CHAPTER IV

EFFECT OF BLENDING OF SISAL ON PULP PROPERTIES OF WASTE PAPER IN HANDMADE PAPERMAKING
4.1 Introduction

The pulp and paper industries not only in India but throughout the globe are encountering the critical situation of sustainability chiefly because of their huge dependency on forest based resources like wood (hardwood and soft wood) and bamboo, whose availability in the existing scenario is strictly limited and on the verge of steep declination. The condition is more aggravated due to the vast consumption of chemicals necessary for their processing to manufacture paper of desired quality leading to high toxicity levels in the discharged stream, causing severe water pollution. In the wake of serious environmental implications accompanied by stringent rules and regulations imposed by the government, paper industries (large, medium or small scale) have been forced to divert from the consumption of conventional wood based resources to alternative substitutes having a sustainable nature. In this context, secondary fibres like waste or recycled papers possessing sufficient cellulose (the basic structural component of the paper), have an important and leading role to play as alternative fibrous sources in the future. Their growing utility rates justify this trend as more than one third of the paper produced worldwide is already from the recycled pulp [1]. Paper produced from waste papers has a great potential to reduce the consumption of conventional resources along with some other important benefits like decrease in the pollution load and considerably lower consumption of energy during paper production by recycling them.

Owing to the increasing reliance on secondary fibres for paper production and the inherent drawbacks associated with these fibres, methods and techniques are essential to address and overcome them. This will further help and ensure to consolidate the position of the secondary fibres in the production of papers and its allied products. Of the multifarious problems associated with the use of secondary fibres (which mostly comprise of waste/ recycled papers) in papermaking, one of the major concern is the reduction in strength properties of the paper produced from them as compared to the sheets produced from their virgin counterparts. High drainage resistance of the pulps produced from secondary fibres and their timely unavailability (due to poor infrastructural facilities in their collection), with the high cost involved in deinking processes are some of the few other major challenges limiting their huge reliance and preventing their wide adaptability in paper industries.
Blending has been one of the various techniques employed in papermaking to revive or restore the loss in recyclability of the secondary fibres [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]. Enzymatic treatments of secondary fibres have also been recently discovered to improve the drainage property of the pulp [1, 8, 9, 10], which further contribute in enhancing the strength characters of the final paper sheets.

Generally, the softwood kraft pulps are used by the paper industries to reinforce the weaker papermaking furnishes. But owing to the shift in attention from wood based resources to the non-woods, suitable plant fibres are acquiring importance as reinforcing agents to the comparatively weaker pulps, provided their availability is not a constraint. It has been estimated that the total availability of non-woody fibrous plant is 2300 million tones of which about 50% are agro residues like straws [11] but, owing to the short fibre nature of most of these agro wastes they may not be as suitable for producing papers possessing good strength characteristics as many of the non-woody plant fibres. 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 [12 - 15], abaca [16], kenaf [17 - 20], banana [21] and even the oil palm. It has been found that with the addition of as little as 20% of virgin unbeaten pulp and considerably lesser amount (ca. 10%) of virgin beaten pulp of oil palm fibres, it was sufficient to completely restore the strength of the recycled paper [22]. An improvement in the folding endurance of recycled bagasse paper has also been detected when blended with long fibered bleached bamboo pulp [23].

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. An initiative has therefore, been taken towards this direction by analysing the various properties of the paper samples prepared by the blend of the locally and sufficiently available sisal fibres with the secondary fibres and comparing their properties with those of the unblended pulps. Physico-chemical characteristics of the sisal fibres have also been studied to highlight its papermaking potential and have been compared with the properties of another established and reinforcing papermaking fibre like kenaf, as it would render support and help to predict the papermaking potentials of sisal.

Sisal is an interesting and hard leaf fibre which has been placed next to Manila in durability and strength [24]. 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. Traditional uses of sisal for making ropes and twines, coarse textile materials and carpet backing, as well as in the production of many craft and decorative materials throw some light towards its twin but complementary characters of strength and flexibility. 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 [25-47], SBS matrices [48], polyester composite resins [49, 50, 51] and polymer matrices [52-55], 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. Different chemical treatments of the sisal fibres in varying degrees during composite formation have also been observed to empower the products to various extents in different dimensions. Applications of sisal in many bio-composites have also been cited in the literature.

Thus, the utility of sisal in various fields exposes the versatile nature of its fibre and motivates us to employ them in papermaking, particularly emphasizing its
reinforcing potential when mixed with highly recycled content fibres or comparatively weak fibres, for producing strong eco-friendly handmade papers.

4.2 Experimental

4.2.1 Materials and Methods

Decorticated sisal fibres were procured from a private decortication plant at Nildungri in Sambalpur district of Orissa due to the proximity of this fibre extraction unit to the research area. 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. The presence of pithy materials in the sisal fibre may hamper the pulping process and its presence in the sisal pulp would also influence the quality of the end products as the pithy materials mainly consist of very small fibres or the parenchyma cells which are not suitable for paper formation.

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 [56] as follows: T 222 OM-88-lignin (acid insoluble) and T 212 OM-88 for 1% alkali solubility. The cellulose content was determined according to the modified method of Sarkar et al. [57]. 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. [58]. 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, which gave the percentage of acetone extractives. 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 Rayagarga, Orissa. The results of the various observations and estimations have been presented in Table 4.1 and they have been compared with the properties of another non-wood pulp fibre of kenaf, whose reinforcing potential in paper-making has already been
established as mentioned earlier. The chemical characteristics of the waste paper has also been reported in Table 4.1 for the sake of comparison.

Table 4.1. Physico-chemical characteristics of sisal, waste paper and kenaf fibres

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Properties</th>
<th>Sisal leaf fibres</th>
<th>Waste paper</th>
<th>Kenaf bast fibres (Ref)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Cellulose (%)</td>
<td>67.19</td>
<td>87.45</td>
<td>63.5±0.5 [60]</td>
</tr>
<tr>
<td>2.</td>
<td>Hemicellulose (%)</td>
<td>21.45</td>
<td>5.8</td>
<td>17.6±1.4 [60]</td>
</tr>
<tr>
<td>3.</td>
<td>Lignin (%)</td>
<td>10.22</td>
<td>2.23</td>
<td>12.7±1.5 [60]</td>
</tr>
<tr>
<td>4.</td>
<td>Extractives (%)</td>
<td>5.23</td>
<td>6.34</td>
<td>4.0±1.0 [60]</td>
</tr>
<tr>
<td>5.</td>
<td>Ash (%)</td>
<td>1.27</td>
<td>3.21</td>
<td>2.2±0.8 [60]</td>
</tr>
<tr>
<td>6.</td>
<td>1% NaOH Solubility (%)</td>
<td>22.8</td>
<td>15.31</td>
<td>-</td>
</tr>
<tr>
<td>7.</td>
<td>Fibre Length (mm)</td>
<td>3</td>
<td>-</td>
<td>5 [61]</td>
</tr>
<tr>
<td>8.</td>
<td>Fibre Width (μm)</td>
<td>20</td>
<td>-</td>
<td>21 [61]</td>
</tr>
<tr>
<td>9.</td>
<td>Tensile Strength (GPa)</td>
<td>6.1*</td>
<td>-</td>
<td>11.9 [59]</td>
</tr>
</tbody>
</table>

* 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%.

4.2.2 Blending of Sisal with Waste Paper (Discarded Note-books) in Different Ratios

Since, pulping during papermaking in the handmade sector usually involves the mechanical process, our method of paper production basically followed the same method due to the advantages like high pulp yield, environmental friendliness (because of minimum chemical consumption) and cost effectiveness of the final products. Cleaned and uniformly cut (2-4 cm) sisal fibres were soaked in clean water for at least one hour prior to their subject 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.

Table 4.2 Blending effects of sisal with waste paper (discarded note-books) in various proportions

<table>
<thead>
<tr>
<th>Sisal</th>
<th>Waste Paper</th>
<th>Basis Weight (GSM)</th>
<th>B.L. (mtr)</th>
<th>T.F. (gfm²/g)</th>
<th>B.F. (gfcm²/m²/g)</th>
<th>Double Fold (M.I.T.)</th>
<th>Brightness (% ISO)</th>
<th>Yellow Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0</td>
<td>74</td>
<td>1654</td>
<td>147</td>
<td>11.7</td>
<td>4</td>
<td>45.7</td>
<td>30.56</td>
</tr>
<tr>
<td>89</td>
<td>1642</td>
<td>1505</td>
<td>97</td>
<td>10.8</td>
<td>0</td>
<td>44.8</td>
<td>28.90</td>
<td></td>
</tr>
<tr>
<td>95</td>
<td>1599</td>
<td>1505</td>
<td>97</td>
<td>9.7</td>
<td>0</td>
<td>44.8</td>
<td>28.22</td>
<td></td>
</tr>
<tr>
<td>97</td>
<td>1586</td>
<td>105</td>
<td>110</td>
<td>7.0</td>
<td>3</td>
<td>52.8</td>
<td>29.06</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>1941</td>
<td>74</td>
<td>11.3</td>
<td>4</td>
<td>52.1</td>
<td>20.99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>87</td>
<td>1772</td>
<td>77</td>
<td>11.0</td>
<td>5</td>
<td>52.0</td>
<td>21.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>81</td>
<td>1375</td>
<td>99</td>
<td>11.2</td>
<td>5</td>
<td>51.5</td>
<td>21.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>84</td>
<td>2725</td>
<td>84</td>
<td>13.2</td>
<td>7</td>
<td>52.2</td>
<td>18.83</td>
<td></td>
<td></td>
</tr>
<tr>
<td>86</td>
<td>2602</td>
<td>88</td>
<td>13.1</td>
<td>6</td>
<td>52.4</td>
<td>18.77</td>
<td></td>
<td></td>
</tr>
<tr>
<td>88</td>
<td>2399</td>
<td>90</td>
<td>12.9</td>
<td>7</td>
<td>52.6</td>
<td>18.59</td>
<td></td>
<td></td>
</tr>
<tr>
<td>83</td>
<td>2222</td>
<td>77</td>
<td>11.7</td>
<td>4</td>
<td>56.2</td>
<td>17.73</td>
<td></td>
<td></td>
</tr>
<tr>
<td>73</td>
<td>2001</td>
<td>98</td>
<td>11.2</td>
<td>3</td>
<td>55.0</td>
<td>17.82</td>
<td></td>
<td></td>
</tr>
<tr>
<td>88</td>
<td>1591</td>
<td>114</td>
<td>10.8</td>
<td>0</td>
<td>51.6</td>
<td>22.39</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>470</td>
<td>50</td>
<td>3.5</td>
<td>0</td>
<td>47.9</td>
<td>17.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>81</td>
<td>1197</td>
<td>46</td>
<td>4.0</td>
<td>0</td>
<td>48.8</td>
<td>17.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>92</td>
<td>1008</td>
<td>42</td>
<td>4.6</td>
<td>0</td>
<td>50.7</td>
<td>13.89</td>
<td></td>
<td></td>
</tr>
<tr>
<td>77</td>
<td>275</td>
<td>25</td>
<td>0.9</td>
<td>0</td>
<td>50.67</td>
<td>14.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>81</td>
<td>327</td>
<td>27</td>
<td>0.88</td>
<td>0</td>
<td>51.33</td>
<td>13.91</td>
<td></td>
<td></td>
</tr>
<tr>
<td>88</td>
<td>331</td>
<td>27</td>
<td>1.1</td>
<td>0</td>
<td>49.89</td>
<td>14.12</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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. Moreover, simultaneous beating of the two types of fibre will help to save beating time and energy, an important factor to produce cost effective products. The beating was
done till the blend pulp freeness reached 15-21 °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. Addition of any other beater additives were avoided during pulping in order to eliminate the influence of such chemicals on the properties of the final test samples.

Similar method was adopted for each proportion of fibre blending. After each set of pulping, hand sheets were prepared by the usual handmade technique of 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, to dehydrate the sheets, in order to promote the inter-fibre bond formation and hence, the building up of paper structure. After proper conditioning, the sheets were subjected to various types of physical examinations and the test results have been tabulated below (Table 4.2):

4.2.3 Blending of 50% by Weight of Chemically Cooked Sisal with Waste Press Cuttings

A number of sample sheets were also 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. After 45min of beating 200g of waste papers (white color waste press cuttings) were added to the beater stock and the beating continued for another 45 min. The waste papers were cut to small sizes and soaked in clean water for half an hour prior to beating so as to facilitate fibre swelling of the cellulose fibres present in the discarded papers. White color of the press cuttings has an advantage over the colored ones as it would reduce the consumption of bleach chemicals as well as minimize the influence of dye chemicals (present in
printed or colored papers) on the properties of the blended sheets. The blended stocks were beaten at 4% pulp consistency to a pulp freeness of 15°- 20° SR. Near to completion of the beating, mild quantity of sizing chemicals (a mixture of rosin and alum) were added to the beater stock and the beating continued at a lighter mode till the end. 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 were prepared of varying grammage by the handmade technique. After pressing, 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 compared with those of the blended sheets containing 50% of untreated sisal fibres and the overall results have been summarized in Table 4.3. The approximate thickness of the paper sheets were measured with the help of a screw gauze and the the observations highlighted in the same table.

Table 4.3 Blending effect of waste papers (press cuttings) with 50% of chemically digested sisal for varying time intervals

<table>
<thead>
<tr>
<th>Sheet No.</th>
<th>Period of Digestion (hr)</th>
<th>Basis Weight (GSM)</th>
<th>Thickness (~mm)</th>
<th>Burst Factor (gfcm²/m²/gm)</th>
<th>Cobb Size₆₀ (g/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.00</td>
<td>115</td>
<td>0.185</td>
<td>19.78</td>
<td>39.21</td>
</tr>
<tr>
<td>2</td>
<td>1.15</td>
<td>176</td>
<td>0.175</td>
<td>20.23</td>
<td>41.52</td>
</tr>
<tr>
<td>3</td>
<td>1.30</td>
<td>106</td>
<td>0.205</td>
<td>19.89</td>
<td>40.18</td>
</tr>
<tr>
<td>4</td>
<td>1.45</td>
<td>182</td>
<td>0.185</td>
<td>21.65</td>
<td>41.67</td>
</tr>
<tr>
<td>5</td>
<td>2.00</td>
<td>115</td>
<td>0.175</td>
<td>23.26</td>
<td>35.50</td>
</tr>
<tr>
<td>6</td>
<td>2.15</td>
<td>170</td>
<td>0.185</td>
<td>24.73</td>
<td>37.33</td>
</tr>
<tr>
<td>7</td>
<td>2.30</td>
<td>110</td>
<td>0.185</td>
<td>22.45</td>
<td>36.78</td>
</tr>
<tr>
<td>8</td>
<td>2.45</td>
<td>185</td>
<td>0.185</td>
<td>22.17</td>
<td>36.54</td>
</tr>
<tr>
<td>9</td>
<td>3.00</td>
<td>108</td>
<td>0.205</td>
<td>18.31</td>
<td>37.45</td>
</tr>
<tr>
<td>10</td>
<td>3.15</td>
<td>177</td>
<td>0.195</td>
<td>19.66</td>
<td>39.43</td>
</tr>
<tr>
<td>11</td>
<td>4.00</td>
<td>185</td>
<td>0.205</td>
<td>17.78</td>
<td>39.50</td>
</tr>
<tr>
<td>12</td>
<td>0.00</td>
<td>154</td>
<td>0.185</td>
<td>12.58</td>
<td>50.55</td>
</tr>
</tbody>
</table>
4.3 Results and Discussion

4.3.1 Analysis of Sisal, Kenaf and waste paper fibres

Chemical characteristics of sisal leaf fibre shows great similarity with those of kenaf bast fibre as observed from the data presented in Table 4.1. Both the fibres were found to be rich in their cellulose content. In fact, higher 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), not only suggests the capability of sisal in papermaking but also points towards its better pulping efficacy than kenaf. The cellulose content of the waste paper fibres was found to be much higher (87.45) than for both sisal (67.19) and the kenaf fibres (63.5) as can be visualized from the Table 4.1. The hemicelluloses and lignin contents of the waste paper fibres was observed to be much lower than those of the sisal and the kenaf fibres. The hemicelluloses content in sisal were also found to be slightly more than those in kenaf (Table 4.1).

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 [62]. 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 (1.27) in sisal as compared to the percentage of ash in kenaf fibres (2.2), is clearly indicative of the less silica content in sisal (as silica constitutes the major inorganic portion of the ash) and 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, a negative factor in producing bright and good quality papers. The ash content of the waste papers was also determined to be slightly higher than the sisal
fibres which would have been the consequence of 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. Thus, it may be inferred from the chemical analysis that 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 4.1). Less aspect ratio (fibre length/fibre width) of sisal as compared to kenaf and almost half the tensile strength of sisal (6.9 GPa) in comparison to kenaf fibre (11.9 GPa), 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) [59] and banana (540 MPa) [63]. 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 [64], is greatly suggestive of producing strong papers from sisal fibres as the aspect ratio is a good indicator of paper strength.

4.3.2 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 significantly in particular, the strength properties as can be seen from the values of burst factor, tear factor, breaking length and double fold of the blended sheets that are presented in Table 4.2. 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 or absorption of water by the fibres. Further, the water absorption of fibres is dependent 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 \[65\] 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 \[66\]. So, 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, causing more fibrils to come into close contact with each other. 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 which are the bonding dependent properties, 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 as can be seen from the results of the various tests presented in Table 4.2. 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 [67]. 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 as observed from the data presented in table 4.2. Because, the tearing resistance in conjunction with the tensile strength of paper handsheets is commonly considered to be the direct measurement of paper strength potential [68], an increase in the values of both of these parameters is greatly suggestive of the reinforcing potentials of sisal fibres in papermaking although, a slight reduction in the tear factor of the blended sheets containing sisal fibres can be observed with the less percentage of sisal fibres in different blend ratios.

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 4.2). 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.

But the modifications in the optical properties of the blended sheets have not been that significant in comparison to the strength properties as can be seen from the brightness percentage and yellow index values of the blended sheets which have also been compared with the properties of the unblended sheets of sisal (100%) and waste
paper pulp (100%). Comparing the percent brightness of paper produced from sisal pulp and waste paper pulp, not much difference can be marked but it appears that the sisal paper is slightly less bright than the recycled paper which possibly is a consequence of the high residual lignin content of sisal pulp and the presence of some bleach chemicals or whitening agents in the waste paper pulp that may have been used during its manufacture. No significant change or any regular trend in the brightness values of the blended sheets can be detected except for a marginal improvement in their brightness as compared to the brightness of the sisal paper. This probably was due to the release of brightness enhancing chemicals from the waste papers into the mix pulp furnish during recycling in paper production. The slightly decreasing yellow index values of the blended sheets with the increasing proportion of waste paper, justifies this trend to some extent as yellow index is a property that is complementary or inversely proportional to the brightness property. No considerable development in the optical properties of the blended papers possibly would have been the effect of the dissolution of the ink particles from the waste papers during pulping into the blend pulp stock.

4.3.3 Analysis of Blended Sheets Containing Chemically Cooked Sisal Fibres

Thermal behaviour of sisal fibre and its constituents has been found to be similar to other plant fibres like jute and hemp. TGA and DSC studies have revealed the thermal stability of these fibres upto 185°C as, it has been observed that the degradation of their chemical components like cellulose and hemicelluloses commences at 186°C [69], which justifies the chemical digestion of the sisal fibres performed under steam or pressurized conditions, that can attain a maximum temperature of 100°C (i.e., the boiling temperature of water). Pressurized digestion has been further considered to save time and energy, which may ultimately play an important and decisive role in producing simultaneously economically attractive as well as ecologically sound products, which is the need of the hour.

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 as observed from the data given in Table 4.3. The maximum increase in burst
factor (24.73) was observed for the blended sheets containing sisal fibres chemically steam digested for 2.15 hr prior to their subjection to the beating process. 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. Chemical digestion of the sisal fibres prior to the mechanical beating process also facilitates fibrillation of the fibres by the separation of the microfibrils building up the fibre bundle (as a result of the removal of their cementing materials), of which the sisal fibre is morphologically composed of. The degummmification is also substantiated by the considerable reduction in the beating time and energy of the chemically cooked fibres than the uncooked ones.

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 4.3. 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 with the prolonged but optimum exposure of these fibres to the thermal treatment. 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 [70]. So, the cellulose microfibrils can actually be considered to be nanofibres since by definition a nanofibre is a size < 100 nm in one dimension [71]. More the generation of microfibrils or even the nanofibrils with much smaller diameters in comparison to the thickness of the fibre as a whole, more is the aspect ratio of the fibrils involved in bonding within the sheet web structure and it is a known fact that higher the aspect ratio of fibres involved in bonding, greater is 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 [72].

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 as can be seen from the data given in Table 4.3. 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 4.3 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.

4.4 Conclusion

Blending of sisal pulp with the comparatively weaker pulp fibres may be regarded as a better technique to improve the strength properties of the paper sheets particularly, in the handmade sector as it seems to be a viable option to preserve its eco-friendly nature with simultaneous development in paper qualities. Physico-chemical analysis of sisal fibres gives a positive signal for utilizing them as a blending additive in papermaking. Development of strength characters in the blended sheets containing sisal and waste paper fibres, without adverse effect on other properties like optical (measured in terms of brightness and yellow index) and water absorption (measured in terms of cob values), exposes the papermaking potentials of sisal as well as prove its compatibility with other papermaking fibres like the secondary fibres, which have useful implications in papermaking. From the analysis of the results of the different blending types, an
important conclusion may be drawn that chemically digested sisal fibres were more influential in modifying sheet characteristics than the unmodified fibres. The ease of cultivation of sisal plant having short renewing time periods (7-10 years), thriving potential in all types of soil and environment with minimum fertilizer input clearly, sends a positive signal for their use in papermaking applications which would help to combat the resource scarcity substantially by a considerable reduction in the consumption of conventional raw materials. Improvement in the various strength properties of the sheets produced from waste papers containing sisal fibres in optimum doses, clearly indicates the reinforcing potential of the sisal fibres in papermaking. This conclusion is also supported by other researchers who have suggested the cost-effective replacement of long-fibred chemical wood-pulp for reinforcement or basis-weight reduction of many paper grades by the sisal pulp [73].

From this piece of study, it may be recommended that more research may be carried out with the involvement of proper enzymes and surfactants along with the newly identified and suitable fibres like sisal as enzyme/surfactant assisted papermaking may also help to produce papers possessing both good strength as well as optical characteristics in an environmentally benign manner. In order to comply with the increasing stringent environmental regulations, many countries in the developed regime like Europe and North-America have already started adopting the enzyme technology in their pulp and paper industries [74]. Various utility and importance of enzymes and surfactants for papermaking have already been discussed in chapter 1. Therefore, their optimum use along with the sisal fibres may help to address and combat some of the grave concerns especially the ecological and economical aspects in papermaking.
4.5 References


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