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Effect of post- and pre-crosslinking of cotton fabrics on the efficiency of biofinishing with cellulase enzyme

Ali Hebeish [a], Mohamed Hashem [a,*], Nihal Shaker [b], Mohamed Ramadan [a], Bahiya El-Sadek [b], Marwa Abdel Hady [a]

[a] Textile Division, National Research Centre, Dokki, Cairo, Egypt
[b] Faculty of Science, Al-Azhar University (Girls), Cairo, Egypt

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ABSTRACT

Four different types of cotton-based fabrics, namely, loom-state cotton, cotton/polyester (50/50), cotton/polyester (35/65) and grey mercerized fabrics were bioscoured and bleached. The four substrates are given enzymatic treatment using cellulase enzyme to affect bio-polishing followed by crosslinking using *N*,*N*-dimethylol 4,5-dihydroxyethylene urea (DMDHEU) to affect easy care finishing. In another series of experiments the said bioscoured–bleached substrates were similarly crosslinked followed by bio-polishing. Technical properties of the treated fabric that were monitored include: nitrogen content, loss in fabric weight, tensile strength, elongation at break, tear strength, whiteness index, surface roughness and wrinkle recovery angle. Scanning electron micrograph was also examined. Conclusions arrived at from these studies indicated that: post-crosslinking and pre-crosslinking revealed marginal differences in *N*%, wrinkle recovery angle and whiteness index, a point which validates the argument that cellulase enzyme could not break down the DMDHEU crosslinks within the molecular structure of cotton-containing fabrics. Meanwhile the surface roughness obtained with pre-crosslinking is a bit higher than those of post-crosslinking. Moreover, post-crosslinking caused higher losses in strength properties than pre-crosslinking. Scanning electron micrograph shows that cotton sample pre-crosslinked is almost smooth than those post-crosslinked.

1. Introduction

Enzyme treatments have become one of the most commonly used wet processing techniques in industry (Duran & Marcela, 2000; Tyndall, 1992). Enzyme technology has been applied to improve handle, appearance, and other surface characteristics of cotton and cotton blends (Duran & Marcela, 2000; Tyndall, 1992). One example of such successful applications of enzyme technology is the replacement of traditional stone washing in denim processing by cellulase washing (Klahorst, Kumar, & Mulline, 1994). Hydrolysis of cellulose with cellulase is useful for bio-polishing cotton fabrics, which enhances their aesthetic performance by specific cleavage of glycosidic bonds in cellulose molecules (Walker & Welson, 1991).

Durable press (DP) finishing is a process to impart easy-care properties to cotton fabrics by crosslinking cellulose molecules (Petersen, 1983). *N*-methylol reagents such as *N*,*N*-dimethylol 4,5-dihydroxyethylene urea (DMDHEU) have long been used by textile industry as a durable press (DP) finishes producing wrinkle resistant cotton fabrics (Petersen, 1983). However, crosslinking of cellulosic fabrics reduces its mechanical strength and whiteness index (Kang, Yang, Wei, & Lickfield, 1998; Morris & Harper, 1994). The DP finishing process reduces fiber flexibility, thus having adverse effects on fabric handle. Cellulase treatments have been successful at improving the handle of cotton (Kang et al., 1998; Morris & Harper, 1994).

In our previous work (Hebeish et al., 2009), loom-state cotton and cotton/polyester fabrics were bio-desized using amylase enzyme. The obtained fabrics were bioscoured using alkaline pectinase enzyme and bleached using a method based on *in situ* generation of peracetic acid. To complete processing of these fabrics, the later are exposed in current work to the action of cellulase enzyme under a variety of conditions. This is done to clarify the impact of bio-treatments using cellulase enzyme, when applied to the said fabrics prior and after DMDHEU finishing, on the ease of care characteristics of these fabrics.

Stated in the other words, the present work is an integral part of the work presented elsewhere (Hebeish et al., 2009). While the latter addresses the preparation of cotton-based textiles including biodesizing, bioscouring and environmentally safe bleaching, this

* Corresponding author. Tel.: +20 2 33371635, +20 2 37222268; fax: +20 2 33363261.
E-mail address: mmhashem@ncsu.edu (M. Hashem).

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work focused on the effects of cellulase enzyme on easy-care properties of these textiles. The easy-care properties are conferred on cotton textiles through crosslinking using DMDHEU. We intend to clarify the effects of the biotreatment using cellulase enzyme on fabric performance when the biotreatment was carried out before crosslinking. We also intend to clarify these effects when the bio-treatments is conducted after crosslinking. Furthermore we intend to establish optimal conditions for biotreatment in combination with the preparation treatments thereby setting up a complete biochemical chain for preparation (pretreatment) and finishing of cotton textiles.

2. Experimental

2.1. Materials

Four different types of cotton-based fabrics were used. These comprised loomstate 100% cotton fabric (160 g/m^2), grey mercerized cotton fabric (160 g/m^2), loom-state cotton/polyester (50/50) blended fabric (160 g/m^2) and, loom-state cotton/polyester (35/65) blended fabric (224 g/m^2). For convenience, these four cotton-based fabrics will be referred to as substrate I, substrate II, substrate III and substrate IV, respectively. All substrates (fabrics) were sized using the same sizing recipe. The cotton/polyester blend fabrics were sized using a size base consisting of starch along with PVA. Also all fabrics will be bioscoured followed by bleaching before use. All fabrics were supplied by EL-Nasr Company for Spinning, Weaving and Dyeing, Mehala EL-Kubra, Egypt.

Sodium acetate, acetic acid, magnesium chloride hexahydrate were of laboratory grade chemicals. Egyptol® (nonionic wetting agent based on ethylene oxide condensate) Fixapret® CPN (Finishing agent based on dimethyloldihydroxyethylene urea DMDHEU) were of technical grade chemicals. One commercial grade enzyme, namely, Cellusoft® conc. L (cellulase enzyme with an activity equal 1500 EGU/g) was kindly supplied by Novo-Nordisk A/S, Copenhagen, Denmark.

2.2. Cellulase treatment (bio-polish finishing)

Bleached and bleached then crosslinked cotton fabrics were subjected to biopolished using cellulase enzyme. This biotreatment was conducted in acetate buffer containing Egyptol® (0.5 g/l) at pH 4.8 and material to liquor ratio 1:50 in a mechanical washing machine. Five balls were added for each gram of the fabric tested. The biotreatment was carried out at different concentrations of cellulase enzymes (1–5%), temperatures (40–60 °C) for 45 min. After desirable time the temperature was raised to 100 °C for 10 min to stop the enzyme action. The fabrics were then washed with hot water then washed with cold water and finally dried at ambient conditions.

2.3. Post and pre-crosslinking treatment

Portions of the bio-polishing fabrics along with bleached (control) were padded twice in a finishing formulation containing Fixapret® CPN (crosslinking agent based on DMDHEU) (50 g/l), the catalyst $MgCl_2 \cdot 6H_2O$ (5 g/l), and Egyptol® (2 g/l). The catalyst was added to the formulation immediately before application. The padded fabrics were squeezed to a wet pick-up of 85%, then dried at 85 °C for 3 min and cured at 160 °C for 3 min in a circulating air oven. Bleached and crosslinked cotton fabric was then proceed for bio-polishing.

2.4. Testing and analysis

All fabrics were conditioned in 65% RH and 30 °C for 24 h before testing.

- Weight loss (%) in fabric weight was calculated from the difference in fabric weight before and after the treatment.
- Tensile strength and elongation at break was determined by the strip method according to ASTM D 1682-64.
- Whiteness index was evaluated with a Color-Eye 3100 Spectrophotometer from SDL Inter (Welch & Peters, 1997).
- Surface roughness was monitored according to JIS 94 standard, using surface roughness measuring instrument, SE 1700α made in Japan.
- Nitrogen was determined according to Kjeldhal method (Vogel, 1975).
- Standard method was used to measure wrinkle recovery angles (AATCC test method 66-1984).
- Tear strength was measured according to ASTM D 2261-96.
- SEM was studied using a scanning electron probe micro-analyzer (JXA-840A) Japan. The specimens in the form of fabrics were mounted on the specimen stabs and coated with thin film of gold by the sputtering method. The micrographs were taken at magnification of 1000 using (kV) accelerating voltage.

3. Results and discussion

3.1. Cellulase enzyme concentration

Loomstate 100% cotton fabric (substrate I), grey mercerized (substrate II), loom-state cotton/polyester 50/50 (substrate III) and loom-state cotton/polyester 35/65 (substrate IV) were biochemically processed through biodesizing using amylase enzyme, bioscouring using alkaline pectinase enzyme and bleaching using an environmentally friendly method based on *in situ* formation of peracetic acid. Thus processed substrates were subjected to biopolishing treatment using cellulase enzyme and the onset of this on technical properties of the four substrates were examined. Results obtained are summarized in Table 1.

Table 1
Effect of cellulase concentration on some technical properties of bio-desized, bioscoured and bleached cotton-based fabrics.

Cellulase conc. % (owb)	Weight loss (%)				Whiteness index				Tensile strength (kg f)				Elongation at break (%)				Surface roughness (μm)			
	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d
0	4.8	2.9	2.1	2.1	57.7	52.8	61.5	68.4	64	65	79	125	25	18	30	43	20.1	20.80	19.7	19.9
1	5.4	6.9	4.7	2.0	54.8	48.1	59.7	66.5	60	59	68	118	26	20	30	45	19.3	18.5	19	18.5
3	7.1	8.9	6.6	2.3	50.2	45.0	57.3	63.1	55	52	66	110	28	25	33	48	18.2	16.31	17.5	16.8
5	7.4	9.0	7.0	2.6	50.0	44.8	56.1	63.0	52	50	63	107	29	25	34	49	17.8	16.1	17.2	16.3

Where *a*: desized cotton fabric (substrate I); *b*: desized mercerized cotton fabric (substrate II); *c*: desized cotton/polyester blend 50/50 (substrate III); *d*: desized cotton/polyester blend 35/65 (substrate IV).
Values at 0.0 concentration represent the bleached fabrics without cellulase enzyme treatment.
Conditions used for enzyme bio-polishing treatment: [nonionic wetting agent], 0.5 g/l; temperature, 50 °C; time, 45 min; pH; 4.8; MLR; 1:50.

It is seen from Table 1 that: treatment of the four substrates with cellulase enzyme at 1% concentration cause significant increase in weight loss of the fabrics, particularly with cotton-rich substrates (i.e. substrates I–III). By virtue substrates of its higher polyester content, substrate IV displays no practical change in fabric weight loss. It is understandable that cellulase enzyme does not attack polyester. Alternatively, the cellulase enzyme has no ability to attack polyester under the conditions used. The use of higher concentrations of cellulase enzyme (3% and 5%) brings about greater losses in fabric weight. This is observed irrespective of the substrate used, but with the certainty that substrate IV exhibits the least increase in the loss of fabric weight as compared with the other substrates.

It is also seen from Table 1 that, treatment of the cotton-based fabrics under investigation with cellulase enzyme decreases the whiteness index and this decrease is higher at higher enzyme concentrations. The same holds true for the tensile strength. As is evident, the tensile strength of all substrates decreases significantly after they were exposed to cellulase enzyme treatment particularly at higher concentrations of the enzyme.

Elongation at break of the four substrates in question increases significantly after treatment with cellulase enzyme, and the increase is more pronounced at higher enzyme concentration. On the contrary, surface roughness decreases after the cellulase enzyme treatment and the decrease is more significant at higher enzyme concentrations. It is further observed that differences in surface roughness among the four substrates used are not that striking before and after the bio-polishing treatment.

The above findings could be interpreted in terms of the interaction occurring between the cellulase enzyme and the substrate. Cellulase enzyme penetrates the cuticle of cotton in aqueous solutions through cracks or micro-pores in the cuticle and makes contact with the primary wall. The part of the primary wall at the contact point is hydrolyzed by the catalysis of the cellulase enzyme. After that, both the cellulose of the primary wall and the cellulose of the secondary wall are present for cellulase digestion. The cellulase, however, will catalyze the hydrolysis of the more amorphous primary wall instead of the hydrolysis of the secondary wall because natural crystalline cellulose is very resistant to cellulase digestion (Wlker & Welson, 1991). The result of this reaction is that the outside layer of the fiber is loosened and broken down with the help of mechanical forces. The effect of the extent of the reaction depends on the conditions of the treatment. At any event, however, the increased loss in fabric weight would certainly affect the other properties, namely, tensile strength, elongation at break, whiteness index and surface roughness.

Table 1 contains results of% loss in fabric weight for cotton-based fabrics. As is evident cellulase is more active for mercerized cotton (substrate II) than for cotton either 100% (substrate I) or cotton/polyester blend (substrates III and IV). This is rather logical since mercerization of cotton lowers the crystallinity of the substrate, and the cellulase catalytic reaction proceeds preferentially in the less crystalline regions of the substrate.

Table 3
Physico-chemical properties of different biotreated and crosslinked cotton-based fabric.

Treatment sequence	Property	Substrate			
		I	II	III	IV
Bioscoured bleached	*N* (%)	0.0	0.0	0.0	0.0
	WRA°	170	185	213	217
	Roughness (μm)	19.9	17.3	19.8	17.0
	Tear strength (kg f)	2.15	2.3	2.0	2.15
	Tensile strength (kg f)	62	63	71	125
	Whiteness index	57.8	52.8	61.8	68.6
Bioscoured bleached bio-polishing	*N* (%)	0.0	0.0	0.0	0.0
	WRA°	170	185	213	217
	Roughness (μm)	18.2	16.3	17.5	16.8
	Tear strength (kg f)	2.15	2.29	2.00	2.13
	Tensile strength (kg f)	52	53	66	97
	Whiteness index	50.2	45.0	57.4	59.6
Bioscoured bleached crosslinked	*N* (%)	0.70	0.66	0.62	0.42
	WRA°	272	252	266	268
	Roughness (μm)	20.4	20.1	21.1	22.7
	Tear strength (kg f)	1.2	1.8	1.62	1.85
	Tensile strength (kg f)	57	58	69	110
	Whiteness index	47.4	45.3	56.3	63.1

Where: Substrate I: desized cotton fabric; Substrate II: desized mercerized cotton fabric; Substrate III: desized cotton/polyester blend 50/50; Substrate IV: desized cotton/polyester blend 35/65.

It is also seen from Table 1 that all the substrates have loss in tensile strength. This was evidently caused by the enzymatic hydrolysis of cellulose chains, in accordance with the literature (Wlker & Welson, 1991).

3.2. Temperature of the bio-polishing treatment

Treatment of cotton-based fabrics, represented by substrates I–IV, with cellulase enzyme was performed under the influence of 40, 50 and 60 °C. The onset of temperature on loss in fabric weight, whiteness index, tensile strength, elongation at break and surface roughness is shown in Table 2. By and large the results disclose that (a) the loss in fabric weight exhibit values which are comparable at 50 and 60 °C but substantially higher than values obtained at 40 °C which, in turn, are higher than values before the bio-polishing treatment, (b) temperatures of bio-polishing treatment, specifically 40 and 50°C, decrease the whiteness index; higher temperature, i.e. 60 °C does not cause further decrease in whiteness index, (c) raising the bio-polishing treatment from 40 to 60 °C has an adverse effect on tensile strength; the latter decreases by increasing the biotreatment temperature, (d) in contrast with tensile strength the elongation at break increases by elevating the bio-polishing temperature within the range studied and (e)

Table 2
Effect of bio-polishing temperature on some technical properties of biochemically prepared cotton-based fabrics.

Temp. (°C)	Weight loss (%)				Whiteness index				Tensile strength (kg.f)				Elongation at break (%)				Surface roughness (μm)			
	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d
30	4.8	2.9	2.1	2.1	57.7	52.8	61.5	68.64	64	65	79	125	25	18	30	43	20.1	20.8	19.7	19.9
40	5.4	6.5	3.9	2.0	55.9	55.9	59.9	67.11	63	60	73	122	25	21	31	45	19.3	18.0	19.0	18.5
50	7.2	8.9	6.6	2.3	50.2	45.0	57.4	63.10	55	52	66	110	28	25	33	48	18.2	16.3	17.5	16.8
60	7.2	8.9	6.8	2.3	50.0	46.0	58.1	63.32	54	50	65	109	29	27	34	48	18.1	16.2	17.5	16.5

Where *a*: desized cotton fabric (substrate I); *b*: desized mercerized cotton fabric (substrate II); *c*: desized cotton/polyester blend 50/50 (substrate III); *d*: desized cotton/polyester blend 35/65 (substrate IV).
Conditions used: [cellulase enzyme], 3%; [nonionic wetting agent], 0.5 g/l; time, 45 min; pH; 4.8; MLR; 1:50.

Table 4
Effect of post and pre bio-polishing treatment on physico-chemical properties of crosslinked cotton-based fabrics.

Treatment sequence	Property	Substrate			
		I	II	III	IV
Bioscoured bleached biopolished crosslinked	*N* (%)	0.67	0.65	0.59	0.39
	WRA°	256	257	268	275
	Roughness (μm)	17.2	15.8	18.1	16.1
	Tear strength (kg f)	1.1	1.25	1.5	1.7
	Tensile strength (kg f)	48	40	62	94
	Whiteness index	48	43.4	55.8	57.5
Bioscoured bleached crosslinked biopolished	*N* (%)	0.7	0.64	0.61	0.40
	WRA°	269	250	265	268
	Roughness (μm)	19.6	16.5	18.8	16.7
	Tear strength (kg f)	1.15	1.8	1.61	1.84
	Tensile strength (kg f)	55	54	65	99
	Whiteness index	47	44	53	59

Where: Substrate I: desized cotton fabric; Substrate II: desized mercerized cotton fabric; Substrate III: desized cotton/polyester blend 50/50; Substrate IV: desized cotton/polyester blend 35/65.

the positive effect of temperature on surface roughness is clear particularly when bio-polish is performed at 50 and 60 °C.

The differences in the aforementioned technical properties before and after bio-polishing at different temperature are manifestation of the composition of the substrate and the dependence of the interactions of the cellulase enzyme with the cotton textiles. This was also encountered when results of the effect of cellulose enzyme concentration on these technical properties were discussed. Enzymatic hydrolysis of cotton alone and in blending with polyester could be looked upon in this respect.

3.3. Crosslinking of the biopolished cotton-based fabrics (post-crosslinking)

In order to clarify the effect of bio-polishing of cotton and cotton blend fabrics (substrates I–IV), the four substrates were treated with cellulase enzyme to induce the bio-polishing effect. Following this, the biopolished substrates were subjected to crosslinking to impart the ease of care characteristics. Thus treated substrates were monitored for major technical properties and the results obtained are summarized in Tables 3 and 4.

The results (Tables 3 and 4) obtained with the four substrates shows that bio-polishing treatment leaves the values of *N*% and wrinkle recovery angles (WRA) practically unchanged. The same holds true with respect to roughness and tear strength, though improved roughness could be observed after bio-polishing. Different situation is encountered with tensile strength and whiteness index; the two properties decrease substantially after the bio-polishing treatment irrespective of the substrate used. While the decreases in tensile strength could be associated with the enzymatic hydrolysis of the cotton chain molecules by cellulase enzyme, those of whiteness index could be ascribed to presence of residual cellulase enzyme on the substrates after the bio-polishing treatment. It is rather likely that the cellulase enzyme effects (through biohydrolysis) thinning down of the substrate surfaces and, in so doing, expose different surfaces with less light reflection.

Crosslinking of the four substrates in question brings about easy care finished substrates which acquire higher values of *N*% and WRA. This is against decrements in tear strength, tensile strength and whiteness index (Tables 3). On the other hand, roughness remains almost intact.

Enhancement of *N*% values is a direct consequence of reaction of DMDHEU with cotton-containing substrates through crosslinking and, indeed, the latter is responsible for the significant increase in WRA. The decrease in strength properties is also due to factors associated with crosslinking leading to fabric rigidity. In combination with this is the molecular degradation of cotton under the influence of the crosslinking catalyst and heat. The catalyst and heat in addition to crosslinking via reactions of DMDHEU with cotton-containing fabrics may also alter the light reflection ability of the fabrics thereby decreasing the whiteness index.

3.4. Bio-polishing of crosslinked cotton-based fabrics (pre-crosslinking)

Tables 3 and 4 show results of technical properties of bioscoured–bleached fabrics, bioscoured–bleached–crosslinked fabrics and, bioscoured–bleached–crosslinked fabrics after being biopolished. Results refer to certain improvement in WRA as a result of crosslinking of bioscoured–bleached fabrics. The reverse is the case with roughness, strength properties and whiteness index. This is rather in accordance with previous reports (Yang & Zhou, 2003) which ascribed the decrease in the said properties to rigidity conferred on the fabric due to crosslinking, as well as to molecular degradation of cotton-containing fabrics under the influence of catalyst and heat (Yang & Zhou, 2003). It is generally agreed that WRA stands as an inverse function to strength properties. Our results are in conformation with this. On the other hand alteration of the surface of fabrics due to crosslinking may be responsible for the decrease in whiteness index. Increments in nitrogen are unequivocally owing to the crosslinking reaction occurring between DMDHEU and cotton hydroxyls.

A comparison between the technical properties of bioscoured–bleached–crosslinked cotton before and after bio-polishing using cellulase enzyme would reveal the following:

- Bio-polishing has very marginal effect on the nitrogen percent and so does with strength properties and whiteness index.
- Bio-polishing has a strong tendency to improve surface roughness of the fabrics in question.

3.5. Comparison between bio-polishing before and after easy care finishing with DMDHEU

Figs. 1–6 show a comparison of the technical properties of cotton and cotton/polyester blend fabrics that have been subjected to bio-polishing before crosslinking and those biopolished after being crosslinking.

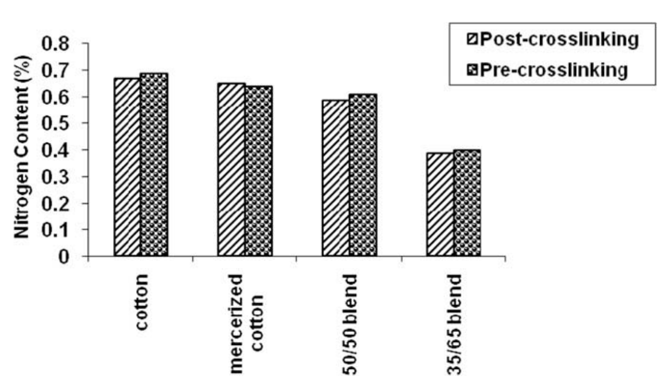

Fig. 1. Nitrogen content of pre-crosslinked and post-crosslinked of biopolished cotton fabrics.

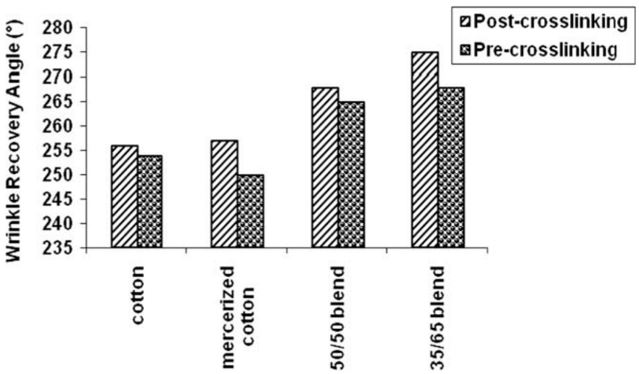

Fig. 2. Dry wrinkle recovery angle of pre-crosslinked and post-crosslinked biopolished cotton fabrics.

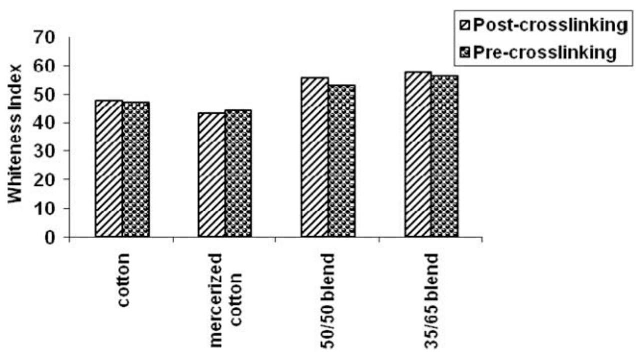

Fig. 3. Whiteness index of pre-crosslinked and post-crosslinked biopolished cotton fabrics.

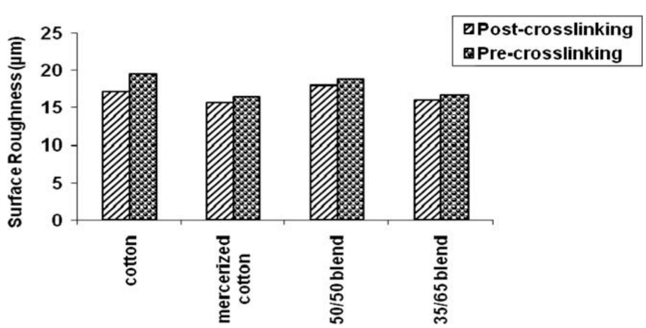

Fig. 4. Surface roughness of pre-crosslinked and post-crosslinked biopolished cotton fabrics.

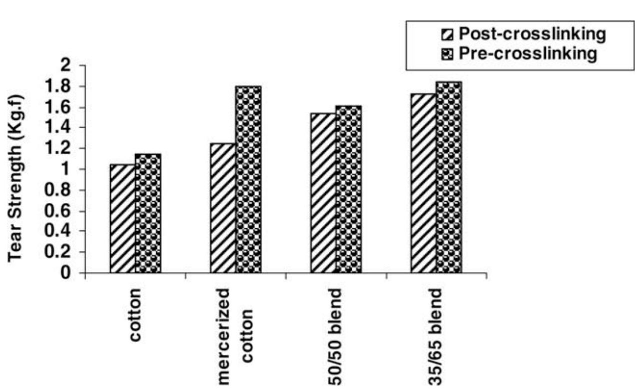

Fig. 5. Tear strength of pre-crosslinked and post-crosslinked biopolished cotton fabrics.

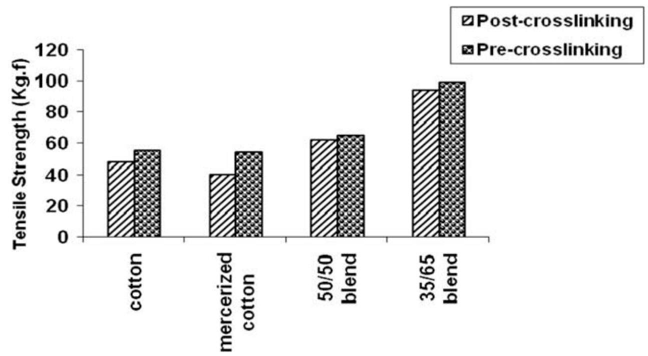

Fig. 6. Tensile strength of pre-crosslinked and post-crosslinked biopolished cotton fabrics.

The comparison indicates that there are marginal differences in nitrogen content, wrinkle recovery angle and whiteness index values between biopolished–crosslinked substrates and crosslinked biopolished substrates.

The marginal differences observed among the aforementioned technical properties suggest that the attack of cellulase enzyme on the bioscoured–bleached fabrics is almost the same as the attack of the same enzyme on bioscoured–bleached–crosslinked fabrics when such attack is based on measured properties, namely, *N*%, WRA and whiteness index. The insignificant differences in the values of *N*% and WRA for fabrics processed as pre-crosslinking and those of the post-crosslinking may be taken to validate the argument that cellulase enzyme could not break down the DMDHEU crosslinks within the molecular structure of cotton-containing fabrics.

Figs. 5 and 6 show that bio-polishing of the fabrics under investigation by cellulase enzyme prior to crosslinking (post-crosslinking) causes higher losses in tear strength and tensile strength than when bio-polishing was done on crosslinked fabrics. For pre-crosslinking treatment, all substrates are crosslinked by DMDHEU before cellulase treatment. It is understandable that, crosslinking increases the rigidity of cellulose molecules in the fibers' amorphous regions and reduces the mobility of cellulose chains during hydrolysis, therefore reducing the effectiveness of the cellulase-catalyzed hydrolysis, since enzymatic catalysis is stero-specific. Crosslinking of cellulose also reduces the swellability of the cotton fibers, which may also reduce the effectiveness of the cellulase (Eriksson & Paulo, 1998). Consequently, both loss in tear strength and tensile strength for pre-crosslinked finished and biopolished fabrics are minimal.

3.6. Scanning electron micrograph

Scanning electron microscopy was done on the untreated sample (desized cotton), bioscoured and bleached sample, biopolished sample, crosslinked before biopolished sample (pre-crosslinking) and crosslinked after biopolished sample (post-crosslinking). The bio-polishing treatment is effected by cellulase enzyme treatment. Fig. 7 shows scanning electron micrograph of desized cotton (untreated sample), the figure shows parallel ridges which are characteristic of cotton fiber.

Examination of bioscoured and bleached cotton (Fig. 8) shows typical fibers with twisted, wrinkled surfaces that are produced when fibers from the boll dehydrate upon boll opening. Occasional breaks, tears, and abrasions were due to ginning and processing.

Fig. 9 shows scanning electron micrograph of bioscoured–bleached and biopolished fabric, the figure reveals smoothened faces. As mentioned previously, (Li & Hardin, 1998; Betrabet, Paralikar, & Patil, 1980) the enzyme attacks the cellulose of cotton progressively, the primary wall being the first target. The enzyme

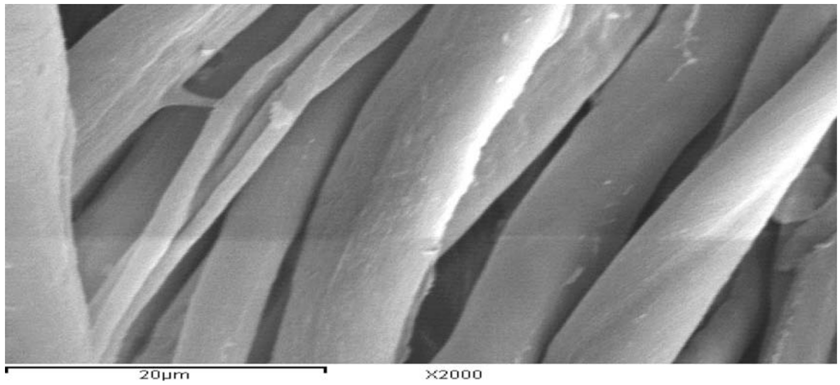

Fig. 7. Scanning electron micrograph of desized cotton fabric (Blank).

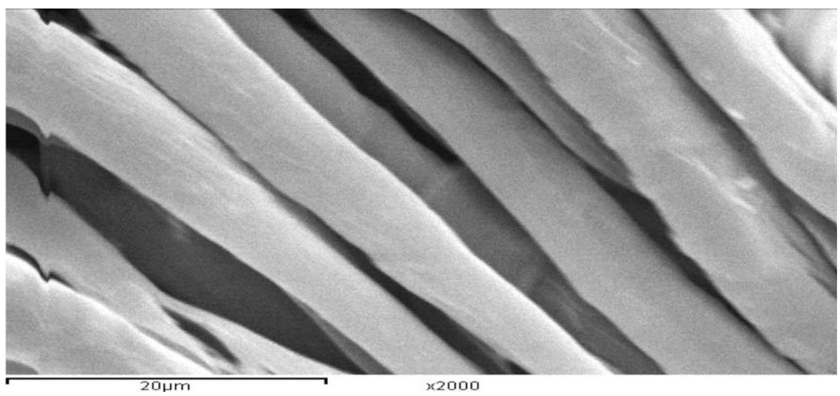

Fig. 8. Scanning electron micrograph of cotton fabric after bioscoured and bleached.

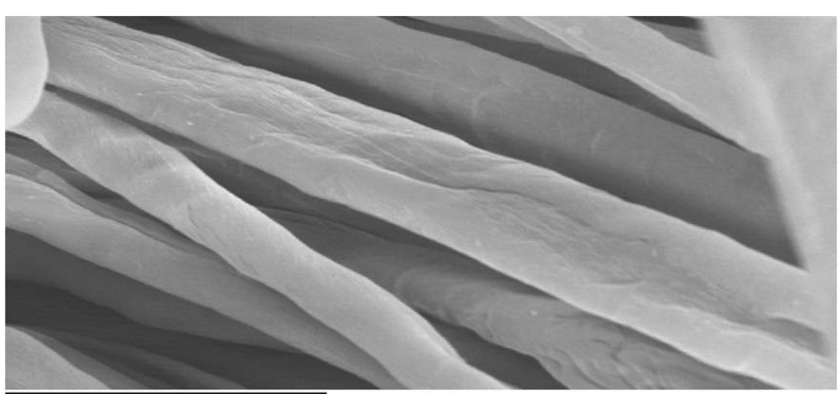

Fig. 9. Scanning electron micrograph of cotton fabric after cellulase treatment.

peels off the cellulose which results in the formation of protruding fibrils and formation of more polished faces. The ridges that were present in the untreated fiber sample are not seen in the case of the cellulase- treated fiber.

Fig. 10 shows the effect of crosslinking on bioscoured and bleached cotton fibers. As observed from the figure there are more cracks on the surface of fibers. This could be a direct consequence of the extent of crosslinking.

On the other hand Figs. 11 and 12 show the effect of pre-crosslinking and post-crosslinking cellulase biopolished fiber, respectively. It is observed from Fig. 11 that, all the fibers are almost smooth than the fibers in Fig. 12. The smoothness in pre-crosslinking of cellulase biopolished fibers is mainly due to the enzymatic removal of surface fibers. This could not be achieved with post-crosslinking because the latter seems to confer high resistance on the fibers surfaces to enzymatic attack.

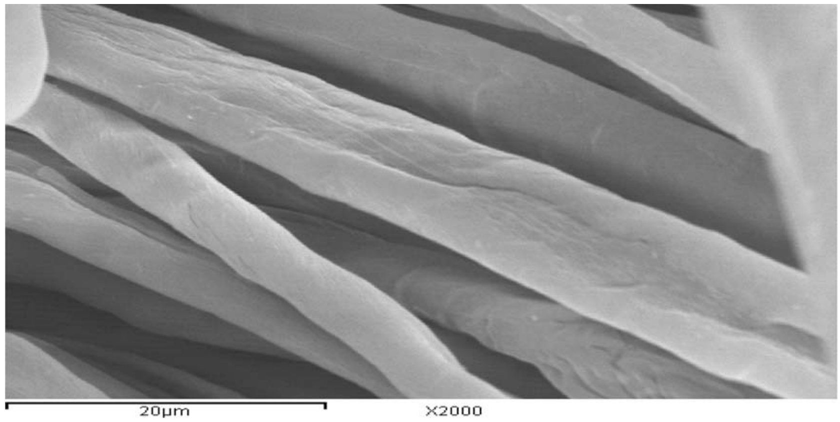

Fig. 10. Crosslinked cotton fibers.

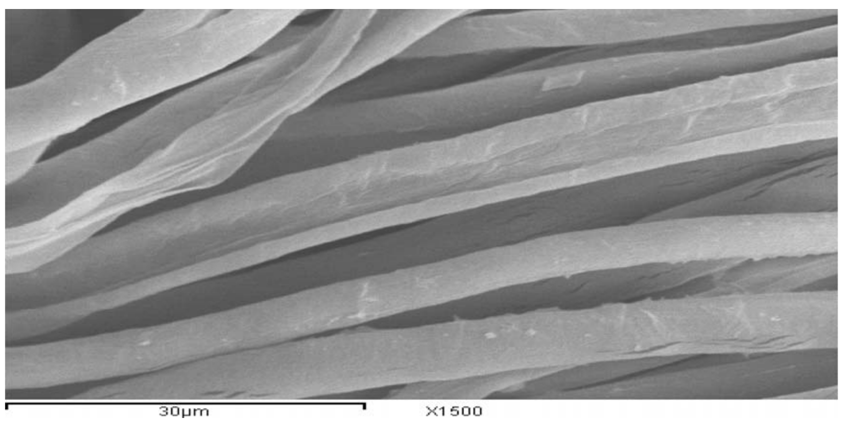

Fig. 11. Pre-crosslinking of biopolished cotton fibers.

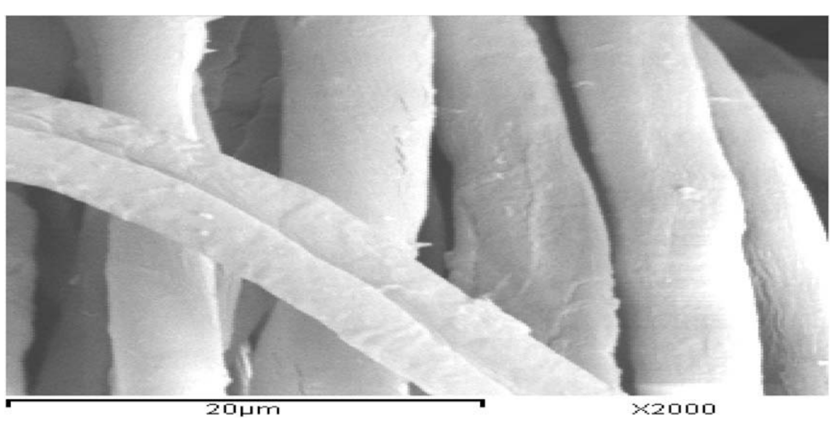

Fig. 12. Post-crosslinking of biopolished cotton fibers.

4. Conclusion

The effect of bio-polishing of the four substrates under investigation could be realized by comparing the technical properties, namely, nitrogen content, tensile strength, tear strength, whiteness index, surface roughness and wrinkle recovery angle before and after bio-polishing. Fabric bio-polishing treatment had practically no effect on wrinkle recovery angle (WRA). The same holds true with respect to surface roughness and tear strength though, the former disclosed marginal improvement. On the other hand, the strength properties and whiteness index decrease after bio-polishing treatment. Crosslinking of the four biopolished substrates caused enhancement in *N*% and WRA. Meanwhile, tear strength, tensile strength and whiteness index are decreased. The surface roughness obtained with pre-crosslinking is a bit higher than those of post-crosslinking. Moreover, post-crosslinking caused higher losses in strength properties than pre-crosslinking. Examination of the bioscoured–bleached–crosslinked fibers shows more cracks on the surface of fibers but it shows typical fiberss with twisted, wrinkled surfaces for the bioscoured–bleached fibers. It is further noted that pre-crosslinked cotton sample are almost smoother than the post-crosslinked cotton sample.

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