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Effect of Blending of Sisal on Pulp Properties of Waste Papers in Handmade Papermaking

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In an attempt to improve the quality of the waste paper in recycling in paper manufacturing, sisal (a hard fiber) is blended with. The proximate analysis of sisal fibre has been compared with that of the kenaf and waste paper. A high cellulose content in sisal (67.19%) than the kenaf bast fibre (63.5%) and a slightly less lignin percent of sisal (10.22) in comparison to kenaf (12.7) suggest the suitability of sisal fiber for better pulping efficacy and hence paper making. The high tensile strength of sisal fiber is an important cause for blending with weak recycled fibers of waste paper. The preparation of strong paper has been optimized by varying the amount of constituents and modifying sisal fibers.

Keywords: Sisal, waste paper, handmade paper.

Introduction

Blending has been one of the various techniques employed in papermaking to revive or restore the loss in recyclability of the secondary fibres[1,2], whose papermaking potentials generally deteriorate with the extent of recycling. This behavior of the recycled fibres is mainly attributed to the phenomenon of hornification or irreversible hardening of the fibres due to the repeating cycles of drying and rewetting during paper formation[3]. Besides blending, other methods that have been generally used to regain the bonding potential or improve the strength of sheets prepared from secondary or weak fibres are mechanical beating and refining[4], use of chemical additives[5] and physical fractionation[6]. Recent research has revealed that gentle fibrillation of fibre surfaces may be a preferred strategy of preserving the fibre integrity making it possible to recycle them several times[7]. Generally, the softwood kraft pulps are used by the paper industries to reinforce the weaker papermaking furnishes. Results of several investigations have corroborated the reinforcing potential of many virgin non-woody plant fibres in papermaking especially, the long fibres obtained from plants like jute[8], abaca[9], kenaf[10], banana[11] and even the oil palm[12]. In view of these considerations, it has been contemplated and anticipated that blending of a strong vegetable fibre obtained from the lanceolate leaves of the sisal plant (belonging to the Agavaceae family) with the weaker pulps (produced from waste press cuttings and used notebooks), may be useful in positively modifying the sheet properties especially, the strength characters in comparison to the properties of the pulp produced from waste papers only. Sisal is an interesting and hard leaf fibre which has been placed next to Manila in durability and strength. The plant is mostly found in the tropical and subtropical regions of the world and is abundantly available in Orissa particularly, in its western belt with decortication (fibre extraction from their leaves) units in some places, and is locally known by different names. Past few decades have also witnessed a growing interest in sisal as a reinforcing additive in different composites used as building materials like cement, concrete and mortar based[13], polyester composite resins[14] and polymer matrices[15], basically due to its biodegradability, renewability, lower cost in comparison to the conventional reinforcing fibres (carbon, steel, acramid etc.), and the most important reason being the improvement of strength characters in the ensuing products basically due to its good mechanical properties and compatibility with other substances.

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Experimental

Materials & Methods

Decorticated sisal fibres were procured from a private decortication plant at Nildungri in Sambalpur district of Orissa. The off-white colored decorticated sisal fibres were cleaned by hand scraping to remove the residual pithy materials attached to the fibres, washed them with distilled water and air-dried. Properly cleaned and uniformly cut (4-5 cm) sisal fibres were subjected to various types of physico-chemical analysis and further used for blending in papermaking. The laboratory scale investigations were initially performed to determine the physico-chemical characteristics of the sisal fibre by following TAPPI Standard Methods[16]. The cellulose content was determined according to the modified method of Sarkar *et al.*[17]. The hemicelluloses percentage was calculated by deducting the α-cellulose content from the holocellulose composition of the sisal fibres which had been evaluated earlier with the method adopted by Wise *et al*.[18]. The ash percentage was determined gravimetrically and extractives content was evaluated by refluxing the sisal fibres with acetone in a soxhlet apparatus for 9 hrs and observing the weight difference of the sisal fibres before and after reflux. Values of some of the physical characters like fibre dimension and tensile strength of sisal fibres were also determined by taking the help of Pulp and Paper Research Institute (PAPRI) at Rayagarha, Orissa. The results of the various observations and estimations have been presented in Table 1 and compared with the properties of another non-wood pulp fibre of kenaf, whose reinforcing potential in paper-making have already been established as mentioned earlier. The chemical characteristic of the waste paper has also been reported in Table 1 for the sake of comparison.

Blending sisal with waste paper in different ratios

Cleaned and uniformly cut (2-4 cm) sisal fibres were soaked in clean water for at least one hour prior to their subjection to the beating process in order to facilitate fibre swelling by increased hydration. The beating was performed in an experimental beater of Hollander type of 25 l capacity with a pulp consistency of 4-5% in order to mechanically disintegrate the fibre bundles of which the sisal fibre is structurally composed of and generate the fibrils with enlarged surface area into the pulp stock. After beating the sisal fibres for nearly 45 min, the waste paper (used notebooks) cut into small pieces were added to the beater stock and the beating continued for another 45 min. The small pieces of used notebooks were soaked in water for half an hour before their addition to the beater stock. Due to the soft and short nature of the waste paper fibres as compared to the stiff and hard sisal fibres, they were soaked in water for a comparatively less time period and added to the beater stock while pulping at a later stage as they require less beating time than the virgin sisal fibres to arrive at nearly the same degree of freeness as experimented earlier. The beating was done till the blend pulp freeness reached 15-21 ^{0}SR, which was measured with the help of a Schopper Reigler Freeness Tester. Near to the completion of beating, necessary sizing chemicals (a mixture of rosin and alum in 2/3 proportion respectively) in moderate doses were added to the pulp stock and the beating continued at a lighter mode for another 5-10 min.

After each set of pulping, hand-sheets were prepared by the usual handmade technique of

Table 1—Physico-chemical characteristics of sisal, kenaf and waste paper fibres

No	Properties	Sisal leaf fibres	Kenaf bast fibres	Waste paper	Reference
1	Cellulose (%)	67.19	63.5±0.5	87.45	19
2	Hemicellulose (%)	21.45	17.6±1.4	5.8	19
3	Lignin (%)	10.22	12.7±1.5	2.23	36
4	Extractives (%)	5.23	4.0±1.0	6.34	19
5	Ash (%)	1.27	2.2±0.8	3.21	19
6	1% NaOH Solubility (%)	22.8	-	15.31	
7	Fibre Length (mm)	3	5	-	20
8	Fibre Width (μm)	20	21	-	20
9	Tensile Strength (GPa)	6.1*	11.9	-	21

*fibre strength is for fibre bundles in case of sisal

All the experiments were repeated at least three times and the values have been averaged within an error of 5-6%.

hand-lifting the pulp from the pulp-stock at a lower consistency with a compatible mold of 30 mesh size, followed by couching, pressing and drying in air. After proper conditioning, the sheets were subjected to various types of physical examinations like mass (gram in square meter:GSM), breaking length (B.L.), tensile force (T.F.), bursting factor (B.F.), folding endurance through double fold (MIT) method, brightness and yellow index, and the test results have been tabulated below (Table 2):

Blending of 50% of chemically cooked sisal with waste press cuttings

A number of sample sheets were prepared by blending 50% by weight of sisal fibres chemically digested to various degrees, with white colored press cuttings papers and tested for their physical properties like strength (by measuring their Burst Factor) and water absorption (by measuring their 1-min Cobb Values). 200g of the uniformly cut (2-3 cm) and thoroughly cleaned sisal fibres were pressure-digested in a 5 litre capacity pressure cooker in a 10% alkaline-peroxide solution for varying time intervals (1 hr, 1.15hr, 1.30 hr etc.). On completion of the digestion, the fibres were washed thoroughly with clean water till free of the alkali and subjected them to the beating process in order to facilitate fibrillation by the mechanical process as mentioned earlier.After completion of the beating process, the blended stock was transferred to another chest and diluted with water to lower the consistency to 2-3% from which sample sheets of varying grammage were prepared by the handmade technique. After proper drying and conditioning of the blended sheets (containing 50% of chemically digested sisal fibres), they were subjected to various types of physical tests and the results were compared with those of the blended sheets containing 50% of untreated sisal fibres and the overall results have been summarized in Table 3. The approximate thickness of the paper sheets were measured with the help of a screw gauze.

Result and Discussion

Analysis of sisal, kenaf and waste paper fibres

Chemical characteristics of sisal leaf fibre show great similarity with those of kenaf bast fibre as observed from the data presented in Table 1. Both the fibres were found to be rich in their cellulose content. Higher cellulose content in sisal and less lignin

Table 2—Blending effects of sisal with waste paper in various proportions

Fibre proportion (%)		Properties						
Sisal	Waste Paper	Basis Weight (GSM)	B.L. (mtr)	T.F. (gfm^2/g)	B.F. ($gfcm^2m^2/g$)	Double Fold (M.I.T.)	Brightness (% ISO)	Yellow Index
100	0	74	1654	147	11.7	4	45.7	30.56
		80	1505	150	11.2	2	44.2	31.04
		89	1599	149	10.8	0	44.8	28.90
93	7	91	1642	97	9.7	3	54.4	28.22
		95	1599	105	7.2	3	52.8	29.06
		97	1586	110	7.0	3	52.6	28.04
87	13	75	1941	74	11.3	4	52.1	20.99
		78	1772	77	11.0	5	52.0	21.02
		81	1375	99	11.2	5	51.5	21.55
80	20	84	2725	84	13.2	7	52.2	18.83
		86	2602	88	13.1	6	52.4	18.77
		88	2399	90	12.9	7	52.6	18.59
73	27	83	2222	77	11.7	4	56.2	17.73
		85	2001	98	11.2	3	55.0	17.82
		88	1591	114	10.8	0	51.6	22.39
25	75	75	470	50	3.5	0	47.9	17.32
		81	1197	46	4.0	0	48.8	17.05
		92	1008	42	4.6	0	50.7	13.89
0	100	77	275	25	0.9	0	50.67	14.00
		81	327	27	0.88	0	51.33	13.91
		88	331	27	1.1	0	49.89	14.12

Table 3—Blending effect of waste papers (press cuttings) with 50% of chemically digested sisal for varying time intervals

Sheet No.	Period of Digestion hr	Properties			
		Basis Weight GSM	Thickness ~(mm)	Burst Factor ($gfcm^2m^2/gm$)	Cobb $Size_{60}$ (g/m^2)
1	1.00	115	0.185	19.78	39.21
2	1.15	176	0.175	20.23	41.52
3	1.30	106	0.205	19.89	40.18
4	1.45	182	0.185	21.65	41.67
5	2.00	115	0.175	23.26	35.50
6	2.15	170	0.185	24.73	37.33
7	2.30	110	0.185	22.45	36.78
8	2.45	185	0.185	22.17	36.54
9	3.00	108	0.205	18.31	37.45
10	3.15	177	0.195	19.66	39.43
11	4.00	185	0.205	17.78	39.50
12	0.00	154	0.185	12.58	50.55

percent in comparison to kenaf not only suggests the capability of sisal in papermaking but also points towards its better pulping efficacy than kenaf. The trend in cellulose content is waste paper fibre >> sisal > kenaf fibres The hemicelluloses and lignin contents of the waste paper fibres are much lower than those of the sisal and the kenaf fibres. The hemicelluloses content in sisal was also found to be slightly more than that in kenaf. A comparatively higher proportion of extractives in sisal (5.23%) as compared to the kenaf bast fibres (4.0%), perhaps is a consequence of the presence of a good amount of easily extractible chemicals like fats, fatty acids, fatty alcohols, phenols, terpenes, steroids, resin acids, waxes etc. in sisal which can be removed by the commonly used solvents like acetone. The existence of a large variety of such chemicals in micro scales in the lipophilic extract of sisal fibres has also been confirmed by the gas chromatography (GC) and gas chromatography/ mass spectrometry (GC/MS) analysis[22]. A comparatively and marginally high proportion of extractives in the waste paper may have been the result of the different types of additives or bleach/dye chemicals used during the manufacturing of the concerned paper. A marginally less percent of ash in sisal as compared to the percentage of ash in kenaf fibres is clearly indicative of the less silica content in sisal (as silica constitutes the major inorganic portion of the ash) than kenaf fibres, which is a positive signal for paper manufacturing as the presence of silica in excess may damage the beating equipment by its abrasive nature as well as contribute to increase the dirt count in the final sample sheets. The high ash content in the waste papers may be due to the presence of inorganic fillers or different additives used during its manufacturing process. The chemical analysis of these fibres strongly indicates the considerably less consumption of beating time and energy by the waste papers during their recycling than the virgin non-wood fibres like sisal and sisal is quite competitive with the kenaf bast fibres in its papermaking qualities. However, contrary to the minor differences in the chemical properties of the two types of fibre, a remarkable distinction appears in their physical characters as can be observed from the fibre dimension and the tensile strength values of these fibres (Table 1). Less aspect ratio (fibre length/ fibre width) and tensile strength of sisal in comparison to kenaf fibre point towards a mechanically stronger nature of kenaf bast fibre than the sisal leaf fibre. These physical differences may have originated from the varying structural and morphological features of sisal and the kenaf fibres and also may have arisen from the different parts of the plant from which these fibres are extracted (sisal being a leaf fibre and kenaf being a bast fibre). However, despite the lower mechanical strength of sisal in comparison to kenaf, it has a tensile strength superior or comparable to many other strong non-woody papermaking fibres like cotton (3.5 GPa) [21] and banana (540 MPa)[23] . Moreover, the high aspect ratio of sisal (180:1) in comparison to many other papermaking fibres like jute (100:1), softwoods (100:1), hardwoods (50:1) and cotton linters (165:1) as reported in the literature[24], is greatly suggestive of producing strong papers from sisal fibres as the aspect ratio is a good indicator of paper strength.

Effect of blending sisal fibres in different ratios on strength and optical properties of the recycled pulps

Blending of sisal with waste paper pulp has been found to influence the sheet properties like burst factor, tear factor, breaking length and double fold of the blended sheets significantly (Table 2). The overall improvement in the strength characters of almost all the blended sheets may be ascribed to the presence of virgin sisal pulp fibres in the blend mixture, which increases fibre swelling during pulping. Fibre swelling is an important phenomenon in pulping which is dependent on the water uptake of the fibres, which depends on the number of ions trapped in the fibres since swelling is driven by osmosis. The important charge groups in fibres are carboxylic acids found in the hemicelluloses component and in this respect, the total charge on the virgin sisal pulp may be regarded to be quite higher than the recycled pulp fibres due to the removal of hemicelluloses from them during the recycling process[12]. The presence of sufficient amount of sisal fibres in the pulp furnish with a higher composition of hemicelluloses contributes adequately to the increase in pulp swelling, as proper swelling of the fibres would reduce the inter fibrilar bond distances. Thus it enhances the possibility of inter-fibrilar bond formations between both the types of fibre, due to the hydroxyl groups (-OH) residing in the cellulosic chains of the microfibrils generated from both the fibre types during pulping.Improvement in the tensile strength (in terms of breaking length), as well as the burst strength of almost all the blended sheets points towards the increase in number of inter fibrilar hydrogen bondings within the sheet structure that may have resulted from the extensive defibrillation and effective swelling of the virgin sisal pulp fibre. The presence of an adequate number of highly fibrilated sisal fibrils possessing sufficient pliability in the weaker pulp furnish increases the interaction between the two types of fibre as well as the interactions within the sisal fibrils themselves. Increase in strength due to intensive interactions between the sisal fibre and the waste paper fibre points towards the compatibility and conformability of sisal fibres when mixed with the other weak and/or highly recycled content fibres. An appreciable improvement in almost all the strength parameters appears to have taken place with the increase in the proportion of sisal fibres in different blending ratios, but the maximum and optimum enhancement in the strength characters of the blended sheets seems to have resulted from the sisal: wastepaper proportion of 80: 20 (Table 2). The enhancement in the breaking length, tear strength and the burst strength of the blended handsheets with the increase of sisal dose in the pulp admixture at even moderate beating, probably, is the result of the presence of adequate number of strong and flexible sisal microfibrils possessing greater ability to form bonds than the fibres from the waste papers, as the papermaking properties of these fibres diminish due to the degradation in their bonding potentials with the extent of recycling. Increase in the breaking length, burst factor and the folding endurance values has been found to be maximum with 80% of sisal dose while a reduction in these values can be visualized at a higher proportion of sisal fibres in the blended sheets. This trend may be explained by the predominance of stiff and hard sisal fibres at an excessive dose of sisal in the pulp mixture and their inability to respond to the beating process properly. It would restrict or resist the inter-fibre bond formations amongst themselves as well as with the waste paper fibres leaving a lot of gaps and voids within the sheet structure, causing a reduction in the sheet density which ultimately have an adverse impact on the strength properties.However, the improvement in folding endurance values of the blended sheets was appreciable only at a higher sisal dose in the pulp blend as even a 25% of sisal dose was found to be ineffective in modifying the folding endurance values of the sheets produced from recycled pulps. Increase in the tearing resistance and tensile strength suggests the existence of reinforcing potentials of sisal fibres in papermaking.Despite the low basis weight of the sheets (as observed from the GSM values), the strength characters of the sheets have shown an improvement in their values (Table 2). Hence, a useful and valuable conclusion may be drawn from these findings that high strength blended papers can be produced with lower grammage, an important feature to reduce the resource consumption and improve product quality in a concerted manner.

Analysis of blended sheets containing chemically cooked sisal fibres

A noticeable increment in the burst values of the blended sheets (50:50) can be observed with the increase in cooking time from 1.00 -2.15 hr but no further increase in the strength properties of the sheets can be detected on further increasing the cooking time period (Table 3). The maximum increase in burst factor was observed for the blended sheets containing

sisal fibres chemically steam digested for 2.15 hr. But the optimum increase in the burst factor seems to be for sisal fibres digested for 2.00 hr as this is also accompanied by the lowest cob value (35.50), which is a measure of the extent of sizing of the sheets. Alkaline digestion of the sisal fibre seems to have accelerated the delignification of the fibres by dissolution of the lignin and other gummy substances present on the fibre surface and within the fibre.

Improvement in the strength character of the blended sheets with the increase in cooking time from 1.00 - 2.15 hr can be noticed by the increase of burst values as summarized in Table 3. The trend in the improvement of strength character of the blended sheets with the increase in cooking time period, may be ascribed to the generation of more microfibrils as a result of the penetration of the cooking liquor intensively and extensively into the inter fibrillar regions of the sisal fibre. Microfibrils, are generally the cell wall components of the lignocellulosic fibres, which are approximately 30-100 nm in diameter and a few micrometers in length[25]. So, the cellulose microfibrils can actually be considered to be nanofibres since by definition a nanofibre is a size < 100 nm in one dimension[26]. More the generation of the nanofibrils more is the aspect ratio of the fibrils involved in bonding within the sheet web structure resulting in increase in the strength of the ensuing paper sheets. Moreover, thinner fibrils provide a conducive environment for inter-fibrilar bonding to take place by exposure of more surface area for fibre swelling and thereby, increasing the flexibility and pliability of the fibres even with less beating. Larger the fibre swelling, more intense will be the inter-fibrilar hydrogen bonding due to the proximity of the fibres to each other in the sheet structure which will positively influence the strength properties especially, those which are dependent on the degree and strength of bonds within the fibrous network of the paper sheets like the burst strength, a parameter that is a good indicator of the resistance of paper or paperboard to internal mechanical stresses.Decrease in the burst strength of the blended sheets can be observed with further increase in the cooking time (> 2.15 hr) of the sisal fibres (Table 3). This behavior may be attributed to the intra microfibrillar penetration of the cooking liquor as a result of prolonged heating. Penetration of the liquor into the intra microfibrillar regions may dissolve away some of the useful chemicals imparting strength and stability to the micro fibrils thereby, weakening the fibrils and damaging the integrity of the fibre as a whole, ultimately, resulting in reduction of the strength of the sheets containing these fibres.The water absorption of the blended sheets containing thermally and chemically treated sisal fibres does not undergo any significant change as measured from their 1 min cob values, highlighted in Table 3 which does not represent any regular trend. A slight reduction in the cob values for the sheets comprising of chemically cooked fibres may have resulted from the reduction in gaps or empty spaces within the fibrous network of the sheet structure due to extensive and effective bonding between the fibres.

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Reference

1 Singh R & Bhardwaj N K, Enzymtic treatment of secondary fibres for improving drainage: an overview, *IPPTA J*, **23** (2011) 121-25.

2 Somwang K, Enomae T & Onabe F, Effect of fiber hornification in recycling on bonding potential at interfiber crossings: confocal laser-scanning microscopy (CLSM), *Japan Tappi J*, **56** (2002) 239-245.

3 Minor J L, Hornification—its origin and meaning, *Progr Pap Recycling*, **3** (1994) 93–95.

4 Howard R C & Bichard W, The basic effects of recycling on pulp properties, *J Pulp Paper Sci,* **184** (1992) J151-J159.

5 Gurnagul N, Sodium hydroxide addition during recycling: effects on fibre swelling and sheet strength, *TAPPI J*, **78** (1995) 119-124.

6 Putz H J, Torok I & Gottsching L, Making high quality board from low quality waste paper*, Paper Tech Ind,* **30**(1989) 14-20.

7 Somboon P, Vuorela J, Pynnonen T & Paulapuro H, Grit segments in TMP refining, Part 1: Operating parameters and pulp quality, *APPITA J,* **62** (2009) 37-41.

8 Jahan M S & Rawshan S, Reinforcing potential of jute pulp with *Trema orientalis* (Nalita) pulp, *BioResources,* **4** (2009) 921-931.

9 Karlsson H, Beghello L, Nilsson L & Stolpe L, Abaca as a reinforcement fibre for softwood pulp, *TAPPI J,* **6**(2007) 25-32.

10 Latifah J, Aimn Z M A, Rushdan I & Mahmudin S, Restoring strength of recycled fibres by blending with kenaf pulp, *Malaysian J Sci,* **28** (2009) 79-87.

11 Goswami T, Kalita D, Ghosh S K & Rao P G, Utilization of banana fibre for making certain specialty paperboards using eco-friendly processes, *IPPTA J*, **18** (2006) 39-43.

12 Wanrosli W D, Zainuddin Z & Roshan S, Upgrading of recycled paper with oil palm fiber soda pulp, *Indust Crops Prod*, **21** (2005) 325-329.

13 Toledo Filho RD, Silva F A, Fairbairn E M R & Melo Filho JA, Durability of compression molded sisal fibre reinforced mortar laminates, *Construct Build Mater,* **23** (2009) 2409-2420.

14 Gupta M, Verma A & Singh B, A note on the investigation of fibre-matrix adhesion in sisal fibre-polyester composites. *Current Sci,* **74** (1998) 526-529.

15 Pimenta M T B, Carvalho A J F, Vilaseca F, Girones J, Lopez J P, Mutje P & Curvelo A A S, Soda-treated sisal/ polypropylene composites, *J Polym Environ,* **16** (2008) 35-39.

16 TAPPI Standard and Suggested Methods (Technical Association of the Pulp and Paper Industry) New York, 1971.

17 Sarkar P B, Majumdar A K & Pal K B, The hemicelluloses of jute fibre, *J Text Inst,* **39** (1948) (T-44) 44-58.

18 Wise L E, Murphy M & d'Addieco A A, Chlorite holocellulose, its fractionation and bearing on summative wood analysis and studies on the hemicelluloses. *Paper Trade J,* **122** (1946) 35-43.

19 Janoobi M, Harun J, Shakeri A, Misra M & Oksman K, Kenaf composition and nanofibres. *Bioresources,* **4** (2009) 626-639.

20 Ilvessalo-Pfaffli M-S, Fibre atlas identification of paper making fibres, Springer, (1995) 290-299.

21 Rowell R M, Han J S & Rowell J S, *Nat polym agrofibres compos* In: Frollini E, Leao A L & Mattoso L H C, San Carlos-Brazil, 2000.

22 Gutierrez A, Rodriguez I M & del Rio J C, Chemical composition of lipophilic extractives from sisal (Agave Sisalana) fibres, *Ind Crop Prod*, **28** (2008) 81-87.

23 Pavithran C, Mukherjee P S, Brahmakumar M & Damodaran A D, Impact properties of natural fibre composites, *J Mater Sci Lett,* **6** (1987) 882-884.

24 Hurter A M, Utilization of annual plants and agricultural residues for the production of pulp and paper, *Nonwood Plant Fibre Pulping Progress Report 19, Tappi Press*, Atlanta, Georgia, 1991.

25 Wang B, Sain M & Oksman K, Study of structural morphology of hemp fibre from the micro to the nanoscale,*Appl Compos Mater,* **14** (2007) 89-103.

26 Gardner D J, Oporto G S, Mills R & Samir M, Adhesion and surface issues in cellulose and nanocellulose, *J Adhesion Sci Technol,* **22** (2008) 545-554.