

Mechanical Strength of Durable Press Finished Cotton Fabric Part V: Poly(vinyl alcohol) as an Additive to Improve Fabric Abrasion Resistance

Wenlong Zhou,¹ Charles Q. Yang,¹ Gary C. Lickfield²

¹Department of Textiles, Merchandising and Interiors, The University of Georgia, Athens, Georgia 30602

²School of Textiles, Fiber and Polymer Science, Clemson University, Clemson, South Carolina 29634

Received 1 July 2003; accepted 12 October 2003

ABSTRACT: Multifunctional carboxylic acids, such as 1,2,3,4-butanetetracarboxylic acid (BTCA), are effective crosslinking agents for cotton cellulose and have become the most promising nonformaldehyde durable press (DP) finishing agents to replace the traditional formaldehyde-based dimethyloldihydroxyethyleneurea (DMDHEU) and its derivatives. DP finishing imparts wrinkle resistance to cotton fabrics and also severely reduces the strength and abrasion resistance of finished fabrics. In this research, we investigated the use of poly(vinyl alcohol) (PVA) as an additive to improve the abrasion resistance of the cotton fabric crosslinked by BTCA. We found that addition of PVA improves the abrasion resistance of the crosslinked cotton fab-

ric when the concentration of PVA exceeds 0.6% in the finish solution. We also found that the use of PVA as an additive has no negative effect on the wrinkle recovery angle (WRA), DP rating, and tensile strength of the treated cotton fabric. This is probably because the molecules of PVA stay on the surfaces of the cotton fibers due to their large molecular sizes. PVA competes with cellulose to esterify BTCA, thus reducing the number of crosslinkages formed on the cotton fiber surface. The reaction of PVA and BTCA may also form a protective layer on the fiber surface, thus reinforcing the mechanically weak points on the fiber surface. © 2004 Wiley Periodicals, Inc. *J Appl Polym Sci* 91: 3940–3946, 2004

INTRODUCTION

Durable press (DP) finishing is a widely used functional finishing process to produce wrinkle-resistant cotton fabrics and garments.^{1,2} Since the late 1980s, extensive efforts have been made to develop multifunctional carboxylic acids, such as 1,2,3,4-butanetetracarboxylic acid (BTCA), as new formaldehyde-free DP finishing agents to replace the traditional formaldehyde-based DMDHEU and its derivatives.^{1,3–5} Several polycarboxylic acid-based DP finishing systems are currently under commercial development.^{6,7}

A DP finishing agent crosslinks cellulose molecules inside a cotton fiber, thus imparting wrinkle resistance to the cotton fabric at the expense of its tensile strength and abrasion resistance.⁸ Significantly reduced abrasion resistance is the major disadvantage of DP-finished cotton fabrics. It shortens the wear life of the garment and has become the chief obstacle for the application of crosslinking agents to a wider range of cellulosic fabrics and garments.

Previously, we studied the reduction in fabric strength and abrasion resistance of cotton fabric

crosslinked by polycarboxylic acids.^{9,10} We found that the strength loss is caused by acid-catalyzed depolymerization and crosslinking of cellulose molecules.⁹ The loss in abrasion resistance of the cotton fabric crosslinked by a polycarboxylic acid is also attributed to irreversible acid-catalyzed depolymerization and reversible crosslinking of cellulose molecules.¹⁰

Various researchers investigated the abrasion resistance of DP-finished cotton fabrics.^{11,12} Fabric softeners, including aminofunctional silicone polymers and high density polyethylene emulsions, were used to improve the abrasion resistance of DP-finished cotton fabric with limited success. Hydroxyl-functional compounds, such as diethylene glycol and triethanolamine, were investigated as additives to improve the abrasion resistance of the DP-finished cotton fabrics.^{13–16} Those reactive additives are all small molecules and are able to penetrate into the fiber interior and to react with the crosslinking agents inside the fiber. Consequently, the use of those reactive additives reduces the amount of crosslinking inside the cotton fiber, thus having a negative effect on the wrinkle resistance of the crosslinked cotton fabrics.^{15,16}

A DP finishing agent forms covalent crosslinkages between cellulose molecules in cotton fibers to impart wrinkle resistance to cotton fabric. The wrinkle resistance of a crosslinked cotton fiber is determined by the amount of crosslinking across the entire fiber. The abrasion and wear of a crosslinked cotton fiber, on the other hand, is a surface phenomenon. If the crosslink-

Correspondence to: C. Q. Yang (cyang@fcs.uga.edu).

Current address for W. Zhou: College of Materials and Textiles Engineering, Zhejiang Institute of Science and Technology, Hangzhou 310012, China.

TABLE I
The Molecular Weight and Hydrolysis Rate of the PVA Samples Used in This Study

PVA sample description	Viscosity (cps)	Range of weight-average molecular weight	Hydrolysis rate (%)	Abbreviation	Trade name
Higher molecular weight, nearly full-hydrolyzed	62–72	146,000–186,000	98.0–98.8	HMW-NH	Celvol350
Lower molecular weight, nearly full-hydrolyzed	28.0–32.0	85,000–124,000	98.0–98.8	LMW-NH	Celvol321
Lower molecular weight, full-hydrolyzed	28.0–32.0	85,000–124,000	>99.3	LMW-FH	Celvol125

ing on a fiber's surface can be reduced while the crosslinking in the interior of the fiber is maintained, the abrasion resistance of a DP finished cotton fabric can be improved without reducing its wrinkle resistance. In this research, we studied the use of poly(vinyl alcohol) (PVA) as an additive, which stays on fiber surface due to high molecular weight, to improve the abrasion resistance of the treated cotton fabric without diminishing its DP performance.

EXPERIMENTAL

Materials

The cotton fabric was desized, scoured, and bleached print cloth (Testfabrics Style 400). BTCA, sodium hypophosphite (NaH_2PO_2), and sodium hydroxide were reagent grade chemicals supplied by Aldrich (Wisconsin). The PVA samples used in this study were commercial products supplied by Celanese (New Jersey) and are described in Table I.

Fabric treatment procedure

The cotton fabric was first immersed in a finish solution containing 6% BTCA, 4% NaH_2PO_2 , and PVA with a specified concentration and then passed through a laboratory padder with two dips and two nips. All of the concentration was based on the percent weight of bath (w/w, %). The wet pick-up was in the range of 100–110%. The impregnated fabric was first

dried at 90°C for 3 min and then cured at a specified temperature for 2 min.

Evaluation of fabric tensile strength, flex abrasion resistance and conditioned wrinkle recovery angle (WRA)

Tensile strength and flex abrasion resistance of the treated cotton fabric were tested according to ASTM Methods D5035–95 and D3885–92, respectively. For the flex abrasion resistance test, the head/tension weight was 0.5/2 lb., respectively. Six specimens were used for each flex abrasion resistance data point. The conditioned WRA and DP rating of the treated cotton fabric were measured according to AATCC Standard Methods 66–1990 and 124–1992, respectively. The fabric properties were measured after one home laundering cycle unless specified otherwise. AATCC Standard Reference Detergent 1993 was used to conduct the laundering procedure. The water temperature was approximately 46°C.

Thermal gravimetry (TG) measurements

A Mettler TG50 Thermobalance was used for TG measurements. All of the samples were heated from room temperature (25°C) to 190°C at a rate of 10°C/min with a continuous nitrogen flow at a rate of 10 mL/min. The sample weight was approximately 9 mg.

Scanning electron microscopy (SEM) experiments

SEM images were obtained with a LEO 982 field emission scanning electron microscope (LEO Electron Mi-

TABLE II
The Flex Abrasion Resistance of the Cotton Fabric Treated with 6% BTCA, 4% NaH_2PO_2 in Combination with PVA After One and Five Laundering Cycles

PVA	No. of laundering cycles	Concentration of PVA (%)						
		0.00	0.05	0.10	0.20	0.40	0.60	0.90
HMW-NH	1	206 ± 36.4	209 ± 45.9	186 ± 32.8	195 ± 57.9	196 ± 57.5	262 ± 19.6	272 ± 35.2
	5	187 ± 35.1	190 ± 15.1	190 ± 28.8	180 ± 39.6	218 ± 42.2	262 ± 52.7	243 ± 48.8
LMW-NH	1	206 ± 36.4	218 ± 25.4	234 ± 41.0	227 ± 40.5	220 ± 39.3	281 ± 34.3	262 ± 42.4
	5	187 ± 35.1	178 ± 30.0	180 ± 40.8	208 ± 69.6	185 ± 53.4	300 ± 38.4	249 ± 11.4
LMW-FH	1	206 ± 36.4	205 ± 22.5	216 ± 36.9	237 ± 41.0	205 ± 32.9	326 ± 61.8	303 ± 53.2
	5	187 ± 35.1	168 ± 69.0	168 ± 59.0	203 ± 53.7	221 ± 50.7	291 ± 62.3	263 ± 58.6
Control	0				897 ± 117.1			

Values are means ± SD.

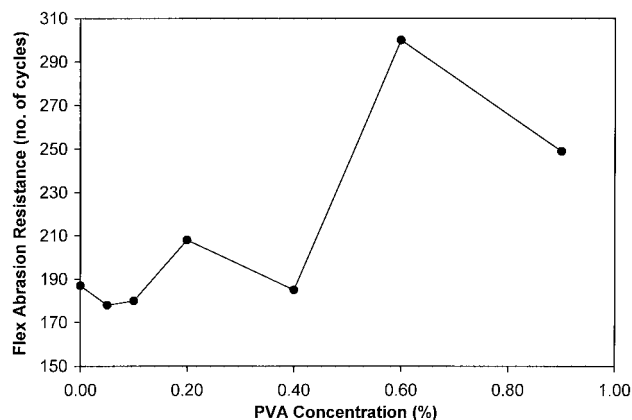


Figure 1 The flex abrasion resistance of the cotton fabric treated with 6% BTCA and 4% NaH_2PO_2 in combination with 0.60% PVA (lower molecular weight, nearly full hydrolysis), cured at 180°C for 2 min, and finally subjected to five laundering cycles.

croscopy, New York). All samples were coated with a 76.5 Å thick gold-palladium layer by an API Module Sputter Coater prior to a SEM experiment.

RESULTS AND DISCUSSION

Three PVA samples with different molecular weight (MW) and hydrolysis rates were used in this study (Table I). One PVA has an MW range of 146,000–186,000 with a hydrolysis rate of 98.0–98.8% (HMW-NH) and the other two PVA samples have the same MW range of 85,000–124,000 and different hydrolysis rates (98.0–98.0% and >99.3%) (LMW-NH and LMW-FH, respectively).

The cotton fabric was first treated with 6% BTCA and 4% NaH_2PO_2 in combination with the three different PVA samples at concentrations ranging from 0.05% to 0.90%, cured at 180°C for 2 min, and finally subjected to one and five home laundering cycles. The flex abrasion resistance and its standard deviation in the filling direction of the cotton fabric thus treated are presented in Table II. The flex abrasion resistance appeared to be statistically unchanged when the PVA concentration was between 0.05 and 0.40% (Table II). As the concentration of all three PVA samples was increased to 0.60% and beyond, however, the flex abrasion resistance was significantly increased. The flex abrasion resistance after one laundering cycle was 206 cycles when no PVA was present in the BTCA/ NaH_2PO_2 solution, and it increased to 262, 281, and 326 cycles when 0.60% PVA (HMW-NH, LMW-NH, and LMW-FH, respectively) was used as the additive in the DP finish (Table II), which represents a 27–65% increase of fabric abrasion resistance.

The BTCA-treated cotton fabric was subjected to an additional four laundering cycles, and we found that the effects of PVA on the flex abrasion resistance of the

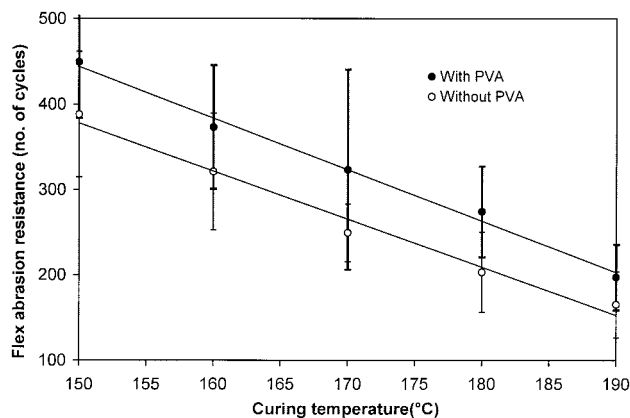


Figure 2 The flex abrasion resistance with SD error bars of the cotton fabric treated with 6% BTCA and 4% NaH_2PO_2 in combination with 0.60% PVA (lower molecular weight, nearly full hydrolysis), cured at different temperatures for 2 min, and finally subjected to one laundering cycle.

BTCA-treated cotton fabric remained after five laundering cycles. After a total of five laundering cycles, the flex abrasion resistance of the treated fabric increased from 187 with no PVA added to 262, 300, and 291 cycles when 0.60% of PVA (HMW-NH, LMW-NH, and LMW-FH, respectively) was added to the BTCA solutions (Table II). The cotton fabric treated with 6% BTCA and 4% NaH_2PO_2 in combination with PVA (LMW-NH) and subjected to five laundering cycles is plotted against the PVA concentration in Figure 1. The data presented here clearly demonstrate that the addition of PVA at a concentration equal or higher than 0.60% notably improves the abrasion resistance of the DP-finished cotton fabric, and the improved fabric abrasion resistance was retained after multiple home laundering cycles. The fact that the superior abrasion resistance of the fabric treated with BTCA/PVA remains after multiple laundering cycles indicates that

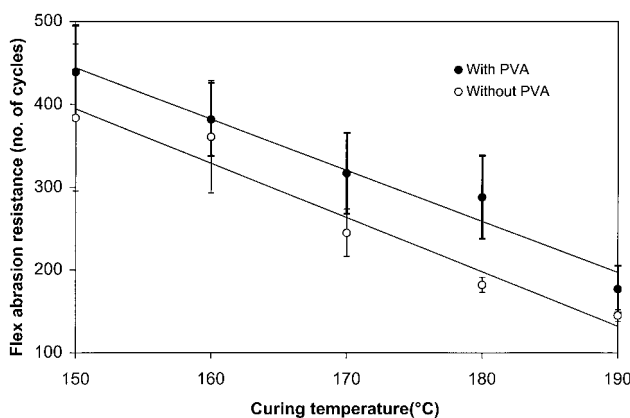


Figure 3 The flex abrasion resistance with SD error bars of the cotton fabric treated with 6% BTCA and 4% NaH_2PO_2 in combination with 0.60% PVA (lower molecular weight, nearly full hydrolysis), cured at different temperatures for 2 min, and finally subjected to five laundering cycles.

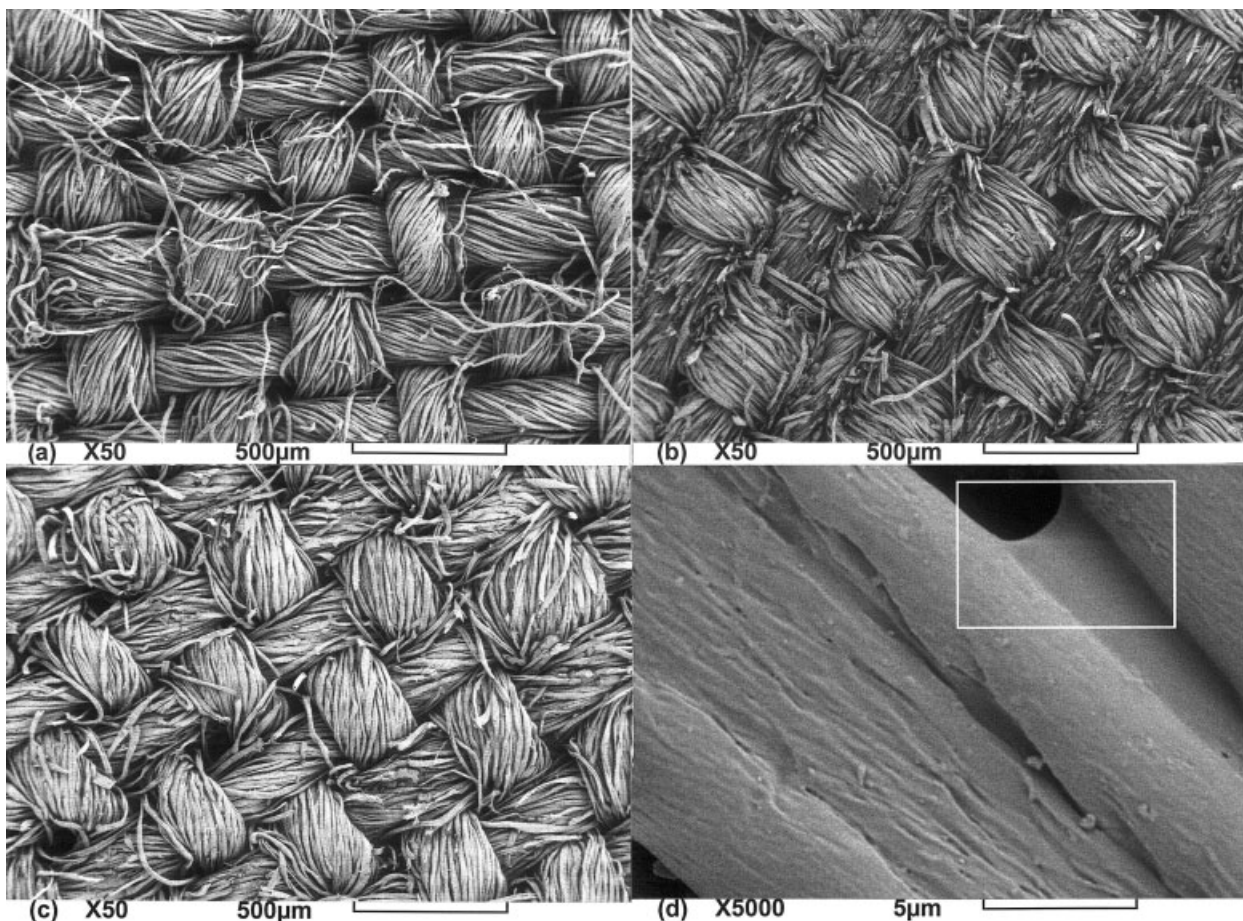


Figure 4 Micrographs of surface of (A) the cotton fabric treated with 6% BTCA and 4% NaH_2PO_2 without the use of PVA, cured at 180°C for 2 min, and finally subjected to one laundering cycle; (B) same as A, after 200 flex abrasion tester cycles; (C) the cotton fabric treated with 6% BTCA, 4% NaH_2PO_2 , and 0.6% PVA (lower molecular weight, nearly full hydrolysis), cured at 180°C for 2 min, and after 200 flex abrasion tester cycles; (D) the cotton fabric treated with 6% BTCA, 4% NaH_2PO_2 , and 0.6% PVA (lower molecular weight, nearly full hydrolysis), cured at 180°C for 2 min, and after one laundering cycle.

PVA must have reacted with BTCA, because any PVA physically absorbed onto the fiber without covalent bonding to the fiber must have been washed off after the five home laundering cycles.

We studied the abrasion resistance of the cotton fabric treated with BTCA and PVA and cured at different temperatures. The cotton fabric was treated with 6% BTCA and 4% NaH_2PO_2 in combination with 0.60% PVA (LMW-NH) and then cured at temperatures ranging from 150 to 190°C for 2 min. The flex abrasion resistance of the BTCA-treated cotton fabric with and without PVA after one and five home laundering cycles was presented against the curing temperature in Figures 2 and 3, respectively. The flex abrasion resistance of fabric decreases as the curing temperature increases, evidently due to the increasing amount of crosslinkages formed in the cotton fibers as a result of the elevated curing temperature. The cotton fabric treated with PVA as the additive showed significantly improved flex abrasion resistance compared with that without PVA after both one and five laundering cycles (Figs. 2 and 3, respectively). When the

fabric was cured at 150°C for 2 min, the flex abrasion resistance of the cotton fabric treated with BTCA without PVA was 388 cycles. It increased to 449 cycles when PVA was added to the BTCA solution, which

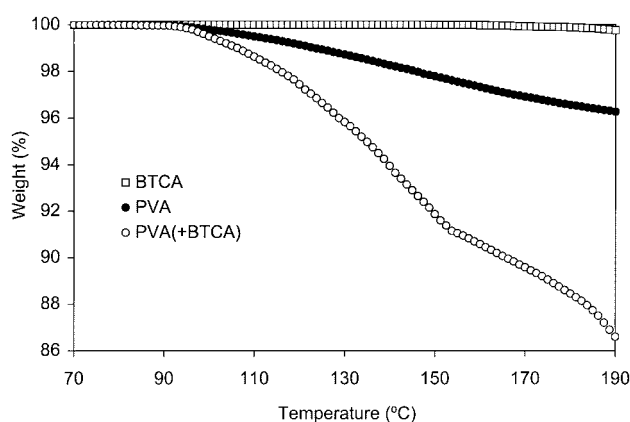
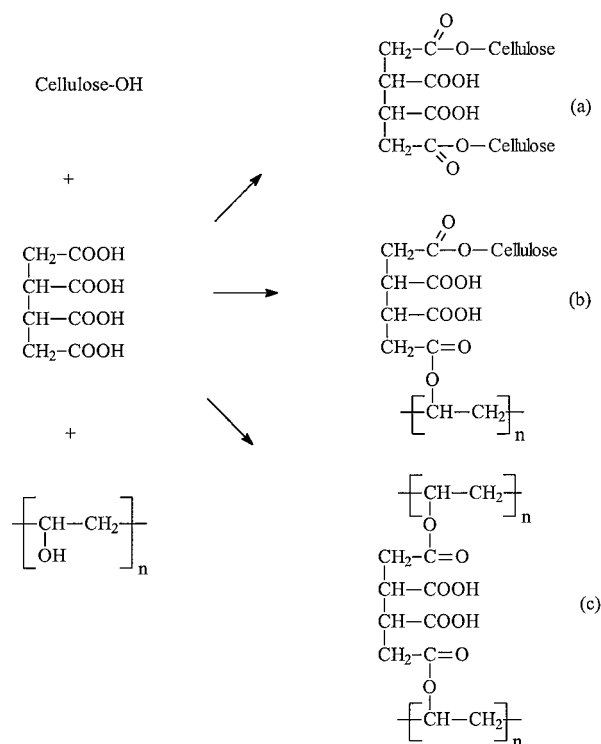


Figure 5 TG curves of BTCA, PVA, and the mixture of BTCA and PVA (4 :1, w/w).



Scheme 1

represents a 24% increase in the flex abrasion resistance (Fig. 2). When the curing temperature was increased to 180°C, the flex abrasion resistance of the fabric was 203 cycles without PVA, and it increased to 274 cycles after PVA was added, which represents a 35% increase (Fig. 2). After five laundering cycles, the flex abrasion resistance of the fabric treated with BTCA/PVA was still significantly higher than that treated with BTCA alone in the entire curing temperature region (Fig. 3), and the magnitude of the improvement in fabric abrasion resistance is similar to that after one laundering cycle (Fig. 2). Thus, the data presented above confirm the effectiveness of PVA in improving the abrasion resistance of the cotton fabric crosslinked by a polycarboxylic acid.

The improved abrasion resistance of the cotton fabric treated with the combination of BTCA and PVA was also investigated by SEM. Presented in Figures 4(A) and (B) are the SEM micrographs of the cotton fabric treated with 6% BTCA and 4% NaH_2PO_2 and cured at 180°C for 2 min before and after 200 cycles of flex abrasion, respectively. One observes the loose fibers on the fabric surface in the micrograph of the fabric before flex abrasion [Fig. 4(A)]. After the flex abrasion, almost all the loose fibers disappeared and severe yarn damage was evident in Figure 4(B). The SEM micrograph of the cotton fabric treated with BTCA in combination with 0.60% PVA (LMW-NH) after 200 cycles of flex abrasion is shown in Figure 4(C). The contrast between the micrograph of the fabric treated without PVA and that with PVA after the same number of flex abrasion cycles, as shown in Figures 4(B) and (C), respectively, is obvious. One observes the wear on the surface of the fabric treated with BTCA/PVA as a result of the flex abrasion [Fig. 4(C)], but the damage to the yarns is far less severe than that treated without PVA [(Fig. 4B)]. Thus, the SEM study provides additional evidence that the use of PVA as an additive significantly improves the abrasion resistance of the cotton fabric crosslinked by BTCA.

Presented in Figure 5 are the TG curves of BTCA, PVA (LMW-NH), and the mixture of BTCA and PVA at a 4 : 1 ratio (w/w). In our previous research, we found that BTCA starts to lose weight through dehydration to form an anhydride only when its temperature reaches its melting point (196°C).¹⁷ BTCA appears to lose little weight under 190°C as shown in Figure 5. PVA starts to lose weight as the temperature reaches approximately 100°C, and it loses 3.7% of its original weight at 190°C (Fig. 5). The weight loss of PVA in the 100–190°C temperature range is probably due to the evaporation of the absorbed moisture and due to possibly dehydration of PVA. The weight loss of the mixture of BTCA/PVA, as shown in Figure 5, is the weight loss based on PVA only, because BTCA by itself does not lose weight below 190°C. PVA by itself loses 3.1% weight at 170°C, and its weight loss increases to 11.4% when PVA is mixed with BTCA. In our previous research, we also found signifi-

TABLE III
The Conditioned WRA of the Cotton Fabric Treated with 6% BTCA and 4% NaH_2PO_2 in Combination with PVA and Cured at 180° for 2 Min

PVA	No. of laundering cycles	Concentration of PVA (%)						
		0.00	0.05	0.10	0.20	0.40	0.60	0.90
HMW-NH	1	293	297	294	294	296	302	298
	5	292	290	295	294	289	290	287
LMW-NH	1	293	288	295	299	295	299	300
	5	292	288	286	290	296	289	285
LMW-FH	1	293	295	296	304	301	302	299
	5	292	290	291	289	292	289	288
Control	—				178			

Values are degrees.

TABLE IV
The Conditioned WRA of the Cotton Fabric Treated with 6% BTCA and 4% NaH₂PO₂ in Combination with 0.6% PVA (LMW-NH) and Cured at Different Temperatures for 2 Min

Curing temperature (°C)	WRA (°, w + f), after 1 laundering cycle		WRA (°, w + f), after 5 laundering cycles	
	Without PVA	With PVA	Without PVA	With PVA
150	245	249	239	246
160	273	270	263	265
170	286	291	276	274
180	299	293	282	285
190	293	294	287	291

cant weight loss when PVA is mixed with poly(maleic acid) at elevated temperatures.¹⁸ The drastically increased weight loss of PVA in the presence of BTCA indicates that esterification between BTCA and PVA takes place at elevated temperatures.

The improved abrasion resistance of the cotton fabric treated with BTCA/PVA is most likely a result of a reaction between BTCA and PVA. Because of its large molecular size, PVA stays on the surface of the cotton fiber whereas BTCA penetrates into the fiber interior to form crosslinking among cellulose molecules. Three different reactions (crosslinking among cellulose, crosslinking among PVA, and crosslinking between cellulose and PVA), as shown in Scheme 1, take place on the cotton fiber surfaces when the treated cotton fabric is cured at an elevated temperature. Because PVA and cotton cellulose compete to esterify BTCA, the amount of crosslinking among cellulose on the surfaces of the cotton fiber is reduced when PVA is added. The reduced cellulose crosslinking on the fiber surface improves the abrasion resistance of the fabric.

When the cotton fabric is treated with BTCA/PVA, PVA goes to pores and cracks on the fiber surface under capillary force. Thus, PVA may also repair the weak points on the cotton fiber surface. The crosslinking between cellulose and PVA makes those PVA molecules durable to home laundering. One observes the formation of a film between two cotton fibers in the SEM micrograph [Fig. 4(D)]. The film is probably the crosslinked networks of PVA/BTCA. The networks must have covalently bound to the fibers through BTCA because the film is observed after one home laundering cycle. The crosslinked networks of PVA/BTCA on the cotton fiber surfaces may also contribute to the improved abrasion resistance of the cotton fabric treated with BTCA/PVA.

We investigated the change in fabric WRA as a result of the use of PVA. The conditioned WRA of the cotton fabric treated with 6% BTCA and 4% NaH₂PO₂ in combination with three PVA samples at different concentration levels was presented in Table III. The WRA of the cotton fabric treated with BTCA without PVA was 293° after one laundering cycle, and it remains statistically unchanged when the PVA at different concentrations is used as the additive (Table III). One observes a similar phenomenon after the treated fabric was subjected to an additional four laundering cycles (Table III).

The conditioned WRA of the cotton fabric treated with 6% BTCA and 4% NaH₂PO₂ with and without 0.60% PVA (LMW-NH) and cured at different temperatures is shown in Table IV. The data presented indicate that the WRA of the fabric treated with BTCA/PVA and that treated with BTCA alone are statistically the same both after one laundering cycle and after five laundering cycles (Table IV). Thus, the data shown above confirm that the use of PVA does not have a negative effect on the wrinkle resistance of the crosslinked cotton fabric.

Presented in Table V is the DP rating of the cotton fabric treated with 6% BTCA and 4% NaH₂PO₂ in combination with PVA (LMW-NH) at different concentrations and cured at 180°C for 2 min. The data show that the use of PVA as an additive at a concentration equal or higher than 0.60% in the BTCA solutions slightly enhances the DP performance of the cotton fabric crosslinked by BTCA.

The performance of the cotton fabric treated with BTCA/NaH₂PO₂ in the presence of a polymeric hydroxy-functional compounds, such as the three PVA samples used in this research, is completely different from that treated with a hydroxy-functional com-

TABLE V
The DP Rating of the Cotton Fabric Treated with 6% BTCA and 4% NaH₂PO₂ in Combination with PVA (LMW-NH) at Different Concentrations and Cured at 180°C for 2 Min

Concentration of PVA (%)	0.00	0.05	0.10	0.20	0.40	0.60	0.90
After 1 laundering cycle	3.8	4.0	3.9	4.0	3.9	4.1	4.2
After 5 laundering cycles	3.7	3.8	3.8	3.7	3.9	4.2	4.0

pound with small molecules, such as triethanolamine (TEA), previously reported in the literature.^{15,16} It was reported that the conditioned WRA of the treated cotton fabric decreases whereas its tensile strength increases when TEA is used as an additive to the BTCA solution.^{15,16} This is because TEA with MW of 140 is able to penetrate into the interior of a cotton fiber, and its hydroxy groups compete with the cellulose hydroxyl group to esterify BTCA. Consequently the reaction between TEA and BTCA reduces the number of the crosslinkages formed among cellulose molecules by BTCA, thus decreasing the WRA of the treated cotton fabric.

For PVA with MW in the vicinity of 100,000 or above, such as the PVA used in this study, its molecule can only react with the BTCA on the cotton fiber surface and is not able to penetrate into a cotton fiber's interior, therefore, the number of crosslinkages in the entire cross section of a cotton fiber is nearly the same as those of the treated fabric without the addition of PVA. Consequently, the reaction between PVA and BTCA on the fiber surface does not diminish the wrinkle resistance of the crosslinked fabric. On the contrary, the formation of the crosslinking networks of PVA/BTCA enhances the smooth appearance of the treated fabric, as shown in Table V.

Presented in Table VI is the tensile strength retention in the filling direction of the cotton fabric treated with 6% BTCA and 4% NaH₂PO₂ in combination with different PVA samples. When no PVA was used, the strength retention of the finished cotton fabric was 44% after one laundering cycle. The fabric strength retention did not decrease when PVA with different concentrations was added to the BTCA solutions (Table VI). The strength retention of the cotton fabric treated with 6% BTCA and 4% NaH₂PO₂ in combination with 0.6% PVA (LMW-NH) and cured at different temperatures (150–190°C) is shown in Table VII. One observes that addition of 0.6% PVA (LMW-NH) to the

TABLE VI
The Percentage Tensile Strength Retention of the Cotton Fabric Treated with 6% BTCA and 4% NaH₂PO₂ in Combination with PVA at Different Concentrations and Cured at 180°C for 2 Min

PVA	Concentration of PVA (%)						
	0.00	0.05	0.10	0.20	0.40	0.60	0.90
HMW-NH	44	41	40	39	44	51	51
LMW-NH	44	42	45	44	47	49	50
LMW-FH	44	47	47	46	46	49	46

TABLE VII
The Percentage Tensile Strength Retention of the Cotton Fabric Treated with 6% BTCA and 4% NaH₂PO₂ in Combination with 0.6% PVA (LMW-NH) at Different Concentrations and Cured for 2 Min at Different Temperatures

Curing temperature (°C)	Percent tensile strength retention (%)	
	With PVA	Without PVA
150	76	71
160	63	60
170	55	48
180	49	44
190	47	39

BTCA solution slightly improves the strength retention of the treated cotton fabric (Table VII).

CONCLUSION

The use of PVA as an additive significantly improves the abrasion resistance of the cotton fabric treated with 6% BTCA and 4% NaH₂PO₂ without creating negative effects on the wrinkle resistance of the fabric when the concentration of PVA reaches 0.60% or higher. The PVA as an additive reacts with BTCA, thus probably reducing the amount of crosslinkages on the cotton fiber surface and also reinforcing the mechanically weak points on the fiber.

References

- Petersen, H. A. *Chemical Processing of Fibers and Fabrics: Functional Finishing, Part A*; Lewin, M., Sello, S. B., Eds; Mercel Dekker: New York, 1983, pp 47–327.
- Welch, C. M. *Surface Characterization of Fibers and Textiles*; Pastore, C. M., Kiekens, P., Eds; Mercel Dekker: New York, 2000, pp 5–25.
- Welch, C. M. *Textile Res J* 1988, 58, 480.
- Andrews, B. A. K. *Textile Chem Color* 1990, 22, 63.
- Yang, C. Q., Xu, L., Li, S., Jiang, Y. *Textile Res J* 1998, 68, 457.
- Yang, C. Q., U. S. Patent 6 165 919 assigned to University of Georgia Foundation, December 26, 2000.
- Yang, C. Q., Lu, Y., Lickfield, G. C. *Textile Res J* 2002, 72, 817.
- Wei, W., Yang, C. Q. *Textile Res J* 1999, 69, 145.
- Kang, I., Yang, C. Q., Wei, W., Lickfield, G. C. *Textile Res J* 1998, 68, 865.
- Yang, C. Q., Qian, L., Lickfield, G. C. *Textile Res J* 2001, 71, 543.
- Morris, C. E., Harper, R. J. *Am Dyestuff Rep* 1994, 83, 34.
- Morris, C. E., Parto, H. H. *Textile Res J* 1975, 45, 395.
- Turner, J. D. *Textile Chem Color* 1988, 20, 36.
- Welch, C. M., Peters, J. G. *Textile Chem Color* 1993, 25, 25.
- Welch, C. M. *Textile Chem Color* 1997, 29, 21.
- Welch, C. M. *Textile Chem Color* 1991, 23, 29.
- Yang, C. Q., Wang, X. *J Appl Polym Sci* 1998, 70, 2711.
- Xu, G., Yang, C. Q. *J Paper Pulp Sci* 2001, 27, 14.