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Effect of Softeners and Crosslinking Conditions on the Performance of Easy-care Cotton Fabrics with Different Weave Constructions

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Abstract: This study reports an experimental investigation on the effect of softeners, crosslinking conditions, and laundering on the comfort related and low stress mechanical properties of cotton fabrics with different weave constructions. Softeners with different chemical natures, in conjunction with the crosslinking agent and catalyst, were padded onto the cotton fabrics of three types of weave constructions, viz. plain, twill, and a newly developed plant-structured weave design. Two crosslinking conditions, namely dry and moist curing conditions, were compared. Scanning electron microscope (SEM) and Fourier transform infrared (FTIR) spectroscope were used to visualize and quantify the morphological and chemical changes on fabrics. The experimental results showed that the dry-crosslinking condition is preferable to achieve better comfort and easy-care properties, while moist-crosslinking condition is a better choice when strength-related properties are the main requirement. The study further showed that silicone elastomer softener can be applied to improve fabric strength whereas micro-emulsion of functional amino-polysiloxane plus emulsion containing polyalkylene is beneficial for comfort characteristic. The plant-structured cotton fabric finished in the dry-crosslinking condition with softener in nano-emulsion form can result in superb water absorption, excellent air permeability, good handle, acceptable strength, and improved easy-care property.

Keywords: Easy-care, Cotton, Softener, Crosslinking method, Plant-structured fabric

Introduction

Cotton has numerous end-use advantages. It is comfortable, dyeable, and launderable, so it has been widely used in apparel articles. Cotton fabric with plant-structured design could even boost its attractiveness - superb water absorption property, excellent air permeability, soft handle, and high tear strength [1-3]. However, same as the conventional fabric structure, it is prone to wrinkle and is dimensionally unstable. Hence, easy-care treatment was studied on different cotton fabrics including recently developed plant-structured fabric [2,3]. Researchers have attempted to improve the easy-care property of cotton fabrics by optimizing i) the types of crosslinking agent [4-7], ii) the crosslinking conditions [8-12], iii) the distribution and location of the crosslinks [13-15], iv) the types of additives in the resin treatment bath such as catalyst and softeners [16-18], and v) the fabric constructions [19,20].

Despite much research work carried out on easy-care cotton fabric, majority of the studies concentrated on the mechanical properties of the treated fabrics [21,22] and the problem of poor water absorbency of the treated fabric is largely neglected and persisted. Lau *et al*. [23] reported the incorporation of a hydrophilic softener with the crosslinking agent to improve water absorbency, however, the improvement was small and not durable to repeated laundering, besides it resulted in a slight deterioration in fabric handle, resilience, and surface smoothness. To improve fabric handle and comfort related properties, modified DMDHEU (Low formaldehyde) was used and combined with various softeners under either Pad-Dry-Cure or Pad-Dry-Moist cure treatment conditions. Comfort-related and mechanical properties were measured before and after laundering. In this work, three types of fabrics, viz. plant-structured, plain, and twill fabric were investigated. One objective of the present study is to investigate how the resultant properties can be optimized by fabric structure, crosslinking condition, and type of softeners.

Experimental

Material

Three types of 100 % cotton woven fabric with similar weight and thickness were used in this study, namely plant-structured, plain, and twill fabrics. The plant-structured fabrics, conceptualized from trees' branching network, were developed on a 16 heald dobby loom whilst the plain and the 2/1 twill fabrics were purchased from the market. The construction details of these three types of fabrics are presented in Table 1.

Table 2 lists the details of crosslinking resins, catalysts, and softeners used in this paper. Among them, the resin for dry-crosslinking (Fixapret F-ECO) and the nano-emulsion (Siligen SIM) were supplied from BASF, $MgCl_2{\cdot}6H_2O$ was from Advanced Technology and Industrial Company Ltd., and the rest were from Huntsman.

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Table 1. Construction details of various fabrics

	Plant		Plain		Twill	
	Warp	Weft	Warp	Weft	Warp	Weft
Yarn count (tex)	9.56	7.29	13.97	13.92	14.38	13.78
Yarn density (per centimeter)	75	68	55	32	48	40
Ratio of warp and weft weight	0.7084		0.5529		0.6910	
Fabric weight (g/m^2)	136.1		135.9		122.1	

Table 2. Details and descriptions of chemicals

	Product name (Abbreviation)	Nature	Expected properties
Resin	Knittex FA Conc (FA)	Modified-DMDHEU, especially for moist-crosslinking (Non-ionic)	- Easy-care - Anti-shrink
	Fixapret F-ECO (ECO)	Modified-DMDHEU	- Easy-care - Very low chlorine retention - Durable finish effect of washing and dry cleaning
Catalyst	Knittex CAT UMP (CAT)	Aqueous solution of inorganic and organic acids, especially for moist-crosslinking	Nil
	$MgCl_2{\cdot}6H_2O$ (MG)	Highly soluble in water	Nil
Softener	Ultratex FH New (FH)	Hydrophilic polysiloxane aqueous solutions (Non-ionic)	- Improve moisture absorbency - Enhance soil release property
	Ultratex FMW (FMW)	Micro-emulsion of functional amino-polysiloxane (Cationic)	- Soft handle with a silky touch - Improve moisture absorbency - Strength improvement - Non-yellowing
	Turpex ACN New (ACN)	Emulsion containing polyalkylene (Non-ionic)	- Improve abrasion resistance and tear strength
	Dicrylan WK New (WK)	Crosslinking silicone elastomer, Emulsion of functional polydimethyl siloxane (Non-ionic)	- Smooth and soft handle - Improve fabric resilience and crease recovery, particularly under humid conditions
	Siligen SIM (SIM)	Nano-emulsion (Non-ionic)	- Soft and smooth handle - Excellent hydrophilicity - Provide antistatic feature - Improve resilience, tear strength, abrasion resistance and shear stability

Sample Preparation

All three types of fabrics underwent the same conventional desizing, scouring, and bleaching process prior to the finishing. These fabrics were treated selectively by some of the commercial products listed in Table 2. Fabric samples were dipped and nipped twice in a laboratory scale padding machine at 3 kg/cm^2 pressure and moving speed of 2 m/min to achieve 70 % wet pickup. Seven recipes shown in Table 3 were used for testing the fabrics. Within the same crosslinking condition, the major difference of various recipes is the use of the softeners. Since the processing condition (i.e. temperature, pH, time) for the moist- and dry-crosslinking is remarkably different, two types of resins and catalysts were used. In recipe M1 and D5, M2 and D6, same softener combinations had been selected with the aim to study their effectiveness on different crosslinking conditions. After padding, fabrics were held under same tension and dried on the tenter frame. For moist-crosslinking, the padded fabrics were dried at 90 ^{o}C for 1 min so that 7±1 % of moisture was remained in the samples. The partially dried samples were then packed in-between low density polyethylene sheets, cured in a relatively low temperature of 32±1 ^{o}C for 24 h, rinsed with deionized water and pressed. As for dry-crosslinking, the freshly padded fabrics were dried at 110 ^{o}C for 2 min. The almost completely dried fabrics were then cured at 150 ^{o}C for 5 min.

After the finishing process, half of the fabric samples were cut for testing and the rest were washed for 5 cycles (followed the normal washing machine condition at 27±3 ^{o}C and tumble dried according to AATCC 135-2004) prior to

Table 3. Formulations for each recipe

Moist-crosslinking				Dry-crosslinking			
Sample. no	Product	Concentration (g/*l*)	pH	Sample. no	Product	Concentration (g/*l*)	pH
M1	FA	200	1.5	D5	ECO	80	5
	CAT	100			MG	18	
	ACN*	20			ACN*	20	
	FH*	20			FH*	20	
M2	FA	200	1.5	D6	ECO	80	5
	CAT	100			MG	18	
	ACN*	20			ACN*	20	
	FMW*	20			FMW*	20	
M3	FA	200	1.5	D7	ECO	80	5
	CAT	100			MG	18	
	ACN*	20			SIM*	20	
	WK*	20					
M4	FA	200	1.5				
	CAT	100					
	WK*	30					

*Softener.

testing. All the samples were pre-conditioned at 20±1 °C and 65±5 % R.H. for 24 h before tests were conducted.

Testing of Fabric Samples

The fabric thickness was measured by Kawabata Evaluation System for Fabric (KES-FB3), whilst the fabric mass was determined according to EN12127:1997. Dry crease recovery angles (*DCRA*) were assessed according to AATCC 66-2008. To measure the absorption property of textiles, drop test was performed by employing 0.02 m*l* of water droplet onto the fabric at 1 cm distance and the time required for the drop of water to lose its specular reflectance was recorded. Tearing strength was determined according to ASTM D1424-09. The air resistance was measured by the KES-F air-resistance tester (KES-F8-AP1). In addition, the low stress mechanical properties of fabrics including bending, shearing, tensile, and resilience properties were measured using KES-F. The bending rigidity (*B*) and shear stiffness (*G*) shows the ability of the fabric to resist bending and shear stress, respectively.

The chemical compositions of the easy-care treated fabrics were examined by FTIR spectrophotometer (Perkin-Elmer Spectrum 100), with the scanning range between 4000 and 650 cm^{-1}. The fabric samples were cut into small pieces and 0.005 g of it was mixed with the 0.2 g potassium bromide (KBr) powder. This method takes the whole fiber into account. In addition to the KBr disc method (FTIR-KBr), FTIR-attenuated total reflectance (FTIR-ATR) spectroscopy was used to characterize the surface chemical properties of the treated-fabrics since this measurement focused to a depth of a few micrometer [24]. By normalizing the absorbance curve of each sample, the amount of chemical present on fabrics and in fibers can be determined. The morphology of the fabrics was investigated by scanning electron microscopy (Hitachi^{TM}, model: TM3000) with the magnification of 1500x.

Statistical Analysis

In this study, the effect of softeners, crosslinking conditions, fabric constructions, and laundering were investigated. In order to determine the effect of these variables and their interactions, General Linear Model (GLM) Univariate Analysis was carried out by SPSS 19.0. The significance level of the statistical analysis conducted in this study was set at 0.05. For the comparisons of different crosslinking conditions, fabric constructions, softeners, and wash effect, paired t-test was conducted to determine the significance of the differences between two sets of samples. Also, independent t-test was used when the number of samples is different between two groups or when two groups of data is independent. In the subsequent discussion, in order to specify which test conducted to generate the p-value, a subscript was added to the p-value, viz. p_A (p-value from ANOVA test), p_p (p-value from paired t-test), and p_i (p-value from independent t-test).

Results and Discussion

In the following first section, recipe M1, M2 is compared against D5, D6. Other potential softeners will be introduced in the following second section and the main purpose is to study the effect of softener under different crosslinking conditions, among various fabric constructions, and concerning

Table 4. GLM univariate analysis for recipe M1, M2, D5 and D6 (Tests of Between-Subjects Effects)

P value	Weight	T_M	Air resistance	DCRA	B	G	WT	RT	Tearing strength	Drop test
Crosslinking	**.000**	**.000**	**.000**	**.000**	**.000**	**.000**	**.000**	**.000**	**.000**	**.000**
Softener	.713	.131	.134	.083	.089	**.000**	**.002**	.213	**.000**	**.000**
Wash	**.000**	.365	**.011**	**.000**	.110	.798	.735	**.000**	**.004**	**.000**
Construction	**.000**	**.000**	**.000**	**.000**	**.000**	**.000**	**.000**	**.000**	**.000**	**.000**
Crosslinking * Softener	.996	.483	.213	**.000**	**.004**	.163	**.042**	.300	.333	**.000**
Crosslinking * Wash	.269	.932	**.009**	**.000**	**.002**	**.001**	**.001**	.084	.308	**.000**
Crosslinking * Construction	**.038**	.126	**.000**	**.000**	**.000**	**.000**	**.034**	**.000**	**.000**	**.000**
Softener * Wash	.586	.797	.612	.265	.044	.002	.585	.703	**.019**	**.000**
Softener * Construction	.280	.096	.771	**.000**	.079	.009	**.000**	.066	**.000**	**.000**
Wash * Construction	.565	.196	.598	**.001**	.430	**.000**	**.000**	.048	**.011**	**.000**
Crosslinking * Softener * Wash	.679	.115	.852	.366	.914	.848	**.022**	.859	**.000**	**.000**
Crosslinking * Softener * Construction	.630	.431	.419	**.000**	.913	.381	**.025**	.715	.202	**.000**
Crosslinking * Wash * Construction	.827	**.029**	.070	**.000**	.471	.645	.085	.772	**.000**	**.000**
Softener * Wash * Construction	.768	.233	.705	**.040**	.074	.010	.312	.142	.614	**.000**
Crosslinking * Softener * Wash * Construction	.880	**.008**	.907	.869	**.016**	.079	.348	.478	**.001**	**.000**

the washing effect.

Comparisons between Moist- and Dry-crosslinking Conditions

The main effect of each variable and their interaction effect are listed in Table 4. It demonstrated that the crosslinking effect is significant in all measured properties ($p_A = 0.000 \leq 0.050$). Fabric weight ($p_p = 0.000 \leq 0.050$) and fabric thickness ($p_p = 0.000 \leq 0.050$) for the moist-crosslinked fabric is significantly higher than the dry-crosslinked one. This may be due to the damp and prolonged curing condition which causes cotton fibers to increase its volume. Its air resistance is also higher ($p_p = 0.000 \leq 0.050$), so it can be interpreted that the porosity or the connectivity of the pores of the fabric is lower. Lower porosity might be because of the replacement of air gap by the chemical as a result higher weight and thickness is associated with significantly poorer absorption property ($p_p = 0.000 \leq 0.050$). Additionally, the coarser fiber of the moist-crosslinked fabric would possibly contribute to higher *WT* and tearing strength ($p_p = 0.000 \leq 0.050$). On the other hand, the dry-crosslinked fabrics are significantly softer ($p_p = 0.000 \leq 0.050$). To interpret the difference between the moist- and dry-crosslinked samples, FTIR and SEM analysis was performed to visualize the chemical and morphological alternation of the treated fabrics.

FTIR Analysis

The FTIR spectrum of control and various modified DMDHEU treated fabrics are illustrated in Figure 1. Figure 1(a)-(b) show FTIR-KBr absorbance spectra. The board peak at 3300 cm^{-1} is ascribed to the stretching vibrations of -OH and H_2O [5,6]. The absorption peaks from 2900 to 2800 cm^{-1} are due to the C-H stretching vibration [5,25]. An additional band, visible at 1711 cm^{-1}, is absent for the control fabric [25], but exists in both moist-crosslinked and dry-crosslinked fabrics. This band is attributed to the stretching vibration of the ester carbonyl bond [5,26] and can be assigned to the finishing (i.e. crosslinking agent as well as the softener). A quantitative comparison of this band is illustrated in Figure 1(b). It shows that the within group difference, either for moist- or dry-crosslinking condition, is comparatively small. However, more surprisingly, the absorbance in 1711 cm^{-1} for the moist-crosslinked fabrics (solid lines) is remarkably higher than the dry-crosslinked fabrics (dotted lines). On the whole, this reflects that more chemical is presented in the moist-crosslinked fabrics.

The FTIR-ATR spectrum of various modified DMDHEU treated fabrics are illustrated in Figure 1(c)-(d). It is manifested that a sharp band existed in the fingerprint region (i.e. 1225-950 cm^{-1}) of the scoured cotton fabric [25]. Except for the fingerprint band, another predominant band is observed at 1700 cm^{-1}, but this is not found in the control fabric. This band may also be ascribed to C=O stretching [27]. As shown in Figure 1(d), the absorbance in 1700 cm^{-1} is not distinguishable between the moist- and the dry-crosslinked fabrics where the within and between group differences overlapped without profound differences. Since FTIR-ATR characterizes predominantly the surface profile, it suggests that the amount of chemicals on fiber surface has no significant difference for different processing conditions and for various recipes.

From Figure 1(b) and 1(d), it can be interpreted that the distribution of crosslinking chemicals varies with different processing conditions. The crosslinking agent in the moist-crosslinked fabrics is not only attached to the fiber surface,

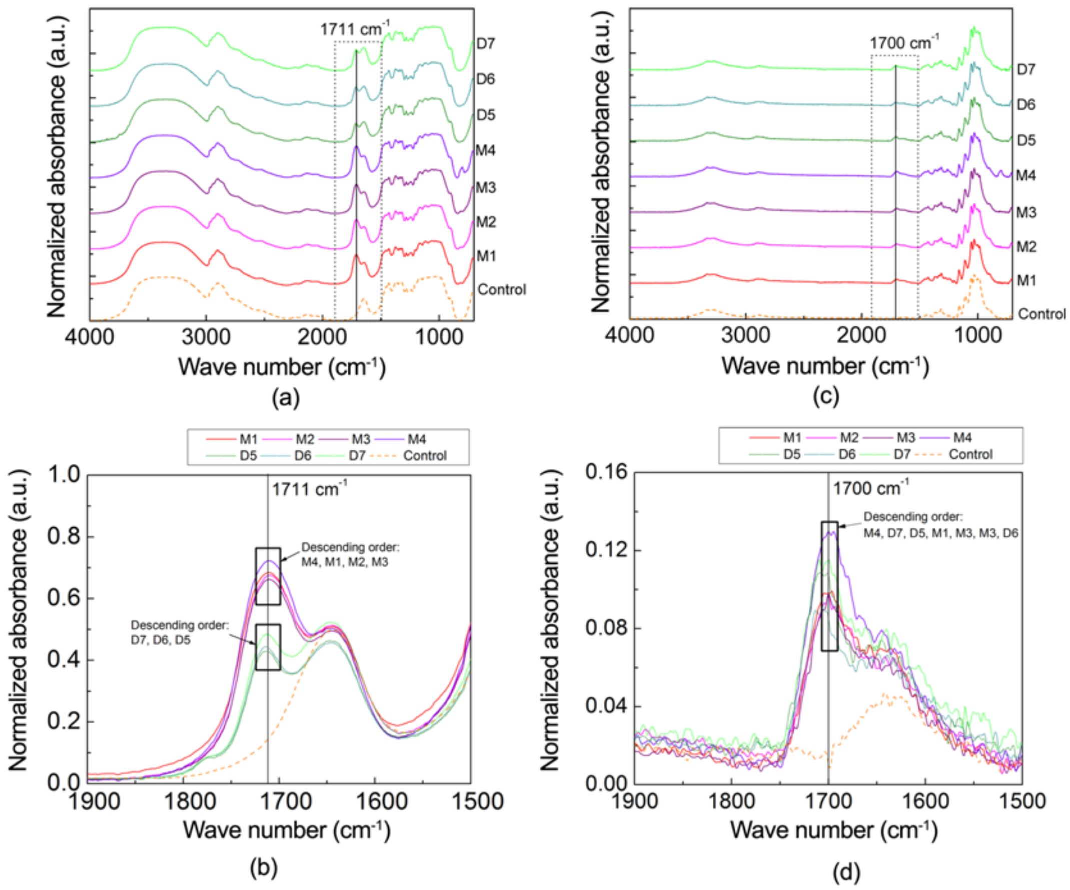

Figure 1. Effect of moist- and dry-crosslinking on cotton fabrics treated by various recipes; (a) and (b) FTIR-KBr absorbance spectra, (c) and (d) FTIR-ATR absorbance spectra.

but has penetrated into the amorphous regions within the fiber. With higher moisture level and longer reaction time, the crosslinking agent could deeply penetrate into the interior of the cellulose fibers. The moist-crosslinked fibers are thereby highly crosslinked. The relatively higher values of tensile energy ($p_p=0.000\leq 0.050$), bending rigidity ($p_p=0.000\leq 0.050$), and shear stiffness ($p_p=0.000\leq 0.050$) and relatively lower value of tensile resilience ($p_p=0.000\leq 0.050$) of moist-crosslinked fabrics may be the results of greater inter-fiber frictional force, which implies stiffer handle and poorer wear comfort.

SEM Images

Apart from the possible changes in chemistry, crosslinking reaction may also alter the morphological form of the fiber and SEM could serve as an effective tool to characterize such changes. The morphologies for the control, moist- and dry-crosslinked fabrics are shown in Figure 2(a), (b), and (c), respectively. The images in 1500x magnification (Figure

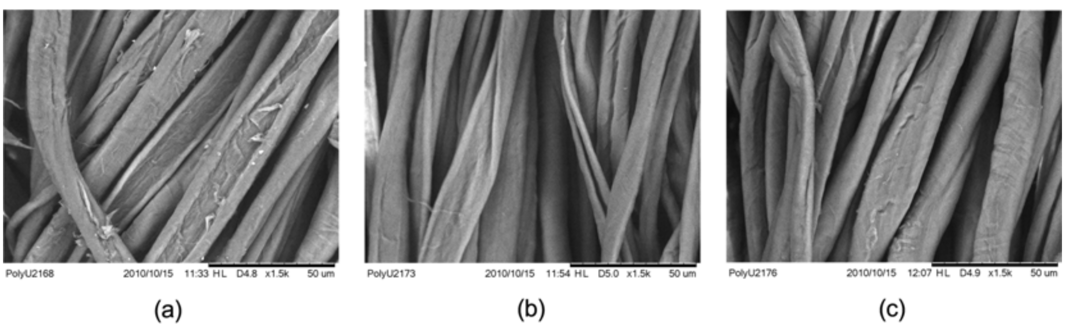

Figure 2. SEM images of various samples (1500×); (a) control fabric, (b) dry-crosslinked fabric, and (c) moist-crosslinked fabric.

2(a), 2(b), 2(c)) show the morphology of the fiber microscopically. The fibers in the control fabric are thinner and rougher with convoluted grooves on the surface whereas fibers in both moist- and dry- crosslinked fabrics have cleaner and smoother appearance. This is partially due to presence of softening agent and the expansion of fibers. Comparing the moist-crosslinked and dry-crosslinked fabric, the moist-crosslinked fibers are coarser with fewer convolutions than those dry crosslinked ones. Coarser moist-crosslinked fibers resulted in greater inter-fiber and inter-yarn friction, thus higher shear stiffness (p_p=0.000≤0.050). As the absorbency of fabric is a function of the absorbency nature of fiber itself and the surrounding void space [28], dry-crosslinked fabric with more irregular fiber cross-section and larger void space between fibers results in better absorption performance (p_p=0.000≤0.050). The reason for having fewer convolutions in the moist-crosslinked fiber can be explained by the principle of drying. It initially starts at fabric surface with pool of water, followed by water on fiber surface and finally is the internal fiber spaces [29]. In the case of the dry-crosslinked fabrics, the drying temperature is so high that the surface as well as the internal fiber space might be dry concurrently, and thus the fibers tend to shrink and convolute. On the other hand, moist crosslinking was carried out at lower temperature for longer duration. The outer part of the fibers dries earlier. Heat then transfers slowly to the inner part by convection, conduction and radiation. Water leaves the fibers slowly; also the surface linkage might hinder the internal fibers to collapse so its fibers are coarser with fewer convolutions.

To evaluate the easy-care performance of a fabric, crease recovery angle and resilience were measured. For the resin-treated fabric, the hydroxyl groups on neighboring fibrils were permanently joined by covalent bond and consequently it has better crease recovery properties relative to the control fabric. Comparing the moist- and dry-crosslinked fabrics, the former have relatively better strength which is consistent with the previous investigation [30,31].

Effect of Softeners

As can be seen from Table 4, the effect of softener is significant in *G*, *WT*, tearing strength, and absorption time by drop test (p_A≤0.050). Among these properties, paired t-test suggests that cationic micro-emulsion of functional amino-polysiloxane (FMW, i.e. Recipe M2, D6) gave significantly higher *G* (p_p=0.000≤0.050), *WT* (p_p=0.011≤0.050), and tearing strength (p_p=0.000≤0.050) than non-ionic polysiloxane aqueous solutions (FH, i.e. Recipe M1, D5), implying that it is soft to touch and is stronger as expected (with reference to the product characteristics listed in Table 2). Besides, the experimental results indicate that fabrics treated with softener FMW give significantly faster water absorption rate (p_p=0.000≤0.050) as illustrated in Figure 3, but no significant effect on fabric weight (p_p=0.576>0.050) and thickness (p_p=0.208>0.050). This is understandable as the softener only accounts for very small percent of fabric weight and thickness.

Effect of Washing

To examine the washability of the finishing, the effect of wash was studied irrespective of crosslinking conditions, softeners, and fabric constructions. Concerning the paired t-test results, significant difference is found in fabric weight, air resistance, *DCRA*, *RT*, and water absorption time by drop test. The reduction in fabric weight (p_p=0.000≤0.050), air resistance (p_p=0.026≤0.050), *DCRA* (p_p=0.000≤0.050), and *RT* (p_p=0.000≤0.050) of the washed samples implies that some crosslinking agents were partially washed out during laundering. This finding is understandable as agitation was involved during laundering and it would weaken the crosslinking bridges. More free sites would be induced to absorb water and so the washed fabrics had better moisture absorbency (p_p=0.000≤0.050). In contrast, bending rigidity (p_p=0.251>0.050), shear stiffness (p_p=0.898>0.050), tensile energy (p_p=0.810>0.050), and fabric thickness (p_p=0.425>0.050) are less likely to be affected by laundering.

Effect of Fabric Constructions

The effect of fabric construction was also assessed. From the p-values of the GLM Univariate Analysis listed in Table 4, we can see that the effect of fabric construction is significant in all the measured properties (p_A≤0.050). Paired t-test results suggested that the treated plant-structured fabrics are significantly superior to the others in terms of the comfort-related properties, including water absorbency (p_p=0.000≤0.050), air permeability (p_p=0.000≤0.050), and *G* (p_p=0.000≤0.050). Possible explanations for achieving these advantages are the difference in surface area in face and back side of the fabric and its branching network [2,3]. Apart from that, the tearing strength of the plant-structured and twill fabrics is significantly higher than that of the plain fabric (p_p=0.000≤0.050), since tearing strength is a function of grouping ability of the yarns in the fabric. Plant-structured fabrics (with combination of 2/2 matt weave and plain weave) as well as twill fabrics allow yarns to group together during tearing and so more than a yarn is broken at a time. However, plant-structured fabrics with finer yarns and higher sett (i.e. shorter float lengths) reduce the path for yarn movement, as a result, its wrinkling performance is poorer (*DCRA*: p_p=0.000≤0.050) and bending rigidity is higher (p_p=0.001≤0.050). On the other hand, plain fabrics with coarser yarns and higher intersection area between yarns can greatly enhance the inter-yarn friction during the application of tensile stress and therefore its WT value is higher (p_p=0.000≤0.050).

Investigating the Effect of Softener under Various Independent Variables

In addition to ACN, FH, and FMW, two other potentially suitable softeners are also investigated. A silicone elastomer (WK) and a nano-emulsion (SIM) were considered for the application. Our preliminary study showed that softener SIM is not suitable for the moist-crosslinking condition since it does not bring any obvious improvement in *DCRA*. Therefore, SIM is only applied to dry-crosslinked fabrics.

Effect of Softener under Different Crosslinking Conditions

The water absorption times of fabrics finished with different recipes are illustrated in Figure 3. Among the moist-crosslinked fabrics, combination of softener ACN and FMW (Recipe 2: p_p=0.000≤0.050) is the best way to achieve high water absorption rate. However, this is not true for fabrics finished in the dry-crosslinked condition. This implies that there is an optimal combination of softener and crosslinking condition. Besides the absorption time for silicone elastomer-treated fabrics (Recipe M3 and M4) is significantly longer. A likely explanation is that polydimethylsiloxane (WK) is mostly non-polar and such surface polymer could perhaps impede the flow of moisture [32].

The tearing strength of fabrics finished with different recipes is shown in Figure 5. Among the moist-crosslinked fabrics, fabrics with only silicone elastomer softener (recipe M4) give significantly highest tearing strength (p_p≤0.050), followed by recipe which incorporated with silicone elastomer and polyalkylene containing softener (Recipe M3). The use of softener WK in Recipe M3 and M4 could promote the formation of an elastomeric layer on fibers. This elastomeric material, acted as a spring "coated" onto the fiber surface, might enable better grouping of fibers and thus improving the tearing strength of the fabric. Under the dry-crosslinking condition, the combination of softener ACN and FMW (Recipe 6) results in the highest tearing strength (p_p≤0.050). On the other hand, fabrics finished with recipes containing hydrophilic polysiloxane aqueous solution (Recipe M1 and D5) have significantly lower tearing strength in both moist- and dry-crosslinking conditions (p_p≤0.050).

Figure 5 shows the shear stiffness (*G*) of fabrics finished with different recipes and it indicates that the fabrics which adopt only silicone elastomer as the softener (Recipe M4) could result in significantly higher *G* (p_p≤0.050). This elastomeric material can create a film-like "coating" which increases the inter-fiber frictional force, so fabric hand for silicone elastomer-treated fabrics is poorer. In both crosslinking methods, combination of softener ACN and FMW (Recipe M2 and D6) tends to give better hand feel. This could attribute to the presence of micro-emulsion (FMW) which is cationic and this finding is consistent with the expected properties of the softener as listed in Table 2.

In light of the dry-crosslinking condition, there is no significant difference among different softeners in terms of *RT*, *G*, and air resistance (p_p>0.050). This underlines the phenomenon that the effect of softener is insignificant in these properties.

Effect of Softener for Fabrics with Different Constructions

From Figure 3, it can be seen that fabrics with nano-emulsion (Recipe D7) results in the shortest absorption time in each fabric constructions; however this is significant in the plain and twill fabrics only. One possible explanation is that the plant-structured fabric has good absorption performance and its absorption time is rather short, so it is not easy to

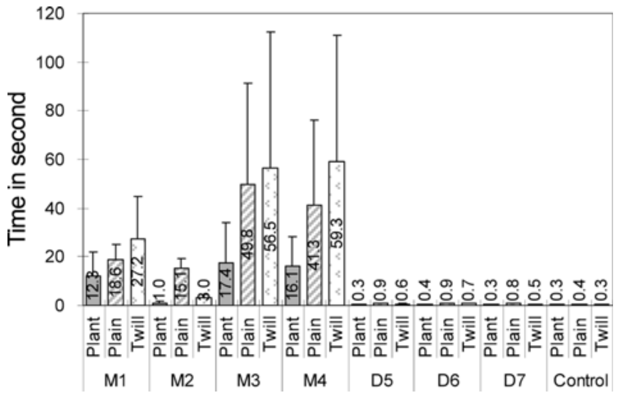

Figure 3. Water absorbency of various recipes under different fabric constructions (Each bar represents mean value of before and after wash samples).

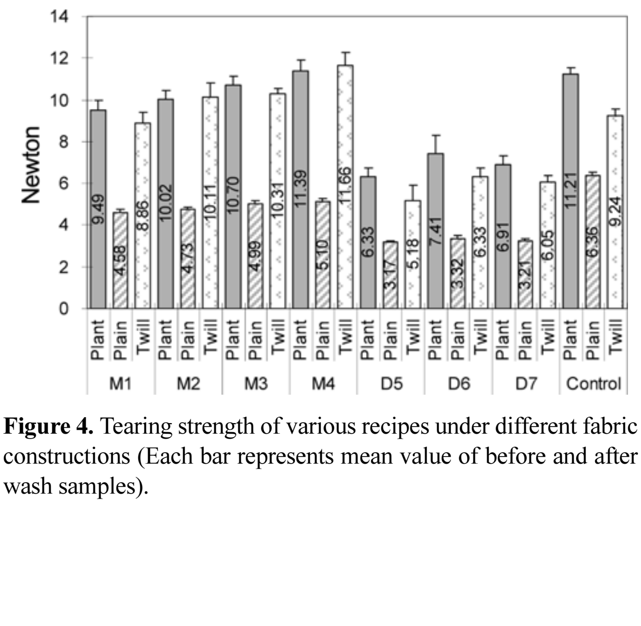

Figure 4. Tearing strength of various recipes under different fabric constructions (Each bar represents mean value of before and after wash samples).

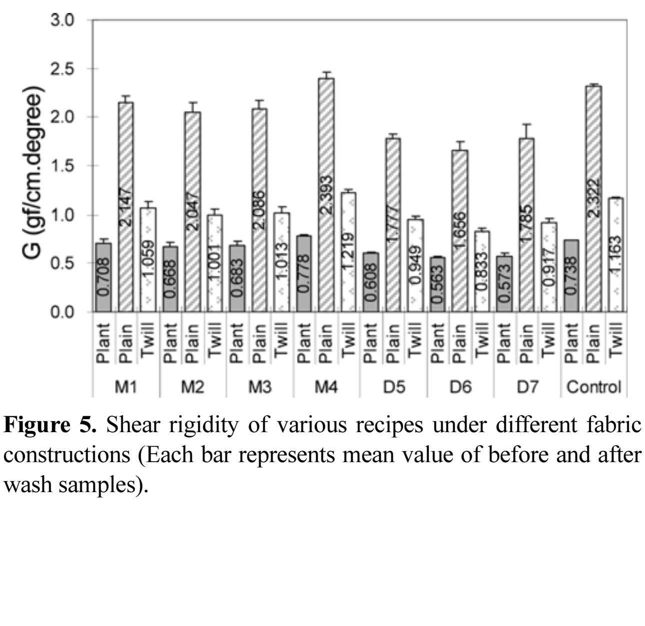

Figure 5. Shear rigidity of various recipes under different fabric constructions (Each bar represents mean value of before and after wash samples).

distinguish which softener is better. In general, the nano-emulsion treatment causes minimal reduction in the fabric porosity. Thus, fabric water absorbency is maintained.

Figure 4 shows the tearing strength of various recipes under different fabric constructions. When silicone elastomer is used (Recipe M3 and M4), it gives better strength among the three fabric constructions. For the twill fabric, the tearing strength of Recipe M4 is even significantly better than recipe M3.

Figure 5 illustrates that the shear stiffness is somehow independent of fabric construction – silicone elastomer alone (Recipe M4) gives the highest *G* in every fabric constructions and paired t-test result has proved its significance (plant-structured: $p_p \leq 0.050$, plain: $p_p \leq 0.050$ and twill: $p_p \leq 0.050$).

Effect of Softener Respective of the Wash Effect

The smaller the difference between the washed and unwashed samples, the more durable the finish is. Softener WK is an emulsion of functional polydimethylsiloxane which attached to the fibers by hydrogen bonds [31]. The bonding between polydimethylsiloxane and cotton fibers, however, will be weakened and replaced by water molecules due to laundering and so the absorption time for the washed samples in recipe 3 and 4 is around 90 % shorter than the unwashed samples as illustrated in Figure 6, implying that silicone elastomer is not as durable to washing as the other softeners.

The *DCRA* of the unwashed and washed samples is shown in Figure 7. For the moist-crosslinked fabrics, there is no significant difference among different recipes in the before washed fabrics. However, the silicone elastomer-treated washed fabrics (Recipe M3 and M4) have remarkably lower *DCRA* than the remaining washed fabrics (Independent t-test: $p_i = 0.000 \leq 0.050$). This agrees with the previous interpretation that silicone elastomer is not as durable to washing as the others. In addition, paired t-test is performed to check with the significance of difference between the washed and unwashed samples in each recipe. The result indicates there is significant difference in most of the recipes except recipe D7 ($p_p = 0.097 > 0.050$). It perhaps suggests that softener SIM is more durable to washing which results in less reduction in *DCRA*.

Figure 8 shows the tensile energy of various recipes before and after laundering. For the ACN-treated moist-crosslinked fabrics (Recipe M1, M2, M3), it appears that the washed samples have lower *WT* than the unwashed one. However, this phenomenon does not exist in the dry-crosslinked condition in which the washed fabrics (Recipe D5, D6) get higher *WT* than the unwashed one. Among all the ACN-treated fabrics (Recipe M1, M2, M3, D5, D6), paired t-test suggests that the effect of washing is only significant in recipe M2 (Washed<Unwashed; $p_p = 0.007 \leq 0.050$) and D6 (Washed>Unwashed; $p_p = 0.033 \leq 0.050$). Actually, these two recipes adopted same mixture of softeners (ACN and FMW) but in different crosslinking condition, implying that it is crosslinking condition dependent.

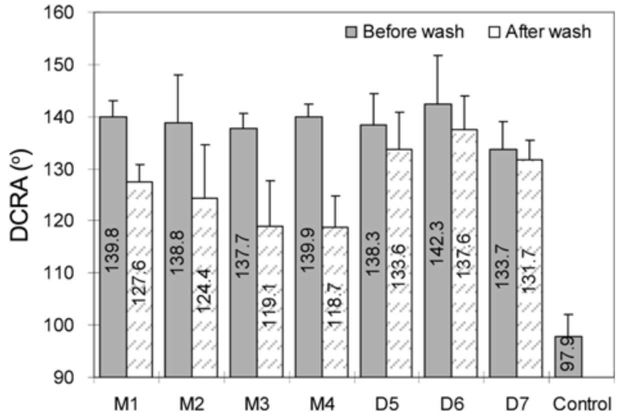

Figure 7. DCRA of various recipes before and after wash (Each bar represents mean value of plant-structured, plain and twill fabrics).

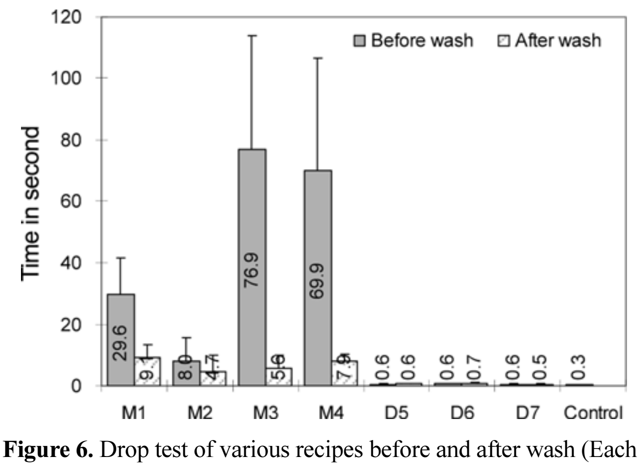

Figure 6. Drop test of various recipes before and after wash (Each bar represents mean value of plant-structured, plain and twill fabrics).

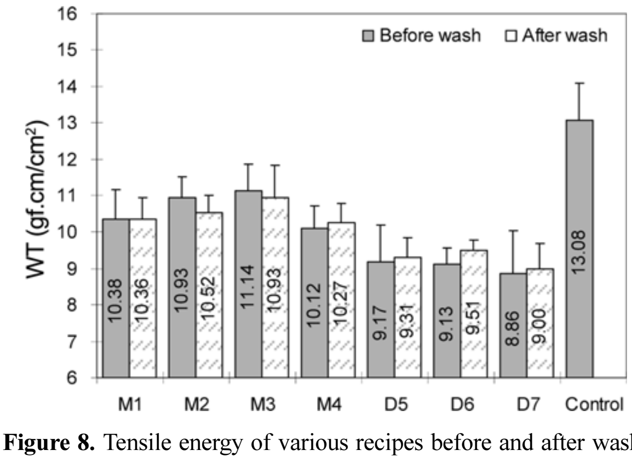

Figure 8. Tensile energy of various recipes before and after wash (Each bar represents mean value of plant-structured, plain and twill fabrics).

Conclusion

This investigation shows that the performance of the fabric is a function of crosslinking condition, softener, fabric construction, and laundering. GLM univariate analysis demonstrated that the crosslinking condition and fabric construction have significant impact on all the measured comfort and handle related properties, air permeability, wrinkle recovery as well as strength. And the effect of softener is significant in shear stiffness, strength, and water absorption rate, whereas effect of wash is significant in air permeability, wrinkle recovery, strength, and water absorption rate. Generally, the moist-crosslinked fabrics tend to have higher tensile energy and stiffer handle than the dry-crosslinked fabrics since its fibers are swollen and crosslinking not only takes place throughout the surface, but also within the inner structure, as substantiated by SEM images as well as FTIR-KBr and FTIR-ATR analysis. Therefore, moist-crosslinked condition is preferred when strength-related properties are more important than fabric handle.

Within the dry-crosslinking system, softener in nano-emulsion form (SIM) gives significantly shorter absorption time in plain and twill fabrics while the combination of cationic micro-emulsion of functional amino-polysiloxane (FMW) and emulsion containing polyalkylene (ACN) is the most preferable recipe in the moist-crosslinking system for the three fabric constructions. In practice, with the aim of maximizing the comfort property of the cotton fabric, silicone elastomer (WK) is not recommended – higher shear stiffness and bending rigidity, poorer absorption associated with lower tensile resilience. As far as fabric strength is concerned, silicone elastomer is the ideal choice since it gives minimal loss of tearing strength when incorporating in the easy-care finish. With regard to the washability of the finished fabrics, silicone elastomer-treated fabrics are less durable to washing whilst nano-emulsion (SIM) is good in this perspective.

Overall, this study demonstrates that the dry-crosslinked plant-structured fabric treated with nano-emulsion could give excellent water absorbency, air permeability and hand feel. Thus, this combination might be a good choice for producing comfortable shirting material for summer wear.

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