International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
Index Copernicus Value (2013): 6.14 | Impact Factor (2013): 4.438

Cotton Spinning Properties of Chemically Modified Hemp Fibres

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Abstract: ***Chemical and enzymatic treatments were carried out to improve the spinning properties of hemp fibres (Cannabis sativa) for cotton spinning systems (CSS). It was found that enzyme treated fibres are not suitable for CSS because this modification process removed the least amount of non-cellulosic materials, however, lost most of the fibre tenacity. Further, enzyme treatment failed to produce essential CSS properties: softness and single entity fibres. Among the chemical treatments, bleaching removed the largest amount of non-cellulosic materials and significantly improved the softness property. Although bleaching treatment did not produce 100% single entity fibre, however, the 'ease of separation' rating showed that these fibres can be separated easily and are suitable for CSS.***

Keywords: Spinning properties, Surface modifications, Weight loss (%), Softness and single fibre entity.

1. Introduction

Hemp is a natural cellulosic fibre extracted from plant stalk [1-2]. Hemp fibre has some excellent properties over most widely used fibres, cotton and polyester, for example, faster transport of moisture, higher hygroscopicity, greater protection from ultra violet and high absorbability of toxic gases [3]. However, due to the presence of 25-37% non-cellulosic materials in its structure, the fibre lacks short staple fibre spinning properties [1].

Short staple fibre (ring and rotor) spinning processes can be used for cotton and synthetic fibres in order to spin high quality finer yarns that are used for apparel (woven and knitted) and smart textiles (woven and knitted bandage) applications [4]. Currently, yarn is spun into yarn from hemp fibre using wet (flyer) spinning system that can only produce coarse and low quality yarns that are used for composite and other niche applications [1]. As a result, in 2002, the use of hemp fibre (0.08 million tons) is very limited compare to cotton (40 million tons) and polyester (36 million tons). Similar problem was encountered for polyester and other synthetic fibres at the beginning of their commercial production; however, these fibres were cottonized by texturization and tow-to-top production process to spin [5-6].

Numerous attempts have been made to remove the non-cellulosic materials in order to improve hemp fibre properties. Wang *et al.* [7] reported that alkaline scouring followed by hydrogen peroxide bleaching removed a higher amount of pectin and lignin than acid scouring. However, the authors did not report changes in spinning properties due to the removal of pectin and lignin. Dryer *et al.* [8] found that the resultant fineness and tenacity of both enzyme and chemically treated hemp fibres were found to be between 10-30µm and 8-30 cN/tex respectively. Although no comparison was made with cotton, looking into the data, it appears that both tenacity and fineness of the treated fibres is suitable for cotton spinning process. However, no data was given regarding other spinning properties. Sedelnik [9] reported that physio-chemical (enzyme and carding) treatment reduced the fibre fineness by 20-40% and length by 80%. However, no explanation was provided for such drastic changes in fineness and fibre length. Further, the length of hemp fibre is very long compared to cotton; therefore, hemp fibre length is always suitable for cotton spinning process.

Cottonization of hemp was claimed in all surface modification studies of hemp; however, the research studies thus far failed to address all critical spinning properties for cotton spinning systems. As a result very small amount of hemp fibre (0.1%) is being used compared to cotton and polyester [1]. It seems that there is a lack of understanding of the spinning properties of fibre among the researchers in this field; therefore, in order to address this issue, we are providing a brief principle of ring spinning system that relates to fibre spinning properties.

Theoretical Background of Spinning Properties

Ring spinning is the most widely used short staple spinning process to produce superior quality (USTER TOP 5%) spun yarn in a wide range of linear densities using different fibers [2]. Ring spinning is mainly a 5 step process: opening/cleaning → carding → (combing) drawing → roving → spinning with an additional step required to spin for combed yarn. The opening process uses whirling beater blades or pneumatic action to beat up or blow up clumps of fibers from fiber bales to make the individual fibre. The carding and combing processes operate hundreds of fine comb wires through the picker roller to align the fibres. To withstand stresses and avoid fibre breakage by these processes, the fibre must be soft and flexible. Roving process prepares the fiber stream for the final twisting by drawing the sliver to appropriate linear density (tex) by drafting. In ring frame, roving is converted into spun yarn by drafting through a drafting zone (Figure 1) with three different sets of drafting rollers in which the front drafting rollers run faster than the back drafting rollers. The differential speed (draw ratio) of drafting rollers is necessary to produce yarn with required

linear density. For example, if the roving linear density is 600 tex and the required yarn count is 20 tex, the draft must be 30, which means the speed of front drafting roller should be 30 times faster than the speed of the back drafting rollers. This creates a tremendous compressive and tensile force on the fibre, and to withstand these stresses, fibre must be soft and strong. Finally, twist is inserted by a traveler which runs at a speed of more than 20000 r.p.m. [10] on a ring around a bobbin to be wounded up as yarn packages (Figure 2). Such high speed is required to insert twist at a rate of TPI = K√Ne [TPI: twist per inch, K: twist multiplier (3.5-5.5) and Ne: yarn count in English Cotton System]. For example, about 20-30 twist per inch is inserted in a 40 Ne yarn as twist per inch (TPI) is TPI = 5.0√Ne, where, twist factor is 5.0 and Ne is the yarn number in the English cotton system [11]. Further, because of the traveler twisting action, the yarn section between the yarn guide and the ring is thrown by centrifugal force to swing a yarn "balloon" thus higher tension is created by faster speed of the rotation (Figure 2).

Cotton spinning systems requires the fibers which are easy to bend so that they do not break due to torsional tension while twisting in simplex and ring frame as well as compressive forces while drafting in mainly in drawing, simplex and ring frame machines. The spindle in a ring frame machine rotates at a speed of 25,000-30,000 rpm in order to insert twist [10]. About 20-30 twist per inch is inserted in a 40 Ne yarn as twist per inch (TPI) is TPI = 5.0√Ne, where, twist factor is 5.0 and Ne is the yarn number in the English cotton system [11].

The variation in fiber length in a bundle of fibers blend/mix during ring spinning must be less than ±3 mm as the ratch (distance between the nip of the drafting rollers) (L) [Figure 1] is set according to the fibre staple length which is 0.91*LL´ in the comb sorter diagram [12]. Further, in the ring spinning process, fibers are required to be in the grip (nip) of either the front or back pair of drafting roller during drafting period in drawing, comber, simplex and ring frame in order to avoid floating fibre. Fibre breakage and droppings occur when the variation in length of fibre is (L+3) mm and (L-3) mm [13]. This causes unevenness and imperfections in the yarn which will be discussed later in the paper.

From the theory of ring spinning, we have identified six spinning properties of hemp fibres and ranked them in the following order from most to least important: strength>bending modulus (breaking twist angle)>softness> length variation>fineness>individual fibre entity. Four of these properties (strength, bending, softness and fibre length) are indicated in Figures 1 and 2 while single fibre entity and fibre fineness are related to yarn quality parameters. In the current research, we will discuss the impact of chemical and enzyme treatments on four (strength, softness, length variation and single fibre entity) of these six critical ring spinning properties of surface modified hemp fibre.

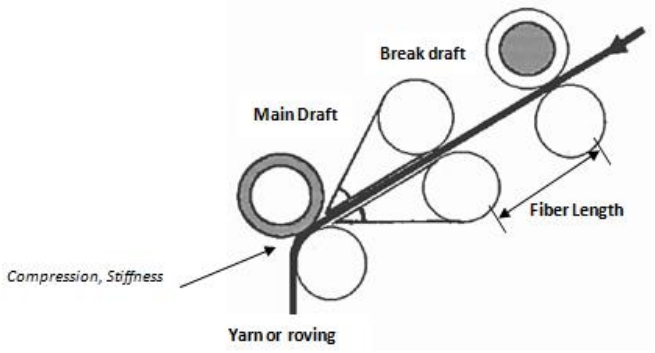

Figure 1: Arrangement of aprons at roving and ring machine [13]

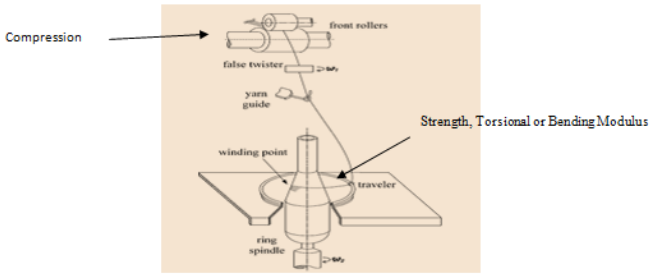

Figure 2: Formation of balloon during ring spinning of cotton. [14]

2. Materials and Methods

2.1 Material

Decorticated hemp fibers (*Cannabis sativa*) were used as virgin hemp fibre material for surface modifications. Prior to surface modifications, decorticated fibers were separated manually to the maximum possible extent, cut to the length of either 30 mm or 40 mm as this length range is used for ring spinning system. Before each treatment, the fibre was conditioned at standard atmospheric conditions at 65% relative humidity and 21°C temperature for 24 hour a procedure described in the American Society for Testing and Materials, ASTM D-1776-04 [15].

2.2 Methods

2.2.1 Chemical/Enzyme Treatments

All chemical and enzyme treatments were conducted using Launder-o-meter (SDL-Atlas) with a machine speed of 40 ± 2 rpm [16]. Four different chemical and two enzyme treatments were carried out which are given in Table 1 with sample identifications.

In the first chemical treatment method, fibres were treated with 1% detergent and then with 3% (W/V) NaOH (Sample ID: C1, Table 1). In the second method, alkaline treatment (5%, W/V) was carried out followed by 5% (V/V) H_2SO_4 (Sample ID: C2; Table 1). In this method, decorticated fiber bundle weighing 0.985 (gm) was placed in a canister and treated with a 300 ml solution of 5% (W/V) sodium hydroxide for 240 minutes at 87°C. The alkali treated fibers were then washed, dried and treated with 300 ml of 5% (V/V)H_2SO_4 at 45°C for 240 minutes. In the third chemical treatment method, H_2SO_4 treatment

(5%, V/V) was carried out followed by 5% (W/V) NaOH (Sample ID: C2). In the fourth chemical treatment method, the fibre was treated with H_2SO_4 and alkali followed by a bleaching treatment using H_2O_2 (Sample ID: C4).

Table 1: Experimental conditions for Chemical and Enzyme Treatments of Hemp Fibers

Modification process	*Process/ Treatment*	*Chemicals and concentration*			*Time (min)*	*Temp. (°C)*	*Sample ID*
Scouring in alkaline medium	Scouring	AATCC Detergent -1%			90	55	C1
	Alkali	NaOH-3%			120	57	
Scouring in alklaine and acid media	Alkaline → Acid	NaOH-5%		H_2SO_4-5%	240	87 & 45	C2
Scouring in acid and alkaline media	Acid → Alkaline	H_2SO_4-5%		NaOH – 5%	240	40 & 92	C3
Scouring and bleaching	Detergent wash	AATCC Detergent -5%			30	42	C4
	Acid	Sulphuric Acid-10%			240	47	
	Alkaline scouring	Na_2CO_3 – 2.3%	Na_2O_3S – 0.6%	$C_{12}H_{25}NaO_4S$- 0.08%	60	90	
	Bleaching (Distilled Water)	H_2O_2- 0.88ml/L	NaOH-0.05 gm/L	Glycerin (Wetting Agent)- 0.2 ml/L	120	90	
Enzyme	Pectinase Aspergillus Aculeatus	1% (pH: 7.66)			240	50	E1
Enzyme	Enzeco Pectinase DV-2	1% (pH: 5.84)			480	50 (+50 steel balls)	E2
Methanol (CH_3OH)	Alcoholic Methanol (CH_3OH)	NaOH – 5% with 50 steel balls			120		M1

After each treatment, to remove remaining chemicals, fibers were washed and neutralized using running tap water for ten minutes by placing the fibres in a Buchner funnel which was placed on top of a beaker. This washing arrangement was necessary in order prevent loss of fibre during washing. The washed fibres were then neutralized and dried by placing in a fume hood for 12 hours. This was necessary to avoid hysteresis effect during conditioning. These dried fibers were then placed in a conditioning environment at standard atmospheric conditions for twenty four (24) hours according to ASTM D 1776-04 [15]. The conditioned fibres were used for weight loss measurement and further analysis.

For enzyme treatment, two different enzymes were used: Pectinase (Aspergillus Aculeatus) and Enzeco Pectinase DV-2. Before enzyme treatments, the decorticated fibers were scoured in a 300 ml solution of 3% (W/V) sodium carbonate at 60°C for 90 minutes in order to remove fats and waxes. Scoured fibers (0.453g) were then treated with 300 ml of 1% (V/V) solution of Pectinase (Aspergillus Aculeatus) (Sample ID: E1, Table 1) at 50°C for four hours in a neutral medium.

For Enzeco Pectinase DV-2 treatment, 0.149 g of scoured fibers was treated with 300ml of 1% (V/V) solution in an acidic environment as suggested by the manufacturer at 50°C for eight hours (Sample ID: E2, Table 1).

2.2.2 Bleaching Optimization Process

Bleaching parameters were optimized to identify the optimum treatment time and temperature for spinning properties, particularly softness of hemp fibre. Pretreatments and bleaching was carried out according to the recipe for sample C4 (Table 1). For the optimum bleaching process three levels of temperature 60°C, 80°C and 95°C and three levels of time 120 min, 180 min and 240 min were considered (Table 2). A full factorial design with four replicates was developed and thirty six (36) experiments were conducted. The experiments were carried out in a random order to increase the validity and reliability of the process.

Table 2: Three levels of time and temperature for bleaching optimization and sample Identification

Temperature (°C)	*Time (min)*	*Sample Identification*	*Temperature (°C)*	*Time (min)*	*Sample Identification*
60	120	G1T1	80	240	G2T3
60	180	G1T2	95	120	G3T1
60	240	G1T3	95	180	G3T2
80	120	G2T1	95	240	G3T3
80	180	G2T1	--	--	--

2.2.3 Weight Loss Measurement

Weight loss was measured by gravimetric method using the following formula:

$$Weight\ loss\ (\%) = \frac{(A-B)}{A}\ x\ 100$$ ---- Equation 1

Where A is the weight of conditioned fibre before treatment, B is the weight of the conditioned fibre after treatment.

2.2.4 Diameter Measurement

Bioquant Life Science System software [17] which is attached with a microscope and camera was used for measuring diameter of hemp fibers. A magnification of 40X was selected and the measurements were taken from twenty (20) different places along the length to minimize any variation in diameter.

2.2.5 Mechanical Properties Measurement

The mechanical properties of fibers were measured by Constant Rate of Extension (CRE) principle using the Instron universal tensile tester (Model: 5965) according to the test method ASTM D1445 / D1445M - 12 [18]. Machine speed was 50mm/min and the load cell of 5N was used while the jaw distance was 15mm. For tenacity measurement diameter data was used to calculate the linear density (tex). Ten (10) fibre specimens were used for each test and the fibre was gripped with the jaws without any aide. Before mechanical properties, fibre samples were condoned according to the ASTM D 1776-04 [15].

2.2.6 Individualization of Fibers

The fiber individualization process was carried out using Planetary Mono Mill (Retsch, Germany). It holds the fibers in a metallic bowl rotating in counterclockwise direction along with balls, offering beating action to fibers. This opening principle of this machine is similar to scutcher action in blow room (opening and cleaning) section of cotton ring spinning process. The details regarding Planetary Mono Mill can be obtained from elsewhere [19].

2.2.7 Evaluation of Softness

A softness standard was developed for subjective evaluation in order to compare the softness and ease of separation of the treated fibers with other commonly used textile fibers such as cotton, wool, flax and olefin as well as with virgin decorticated hemp fibres. The standard fibres were supplied by Tailored Text Custom Publishing (Apex, NC) and AATCC Evaluation Procedure 5-2011 [20] was used as guidelines and the decorticated hemp fibre was obtained from Professor Ying Chen, Biosystem Engineering, University of Manitoba, Winnipeg, Canada. A numeric scale was developed for this purpose with the rank ranging between 1 and 5, where 1 indicates the lowest softness (least easy to separate) and 5 indicates the highest softness (most easy to separate) (Table 3). For this rating, cotton fibre and virgin decorticated hemp fibre are given standard rating of 5 and 1 respectively for both softness and ease of separation. Wool was assessed as 4 while for flax and olefin, the rating was 3 and 2 respectively. All Observers (10) were familiarized with the standard ranking of softness according to AATCC Evaluation Procedure 5 [20]. After being familiarized, observers evaluated the softness by touching the fiber bundles. Each observer assigned a numeric value to each sample based on their touch-feeling about softness and ease of separation. For a specific sample an average of all 10 observations was calculated in order to assign the average final ranking.

Table 3: Standard for softness and ease of separation ranking

Fiber	*Ranking for Softness*	*Ranking for ease of separation*
Cotton	5	5
Wool	4	4
Flax	3	3
Olefin	2	2
Virgin decorticated hemp	1	1

2.2.8 Length Variation

Change in length variation was measured manually using a ruler after chemical and enzyme treatments.

3. Results and Discussion

3.1 Weight Loss (%)

Weight loss (%) represents the amount of non-cellulosic material removed from the fibre. A Change in solution

colour from colorless appearance before treatment to yellow after treatment is indicative of non-cellulosic material removal from the fibers. Weight loss (%) results of chemical and enzyme treated fibers and removal efficiency of non-cellulosic materials are presented in Table 4. The efficiency was calculated using 37% non-cellulosic materials which are given by [1, 21]. From the Table 4 it can be seen that the bleached samples (C4) lost the largest amount of weight (37.4%) while the enzyme treated fibers lost only 13.7% (E1) and 8.3 % (E2) weight.

It seems that chemical treatments removed the maximum amount of non-cellulosic material (C2: 93.8%, C3: 98.6% and C4: 100%) except treatment C1 which removed only 35%, while enzyme treatment removed only 37.00% (E1) and 22.4% (E2) and methanol treated samples (M1) removed 52.7% impurities. Since scouring method C1 and enzyme treatment method E2 (Enzeco Pectinase DV-2) removed the least amount of non-cellulosic materials, therefore materials from these two methods were not used for further analysis. We reported earlier that for enzyme, 50°C is the optimum temperature in order to remove non-cellulosic materials and the removal rate is lower at below and above 50°C [22].

Table 4: Weight loss percentage of treated hemp fibers and removal efficiency of non-cellulosic materials

Sample ID	*Weight loss (%)*	*[a]Removal efficiency (%) of non-cellulosic material*
C1	13.0	35.1
C2	34.7	93.8
C3	36.5	98.6
C4	37.4	100
E1	13.7	37.0
E2	8.3	22.4
M1	19.5	52.7

[a]based on 37% non-cellulosic materials.

3.2 Fiber Strength

Mechanical properties of treated hemp fibers are presented in Table 5. All treatments resulted in loss of breaking load. Breaking load loss (%) was 55.73% and 53.96% for C2 (Alkali → Acid) and C3 (Acid → Alkali) samples respectively. Treatment order of 'Alkali → Acid' or 'Acid → Alkali' has no significant effect on breaking load loss. Bleached samples (C4) lost the largest breaking load (64.9%) among the chemically treated fibres. Enzyme treated fibers produced maximum breaking load loss (%) even with the least amount of weight loss (%). Pectinase Aspergillus Aculeatus enzyme treated fibers (E1) lost 67.6% (weight loss: 13.7%) while the Enzeco Pectinase DV-2 (E2) lost 73.14% of breaking load (weight loss: 8.3%).

The variation in breaking load is very high due to the large variation in fibre diameter. A Similar large variation in hemp fibre diameter was reported elsewhere [22-23]. In order to minimize this variation, we have calculated fibre tenacity for each fibre using the corresponding breaking load and fibre linear density (tex), which was calculated from diameter in the breaking zone. The tenacity and tenacity loss data is given in Table 5. Tenacity loss (%) for chemical treated fibres was 9.14%, 29.00%, 69.7% for C2, C3 and C4 respectively, while for enzyme treated fibres the tenacity loss was 86.1% and 90.37% E1 and E2 samples respectively. Usually, if the chemicals and enzymes do not penetrate inside the fiber then the weight loss (%) is directly proportional with the breaking load (%) and there should not be any tenacity loss (%). From the results of the high tenacity loss (%) to weight loss (%) ratio (E1: 6.3; E2: 10.9), it appears that enzymes ingressed in to the fiber and damaged internal bonds.

For cotton spinning system, the fibers are required to have certain level of tenacity in order to withstand the stresses during drafting, twisting and winding as ring frame rotates at 25,000-30,000 rpm (rotations per minute) [11] and rotor frame rotates at 120,000 rpm [13]. Further, in the ring spinning process, a balloon is formed (Figure 2)at the final stage of spinning just before winding the yarn on a ring bobbin. At this stage, the linear velocity of the yarn is more than the spindle linear speed which creates yarn balloon and because of high speed the yarn balloon faces two types of forces, centrifugal and air drag forces. Due to these forces, the yarn faces severe tension at this point and if the constituting fibers within the yarn structure are not strong enough to withstand these two forces, and then there will be yarn breakage which will cause defects (knot, splice, free end and so forth).

Tenacity of cotton is 0.26-0.44 N/tex, whereas for acetate and acrylic the value is 0.11-0.13 N/tex [24]. All these fibres can be spun using ring spinning system for making high quality fine (≥20Ne) spun yarn. We have found that the tenacity of chemically treated modified fibres was 0.18 N/tex (C2), 0.14 N/tex (C3) and 0.10 (C4) while the tenacity of enzyme treated fibre was 0.03 N/tex (E1), 0.02 N/tex (E2) and for methanol treated fibres, the tenacity was 0.06 N/tex (Table 5). The tenacity results suggest that the enzyme and methanol treated fibres are not suitable for ring spinning process because these fibres cannot withstand the stress during twisting and winding in the ring spinning.

Table 5: Mechanical properties of treated fibres

Sample Id	*Breaking load (N)*	*Breaking load loss (%)*	*Diameter (μm)*	*Tenacity (N/tex)*	*Tenacity loss (%)*
C2	0.78 ± 0.56	55.73	60.49	0.18	9.14
C3	0.81 ± 0.47	53.96	69.70	0.14	29.00
C4	0.55 ± 0.27	64.94	93.50	0.10	69.71
E1	0.57 ± 0.38	67.59	132.08	0.03	86.10
E2	0.47 ± 0.32	73.14	144.73	0.02	90.37
M1	0.62 ± 0.33	64.94	93.50	0.06	69.71

3.3 Length Variation

The length reduction after both chemical and enzyme treatments was not significant as it was found that the reduction was always <3 mm. This indicates that there was no breakage of fibers from the nodes and the fiber did not shrink during treatments. This result contradicts with other published results [9, 25]. One reason could be that

the authors used much longer length (0.9 meter) for treatments than the current study which used 40 mm long fibre, which is much more realistic for the cotton spinning process.

3.4 Softness

A subjective rating was conducted to compare the softness of the treated fibers. For this purpose, the guidelines were taken from the test method AATCC Evaluation Procedure 5-2011 [20]. This method covers the hand properties of fabric, but it was revised to evaluate the fiber softness and ease of separation of individual fibre from bundle of fibres. Three treated samples of hemp, E3 (acid → alkali), E1 (enzyme treated) and C4 (Bleached), and cotton, flax and olefin were ranked by three observers (Observer #1, 2 and 3). Two spinning attributes of these fibers, namely softness (stiffness) and ease of fiber separation were ranked. The scale runs from 5 to 1, where 5 indicates the highest softness while 1 indicates the highest stiffness. Similarly, 5 indicates easy to separate (fibres are not glued to each other) and 1 indicates difficult to separate (fibres are glued to each other). The rating results are shown in Table 6.

Table 6: Comparison of fiber softness and separation

Fiber Sample	*Ranking for Softness*				*Ranking for separation*			
	Observer #			*Avg. rating*	*Observer #*			Avg. rating
	1	2	3		1	2	3	
Cotton	5	5	5	5	5	5	5	5
Wool	4	4	4	4	4	4	4	4
Flax	3	3	3	3	3	3	3	3
Olefin	2	2	2	2	2	2	2	2
Virgin decorticated hemp	1	1	1	1	1	1	1	1
C3	2	2	2	2	2	1	2	1.7
C4	3	3	3	3	3	4	4	3.7
E1	1	1	2	1.3	3	3	3	3.0

It can be seen from the Table 6 that virgin decorticated hemp is the least soft with a ranking of 1, while cotton is the highly soft with a ranking of 5, followed by wool (ranking: 4), flax (ranking: 3). and olefin (ranking: 2), and Among the treated fibers, E1 is the least soft (average ranking 1.33) while C3 is comparatively softer (average ranking 2) and bleached fibers (C4) are the softest with the highest ranking of 3.0.

3.5 Fiber Individualization

For better quality of fabric the constitute yarns should be even throughout the length. More than 75% of yarn irregularities in spun yarns are generated due to fiber bundles made by self-entanglement or cluster with trash [26].Although the treated fibres, particularly of bleached samples (C4) seemed to be individual after treatments, however, multiple fibers within a fiber could be seen under a microscope (Figure 3) and the degree of individualization was much lower than 50% (single fibre * 100/number of fibre in a an apparent single fibre). Attempt was made to make the fibres separate by using the carding machine. However, the fiber bundle was small which created difficulty while processing through the carding machine.

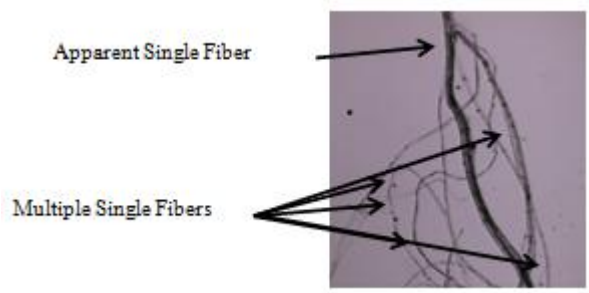

Figure 3: Presence of fibers in bundle form after surface modifications (Sample ID: C4)

In order to understand the ease of separation of individual fibre from an 'apparent single fibre', a subjective method was developed similar to the 'subjective softness measurement' by using AATCC Evaluation Procedure 5-2011 [20] and given in Table 6. In this scale 5 indicates the highest degree of separation while 1 indicates the lowest degree of separation of fibers. It can be noticed from the Table 6 that cotton, wool, flax and olefin fibers have fibre individualization ranking of 5, 4, 3 and 2 respectively while C3, C4 and E1 have ranking of 1.7, 3.7 and 3.0 respectively.

The evenness or imperfections of yarn is expressed in terms of thick places, thin places and neps. If the fibers are in the form of bundles with varying number of fibers in each bundle then the yarn will be imperfect. The current study found that none of the chemical or enzyme treatments produced individual or single entity fibre (Figure 3); however, bleaching treatments produced samples with better softness and individualization.

In a spun yarn, about 150 to 200 fibres are required in the cross-section along the length. If the fibres are in bundle form (more than one fibre and vary) then there will be more or fewer fibre in that specific place of spun yarn resulting in thick and thin places. For apparel applications (woven), for top 5% USTER quality level, a 100% cotton combed ring spun yarn of 20 tex can only have about 10 (+50%) thick places per 1000 meter of yarn [27]. About 10,000 meter yarn is required to make a woven t-shirt. Therefore, a high quality t-shirt can have only 100 (+ve 50%) thick places. Similarly, for the same quality t-shirt the acceptable number of thin places (-ve 50%) are fewer than 10 [27]. Looking at the treated hemp fibres, it can be speculated that the number of thick (+50%) and thin places (-50%) will be much higher than the 5% USTER quality level.

Further, the appearance of imperfections (thick, thin and neps) in woven and knitted fabrics is also determined by their size (+ ve or -ve) as well as the length of the faults. In Classimat yarn faults ('Classimat Faults'), the faults are classified according to length and diameter. For example,

thick places are measured if the mean diameter of a yarn is exceeded by at least +100% in case of short faults (fault length < 8 cm) which are A0, B0, C0 and D0 or by +45% in case of long faults (>8 cm) which are F and G faults [27]. Without single fibre entity in the modified hemp fibre, the ring spun yarn will contain numerous 'long classimat faults' because of the total number of 'draft' [1x(BR)100x(Carding) 6x(DR)10x(SIM) 20x(Ring)] required to make this yarn.

3.6 Optimization of Bleaching Process

Since bleaching (C4) resulted in larger removal (%) of non-cellulosic materials (Table 4), better fiber softness and individualization (Table 6), it was decided to optimize the bleaching parameters (bleaching time and temperature) to achieve maximum removal of non-cellulosic materials and the highest softness.

3.6.1 Weight Loss (%)

For a specific treatment temperature, the weight loss (%) was increased with increasing time. At the first level of treatment temperature (60°C), the average weight loss (%) of four bleached samples for 120 min of treatment time was 19.8 while for 180 min and 240 min the weight loss (%) was 18.8 and 21.8 respectively. For the second level of treatment temperature (80°C), the average weight loss (%) was increased by a factor of 1.1-1.2 from 60°C for all three treatment temperatures. A similar increase in weight loss (%) with a factor of 1.1 to 1.25 was obtained for the third level of treatment which was carried out at 95°C. However, among the three treatment temperatures, the largest weight loss (%) was obtained at 95°C for all treatment times with a factor of 1.1 to 1.25.

Table 7: Weight loss (%) and softness of different bleached samples

Sample ID	Weight loss (%)	Statistical analysis for weight loss data					Softness ranking
		ANOVA			Duncan's Multiple		
		Source	F Value	Pr>F (*p* value)	Source	Group	
G1T1	19.8±1.1	Temp.	6.5	0.005	Temp.	60°C:A 80°C: A	--
G1T2	18.8±1.2	Time	5.06	0.0136	Temp.	80°C: B 95°C: B	--
G1T3	21.8±0.8	Temp*Time	0.77	0.556	Temp.	60°C: C 95°C: D	2.0±0.1
G2T1	21.2±0.3				Time:	120min:A 180min:A 240min:B	--
G2T2	22.1±1.1						--
G2T3	23.1±2.2						2.1±0.1
G3T1	21.8±0.5						--
G3T2	22.8±0.7						--
G3T3	27.0±2.3						2.7±0.25

G1T1: 60°C/120 minute, G1T2: 60°C/180 minute, G1T3:60°C/240 minute.
G2T1: 80°C/120 minute, G2T2: 80°C/180 minute, G3T3:80°C/240 minute.
G3T1: 95°C/120 minute, G3T2: 95°C/180 minute, G3T3:95°C/240 minute.

3.6.2 Statistical Analysis

Variance analysis (ANOVA) showed (Table 7) that the *p*-value for temperature is 0.005 which is less than 0.05 indicating that temperature was a statistically significant variable to affect weight loss (%) of hemp fiber while bleaching. Similarly the *p*-value for treatment time is 0.0136 which is also less than 0.05 specifying the statistically significant effect of time on weight loss during bleaching of hemp fibers. Interaction of time and temperature (temp*time) had a *p*-value of 0.556 which is higher than 0.05 which shows that the interaction of treatment time and temperature did not have a statistically significant effect on the weight loss of bleached hemp fibers.

Duncan's multiple range tests showed (Table 7) that there was a significant difference between the samples treated at 60°C and 95°C (60°C: Group C; 80°C: Group D), however, no statistical significance was found between the 60°C and 80°C (Group A), or 80°C and 95°C (Group B). Similarly, treatment time of 240 minute (Group B) is significantly different than treatment times of 120 minute (Group A) and 180 minute (Group A). No significance was obtained between the treatment time of 120 minute and 180 minute (120 minute: Group A; 180 minute: Group A).

3.6.3 Measurement of Softness

For softness measurement only 240 minute treated sample for all three temperatures were considered. The softness rating is increased with the increasing weight loss (%) (Table 7). It can be observed from the Table 7 that the softness ranking is 2.0 for weight loss (%) of 21.8 at 60°C, 2.1 for weight loss (%) of 23.1 at 80°C and 2.7 for weight loss (%) of 27.0 at 95°C. The largest softness (2.7) which was obtained for 27.0% weight loss at 95°C is close to the softness of flax (softness ranking: 3.0, Table

6) and higher than olefin. In the textile industry cotton/olefin is blended in different proportion to produce spun yarn by using open end spinning system [28]. The softness of bleached fibre at 95°C and 27.0% weight loss is softer than the olefin and considering the softness property, this bleached hemp fibre can be blended with cotton to produce spun yarn using cotton spinning system.

4. Conclusions

Hemp fibers are currently processed through specialized machinery to manufacture low quality yarn to make ropes, cordages and other non-apparel applications. Removal of impurities (weight loss) is one of the important factors to be considered while improving the surface characteristics of the fiber.

Enzyme treated fibres lost more than 90% tenacity and these fibres are not suitable for cotton spinning system. Among the chemically treated fibres, bleaching treatment is the best method as it removed the largest amount of non-cellulosic materials from the fibres. Further, the strength of the bleached fibres, which is the most important spinning property, is suitable for cotton spinning system. Among the other cotton spinning parameters, the staple length and softness property of the bleached fibres are within the tolerance range of cotton spinning system. Although both enzyme and chemical treatment methods in the current study unable to produce single entity fibre, the rating for ease of separation for bleached hemp fibres (Table 6) is higher than flax and olefin. We are concluding that the ease of separation for bleached hemp fibres is suitable for cotton spinning system.

Optimization of bleaching parameters showed that the higher temperature and longer treatment time removed the largest amount of non-cellulosic materials from the fibres and produced the softest fibre. However, we have not measured the breaking twist angle and future work should concentrate on this spinning property.

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