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STUDIES ON NATURAL FIBERS OF BRAZIL AND GREEN COMPOSITES

K. G. Satyanarayana [*1], F. Wypych [1], J. L. Guimarães [1], S. C. Amico [2], T. H. D. Sydenstricker [2] and L. Pereira Ramos [1]
[1] *CEPESQ Centro de Pesquisa em Química Aplicada, Universidade Federal do Paraná, Departamento de Química, CP 19081, 81531-990, Curitiba - PR - Brazil*
[2] *Departamento de Engenharia Mecânica, CP 19011, 81531-990, Curitiba - PR- Brazil*

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Abstract: Natural resource of any country is one of the contributors for its GDP (gross domestic product). Brazil has a number of such resources, which are abundantly available and being not used to its full potential. Plant fibers belong to this category. This paper presents the data on the availability of some of the resources of such fibers, their production, structure and properties along with their present uses. It also briefly gives perspectives being used for their better utilization while giving a brief overview of the R&D carried out in the country in general and UFPR in particular in the synthesis of composites, to meet the ecological aspects and their increased use.

Key-words: Composite, Brazil, natural resource, fiber.

1. INTRODUCTION

Brazil has an area of 8,514,876.599 km^2 (nearly 50% of the South American Continent), population of 169,872,856 [1] and GDP of 2.8 [2]. It occupies fifth position in the world in terms of area, the arable area [used for agriculture] is of 5-6%, and permanent pastures of 22% and forests and woodland of 58%. Besides, it has extremely favourable climatic conditions to the agriculture, fertile soil and is endowed with abundantly available agro-based renewable resources. It may be said that the country has taken necessary steps through funding research projects to find means and ways of utilizing these resources to the maximum through value addition to these resources for both conventional and unconventional applications. One such resource is agro products including plant fibers. They include curauá fibers, banana, sisal, pineapple, coconut fiber and different types of starches and derivatives from sugarcane, rubber and cashew nut shell liquid. The plant fibers are found in many countries, although some of them are mainly abundant in the tropics. Their biodegradability can contribute to a healthy ecosystem. Their low cost and reasonable performance in composites may fulfill economic interest of various industries. Characterization of these fibers is important for two reasons. It would not only help in supplying such data for different segments of the industrial sector, which already use or may use in the future these, but also in finding new uses for these abundantly available resource. New uses could include the development of new materials, which are the main provider of opportunities to improve the standard of living of the people.

In fact, in Europe, the plant fiber incorporated composites [PFIC] have already established their use in automotive applications [3-8]. Presently a lot of PFIC products are being exported to USA and other countries with expected lead of 8 years over others, their Union has a directive for the 'end of life' of vehicles requiring that, by 2015, all new vehicles should use 95% recyclable materials [9]. This underlines the promise of "green" composites will hold for the future. It is believed that time is not far off for the use of PFIC as structural components of automotives, which are presently used only for the interior

* Corresponing author ; E-mail: kgssatya@quimica.ufpr.br, kgs_satya@yahoo.co.in

parts of cars [4]. Thus, while natural fibers are fully biodegradable, their polymeric matrices are not and hence this comes as a limitation for their extensive use. Hence attempts are being made particularly in Europe and USA for the development of natural "green products"- completely biodegradable composites based on natural sources for both matrix (biodegradable polymers such as starches) and the reinforcements (natural fibers such as flax), which should be commercially viable for their industrial applications [3,4,10]. Whilst these fully green composites may find applications in mass-produced consumer products for short time uses, they may be useful in long-term indoor applications.

Generally the main research objectives regarding the use of renewable materials have focused on the preparation and evaluation of mechanical properties of biodegradable composites, encompassing: (i) Chemical modifications of fibers to increase compatibility with the matrix; (ii) Manufacturing of plant fiber (cellulose)-natural polymer composites with different fiber content, and (iii) Characterization of these green composites in terms of their microstructure, physical and mechanical properties to arrive at a series of bio-degradable composites for their possible use in different applications. While doing so, it should be borne in mind that the fibers should be made available in required form [short fibers/mats/fabric] for their use in composite preparation. The long-term objective, on the other hand, may be the proposal of alternatives for the composites based on synthetic polymeric materials.

Brazil, which is a developing country, has been in the forefront of the development of such new materials. There are about 235 Materials and Metallurgical Engineering groups working in Brazil of which at least 28 work in the area of plant fibers, natural polymers and composites based on these natural resources, from which the Southeast and Northeast of the country is responsible to about 90% of this [8]. It is interesting to note that in recent times Brazil is probably the only country to hold five successive International Conferences since 1996-97 on Natural polymers/fibers and their composites [11-15].

Taking cognizance of these, this paper presents the availability of raw materials, status of R&D including processing of composites for better utilization of plant fibers in Brazil and highlighting some of the results obtained in UFPR. It is hoped follow up of these initiatives will open up new avenues of research and potential markets leading to a whole spectrum of opportunities and challenges for Brazil in particular and the world in general.

2. AVAILABILITY, EXTRACTION, CHARACTERIZATION AND APPLICATION

Sisal is an important leaf fiber of Brazil with about 50% of the world market. The annual production is still increasing, representing 171,266 ton in 2002 [1] and 178,611 ton in 2003 (http://www.pt.org.br/assessor/cartlula.htm), from the Northeast of the country. Production data for other fibers in Brazil may be seen in Table I [8]. Availability of fibers such as *Luffa Cylindrica,* straws of wheat and rice, sugarcane bagasse and husks of rice and coffee though reported, are not quantified. The cost of all the plant fibers in Brazil is almost the same, which is about US$ 0.6/kg [16].

It is also reported that Brazil is the third world supplier of Ramie fibers, while about 938,000 tons of cotton fibers, 50 tons of pineapple fibers and 12,000 tons of wool are produced here. Similarly, natural polymeric materials such as cassava starch (428,000 tones in 2003 - http://www.abam.com.br/), natural rubber (4,081 tons in 2002) [1] and cashew nut shell liquid are available in sufficient quantities.

Luffa is the generic name of a group of species known as 'sponges vegetation'. These plants (**Fig. 1a)** are annual and perennial, trailing herbs. Of the eight species of these

Fig.1: (a) Plant of Luffa Cylindrica; (b) Fruit showing the entangled fibers with multi directional arrangement

Fig. 2. Curauá Plants

herbal plants, Luffa Cylindrica M. Gnaw is quite exploited as vegetable sponge. Brazil is a large producer of Luffa, which is used in *wide climbs* as scouring pads for bath, inner soles for shoes and other objects. The fruit of the Luffa Cylindrica has a nucleus with structure similar to beehive surrounded by an entangled fibers arranged multi directionally [12,17,18] (**Fig. 1b**). Nevertheless, not much of information is available in the literature regarding this fiber.

Another interesting plant fiber of Brazil is curauá extracted from the plant - *Ananas erectifolius,* [**Fig. 2**] belonging to pineapple family and a hydrophilous species from Amazon region [19,20]. It is grown with about 10,000 plants per hectare and the plants requiring about 200 mm or more annual precipitation. The plant prefers Silil-humos soils, while it may grow in clay-silic soils. There are two species-one purple red leaf and the other green leaf also called “white curauá”. Each plant yields 50-60 leaves per annum with each leaf being about 1-1.5m long, 5-4 cm wide and about 5 mm thick. Each leaf yields about 5-8% fibers [dry wt. basis]. The fibers are extracted by a primitive process using the same machine [**Fig. 3(a)**] used in the extraction of sisal fibers called “periquita”, followed by washing and then beating the leaves using a rod, kept in water for about 36 hours for ‘mercerizing’ before they are again washed and dried [16,21]. **Figure 3(b)** shows the extracted curauá fibers. These fibers rank third in the economical analysis, fourth in stiffness and are thus more competitive among the traditional fibers in the country [16,21,22].

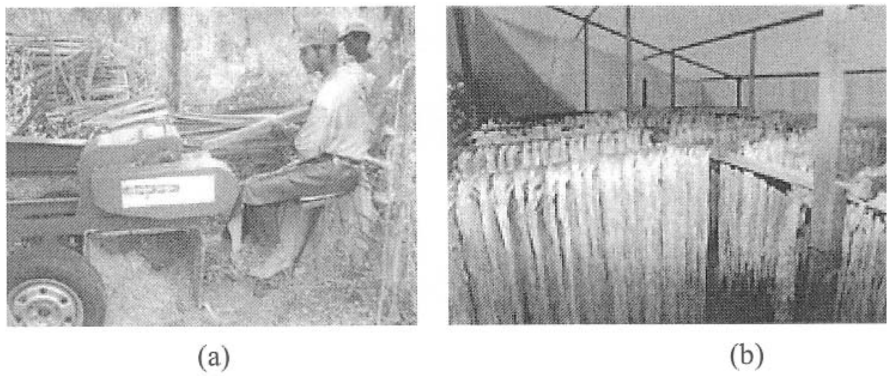

Fig. 3. (a)Fiber Extracter and (b)Extracted Curauá Fibers

Table I. Availability of plant fibres of Brazil (IBGE)		
Fibre	Annual Production (2002)	Region
Sisal	171,266	Northeast only
Piacaba	94,705	Northeast mainly
Malva	8,608	North mainly
Ramie	1,378	South only
Jute	1,459	North only
Curaua	Not available	North only
Coconut fibre	1,000,000	Northeast mainly

The chemical analyses of some of these fibers of Brazil determined [16,17,23] as per TAPPI T19M, TAPPI T13m-54 or TAPPI T222 om-88, ABCPM11/77 or TAPPI T211-om-93, ABTCP M3/69, TAPPI T207-om-93 and TAPPI 212 om-98 is shown in **Table II**.

The apparent density (kgm^{-3}) determined as per standard NBR 11936 and moisture content of these fibers (%) determined by thermogravimetry as per ASTM D2654 are 820, 1260 and 492 respectively for Luffa-cylindrica, sisal and bagasse and 8.0, 11.7 and 7.92 respectively for Luffa-cylindrica, sisal and

Table II. Chemical composition of Plant fibers of Brazil[16,17,23]				
Fiber	Holocellulose (%) (α-cellulose + hemicelluloses)	Lignin (%)	Ash (%)	Extracts (%)
Luffa-cylindrica	82 (62 + 20)	11.2	0.40	3.1
Sisal	84 (74 + 10)	7.6	3.00	6.0
Curauá	91.8	11.1	/.79	2.5 - 2.8#
Bagasse (sugar cane)	84.0	24.4	-	-

from unpublished work

curauá fibers. The crystallinity indices of sisal and Luffa fibers were calculated using the equation [7] :I_{Cr} = Crystalline Area/Total Area, while standard Buschele-Diller and Zeronian method was used for curauá fibers [13]. The values are found to be 59.1, 72.2 and 75.6 respectively. This parameter did not change with different surface treatments for Luffa-cylindrica and sisal fibers [17]. Thermal behaviours of these fibers have been determined using TG and DSC techniques with heating at 10^{o}C/min between 293-873K

Table III. Tensile properties of some plant fibers of Brazil[16-18]			
Fiber	Youngs Modulus [GPa]	Ultimate strength [MPa]	Elongation [%]
Sisal	-	324 - 329	2 - 2.5
Curauá (wet)	10.5	439 (MOR)*	4.5
Curauá (dry)	27.1	117 (MOR)*	3.2

* MOR : Modulus of rupture

and 223 to 693K respectively. Tensile properties of the fibers have been evaluated following suitable ASTM standards. **Table III** lists some of these properties.

Most of these polymers and fibers are used presently for conventional uses including automotive and textile industries with a prediction for higher demand of some of these [E.g. About 15,000 tons/year for curauá fibers]. For example, conventionally curauá fibers are used for hammocks and fishing lines by the indigenous population called "Indians", also as ropes, as nets for sleeping, etc [3]. Sisal fiber is used mainly in making ropes and for producing fancy articles by artisans [24]. Blankets/mats of sisal fabric are produced by compression using a gluing agent. Similarly, blankets of Luffa Cylindrica have been successfully tried with advantages in the preparation of molded composites by compression or resin transfer (RTM); sisal blankets also facilitate the preparation of such materials, wherein one can evaluate interference in the fiber/matrix adhesion.

2. STUDIES ON POLYMER COMPOSITES

Matrices used include polypropylene (PP)/polyester/epoxy/phenolics and natural polymers such as starch, PHB [poly(3-hydroxybutyrate)], rubber and cashew nut shell liquid (CNSL). Fibers used include curauá, coconut, sisal, pineapple, ramie, jute, bagasse and wood flour. Studies have revealed [11-15,25-34] that most of the R&D carried out in Brazil focused on the use of most conventional manufacturing methods used elsewhere and evaluation of various properties of the synthetic polymeric materials reinforced with raw or modified natural fibers, whilst only a few groups are devoted to the studies of natural polymers reinforced with natural fibers and recycling of plastics. However, research related to natural rubber plasticized starch and PHB, including their blend is extensively carried out in the country.

It is found [16] that the maximum fiber content [curauá, coir, sisal, ramie and jute] in the PP composites made by the hot pressing was about 60% irrespective the surface treatments given to the fibers. All the composites showed mostly increasing tensile and flexural properties with decreasing fiber content values as revealed by the following:

Tensile strength (MPa) for Curauá-PP composite decreased from 50.75 for 60% fiber content to 19.98 for 80% fiber content, Young's modulus (GPa) from 3.34 to 1.56, Flexural Strength (MPa) from 24.97 to 14.67 and Flexural modulus (GPa) from 2.53 to 1.44. For sisal-PP composite these values were: 23.25 to 11.12, 1.97 to 1.25, 32.3 to 16.36 and 2.78 to 1.36 respectively for the said fiber contents. On the other hand, at 50% fiber content the above properties except for flexural modulus for the curauá-PP composites were found to be higher [between 9-76%] than those of sisal-PP, jute-PP and ramie-PP composites. Even at 80% fiber content, tensile properties and flexural modulus of curuá-PP composites were higher between 5-43% for sisal and 19.8-71% than those of coir-PP composites. These results appear to indicate the superiority of curauá fibers amongst the plant fibers of Brazil and hinted their composites for possible acoustic and structural applications.

Impact strength of phenolic composites incorporated with sugarcane, bagasse, sisal and curauá fibers individually showed [13] marginal improvement in bagasse containing composite [3.9% and 57.8% with lignin addition] compared to that of sisal composites [2403% and 3070% with lignin addition] and 10% NaOH treated curauá composite [about 41.%]. Coming to the application of plant fiber based composites, cotton phenolics /Jute-polypropylene/Sisal-PF foam are being used as interior trim parts (Roof lining, rear wall lining etc.) in cars produced by Mercedes [8,11-15] coconut fibers for roofing, domestic water reservoirs and other products [29,30], while there are mainly suggestions for the uses of these composites in other sectors.

4. STUDIES AT UFPR

4.1. Characterization of raw materials

Starting from the creation of the "Polymer Group" in the Mechanical Engineering Department of the University in 2000, work in the area of natural fibers and its composites has progressed in a systematic manner. Initially, studies on characterization of sisal and Luffa Cylindrica sponge-gourds, their composites with unsaturated polyester were carried out [17,31-34]. Tables II and III show some of the characterization of fibers of Brazil carried out at UFPR. Various physical and chemical surface treatments have been attempted with a view to improve the composite properties. While a series of chemical agents [NaOH, N-isopropyl acrylamide and methacrylamide] in aqueous solutions have been used as modifiers [**Table IV**], their effect on the fibers was found to depend on the chemical agent, its concentration and/or treatment time.

Table IV. Tensile strength (MPa) of samples of Sisal fibers with different treatments[17,31,33]

Treatment	Tensile strength (MPa)
Nil	324 - 329
NaOH - 0.25%	321 - 350
NaOH - 2.0%	304 - 372
NaOH - 10.0%	242 - 296
2-methyl-propil-acrilamide-	
1.0%	334
2.0%	407
3.0%	414
N-isopropyl acrylamide	
1.0%	331
2.0%	347
3.0%	256

Another interesting and innovative study being attempted in UFPR is the use of natural materials including fibers and residues as absorbents for oil spills in waters [35], which are a major global concern. These act as low cost alternate sorbents for the recovery of crude oil from spills during its exploration, refining and transportation process. Such spills not only represent a great loss of oil but also have a major negative effect on the environment. The water pollution by oils affect aeration and illumination of the water flow due to the formation of an insoluble oil film on its surface, leading to negative effects on natural fauna and flora, in addition to rendering enormous amounts of still water useless. Natural materials used include *cloresea speciosa st. Hill* known as paina, Luffa cylindrica, sawdust, sisal and coconut fibers as well as mixed vegetable residues.

For this purpose, the vegetable fibers were first milled and classified in different granulometric sizes [33,35]. The sorption tests were carried out for each fiber in water medium, at a temperature and pH previously adjusted [20°C, pH 7] in static or agitated system for up to 24 hours. The paina showed an excellent sorbent capacity, reaching 87.11 g /g of sorbent. Sisal, sawdust fibers and coconut fibers presented similar and intermediate results (6.57, 6.52 and 5.76 g /g of sorbent, respectively) whilst luffa fibers and the mixed vegetable residues showed the lowest sorbent capacities (5.07 and 2.95 g and g/g of sorbent, respectively). These preliminary studies have concluded that amongst the various materials tested, paina is found to be an excellent sorbent of petroleum and even better compared to the efficiency of synthetic materials. Besides, with the exception of sisal, all materials presented good buoyancy in water. Compared to peat moss, a commercial vegetable sorbent that presents a sorbent capacity of 10 g/g sorbent, silk floss fibers are more efficient and economical.

4.2. Studies on Composites

Synthesis and characterization of polymer based composites using some of the Brazillian plant fibers have also been carried out [31-34]. Processing has been done mostly by compression moulding. **Table V** shows some of the properties evaluated for both Polyester-Luffa and Polyester- Sisal composites. These results demonstrated that while sisal-polyester composites showed improved strength with surface treatments, Luffa-polyesrer composites did not with any of the treatments.

Studies on injection molding processing and mechanical properties of polypropylene-wood-fiber have also been carried out first compatibilizing the polar fibers to the apolar

Table V. Tensile strength and Impact strength of Polyester -Luffa and Polyester-Sisal Composites[17]

Chemical treatment for 1 hr		Tensile strength (MPa)		Impact strength (J/m^2)	
		Luffa - cylindrica	Sisal	Luffa - cylindrica	Sisal
Non - treated		17.0	24.7	3.5	21.3
NaOH	0.25% w/w	-	28.0	-	24.1
	2.0% w/w	18.2	35.9	3.1	22.8
	10.0% w/w	-	20.0	-	17.0
2-methyl-propyl-acrylamide	1.0% w/w	17.5	20.0	2.8	14.4
	2.0% w/w	16.7	20.9	3.1	13.5
	3.0% w/w	16.2	21.8	3.3	12.1

matrix by reactive extrusion of PP in the presence of maleic anhydride, dibenzoile peroxide and wood residues. The effect of compatibilizing agent content and wood flour granulometry on composites mechanical properties has been studied. The results are shown in Table VI.

4.3. Ongoing Studies

With the expertise available in UFPR in the areas of lignin chemistry, steam explosion, polymers and nanocomposites, etc. a multidisciplinary approach has been initiated by the authors to develop composites including "Green variety" using sisal and curauá fibers as well as bagasse with natural polymers and recycled plastics. Preliminary results of these are summarized below:

Table VI. Performance of wood fiber/polypropylene composites[33]						
Granulometry	Wood fiber (%)	Maleic anhydride (%)	Tensile strength (MPa)	Impact strength (J/m^2)	Elongation (%)	Modulus (MPa)
Powder 3% mesh size 20, 18% 100 and 84% mesh size bigger than 100	10	0	25.00	31	6.7	2515
		1	27.51	34	7.5	2054
		2	27.53	33	7.2	2114
		3	27.76	34	7.6	2065
	30	0	21.28	13	3.8	2843
		1	23.14	10	4.3	3540
		2	25.35	14	3.7	4848
		3	24.21	13	3.1	4019
Saw dust 3% mesh size 20, 18% 40, 30% 60, 22% 100 and 27% bigger than mesh size 100	10	0	26.44	32	6.9	2381
		1	26.93	27	6.1	2539
		2	28.00	32	6.4	2455
		3	28.22	31	6.1	3636
	30	0	23.90	13	3.2	3960
		1	25.00	20	3.4	5426
		2	26.85	15	2.9	4424
		3	27.12	17	2.8	4676
100% PP	0	-	26.21	-	10.9	1591

4.3.1. Starch and Bagasse characterization : Three starch samples- Regular corn starch, Waxy and Amilogino supplied by Corn Products, Brasil were characterized using X-ray diffraction technique [Shimadzu XDR-6000 diffractometer with Cu_K radiation (=1.5418 Å), at 40 kV and 30 mA] and by FTIR spectroscopy [Bio-Rad spectrometer, model FTS 3500GX] using pellets prepared with KBr. The results obtained are shown in below [Fig. 4(a) & (b)].

Main diffractions peaks centred at 15.2, 17.2, 18, 23.3 and 26.5 (in 2) are characteristic of a A-type starch crystalline structure typical of cereals [36]. The FTIR spectra are also characteristic [37]. Samples for evaluating physical and mechanical properties are being prepared using 30% glycerol. Preliminary results indicate the experimental conditions to get good samples are promising. Further studies are in progress to prepare the composites with banana fiber, sisal fiber/mat and bagasse with and without any surface treatments. Similarly, sugar cane bagasse was characterized for its chemical assay in the as-received condition, and after subjected to steam explosion (SE) and then to SE +alkali treatment and the results are shown in Table VII.

XRD studies carried out on these samples in three conditions: as-received (dry), steam explosion [SE] treated and that with SE and further treatment in alkaline solution using similar conditions as those for starch. Figure 5 shows typical X-ray diffraction patterns of the untreated (a), steam explosion treated (c) and SE + alkaline treatment (c) sugar cane bagasse where peaks attributed to 101 and 002 reflections are observed at 15° and 22° (in 2θ), respectively [38]. The peak related to the 002 reflection is slightly displaced from the original position (22.1° - d= 4.02Å) to 22,7° - d= 3.92Å), maintaining the other reflection at

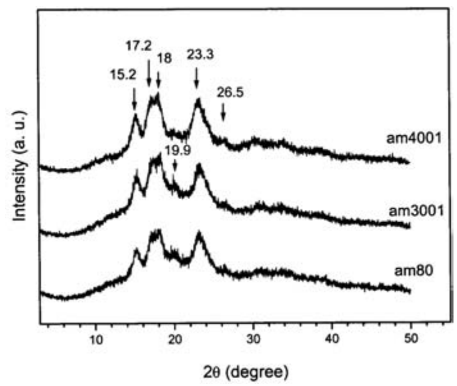

Fig. 4a. XRD patterns of three starch samples

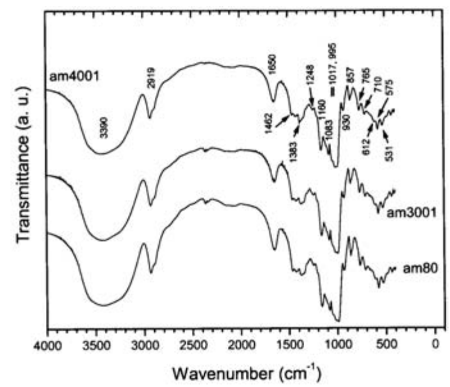

Fig. 4b. FTIR spectra of three starches

Table VII. Chemical composition of bagasse in different conditions

Sample	Cellulose (%)	Hemi-Xylose (%)	Cellulose Arabinose (%)	Acetyl (%)	Soluble Lignin (%)	Insoluble Lignin (%)	Ash (%)
As-received	38.8	19.3	3.4	4.9	1.0	23.1	3.8
Steam Explosion	54.7	1.8	0.9	0.8	0.5	28.8	4.1
Steam Explosion + Alkali	85.9	-	-	0.6	1.2	9.9	4.0

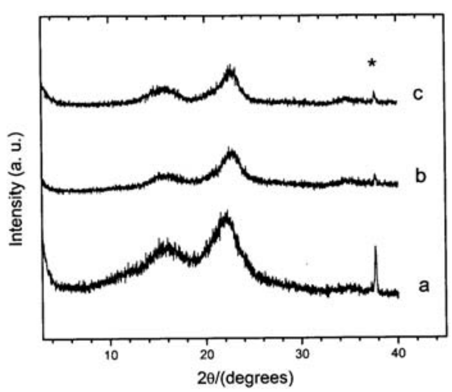

Fig. 5. XRD patterns of (a) untreated sugar cane bagasse (b) steam explosion treated and (c) SE + alkaline treatment (* = Aluminium sampler reflections)

the same position. This behaviour can be interpreted as the lowering of the spacing along the 00l direction after the steam explosion and alkaline treatment. The shrinking of the cell parameter along the 00l direction is also possible when the sample is submitted to different drying procedures. It may also be seen that the peaks related to 002 are becoming sharper with treatments. This could be due to (a) gradual removal of amorphous phases [hemicellulose and lignin] and (b) increasing crystallinity due to reorientation of cellulose molecules primarily at the surface of the crystallites. However, the first effect is expected to be greater because of strong conditions would have been required to cause the effect on crystallinity. These are only preliminary results, which are being verified with more number of tests.

4.3.2. Composites : Composite laminates [size: $25x25cm^2$] of polyester with the above mentioned three types of bagasse [10wt% of fiber] were prepared by hot pressing with pressure of 6 tons and at temperature of 423K. Five samples from each type laminate were prepared for tensile testing. Tensile testing was carried out using DMA [Universal Testing Machine -Emic DL 10.000]. The results of tensile test are shown in **Table VIII**.

Table VIII. Tensile properties of Bagasse - Polyester composites

Sample	Tensile strength (MPa)	Strain at Rupture (%)
Polyester + Bagasse (AR)	10.809	0.614
Polyester + Bagasse (SE)	15.448	0.882
Polyester + Bagasse (SE + A)	12.101	0.742

It can be seen that the SE treatment improves the tensile properties of the composite by about 43% over that with untreated fiber, while it is about 12% for the alkali treated fiber containing composite. Similarly, the strain at maximum load is 11.95% and 20.84% for these composites respectively over the untreated fiber composite [1.68%]. The increase in tensile strength of the composite due to the surface treatments given to the fiber is understandable though it could have been better if the length of the treated fibers were not very short and / or the fiber content is not critical enough. On the other hand, untreated fiber composite is almost 60% lower than that of the matrix [25.74MPa] due to lack of good bonding between the fiber and the matrix as well as probably due to shorter length of the fiber. Further studies are planned to optimize the fiber content to improve the properties suitable for different applications.

5. PERSPECTIVES AND CONCLUSIONS

Brazil has abundantly available natural resources such as plant fibers and natural polymers. Structure properties of these materials are still not comprehensively available. There have been some attempts to find alternate uses for these materials such as green composites through composite technology, but this also needs serious, coordinated and concentrated efforts to make them economically and technologically feasible. The following are some of the steps that need attention for the better utilization of these abundantly available natural resources:

(i) Extending the industrial production to all the plant fibers and their availability, which have potential for use in development of composites for various applications. This would bring the farmers a new source of income in future; (ii) Creation of data bank on structure and technical properties including weathering aspects of all the available plant fibers through basic research; (iii) Development of chemical strategies enabling optimization of their suitable dispersion and compatibility with the polymeric/ ceramic matrices; (iii) Possibility of converting these lignocellulosic materials into carbon, which may then be used to develop interesting building and other useful materials; (iv) Development strategies to produce micro and nano particles of the natural materials to optimize the mechanical properties of the composites through the exciting/emerging nanotechnology; (v) Coordinated research of all the researchers in the area of natural fibers/polymers and their composites by a Federal agency like CNPq for strengthening the activity with focus on development of environmentally sound products and to avoid unnecessary duplication; and (vi) Setting up of specific research institutes working on the processing and utilization of plant based fibers and natural polymers as they exist internationally and a forum under the State or Federal Government to look into various aspects mentioned above on the lines of the European Commission. It is hoped that with the above perspectives and suggested lines for future action, both exciting and promising future lies ahead for the utilization of natural resources of Brazil such as plant fibers and polymers along with the ecology and energy management. This compliments the philosophy of developed countries which have accepted and followed the concept of no waste, to develop new materials for various applications.

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