemental analysis show the enhancement of the relative weight percentages of carbon, hydrogen, nitrogen and the lowering of relative weight of oxygen in LCFs following vegetable oil–resin treatment (Table 2). Increase of weight percentages of carbon and hydrogen could have resulted from the attachment of long hydrocarbon side chain of vegetable oil triglycerides to free hydroxyl group of cellulose or hemicellulose unit following transesterification. Mass percentage of nitrogen increases possibly because of nitrogenous impurities in vegetable oil. Similar improvement of weight % of carbon and hydrogen and reduction of oxygen was reported by Pasquini et al. (2006) in case of surface esterification reaction of microcrystalline cellulose with ethanol/water mixture in heterogeneous condition.

Increase of weight percentages of carbon and hydrogen for NO–resin treatment was found to be more pronounced than that in RBO–resin treatment. This observation indicates that RBO–resin treatment was relatively ineffective in inducing chemical modification in LCFs. As has already been pointed out, enhancements in tensile strength and hydrophobicity were more pronounced in NO–resin treatment compared to RBO–resin treatment. The observations suggest transesterification of OH groups is a major cause for enhancements in tensile strength and hydrophobicity of LCFs.

3.6. Crystallinity

In x-ray diffractograms, all the diffraction peaks for LCFs were observed of the 2θ angles around 16.3°, 22°, and 35°, which represented the cellulose-I structure (Liu, Han, Huang, & Zhang, 2009). Apparent increase in inferred crystallinity of jute and sisal fibers following alkali treatment, Table 3, is possibly because of partial removal of amorphous hemicellulose, lignin and pectin. Inferred crystallinity was found to increase further following vegetable oil–resin treatment for jute fibers. In contrast, for sisal fibers inferred crystallinity reduced marginally after vegetable oil–resin treatment. The reduction is possibly due to the damage in fiber crystals induced by the attachment of long aliphatic chains. Other researchers observed similar reductions in crystallinity in chemical grafting of cellulose with isocyanates (Siqueira, Bras, & Dufresne, 2010). Improved crystallinity resulted from the ordered orientation of fiber crystal following alkali treatment partially imparts

Table 2
Elemental composition of fibers.

Fibers	Treatment	Experimental values (wt%)				
		C	H	O	N	Residue
Jute	Untreated	45.00	6.20	46.30	0.20	2.30
	NO–resin	57.55	8.10	32.30	0.70	1.35
	RBO–resin	53.30	6.60	38.20	0.80	1.10
Sisal	Untreated	43.30	5.20	48.20	0.30	3.00
	NO–resin	53.40	8.10	36.00	0.60	1.9
	RBO–resin	52.10	7.30	38.40	0.80	1.40

Table 3
Crystallinity (%) of fibers.

Fiber	Treatment	Crystallinity index (%)
Jute	Untreated	67.90
	Alkali	71.30
	NO–resin	73.00
	RBO–resin	72.20
Sisal	Untreated	49.70
	Alkali	69.00
	NO–resin	68.10
	RBO–resin	66.80

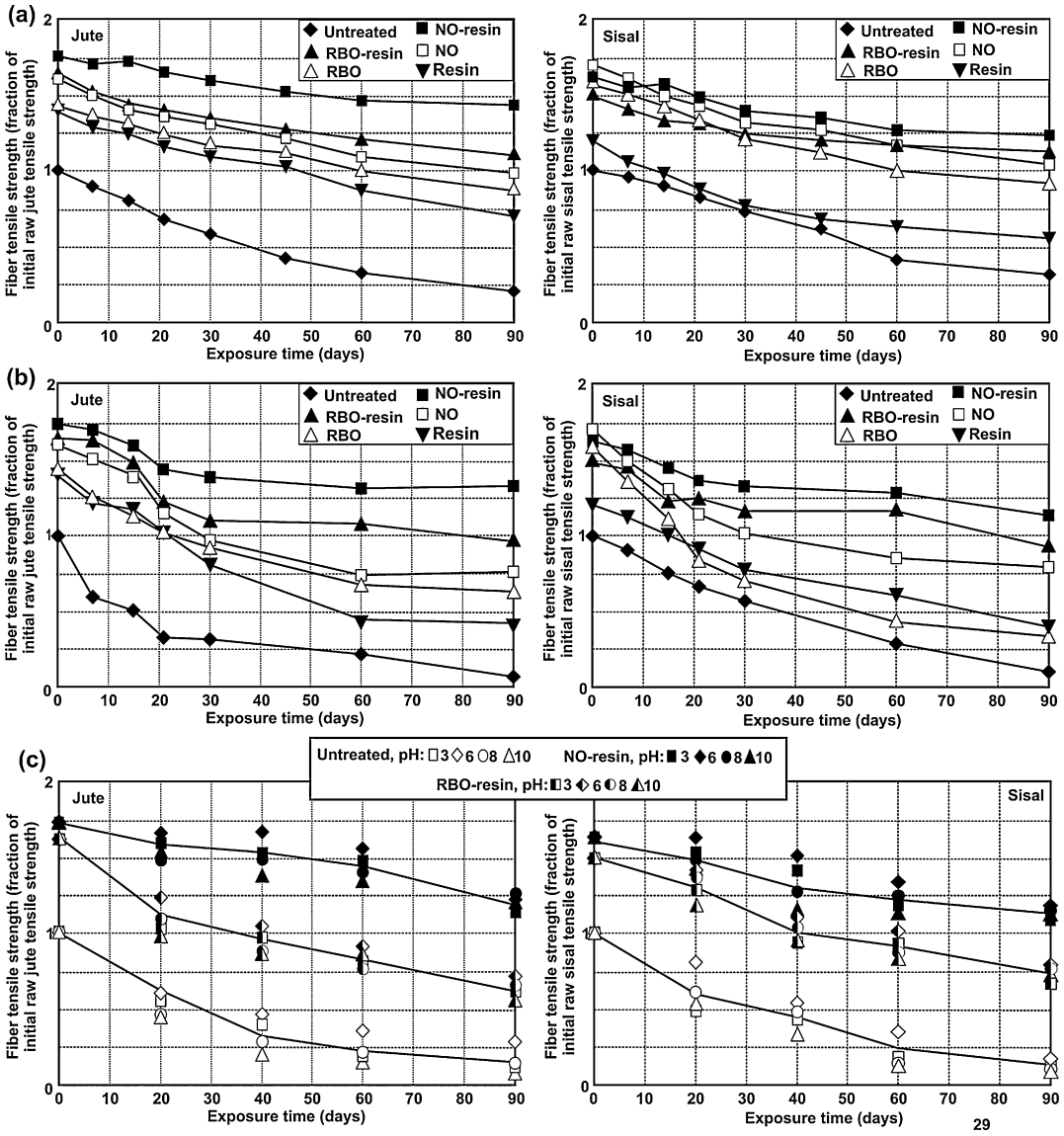

Fig. 4. (a) Degradation of tensile strength upon exposure to composting environment in soil; (b) degradation of tensile strength of LCFs upon exposure to elevated salinity of 3% (by wt) sodium chloride solution; (c) degradation of tensile strength of LCFs upon exposure to different pH environment (pH 3–10).

enhanced tensile strength and hydrophobicity in LCFs (Jacob, Thomas, & Varughese, 2004).

3.7. Durability

Durability of the transesterified fibers was investigated both by exposing the fibers to a composting environment, elevated salinity levels and alkaline and acidic pH conditions. Tensile strength degradation resulting from 90-d exposure to a composting environment is presented in Fig. 4a. These results indicate that vegetable oil–resin treated fibers retain between 70% (for jute) and 63% % (for sisal) of their initial tensile strengths. The corresponding tensile strength retention for untreated fibers was only 28% or less. In fact, the residual tensile strengths for vegetable oil and resin treated fibers exceeded the corresponding initial tensile strengths of untreated fibers by 43% (for jute) to 25% (for sisal).

Tensile strength degradation resulting from 90-d exposure to elevated salinity level is presented in Fig. 4b. These results indicate vegetable oil–resin treated fibers retain between 60% (for jute) and 52% (for sisal) of their initial tensile strengths. The corresponding tensile strength retention for untreated fibers was only 13% % or less. In fact, the residual tensile strengths for vegetable oil and resin treated fibers exceeded the corresponding initial tensile strengths of untreated fibers by 31% (for jute) to 19% (for sisal). Strength loss of LCFs upon saline exposure was resulted from the penetration of NaCl into the void space of fibers (Rowell, 2005).

The LCFs were exposed to series of aqueous solution of different pH ranges from 3 to 10 for 90-d. Degradation was accelerated for LCFs in higher and lower ranges of pH solution (Fig. 4c). Reduction of tensile strength was found to be less prominent for vegetable oil–resin treated LCFs compared to untreated and other treatments. Susceptibility to degradation of LCFs treated with vegetable oil–resin was maximum in solution higher than pH 9. High alkaline pH hydrolyses the ester bond formed in transesterification reaction and results reduction of uniaxial tensile strength. Enhanced degradation in lower pH environment (pH lower than 3) may be due to the presence of higher number of carboxyl groups present on the LCFs surface as stated by Park, Furuno, and Uehara (1996) for wood composites.

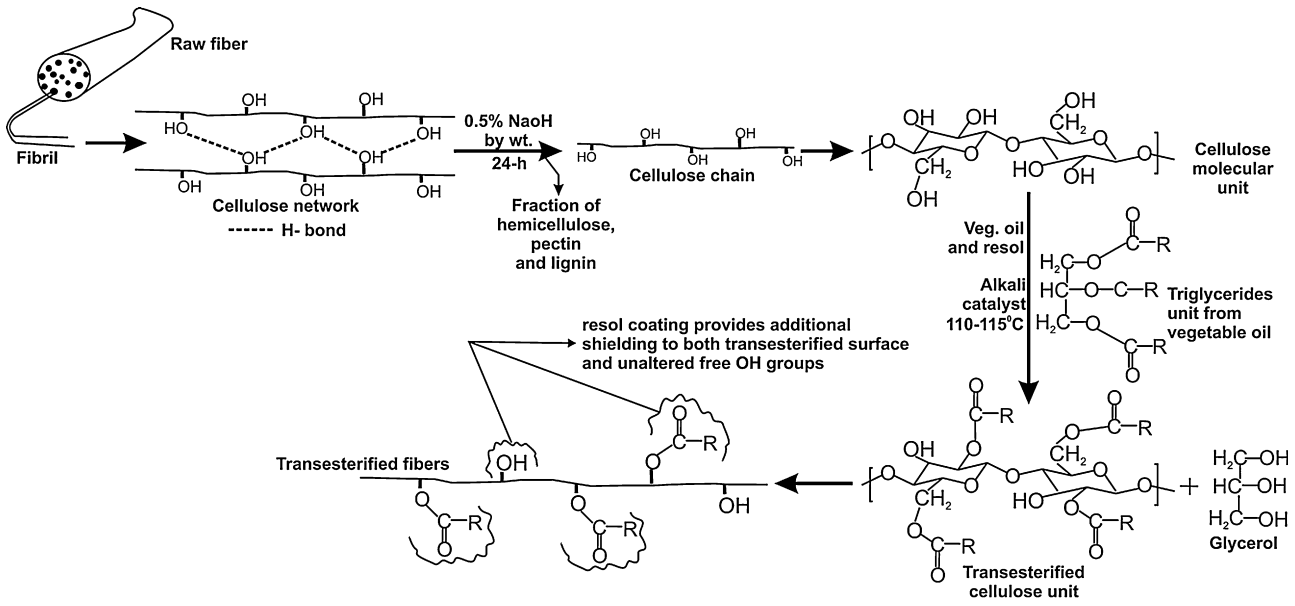

Fig. 5. Schematic representation of probable chemical alteration (transesterification) of fibers during chemical process.

3.8. Inferred chemical changes in LCFs

A schematic mechanism of probable transesterification reaction of LCFs has been shown in Fig. 5. Results obtained from ζ-potential measurement, FTIR-spectroscopy, and elemental analysis were found to point consistently towards possible transesterification of hydroxyl groups in LCFs with triglycerides fatty acid of vegetable oil. The presence of phenolic resin serves its purpose as a coating agent as well a potential antimicrobial agent when used with vegetable oil. Resol coating provides an additional protection to the transesterified fiber surface against the exposure to biological and chemical environments. Hence the durability of the LCFs shows maximum improvement when both vegetable oil along with phenolic resol were used. Less improvement of tensile strength, hydrophobicity and durability of LCFs following phenolic resin treatment only indicates the non-occurrence of the transesterification. It can therefore be proposed from the underlying evidences that transesterification would be the reason for enhanced tensile strength, hydrophobicity and durability for LCFs.

4. Conclusions

A process for transesterifying jute and sisal by treating them with a combination of rice bran oil and neem oil with resorcinol–tannin–cashew nut shell liquid based phenolic resin (resol type) at elevated temperature has been developed for enhancing their hydrophobicity, tensile strength and durability. The treatment involving neem oil and resol caused water absorption to decrease from 255% to 79% for jute fibers and from 185% to 62% for sisal fibers. Correspondingly, short term tensile strength increased by 75% and 61% for jute and sisal fibers. Treatments with combinations of rice bran oil and resol, neem oil or rice bran oil without resol, and resol without neem oil or rice bran oil were found to be relatively less effective.

Neem oil and resol treated jute and sisal fibers were, on an average, found to retain 70% and 63% of their initial tensile strengths, respectively, upon being exposed to biological degradation in a composting condition over 90 days duration. The corresponding tensile strength retention for untreated jute and sisal fibers were only 28% and 32%, respectively.

After 90-day exposure to 3% aqueous saline solution of NaCl, neem oil and resol treated jute and sisal fibers retained 60% and 52% of their initial tensile strength, while untreated jute fibers retained only 9% and sisal fibers 13%. Tensile strength retention for neem oil and resol treated jute and sisal fibers were 48% and 55%, respectively, after 90-day exposure to pH between 3 and 10. In comparison, untreated jute fibers only retained 12% and sisal fibers 10% of their initial tensile strengths.

Acknowledgements

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Durability of transesterified jute geotextiles

Prosenjit Saha [a], Debasis Roy [b,*], Suvendu Manna [a], Basudam Adhikari [a], Ramkrishna Sen [c], Sukumar Roy [d]

[a] Materials Science Centre, Indian Institute of Technology, Kharagpur, West Bengal 721302, India
[b] Department of Civil Engineering, Indian Institute of Technology, Kharagpur, West Bengal 721302, India
[c] Department of Biotechnology, Indian Institute of Technology, Kharagpur, West Bengal 721302, India
[d] KE Technical Textile Pvt. Ltd., Kharagpur, West Bengal 721301, India

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ABSTRACT

A process for transesterifying jute fibers or textiles using reagents largely derived from natural sources has been developed for enhancing the long-term tensile strength and water repellence of fiber or textile samples. Geotextiles woven from treated jute fibers (JG1) and geotextiles treated at the fabric level (JG2) using the process developed in this study were found to retain 50% of their initial tensile strengths after remaining immersed in aqueous solutions with pH between 4 and 9 for 120 days. Correspondingly untreated jute geotextiles (JGU) retained only 15% of its initial tensile strength. Upon being immersed in 3% NaCl solution for 120 days, JG1 retained 82% of its initial tensile strength, while JG2 and JGU retained 64% and 17%, respectively. JG1 samples are estimated to loose 50% of their initial tensile strength after 1115 and 1584 days, respectively, because of UV and moisture related weathering and biodegradation in tropical outdoor environments. The corresponding estimates for JG2 were 881 and 1080 days, respectively. These estimates were about 3–5 times higher than those for JGU. Additionally, degradation of treated fiber or fabric did not produce toxic or hazardous leachate. These enhancements may make jute geotextiles useful in earthworks requiring temporary reinforcement before insitu processes, e.g., vegetation growth, filter cake formation, and development of weak cementation due to biogenic and other processes strengthen the soil obviating further need for reinforcements.

1. Introduction

In recent years natural fibers such as sisal (Sarsby, 2007), palm (Bhattacharyya et al. 2009), bagasse (Dinu and Saska, 2007), flax (Rawal and Anandjiwala, 2007), hemp (English, 1995), jute (Ranganathan, 1994) and coir (Subaida et al., 2008) have been used for manufacturing geotextiles because they are inexpensive, renewable agricultural commodities unlike their manmade, petroleum-based alternatives. Geotextiles based on jute fibers have a number of additional application-specific advantages. For instance, swelling and water absorption of jute fibers lead to reduction in runoff energy and improvement in filtration characteristics of the fabric to provide better stability in an erosion control application. Further, they also prevent extreme variations in soil moisture and temperature (Sutherland and Ziegler, 2007).

Despite their relative advantages, geotextiles based on natural fibers find limited use in many engineering projects because of their relatively low tensile strengths and their susceptibility to biological, chemical and physical degradations. Consequently, they are mainly used to support vegetation growth, which, in turn, imparts mechanical resistance of soils against erosion and sliding.

Attempts have been made to enhance the resistance of jute geotextiles against biological degradation by coating them with bitumen (Sanyal and Chakraborty, 1994) or antimicrobial benzothiazole chemicals (Sinha and Chakraborty, 2004). These techniques are expensive and turn the coated fabric into a potential source of toxic leachates (Basu et al., 2009). In addition, bitumen treatment adversely affects the flexibility and drapability of geotextiles. Geotextiles have also been manufactured from jute fibers blended with synthetic fibers (Rawal and Sawaswat, 2011; Basu et al., 2009) for durability enhancement. However, biodegradation of untreated fibers within such geotextiles is likely to lead to disintegration of fabric structure.

Fiber level and fabric level chemical modification without compromising flexibility appears to be a better alternative than the processes used so far to enhance the resistance of jute geotextiles against degradation. The objectives for this study are to (a) develop a chemical treatment process for jute fibers and fabric for manufacturing more durable biomass-based geotextiles, (b) quantify the long term tensile strength of the product as functions of

* Corresponding author. Tel.: +91 3222 283456; fax: +91 3222 282254.
E-mail address: debasis@civil.iitkgp.ernet.in (D. Roy).

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durations of exposure to controlled chemical, biological and accelerated physical weathering environments in the laboratory, and (c) study the leachate characteristics.

2. Geotextiles

Jute (*Corchorus olitorius*) fibers of TD4 grade (BIS 271, 2003) and commercially available jute fabric with specifications listed in Table 1 were dipped for 24-h within an aqueous emulsion prepared from sodium hydroxide, plant tannin, cashew nut shell liquid, resorcinol, neem oil and formaldehyde in 1:10:8:2:6:4 proportion by weight with pH of 8. A similar emulsion was used by Saha et al. (2012) to treat lignocellulosic fibers for enhancing their tensile strength, water repellence and degradation resistance. Subsequently, the fibers and fabric were recovered, mechanically squeezed and cured in a convection oven at 105 ± 5 °C for 1 h. Particulars of the fabric treated in this manner are summarized in Table 1. Using treated jute fibers 500 m^2 of geotextile was manufactured at a commercial jute mill. Specifications of the fabric manufactured from treated jute fibers are listed in Table 1 as well.

Production costs of geotextiles manufactured from treated jute fibers and from treating commercially available fabric are presented in Table 2. The comparison shows that the production costs of JG2 (jute geotextiles chemically modified at the fabric level) and JG1 (geotextiles woven from chemically modified jute fibers) are lower than those of bitumen coated and HDPE blended jute geotextiles and JG2 and JG1 costs are only marginally higher than that of untreated jute geotextiles (JGU).

3. Filtration characteristics

The apparent opening size, O_{95}, and permittivity at 500 mm constant water head of samples of untreated fabric (JGU), fabric manufactured from treated fiber (JG1) and treated fabric (JG2) are presented in Table 1. These results are not indicative of any adverse impact of chemical treatment on fabric porometry. Bitumen treatment, on the other hand, has a remarkably adverse impact on the filtration characteristics geotextiles (Correia and Bueno, 2011). For jute geotextiles, O_{95} decreases by as much as 50% and permittivity by as much as 60% following bitumen treatment.

4. Short-term tensile strength

Geotextiles samples, 25 mm in width and 150 mm in length, were subjected to tensile loading in a universal testing machine (Hounsfield H10KS) maintaining a deformation rate of 300 mm/min for estimating the "narrow strip" tensile strengths following ASTM D751 (2006). Five specimens each from JG2, JG1, and JGU fabrics were tested in both machine and cross-machine directions and the average of the tensile strength has been reported along with the 95% confidence interval. Elongation at break for the samples was also reported similarly.

The short-term narrow strip tensile strengths and elongation at break for JGU, JG1 and JG2 samples are summarized in Table 3. These results do not indicate any adverse impact of the chemical treatment on tensile strength and flexibility of the geotextiles.

Table 1
Geotextile specifications.

Parameter	JGU	JG1	JG2	Standard
Area density (g/m^2)	700	690	720	ASTM D5261-10
Thickness (mm)	1.4	1.3	1.4	ASTM D5199-11
Yarn linear density (ktex)	0.68,[a] 0.99[b]	0.46,[a] 0.46[b]	0.68,[a] 0.99[b]	ASTM D861-07
Fabric mesh (threads/mm)	5.5,[a] 3.9[b]	7.1,[a] 3.9[b]	5.5,[a] 3.9[b]	BIS 1963-81
Weave pattern	1 up 1 down	1 up 2 down	1 up 1 down	
O_{95} (μm)	235	255	245	ASTM D4751-04
Permittivity (cm/sec)	0.083	0.090	0.083	ASTM D4491-99

[a] Machine direction.
[b] Cross machine direction.

5. Long-term tensile strength

5.1. Chemical degradation

Impact of chemical degradation was investigated by keeping geotextile samples immersed within an aqueous saline solution with 3% by weight of NaCl, and aqueous solutions with pH of 3, 4, 7, 9 and 10 for 120 days and determining the tensile strength retention by testing samples recovered periodically. These data indicate that JG1 and JG2 samples retained 50% of their initial narrow strip tensile strengths when immersed in solutions with pH between 4 and 9, while JGU retained only 15% in similar conditions (Fig. 1). Loss of narrow strip tensile strength was more prominent at pH less than 4 and above 9. JG1 and JG2 samples exposed to aqueous environments of elevated salinity levels, on the other hand, retained 82% and 64% of their initial tensile strengths, respectively, after 120 days (Fig. 2). The corresponding tensile strength retention for JGU was only 17%. Data presented in Fig. 2 indicate that the rate of decrease of narrow strip tensile strength of JG1 and JG2 slows down with increasing duration of exposure to salinity and little reduction is observed when the duration of exposure exceeds 60 days.

5.2. Biological degradation

Effect of biological degradation on narrow strip tensile strength was assessed by burying geotextile samples within a medium prepared by mixing organic black garden soil, sand and cow dung in 2:1:1 ratio (by weight) with 30% water content as suggested in BIS 1623 (1992). A similar approach described in ASTM G160 (1998) is used internationally for assessing biological degradation. However, compared to the 21-d exposure suggested in BIS (1992) and exposure duration of 60-d or more suggested in ASTM (1998) the geotextile samples in this assessment were kept buried for up to 200 days. Also, for tests continuing for more than 7 days, geotextile samples were recovered once every week without inflicting physical damage before reburying them within freshly prepared soil cow dung mixture to simulate an open biodegradation environment better. Six samples of 250 mm × 40 mm size from each of the three batches of jute geotextiles (JGU, JG1 and JG2) were exposed to biodegradation maintaining 1:100 sample-to-compost ratio (by weight) as suggested by Di Franco et al. (2004). The experiment was carried out within an incubator at 35 ± 5 °C and 85 ± 5% relative humidity following BIS (1992) and ASTM (1998). Samples were periodically recovered, washed and tested for narrow strip tensile strength following the procedure discussed earlier. Degradation of JGU sample were found to be more remarkable compared to JG1 and JG2 samples and the resistance of JG2 samples against biodegradation was not as pronounced as that of JG1 (Fig. 3). After 200-d exposure JG1 and JG2 samples retained 48% and 37% of their initial narrow strip tensile strength, respectively, while the tensile strength for JGU could not be measured beyond 90 days of exposure because of complete disintegration (Fig. 4).

Table 2
Pros and cons of jute geotextiles.

Geotextiles	Estimated cost (USD/m^2)	Advantages	Disadvantages
HDPE	1.5–1.6[a]	1. 100 to 200 year service life[b] 2. High strength and productivity	1. Non renewable raw materials 2. Non swelling and water repellent: possibly inferior filtration characteristics
HDPE blended jute	1.5–1.7[a]	1. Service life must be higher than that of 100% jute geotextiles 2. Moderate strength	1. 50% non renewable raw materials 2. Raw jute will degrade within a year limiting service life
Jute (JGU)	1.2–1.3[a]	1. Raw materials are renewable and eco-friendly 2. Good filtration, supports vegetation	1. Low strength 2. Less than 1year service life
Bitumen coated jute	1.7–1.8[c]	1. Service life is up to 3–4 years[c] 2. Moderate strength and productivity	1. Bitumen is a non renewable material and its cost is susceptible to petroleum cost fluctuations 2. Inferior filtration characteristics 3. Generates toxic leachates
Treated jute fabric (JG2)	1.4–1.5	1. Inexpensive relative to alternatives 2. Renewable resource 3. No toxic leachate	1. Limited service life of 4 years 2. Low tensile strength relative to HDPE
Fabric manufactured from treated jute fiber (JG1)	1.3–1.4	1. Inexpensive relative to alternatives 2. Renewable resource 3. No toxic leachate	1. Limited service life of 5 years 2. Low tensile strength relative to HDPE

[a] Estimated using Basu et al. (2009) data and historical spot price trend of HDPE in Asia.
[b] Estimate of Gerard and van Santvoort (1994).
[c] Estimated using Sanyal and Chakraborty (1994) data and crude oil spot price trend in the Indian market.

5.3. Physical degradation

Effect of accelerated physical weathering on geotextiles samples was evaluated using a computer-controlled artificial weather chamber (Suntest XXL/XXL+, Atlas GmbH) following ASTM G-155 (2005) maintaining environmental parameters listed in Table 4. Samples recovered after 150, 300 and 500 hours of exposure were tested for narrow strip tensile strength as discussed earlier. Jute geotextiles were found to lose a significant proportion of their initial narrow strip tensile strength after AAW. After 500-h AAW JG1 and JG2 samples were found to retain 80% and 75% of their initial narrow strip tensile strengths (Fig. 5). In comparison JGU was retained only 33% only.

Table 3
Short-term tensile strength and elongation at break.

Sample	Tensile strength (kN/m) ± CL[a]		Elongation at break (%) ± CL	
	MD[b]	CD[c]	MD	CD
JGU	22 ± 6	21 ± 5	11 ± 1	08 ± 2
JG1	19 ± 2	21 ± 3	12 ± 5	09 ± 3
JG2	25 ± 4	23 ± 3	13 ± 4	09 ± 2

[a] 95% Confidence limit.
[b] Machine direction.
[c] Cross machine direction.

6. Water affinity

Water affinity was estimated by immersing 40 mm × 40 mm geotextile samples in distilled water form 24 h, determining the weight of absorbed water and expressing it as a percentage of the initial sample dry weight (Alvarez and Vázquez, 2006). These data indicate that JGU, JG1 and JG2 absorbed 270%, 90% and 120% water, respectively, in terms of their initial dry weight (Table 5). The chemical treatment appears to make the fabrics less hydrophilic with the fiber level treatment showing greater efficacy than the fabric level treatment.

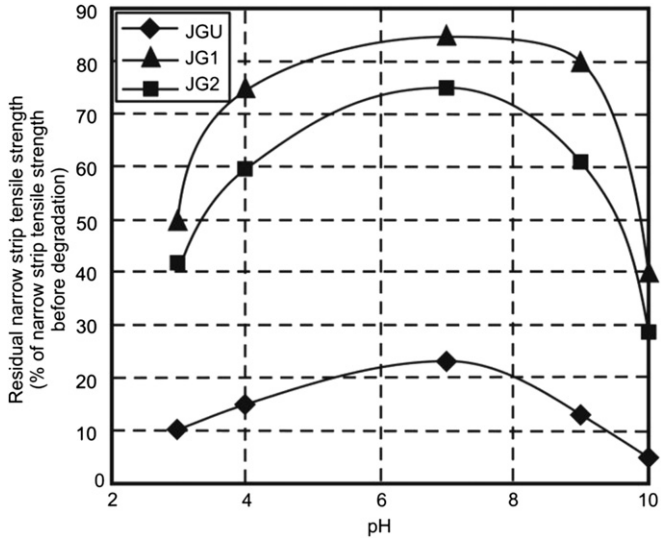

Fig. 1. Residual narrow-strip tensile strength as functions of pH.

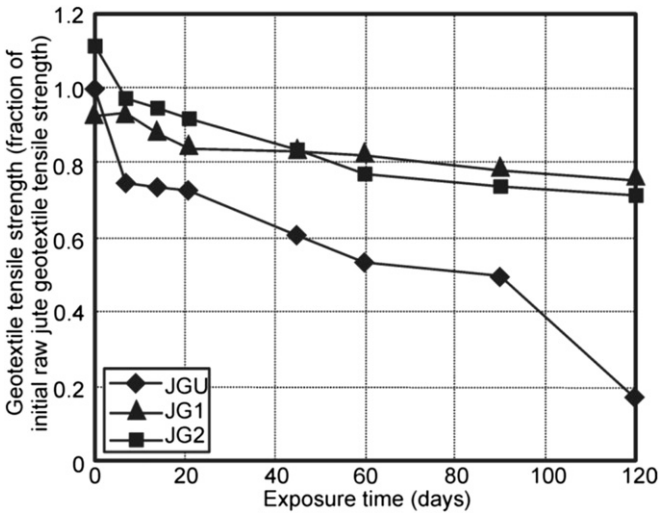

Fig. 2. Salinity-related tensile strength degradation.

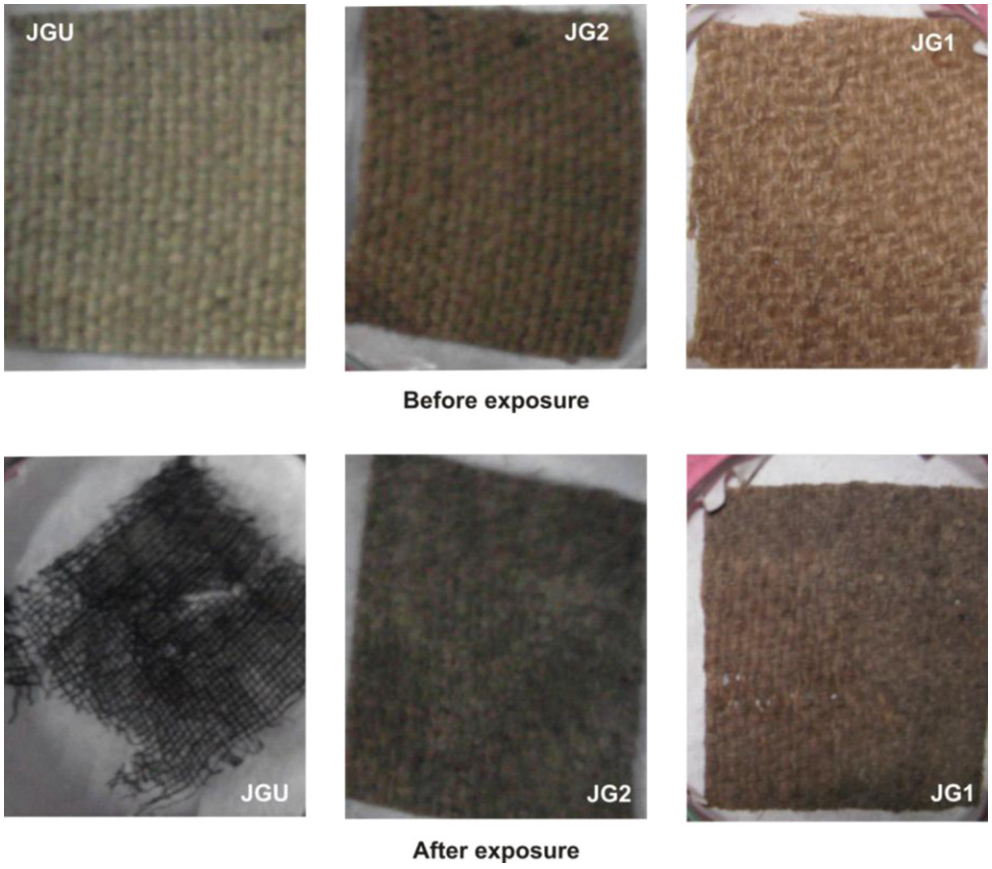

Fig. 3. Photograph of jute geotextiles.

7. Chemistry

Pellets prepared from dried fibers (1–2 mm long) extracted from JGU, JG1 and JG2 fabrics and potassium bromide (KBr) in ratio 1:100 (w/w) were subjected to FTIR spectroscopy in a spectrophotometer (Thermo Nicolet, Nexus 870) for assessing fabric chemistry. Wave numbers between 4000 cm^{-1} and 500 cm^{-1} were covered using 32 scans in the investigation. Baseline corrected (for CO_2 and H_2O molecules) data recorded in the transmittance mode were normalized by dividing the apparent intensities at wave number of 1050 cm^{-1} because FTIR response at this wave number represents C–O stretching vibration, which is relatively insensitive to chemical, biological and physical changes.

For JG1 transmittance in region A of Fig. 6 were less intense compared to that of JGU. Since the response in this region represents OH stretching (Tornc et al., 2007), chemical treatment appears to have altered some of the OH groups of jute fiber cellulose chains. FTIR data also indicate that intensification was more pronounced for JG2 compared to JG1 possibly indicating the extent of OH group alteration was less in the fabric level treatment represented by JG2 samples.

FTIR spectral transmittance in regions B and C of Fig. 6 was most intense for JGU, absent for alkali treated JGU and reappeared relatively more prominently for JG1 and somewhat less prominently for JG2. The responses in these regions representing C=O stretching (region B, Fig. 6) and C–O–C and C–O stretching of ester bonds (region C, Fig. 6) disappeared following alkali hydrolysis of JGU samples and reappeared in JG1 and JG2 samples because of

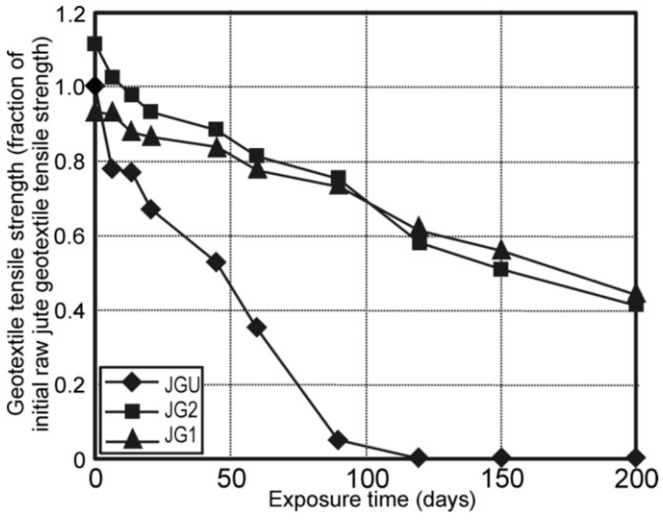

Fig. 4. Biological degradation of tensile strength.

Table 4
AAW testing conditions.

Parameter	Condition
Irradiance at 290–400 nm (W/m^2)	140 ± 10
Black standard temperature (°C)	65 ± 5
Relative humidity (%)	60 ± 5
Water spray/dry cycle (min)	102/18
Water temperature (°C)	23 ± 3
Water pH	7 ± 1

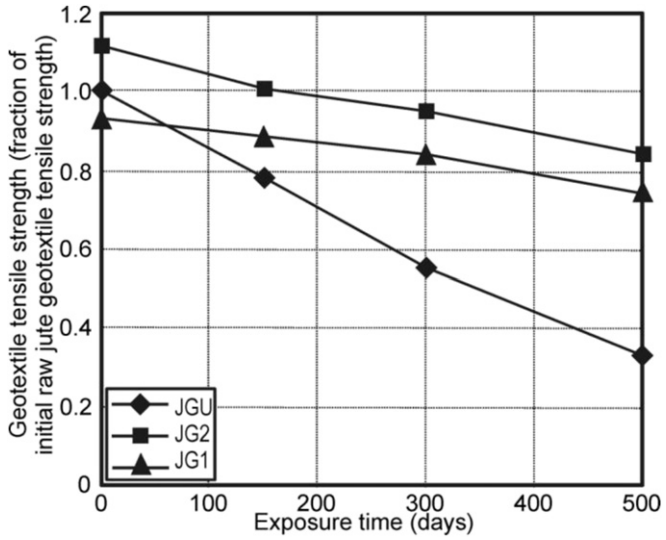

Fig. 5. AAW-related tensile strength degradation.

Table 5
Water absorption.

Sample	Water absorption (% by wt.) ± CL			
	Initial	120-d saline exposure	500-h AAW	200-d soil burial
JGU	270 ± 35	280 ± 52	310 ± 71	287 ± 58
JG1	90 ± 22	110 ± 20	170 ± 21	140 ± 20
JG2	120 ± 30	150 ± 34	210 ± 35	176 ± 22

CL: 95% confidence limit.

transesterification of some of the OH groups due to the chemical treatment (Saha et al., 2012).

Transesterification of jute fiber cellulose chains inferred from FTIR data is confirmed by hydrolyzing the geotextile samples in an alkaline medium. For this JGU, JG1 and JG2 samples were first washed thoroughly with 70% ethanol to remove excess oil and residual chemicals. They were then hydrolyzed in 1% NaOH solution (pH 9) maintaining 1:10 geotextile to solution ratio (by weight) for 1 hour at 100 °C. Spectral responses obtained using a UV spectrophotometer (Systronics model 150) of the hydrolyzate filtrate of JG1 and JG2 showed absorption maxima at 310 nm and 320 nm, which closely matched with the absorption maxima of standard oleic and stearic acids. Since oleic and stearic acids are the main active ingredients in neem oil used in the chemical treatment of this study, their presence in the hydrolyzate filtrate confirms the inference of transesterification reaction. Similar absorption maxima were not observed for JGU hydrolyzate filtrate.

8. Crystallinity

XRD data were obtained by subjecting 1 ± 0.5 g of fibers, each of 5 ± 1 mm length, collected from geotextiles to Cu-Kα radiation for 2θ ranging between 10° and 50° at a scanning speed of 2° per minute using a RIGAKU X-Ray diffractometer (ULTIMA III) operated at room temperature. Crystallinity index, C_r, estimated from the data using $C_r = (I_{22.5} - I_{18.5})/I_{22.5}$, where $I_{22.5}$ and $I_{18.5}$ are the intensities at 2θ values of 22.5° and 18.5°, respectively (Segal et al., 1959) are presented in Table 6. The average crystallite size, D, estimated from $D = k\lambda/(B\cos\theta)$ for 2θ of 22.5° (Gumuskaya et al., 2003), where k is the Scherrer constant (usually ranges between 0.8 and 1 with a value of 0.84 often used for lignocellulosic fibers; Mohkami and Talaeipour, 2011), λ is the x-ray wavelength (equal to 1.54 nm for Cu-Kα radiation), and B is the integral breadth of a reflection (in radians), is also reported in the table.

These results indicate an increased crystallinity index for JG2 and JG1 compared to JGU with the increase for JG1 being more prominent. The average crystallite size also showed a small increase particularly for JG1. The increased crystallinity and crystallite size therefore appears to correlate with the increased tensile strength and resistance against chemical, biological and physical degradation of geotextiles.

9. Leachate characteristics

Leachates collected periodically from the experiments, where geotextiles were exposed to salinity, pH and AAW were

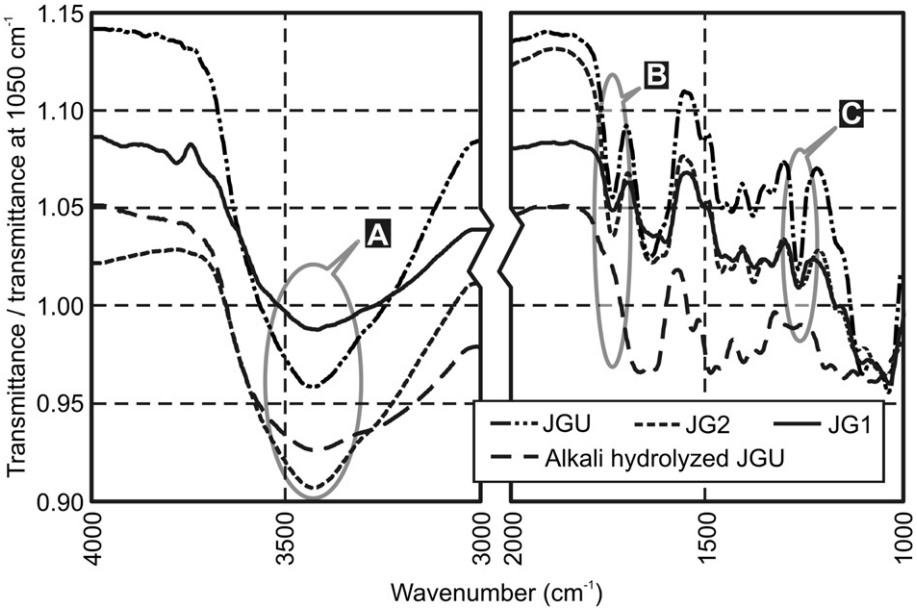

Fig. 6. FTIR transmittance spectra.

Table 6
X-ray diffractometry.

Parameter	JGU	JG1	JG2
C_rI (%)	54	63	58
Crystallite size (nm)	28	32	30

characterized using Systronics 150 UV spectrophotometer to assess possible leachate toxicity due to the presence of free tannic acid and formaldehyde. In the UV spectral response absorption maxima were not detected at around 700 nm (representing free tannic acid) and 434 nm (representing free formaldehyde). No other toxic chemical species are expected to be present in the leachate originating from the geotextile samples.

10. Service life estimation

10.1. AAW half-life

Half-life for JG1 and JG2 geotextile samples was estimated by fitting the AAW data (Fig. 5) to $Y = A + bt$, where Y is the narrow strip tensile strength at time t and A and b are constants, and estimating the time of exposure for 50% degradation of the initial narrow strip tensile strength from the best-fit relationship. Following Koerner et al. (2005), the estimate was scaled with the ratio of total AAW UV irradiation to the yearly UV irradiation of eastern India obtained from Wypych (2008) to obtain the field half-life. These results indicate field half-lives for JGU, JG1 and JG2 geotextiles to be 330, 1115 and 881 days, respectively, for installations under direct sunlight (Table 7).

10.2. Biodegradation half-life

The environment within which geotextile samples were buried in the laboratory-based biodegradation study were more severe compared to typical field installation environments. For instance, laboratory biodegradation experiments indicate complete disintegration of JGU in about 90 days (Fig. 4). In comparison, untreated jute geotextiles comparable to JGU installed in a riverbank environment takes about eight times as long to disintegrate (Ingold and Thomson, 2007). Consequently, the biodegradation-related field half-life was estimated by scaling the half-lives observed in the laboratory-based biodegradation study up by a factor of 8. Accordingly, field half-lives of 384, 1584 and 1080 days were obtained for JGU, JG1 and JG2 geotextiles, respectively (Table 7). Since the field work of Ingold and Thomson (2007) was performed in a tropical environment, use of these field half-life estimates obtained in this study in environments with smaller average ambient temperatures is expected to be conservative (Schwarz, 2001).

Table 7
Half-life of jute geotextiles.

Sample	Test	Y (kN/m), A, b, r^2	Half-life (d)	
			Lab	Field
JGU	AAW[a]	11, 21, -2.9×10^{-2}, 0.99	15	330
	Soil burial	–	48[b]	384
JG1	AAW[a]	10, 20, -7.9×10^{-3}, 0.99	53	1115
	Soil burial	–	198[b]	1584
JG2	AAW[a]	12, 24, -1.2×10^{-2}, 0.99	41	881
	Soil burial	–	135[b]	1080

[a] UV irradiation in 500-h AAW = 250 MJ/m^2. Solar UV irradiation in eastern India in 1 year = 210 MJ/m^2. Consequently, 1-d AAW exposure is equivalent to about 21-d outdoor exposure in eastern India. Different scaling factors will be needed for locations with other values of solar UV irradiation.
[b] Read off Fig. 4.

11. Conclusions

A chemical process has been proposed for enhancing the resistance of jute geotextiles against chemical, biological and physical degradation. The process mainly uses non hazardous, non toxic, plant-based ingredients. Investigation into the chemistry of treated fabric indicated that the process leads to partial transesterificaton of some of the hydroxyl groups present within jute fibers. The treatment led to increased fiber crystallinity. The treated fabrics were less hydrophilic and more resistant to degradation. In addition, the treatment did not adversely affect flexibility, tensile strength and filtration characteristics of the fabrics.

Samples of commercially available untreated jute geotextiles and jute geotextiles manufactured from jute fibers treated with the proposed process were subjected chemical (pH and salinity), biological and physical degradation in the laboratory. Commercially available jute geotextiles were also treated with the proposed chemical process and subjected to similar investigations. Based on these results it is estimated that geotextiles manufactured from treated jute fibers would lose 50% of their initial tensile strength in about 1115 and 1584 days, respectively, due to UV and moisture related weathering and biodegradation in a tropical field installation environment. The corresponding estimates for chemically treated geotextiles were 881 and 1080 days, respectively. These half-lives are about 3–5 times longer than those reported for untreated jute geotextiles. Characterization of the degradation products of geotextiles manufactured from treated jute fibers and treated jute geotextiles did not reveal any toxicity or chemical hazard.

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Appendix 3

Workshop participants

Participants at the workshop in IIT Kharagpur at December 21, 2009

Name & Address	Tel./email
Mr. A. Bhagat, Dy. Chairman, Indian Jute Mills Association (IJMA), 6 Netaji Subhas Road, Kolkata 700001	9831031321
Mr. A. Khastagir, Project Manager, IJSG-NCJD, Govt. of India, Ministry of Textiles, 75C, Park Street, Unit No. G-2A, Ground Floor, Kolkata 700 015	9831275923
Mr. A. Mitra, Consultant, JMDC, 3A Park Plaza, 71 Park Street, Kolkata 700016	
Mr. Abhisekh Kankaria, Executive Director, Ambica Multifibres Ltd., (Unit: Bally Jute Mills), Kankaria Estate (7th floor), 6 Little Russel Street, Kolkata 700001.	9831000110
Mr. Atri Bhattacharya, IAS, Secretary & Executive Director, JMDC & NCJD, 3A Park Plaza, 71 Park Street, Kolkata 700016	
Mr. B. M. Thakkar, President, Ludlow Jute Mills	
Shri D. Banerjee, Consultant, JMDC, 3A Park Plaza, 71 Park Street, Kolkata 700016	
Shri D. K. Bubna, Ludlow Jute Mills, (Prop : Aekta Ltd.), Kankaria Estate, 4th floor, 6 Little Russel Street, Kolkata 700019.	09830264431
Mr. G. K. Roychowdhury, CEO AJHEEI, C/o Hitachi-kk Mafg. Co., 1 BK Pal Ave., Kolkata 700005	
Mr. Mahadeb Dutta, Asst. Director, NCJD, Park Plaza (3rd Floor), 71 Park Street, Kolkata 700016	03364552401/ 09836827323
Mr. N. Sengupta, Chief Finance Officer, JMDC & NCJD, Ministry of Textiles, Govt. of India, 71Park Street, Park Plaza, Kolkata 700016	09831308263
Mr. P. K. Chaudhury, In-charge, Jeotech Cell, Indian Jute Industries' Research Association (IJIRA), 17 Taratola Road, Kolkata 700088	
Mr. P. Roy, Principal, Institute of Jute Technology, 35 Ballygunge Circular Road, Kolkata 700019	
Mr. S. K. Bhattacharya, Exe Vice-Chairman, Indian Jute Mills Association (IJMA), 6 Netaji Subhas Road, Kolkata 700 001,	09830264158
Mr. S. K. Biswas, Director, Jute Development, 234/4 A.J.C. Bose Road, Kolkata 700020	
Mr. S. K. Chandra, Chief Executive, Hooghly Mills Projects Ltd., (Unit : Hukumchand Jute Mill), 10 Dr. Rajendra Prasad Sarani, Kolkata 700 001	
Mr. Soumyadipta Dutta, Technical Officer, Jute Commissioner's Office, Govt. of India, 3rd MSO Building, E&F Wing, CGO Complex, 4th floor, Sector I, DF Block, Salt Lake City, Kolkata 700064	09830219724
Mr. Sushil Khaitan, President, AJHEEI, C/o. Ashoka Exports, 110/1 Dharamtalla Rad, Ghusuri, Howrah 711107	03326583908, 09830050116
Mr. T. Sanyal, Geotechnical Advisor, JMDC, Govt. of India, Ministry of Textiles, 3A Park Plaza, 71 Park Street, Kolkata 700016	
Mr. U Sen, Asst. Director (JM), Ministry of Textiles, Govt. of India, 3rd MSO Building, E&F Wing, CGO Complex, 4th floor, Sector I, DF Block, Salt Lake City, Kolkata 700064	
Mr. Sukumar Roy, KE Tech. Tex. P. Ltd., Kharagpur	
Mr. Nirmalaya Mukherjee, IJMA, Kolkata	
Mr. D. K. Vittina Menon, HCTM	
Mr. Pundarikaksha Roy, JMDC, Kolkata	
Mr. Anil Kr. Kundu, JMDC, Kolkata	
Mr. Rabindra Pandit, Chaplin Club, Trilochanpur, Purba Medinpur	
Mr. Sanjoy Karak, Chaplin Club, Trilochanpur, Purba Medinpur	
Mr. Sandip Basu, IJIRA, Kolkata	
Mr. R. B. Lahati, Ruchi Bags, Kolkata	

Participants at the workshop in IIT Kharagpur at December 21, 2009

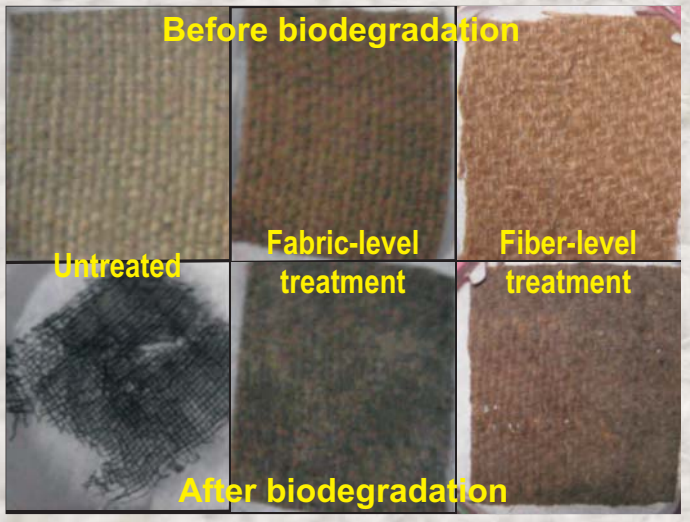
Name & Address	Tel./email
Mr. Kushal Poddar, Poddar Sales Pvt. Ltd.	

Participants at the workshop in Kolkata centre of IIT Kharagpur at April 19, 2012

Name &Address	Tel./email
Mr. A. Khastagir, Project Manager, IJSG-NJB, Govt. of India, Ministry of Textiles, 75C, Park Street, Unit No. G-2A, Ground Floor, Kolkata 700 015	09831275923, jsg_project@yahoo.com
Mr. Abhisekh Kankaria, Executive Director, Ambica Multifibres Ltd., (Unit : Bally Jute Mills), Kankaria Estate (7th floor), 6, Little Russel Street, Kolkata 700 001	
Mr. D. Banerjee, Consultant, National Jute Board, 3A Park Plaza, 71 Park Street, Kolkata 700 016	
Mr. D. K. Chowdhury, Dy. Director General (Eastern Reg.) Bureau of Indian Standards1/14, C.I.T. Scheme VII M V.I.P. Road (Kankurgachi Jn.), Kolkata 700054	
Mr. Mahadeb Datta, Assistant Director, National Centre for Jute Diversification Govt. of India Ministry of Textiles 3A, Park Plaza, 71 Park Street Kolkata 700 016	09830827323, mdatta@yahoo.co.in
Mr. N. Sengupta, Chief Finance Officer National Jute Board, Ministry of Textiles, Govt. of India 71, Park Street, Park Plaza Kolkata 700 016	09831308263 jmdcindia@vsnl.com
Mr. P. K. Chaudhury, Project Co-ord.& In-Charge, Geotech Cell Indian Jute Industries' Research Association, 17 Taratola Road, Kolkata 700 088	09051395619, pradip1451@yahoo.co.in
Mr.P. Chatterjee, Secretary General, Indian Jute Mills Association (IJMA)6, Netaji Subhas RoadKolkata 700 001	
Mr. S. K. Chandra, Chief Executive (Works), Hooghly Infrastructure Pvt. Ltd., Unit: Hukumchand Jute Mills, 10 Clive Row, Kolkata 700 001	9830037285 chandra_samir@rediffmail.com
Mr. Sanjay Kajaria, Indian Jute Mills Association (IJMA) 6, Netaji Subhas Road, Kolkata 700 001	
Mr. T. Sanyal, Geotechnical Advisor National Jute Board (formerly JMDC), Govt. of India, Ministry of Textiles, 3A Park Plaza, 71 Park Street, Kolkata 700 016	03322172107, 03322172540, jmdcindia@vsnl.com
Mr. Ujjal Sen, National Jute Board, Ministry of Textiles, Govt. of India, 3A Park Plaza, 71 Park Street, Kolkata 700 016	jccal@vsnl.com
Mr. Sukumar Roy, MD , Technical Textiles Pvt. Ltd., Vill. Rupnarayanpur, NH-6, P.O. Jakpur, Kharagpur 721 301	03222291521, skr@ketex.com
Mr. S. P. Dutta, Chief Executive, Indian Concrete Association FD 217 – 7, Salt Lake, Kolkata 700 106	9830292214 spdatta1@gmail.com
Mr. Manish Bihani, Synthetic Moulders Ltd., 16, Netaji Subhas Road, Kolkata 700001	98310 02655, sml@cal.vsnl.net.in
Mr. Gangaram Chakraborty, Dy. General Manager (Works), Ramco Industries Limited, Dewanmaro Ayma, P.O. Hariatara, Paschim Medinipur	09434059375, 03222201700, 201773 gcy@ril.co.in
Mr. Shyama Prasad Kundu, Rural Concreting Company of Ghatal Pvt. Ltd., Mahamaya Lodge, Room No. 9, Judges Court Road, Paschim Medinipur, West Bengal 721101.	9434867586, ruralconcretingcompany@gmail.com

Participants at the workshop in Kolkata centre of IIT Kharagpur at April 19, 2012

Name &Address	Tel./email
Mr. Chandan Bose, Proprietor, Bose Abasan Prakalpa Sadarghat, Midnapore 721101	03222-275244, 3222261852 9775594655
Mr. Amitabha Sarkar, Convenor, West Bengal Concrete Pipe Manufacturers Association, 31 Selimpur Road. P.O.- DhakuriaKolkata 700031	033-24158414 wbci.56@gmail.com 9830251399
Mr. Atis Chandra Chanda, Roots & Yards 79/1/A, A.K. Mukherjee Road, Kolkata 700090	09836002746
Mr. Sushanta Agarwal, MD, Kamarhatty Co. Ltd., 16-A, Brabourne Road, 8th Floor, Kolkata 700 001	
Mr. D. N. Singh, President (Works), Kamarhatty Co. Ltd. 1, Graham Road, Kolkata 700 058.	
Mr. Asit Acharya, Engineer (Production & Development), Birla Corporation Limited (Auto Trim Division), P.O. Birlapur 743318, Dist. 24 Parganas (S)	033-24209094/ 9095/ 9513, 033-32571416 9831882571
Dr. A. K. Roy, Principal Scientist & Head, Chemical & Biochemical Processing Division, National Institute for Research on Jute & Allied Fibre Technology, ICAR, 12 Regent Park, Kolkata 700040	03324212115-7, 24119831 ashimroy15@yahoo.co.in
Dr. S. N. Chattopadhyay, Principal Scientist (Textile Chemistry), National Institute of Research on Jute & Allied Fibre Technology, ICAR, 12 Regent Park, Kolkata 700 040	033-24212115/6/7, 26772126 9433825561
Mr Suresh K Chandak, Hansa Polymers Pvt. Ltd., 156a, Kamalaya Centre, G 17 Lenin Sarani, Kolkata 700013	03322152114, 03322159446, 9831075763
Shri D. C. Baheti, Executive Director, Gloster Jute Mills Ltd., 21, Strand Road, Kolkata 700 001.	9830020786 info@glosterjute.com
Mr. Prateek Poddar, C/o. Bagicha 259 & 260 Bankim Mukherjee Sarani, Block "L" New Alipore, Kolkata 700053	
Mr. Manoj Mondal, Industrial Engineering Dept. IIT Kharagpur	9434138989
Mr. Bachcha Singh, Sweta Sales Corporation, Amod Ghata, P.O. Magra, Dist. Hooghly 712148	bachchasingh@gmx.com 9433524759
Prof. Rituparno Sen, Govt. College of Engineering and Ceramic Technology, 73 Abinash Ch. Banerjee Lane, Kolkata 700010	
Prof. A.P. Gupta, Prof-in-charge, IIT Kharagpur Extension Centre, HC Block, Salt Lake Sector III, Kolkata 700106	
Dr Sushmita Ghosh, IJIRA, Kolkata	9051395612
Ms. Aditi Das, IJIRA, Kolkata	9163730090
Mr. Bhaskar Ghosh, Executive Engineer, PWD	9874410301
Mr. S. Saraswati, Jadavpur University, Kolkata	9830332621
Mr. Ritwik Chakraborty, Indian Jute Industries Research Association, Kolkata	9748218720
Dr. Debasish Bandyopadhyay, Jadavpur University, Kolkata	9433068776
Mr. Shyam Sankar, Bhagirathi Print and Process Technology	03324473698
Mr. Sougata Mitra, Bhagirathi Print and Process Technology	9830633518



Debasis Roy, Ph.D. (Brit. Col.)
Associate Professor
Department of Civil Engineering,
IIT Kharagpur, WB 721302, India

debasis@civil.iitkgp.ernet.in
Tel: +91 3222 283456, FaX: +91 3222 282254