Property Modifications of Finished Textiles by a Cationic Surfactant

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Fabrics made of 100% cotton, 100% polyester and a 50/50 cotton/polyester blend with and without functional finishes were treated in aqueous solutions of the cationic surfactant distearyldimethylammonium bromide (DSDMAB). Finishes chosen were dimethyloldihydroxyethyleneurea (DMDHEU), a durable press finish, and poly(acrylic acid), a soil release finish. Selective sorption of the cationic surfactant by finished and unfinished fabrics was quantified. Cotton takes up much larger amounts of DSDMAB than does polyester. In general, acrylic finished fabrics take up more DSDMAB, while DMDHEU finished fabrics take up smaller amounts of DSDMAB as compared to their unfinished controls. These findings indicate that ionic interaction forces play an important role in the sorption process. In order to investigate this, acid numbers were used as a relative measure of negative sorption sites on fabrics. A direct relationship between DSDMAB sorption and the acid numbers of the fabrics was established.

Perceived fabric softness is generally improved by treatments with DSDMAB for all test fabrics. Although cotton fabrics finished with DMDHEU were perceived to be less soft than unfinished cotton, treatment with DSDMAB restored the softness level to that of unfinished cotton. The softness of both cotton and polyester fabrics was greatly lowered by the acrylic finish. The presence of even large amounts of DSDMAB did not restore softness ratings to levels comparable to unfinished controls.

Electrical resistivity and electrostatic clinging measurements were used to assess the effectiveness of DSDMAB as an antistatic agent. DSDMAB reduced the electrical resistivities of all test fabrics. However, relative humidity played a much larger role in reducing the electrical resistivity of fabrics. Clinging times were also reduced by DSDMAB treatments. DSDMAB was particularly efficient in reducing the clinging time of polyester.

Additional moisture related properties were investigated. The presence of DSDMAB on the test fabrics did not significantly alter moisture regain. The application of DSDMAB from aqueous solutions resulted in lower water retention values of the test fabrics after centrifuging at a *g*-factor comparable to home washing machines. This leads to energy savings during drying from 10–24%, depending on the fabric and finish type. However, energy savings due to fiber type were more significant than those due to the cationic surfactant treatment.

KEY WORDS: Cationic surfactant, cotton, distearyldimethylammonium bromide, durable press finish, electrostatic clinging, fabric softening, moisture related properties, polyester, soil release finish and sorption.

Research efforts by the textile industry have resulted in the development of durable finishes for textiles which impart desirable properties. Examples include durable press and antisoiling finishes which improve wrinkle resistance, soil repellency and soil release (1). Along with these developments, the soap and detergent industry formulated additives for use in home laundering which further enhance desirable textile properties. For instance, household fabric softeners were introduced to the U.S. consumer market around 1955 to maintain or even improve the softness of fabric, reduce static electricity build-up and influence moisture related properties (2,3).

The main ingredients in household fabric softeners are cationic surfactants, particularly quaternary ammonium compounds (4,5). Several researchers have investigated the sorption of these cationic surfactants on textiles and have evaluated such performance properties as softening and antistatic behavior (6,7). However, very little work has been done to document property modifications of finished textiles by cationic surfactants (8). Due to the popularity of textile finishes and increasing consumer demands for convenient, multifunctional laundry aids (9), more research is needed to understand the interactions of cationic surfactants with finished textiles and subsequent fabric property modifications.

This study was undertaken to examine the effects of a representative cationic surfactant, distearyldimethylammonium bromide (DSDMAB), on selected properties of both finished and unfinished fabrics. Three types of fabric were chosen for this study: 100% cotton, 100% polyester and a 50/50 blend of cotton/polyester. The two finishes investigated were dimethyloldihydroxyethyleneurea (DMDHEU), a durable press finish, and poly(acrylic acid), a soil release finish. Specific fabric properties studied were fabric softness, electrical resistivity, electrostatic clinging, moisture regain and water retention after centrifuging at a *g*-factor comparable to that obtained in home washing machines.

MATERIALS AND METHODS

Fabrics. 100% cotton, 100% polyester and 50/50 cotton/polyester print cloth in both finished and unfinished variations were supplied by the USDA Southern Regional Research Center (New Orleans, LA). The fin-

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ishes were applied using representative commercial formulas and treatment conditions. Both the cotton and 50/50 blend fabrics were finished with a DMDHEU treatment solution containing 20 lb DMDHEU (Protocol C, National Starch and Chemical Corp., Bridgewater, NJ), 5-lb metal complex catalyst (Curite HC, National Starch and Chemical Corp.), 2.8 lb polyethylene softener, 2.8 lb fatty acid softener, 0.25 lb nonionic wetting agent and 69.15 lb H_2O. Names of commercial products are given solely for the purpose of providing specific information. Their mention does not imply recommendation or endorsement by the authors. Fabrics were padded with the finishing solution, dried on tenter frames at 66°C for 1.5 min and cured at 171°C for 1.5 min with no afterwash. Poly(acrylic acid) was applied to all three fabric types. The finishing solution contained 15.6 lb acrylic polymer (Acrysol® ASE-60, Rohm and Haas Co., Philadelphia, PA), 15.6 lb polyester resin (Glo Rez CP-7, Glo-Tex Chemicals Inc., Roebuck, SC), 9.4 lb wetting agent, 4.4 lb emulsifying agent and 55 lb H_2O. Fabrics were padded with the finishing solution and dried on tenter frames at 110°C for 2 min with no afterwash.

The test fabrics were engineered to eliminate as many variables as possible aside from fiber and finish. Table 1 lists experimentally determined weights and fabric counts which illustrate the uniformity of fabric construction. Data, including fiber staple length, fineness, linear density and twist multipliers, are available upon request.

Cationic surfactant and reagents. ACS grade distearyldimethylammonium bromide (DSDMAB) was obtained from Fisher Scientific Co. (Pittsburgh, PA). It was dried over dessicant (Drierite®, Aldrich Chemical Co., Inc., Milwaukee, WI) prior to use.

All reagents were ACS grade. Hydrochloric acid, sodium hydroxide and potassium hydrogen phthalate were obtained from Fisher Scientific Co. Benzene and bromophenol blue were purchased from MCB Manufacturing Chemists, Inc. (Cincinnati, OH). Sodium carbonate was obtained from Mallinckrodt, Inc., (Paris, KY). Distilled water was used for all testing.

Fabric pretreatment. Test samples were cut to a size of 4 × 4 in. for all experiments except those measuring electrical properties. All samples were extracted with distilled water in Soxhlet extractors for at least 3 hr to remove water soluble impurities and unreacted finishing components. The fabric samples were dried in a drying oven at 105°C overnight and stored in a dessicator.

Cationic surfactant treatment. Aqueous solutions of the dried cationic surfactant, DSDMAB, were prepared at concentrations of 0.0034, 0.01 and 0.02 wt/v%. A liquid to cloth ratio of 30:1 was selected. The dried fabric samples were weighed and appropriate volumes of treatment solution were put into 250-mL Erlenmeyer flasks with glass stoppers. The flasks were placed in an Eberbach Shaker Bath (Eberbach Corp., Ann Arbor, MI) which provided adequate temperature control and constant agitation of 2 cycles/sec. After the solutions reached thermal equilibrium, the test samples were placed in the flasks and allowed to agitate in the DSDMAB treatment solutions. Preliminary kinetic studies were carried out by treating samples for various times at 24, 35 and 44°C. The samples used to evaluate fabric properties were treated for 120 min at 35°C.

After treatment, fabric samples were removed from the flasks and padded between American Association of Textile Chemists and Colorists (AATCC) textile blotting paper under 35 lb of pressure using an AATCC electric wringer and padder (10). Samples were allowed to dry overnight on AATCC paper and were stored in polyethylene bags for future evaluation.

Analysis of cationic surfactant concentration. A two-phase colorimetric procedure developed by Auerbach was selected for this work (11). A known aliquot of the DSDMAB surfactant solution was added to a 125-mL separatory funnel containing 50 mL of distilled water. Five mL of 10% sodium carbonate solution, 1 mL of 0.04% bromophenol blue indicator solution and 10 mL of benzene was added. The anionic indicator solution was prepared fresh each day by dissolving 20 mg of bromophenol blue in 50 mL of distilled water containing 0.5 mL of 0.1 N sodium hydroxide solution.

The contents of the funnel were shaken steadily for 45 seconds and allowed to separate for 2–3 min. The cationic DSDMAB formed a complex with the anionic bromophenol blue, which is soluble in benzene. The lower aqueous layer containing the excess bromophenol blue was discarded. A SP8-200 UV/VIS spectrophotometer (Pye Unicam Ltd., Cambridge, England) interfaced with a Hewlett Packard Model 85 computer (Hewlett Packard Co., Corvallis, OR) was used to measure absorbance of the colored benzene solution at 605 nm. The bandwidth was 1 nm, scan speed was 1 nm/sec and the cuvette path length was 10 mm.

To establish a calibration for determining DSDMAB concentration, absorbance was plotted against concen-

TABLE 1

Characterization of Test Fabrics

Fabric code	Fiber content	Finish	Weight (oz/sq yd)	Fabric count (warp × fill)
1	100% Cotton	None	3.32 ± 0.01	73 × 79
2	100% Cotton	DMDHEU	3.35 ± 0.04	74 × 78
3	100% Cotton	Acrylic	3.59 ± 0.04	72 × 78
4	50/50 Cotton/polyester	None	3.49 ± 0.05	73 × 80
5	50/50 Cotton/polyester	DMDHEU	3.53 ± 0.05	74 × 80
6	50/50 Cotton/polyester	Acrylic	3.63 ± 0.04	74 × 79
7	100% Polyester	None	3.52 ± 0.14	76 × 81
8	100% Polyester	Acrylic	3.92 ± 0.05	73 × 82

tration for a range of known solutions, giving a straight line according to Beer's law. The best fitting line calculated by least squares regression was:

$$\text{Absorbance} = (0.0049)\,(\text{Concentration}) - 0.0604 \quad [1]$$

The correlation coefficient (r) was 0.98. This linear equation was used for quantitative measurements in the range of 0.1 to 1.0 absorbance units with a relative error of 3–5%. The concentration of the DSDMAB solution was measured before and after treatment of the test fabrics. The difference was assumed to be the amount taken up by the fabric.

Acid numbers. A procedure described by Reinhardt *et al.* was used to determine acid numbers, an estimation of carboxyl content of the test fabrics (12). Two samples from each test fabric were soaked in a 2% hydrochloric acid solution for 4 hr at room temperature. A liquid to cloth ratio of 50:1 was selected. Samples were agitated continuously in Erlenmeyer flasks on a Fisher Oscillating Hot Plate (Fisher Scientific Co.). The fabric samples were rinsed with distilled water until neutral and dried overnight in a 105°C drying oven. After being weighed, the samples were placed in Erlenmeyer flasks with aliquots of standardized 0.01 N sodium hydroxide ranging from 50–70 mL. Distilled water was added to equal 100 mL. The flasks were agitated constantly on the oscillating hot plate for 3 hr at room temperature. The excess sodium hydroxide was back titrated with standardized 0.01 N hydrochloric acid to the phenolphthalein endpoint. Carboxyl content was assumed to equal the number of milliequivalents of sodium hydroxide which reacted with the test fabric. Acid numbers are reported as milliequivalents COOH/g dry fabric.

Softness evaluation. Magnitude estimation and paired comparison techniques were used to evaluate fabric softness (13). Only the finished and unfinished cotton (Fabric Code 1,2,3) and polyester (Fabric Code 7,8) test fabrics were evaluated. Fabrics with no treatment and those treated in 0.0034 and 0.01 wt/v% DSDMAB solutions were tested for a total of 15 test samples. The fabrics were dried overnight in a 105°C drying oven and conditioned at 27.2 ± 2.2, 40.1 ± 1.3 and 67.2 ± 1.6% RH at 24.1 ± 1.0°C in controlled chambers. The 3 × 2 ft chambers were equipped with sleeves attached to 9-in. ports so that a subject could reach in and touch the fabrics. A panel of eight subjects evaluated the samples. Prior to testing, all panelists washed their hands and were blindfolded to mask any visual differences between samples.

For the magnitude estimation procedure, each panelist was first sensitized to the softness range within the sample set by touching all test fabrics. The rating scale ranged from 0 (least soft) to 9 (softest), where 5 was assigned to 100% cotton without finish (Fabric Code 1) or cationic surfactant treatment. All panelists were asked to feel each sample and respond with a number on the scale proportional to the softness rating of the cotton standard.

The paired comparison method was used only at 67.2% RH using cotton fabrics with various finishes (Fabric Code 1,2,3) with and without the softener treatments for a total of nine samples. All 36 possible sample pair combinations were randomly presented to each panelist. The panelist was asked to choose one sample in each pair as the softest.

Electrical resistivity of fabrics. Electrical resistivity of the test fabrics was measured using an electrical Resistance Tester, Model CS-51-013 (Custom Scientific Instruments, Inc., Whippany, NJ), as described in AATCC Test Method 76-1978 (14). The resistance tester was calibrated using 21.7 × 10^6 and 10,300 × 10^6 ohm resistors. Two sets of three samples (3/4 × 2 in.) were cut from each test fabric, one in the warp direction and one in the filling direction. Two sets of samples were cut in the same manner from test fabrics treated with 0.0034 and 0.01 wt/v% DSDMAB. All samples were preconditioned for 24 hr at 21.8 ± 0.5% RH, followed by 35.1 ± 0.3 and 65.0 ± 0.9% RH.

Electrostatic clinging of fabrics: Fabric-to-metal test. Relative clinging tendency of the test fabrics due to electrostatic charge generation was evaluated by AATCC Test Method 115–1980 (15). Three test samples from each fabric were cut to 3 × 9 in. with the longer dimension parallel to the warp. Rubbing fabrics were cut to 3 × 9 in. with the longer dimension parallel to the weft from 100% spun polyester (Testfabric No. 767, Testfabrics, Inc., Middlesex, NJ). Test fabrics and rubbing fabrics were conditioned for 24 hr at 38.5 ± 2.0% RH and 25.2 ± 0.4°C. Clinging times for untreated fabrics and fabrics treated with 0.01 wt/v% DSDMAB were measured with a standard stainless steel test plate described in AATCC Test Method 115–1980 (15). If the clinging time exceeded 10 min, the test was discontinued and the time was reported as >600 seconds.

Moisture regain. Moisture regain was determined according to Procedure 1 of ASTM Test Method D2654-76 (16). Three samples of each test fabric were measured at the following treatment levels: no treatment, treatment with 0.0034 wt/v% DSDMAB and treatment with 0.01 wt/v% DSDMAB.

After the DSDMAB treatment, samples were dried overnight in a 105°C drying oven and weights were recorded. The samples were conditoned for 24 hr at relative humidities of 24.1 ± 1.6, 39.7 ± 0.5 and 67.8 ± 2.1%, in that order. Temperature was maintained at 25.2 ± 0.1°C. Moisture regain was determined gravimetrically.

Water retention. Water retention values were obtained for a set of untreated controls and a set of samples treated with 0.01 wt/v% DSDMAB. After surfactant treatment, the samples were drained for 1–3 min and placed in sealed centrifuge tubes as described below. Control samples were placed in tubes after a treatment in distilled water for 60 min at a liquid to cloth ratio of 100:1. A Fisher Oscillating Hot Plate was used at room temperature to provide constant agitation. Preliminary tests showed that accurate results were obtained by this modified procedure for control samples.

A Sorvall® RC-5B Refrigerated Superspeed Centrifuge with a SS-34 head (23-cm diameter) was used for centrifuging (Du Pont Biomedical Products Division, Newtown, CN). Samples were centrifuged in sealed, 50-mL, polypropylene tubes filled to a height of 6 cm with a small rubber cork and 4 mm solid glass beads to allow separation of water from the samples.

Centrifuging was done at 2,000 rpm to produce a radial acceleration force of 312 *g*'s for 30 min. Samples were weighed immediately after centrifuging and reweighed after drying overnight at 105°C. The weight difference, expressed in percent based on dry weight, equals the water retention.

RESULTS AND DISCUSSION

Sorption of cationic surfactant. It is well known that cationic surfactants are preferentially taken up by textiles from aqueous colloidal solutions (2). This phenomenon can be described using the generic term "sorption" since it is not practical to differentiate between adsorption of the surfactant molecules on the fiber surfaces and any possible absorption of the molecules within the amorphous fiber regions. Two mechanisms for surfactant uptake by textiles can be postulated. One involves the limited solubility of the cationic surfactant in water which is governed by the hydrophilic-lipophilic balance of the surfactant. The second involves the interaction forces between surfactant molecules and textile fibers which can be physical and/or chemical in nature (2). If a textile is modified through chemical finishes, it is reasonable to expect that the interaction forces between cationic surfactants and textiles are influenced.

Treatment conditions such as time, temperature and concentration are known to affect the sorption of surfactants (2). In this study, a range of conditions was selected to cover practical use conditions for household fabric softeners added during the rinse cycle. During this cycle, the load is treated in an aqueous solution of fabric softener for 3–6 min (17) to achieve sorption of about 0.08 to 0.20% WOF (weight of fabric) (18).

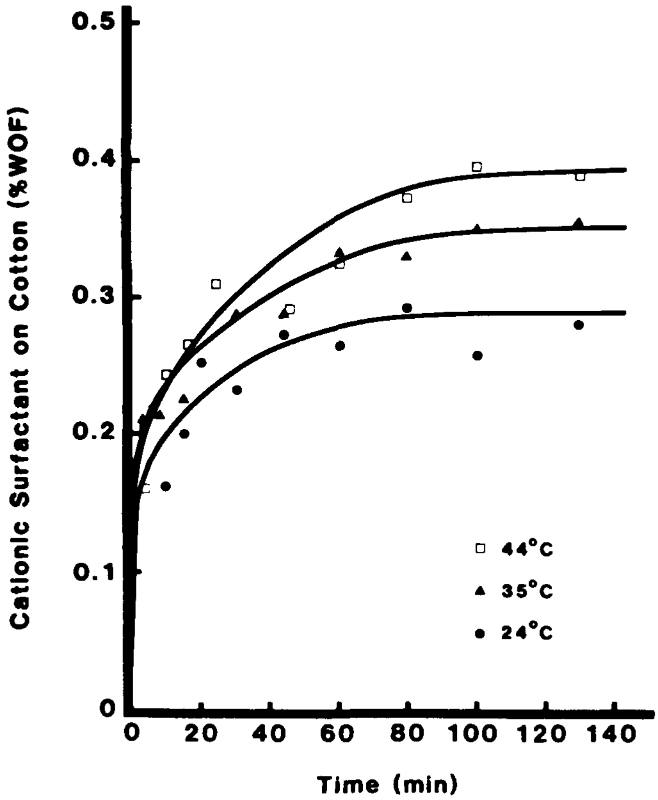

FIG. 1. Sorption kinetics of the cationic surfactant (DSDMAB) on 100% cotton at various temperatures.

A set of preliminary experiments was designed to study the sorption kinetics of the cationic surfactant, DSDMAB, on 100% cotton at 24, 35 and 44°C from 0.02 wt/v% solutions. Figure 1 shows these results. Sorption takes place quickly, with about 60% bath exhaustion during the first 10 min of treatment. Equilibrium sorption, generally observed at about 100 min, increased with temperature. This is contrary to what is generally observed in ideal model systems studied in the field of surface chemistry where physical adsorption, due to van der Waals attraction, occurs (19). However, this trend has been previously reported in the literature to occur with textile/surfactant systems (17). This suggests that the overall process of the system studied here is endothermic in nature. The sorption process is complex since more than one mechanism may be involved. Sexsmith and White (20) have discussed proposed mechanisms for the sorption of cationic surfactants by textiles.

The rate of DSDMAB sorption by 100% cotton also increased with increasing temperature. At each temperature, sorption data were converted to logarithmic form and plotted against time. The resulting linear relationships suggest that the sorption process for cotton follows first order kinetics. Rate constants were derived from these plots and calculated to be 3.9×10^{-3}, 4.8×10^{-3}, and 6.5×10^{-3} min^{-1} at 24, 35 and 44°C, respectively. The Arrhenius equation describes the relation between rate constants and temperature. This equation can be used to determine the energy of activation for a process. Using rate constants at the three temperatures, it was found that the sorption of DSDMAB on 100% cotton required an activation energy of 4.5 kcal/mole.

Based on these preliminary sorption studies, all subsequent treatments of the test fabrics were carried out at 35°C for 120 min to insure equilibrium uptake and reproducibility. Table 2 contains a summary of the average sorption of DSDMAB on all test fabrics from three solution concentration levels. The coefficients of variation for most of the cotton and cotton blend fabrics range from 0.02 to 0.06. Higher variability was observed for the polyester fabrics where coefficients of variation ranged from about 0.10 to 0.20. At a concentration of 0.0034 wt/v%, all fabrics except 100% polyester exhausted the bath completely. This accounts for the similar amounts of DSDMAB taken up by these fabrics. Sorption ranges from 0.088% to 0.101% WOF. For optimum property modifications, a manufacturer suggests surfactant deposits up to 0.20% WOF (18). These levels were achieved by increasing the solution concentrations to 0.01 or 0.02 wt/v%. At the higher concentration levels, differentiations of DSDMAB uptake due to fabric type and finish became apparent, as shown in Table 2. In general, fabrics treated with the acrylic finish showed the highest sorption of DSDMAB.

TABLE 2

Sorption of Cationic Surfactant (DSDMAB) on Test Fabrics from Three Solutions

Fiber content	Finish	Acid number	Sorption in % WOF from DSDMAB solutions (wt/v%) 0.0034	0.01	0.02
100% Cotton	None	0.112	0.097	0.297	0.319
100% Cotton	DMDHEU	0.106	0.095	0.189	0.276
100% Cotton	Acrylic	0.294	0.096	0.320	0.659
50/50 Cotton/polyester	None	0.093	0.101	0.188	0.274
50/50 Cotton/polyester	DMDHEU	0.080	0.094	0.157	0.247
50/50 Cotton/polyester	Acrylic	0.216	0.096	0.279	0.535
100% Polyester	None	0.072	0.024	0.069	0.144
100% Polyester	Acrylic	0.203	0.088	0.286	0.546

The cotton and cotton blend fabrics treated with DMDHEU took up lower amounts of DSDMAB than did their respective unfinished controls.

Differences in DSDMAB sorption due to fabric finish type can be explained by considering ionic interaction forces between the cationic surfactant and the fabric. These forces play an important part in the sorption process. This is confirmed by using the acid number method as a means of characterizing the negative sorption sites on each test fabric. One can assume that a negative site on a fiber surface attracts the positively charged surfactant molecule. Acid numbers of each fabric are included in Table 2. Figure 2 shows the direct linear relationship between the amount of cationic surfactant taken up from 0.02 wt/v% DSDMAB solution by each test fabric and their acid numbers. These findings concur with the theoretical model proposed by Sexsmith and White (20). These sorption studies provided the quidelines for applying DSDMAB on all test fabrics for fabric property evaluations.

Softness Evaluation. One of the most important functions of cationic surfactants is to improve fabric softness. Objective evaluations of fabric softness involving physical laboratory measurements often do not correlate with the subjective response of people (2). Subjective sensory evaluation was therefore selected to assess fabric softness modifications of the test fabrics due to DSDMAB treatment. This is practical since the consumer is the ultimate judge of fabric acceptability.

In subjective sensory evaluation, a person is asked to feel the test fabrics and then give a response that indicates their perception of the softness of each sample. Responses can be absolute or comparative in nature. The magnitude estimation technique requires an absolute response for each test sample and was used for this study since it is recommended when the number of samples is large (13). There are advantages and disadvantages associated with both absolute and comparative responses. To contrast the results of both methods, a small subset of the samples was evaluated using paired comparisons. In this case, a person is given two fabric samples and asked to indicate which is softer. This is repeated until all possible sample pairs have been evaluated. Because the findings of the two methods were not different, only the magnitude estimation results will be discussed.

Initial softness ratings were made at three relative humidity levels in three different environmentally controlled chambers. A statistical evaluation of the data showed that the relative humidity level had no effect on the softness rating of the samples under these experimental conditions. Figure 3 contains a summary of the average ratings given to each fabric by the eight judges. Analysis of variance was used to determine the statistical significance of these results. Softness ratings of cotton fabrics not treated with DSDMAB were in the following order of decreasing softness: no finish, durable press (DMDHEU), and acrylic finish. These differences due to finish type were statistically significant. Treatment of the cotton fabrics with DSDMAB lead to significantly higher softness ratings. It is inter-

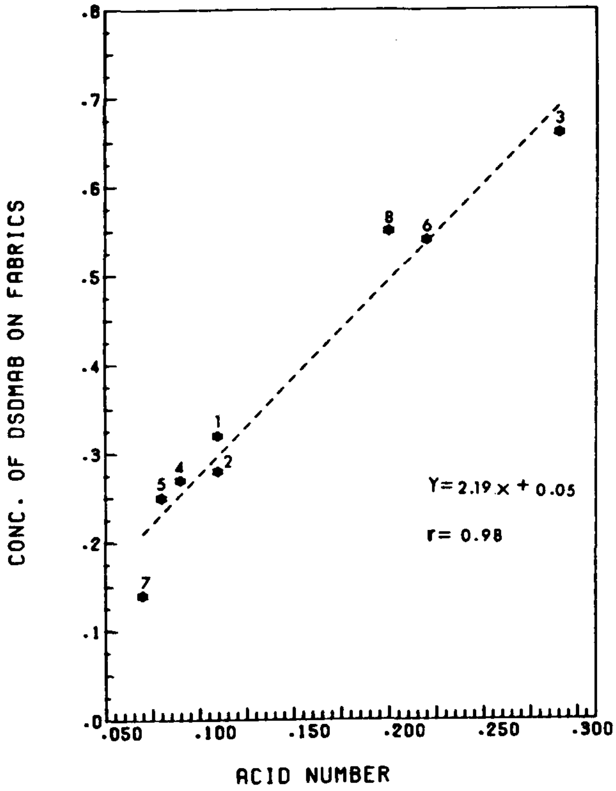

FIG. 2. Correlation between the cationic surfactant (DSDMAB) sorption of fabrics and their acid numbers. (See Table 1 for fabric codes.)

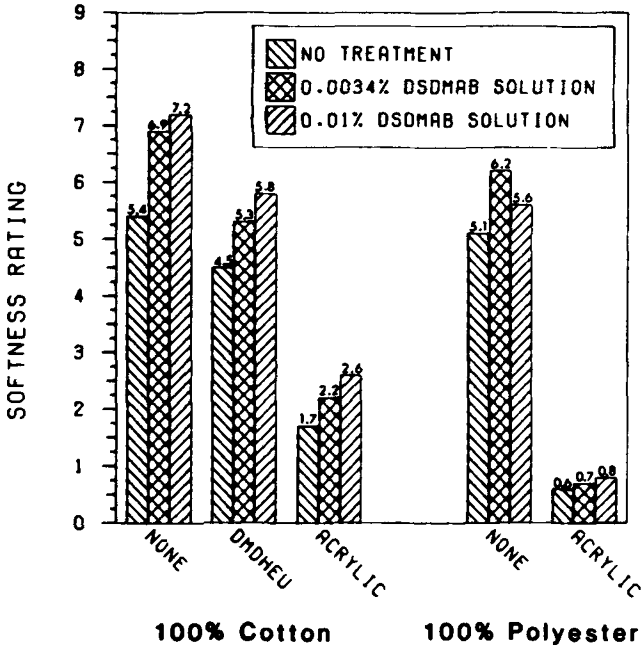

FIG. 3. Softness ratings of test fabrics with and without cationic surfactant (DSDMAB) treatments.

esting to note that the acrylic finished cotton is not rated as soft as the other cotton fabrics, even though Table 2 shows that it picked up one of the highest amounts of the surfactant (0.320% WOF) from the 0.01 wt/v% DSDMAB treatment solution.

The softness rating of the unfinished polyester fabric was similar to that of unfinished cotton. However, the application of the acrylic finish lowered the softness rating even more than in the case of cotton. Again, the sorption of even relatively large amounts of DSDMAB did not improve the low softness rating of acrylic treated polyester to any great extent.

Electrical properties. Along with improving the softness of fabrics, cationic surfactants have also been shown to reduce static electricity build-up on textiles (2). One of the objectives of this study was to determine the effectiveness of DSDMAB as an antistatic agent. Williams *et al.* (21) have shown electrical resistivity measurements of fabrics (AATCC Method 76-1969) to correlate well with results of the Electrostatic Clinging: Fabric-to-Metal Test (AATCC Method 115-1969). Therefore, electrical resistivity measurements were selected as a rapid means of determining the effects of DSDMAB on electrical properties of fabrics.

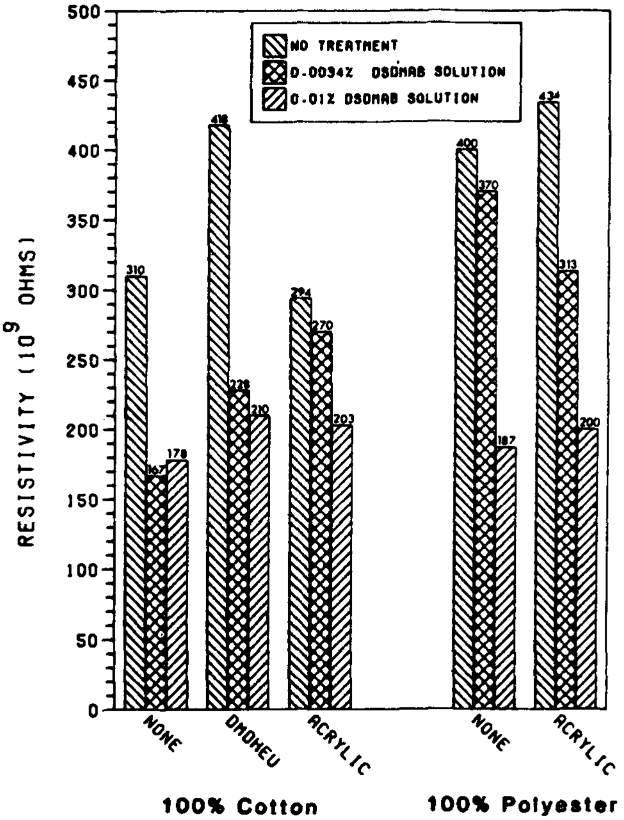

FIG. 4. Electrical resistivity of test fabrics with and without cationic surfactant (DSDMAB) treatments at 35.1% RH.

Figure 4 shows electrical resistivity data at 35.1% RH for three treatment levels. Differences of about 20 × 10^9 ohms or greater are statistically significant at the 95% confidence level. Treatment with 0.0034 wt/v% DSDMAB lowered the electrical resistivity for each test fabric. As stated earlier, all test fabrics except unfinished polyester took up similar amounts of DSDMAB at this treatment level. However, this did not result in similar reductions in electrical resistivity. For example, electrical resistivity was lowered by roughly 45% for both the unfinished and DMDHEU finished cotton, but was lowered only 8% for the acrylic treated cotton. It is possible that fewer cationic surfactant molecules contribute to the hydrophilicity of the acrylic finished cotton due to ionic interactions between the surfactant and finish. In general, the higher DSDMAB treatment level resulted in the lowest resistivity values. Similar trends were observed at 21.8 and 65.0% RH. However, changes in electrical resistivity caused by changes in relative humidity are much more pronounced than those caused by the surfactant treatments, the fiber type or finish. For example, the electrical resistivity of 100% polyester without finish at 35.1% RH was 400 × 10^9 ohms. The treatment with 0.01 wt/v% DSDMAB lowered the resistivity to 187 × 10^9 ohms. In contrast, a change in relative humidity from 35.1 to 65.0% lowered the electrical resistivity to 3.34 × 10^9 ohms. The large effect of relative humidity on electrical resistivity is illustrated in Figure 5. The shaded area is the range within which all data fell when converted into natural logarithms and plotted as a function of relative humidity.

The electrostatic clinging of fabrics (AATCC Test Method 115-1980) was also investigated to determine the effects of cationic surfactant, fiber type and finish on static build-up since it simulates practical conditions (15). Clinging times for all test fabrics, with and without cationic surfactant treatment in 0.01 wt/v% DSDMAB, at 38.5% RH and 25.2°C are reported in Table 3. In each case, clinging time was reduced due

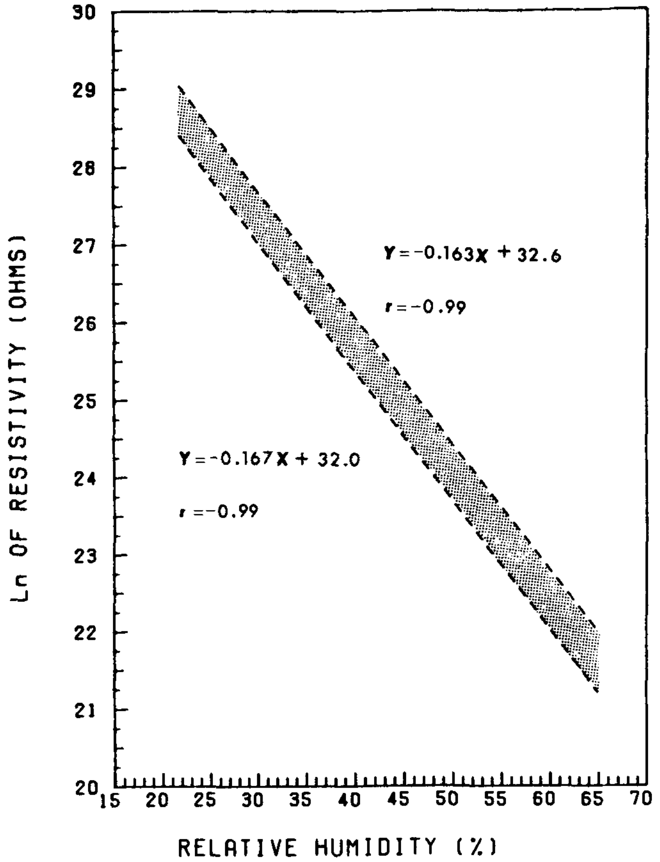

FIG. 5. Range of electrical resistivities of all fabrics with and without cationic surfactant (DSDMAB) treatments as a function of relative humidity.

to the cationic surfactant treatment. Only the differences for unfinished 100% cotton and unfinished 50/50 cotton/polyester were not significant at the 95% confidence level.

Effects of fabric type on clinging time were significant. Cotton had the lowest clinging time, followed by 50/50 cotton/polyester and 100% polyester. This can be explained by the decreasing moisture regain values of this fabric sequence.

Finishes were also found to affect clinging times. The durable press finish, DMDHEU, increased clinging times for each fabric type, although DSDMAB treatment effectively lowered them. The acrylic acid finish increased the clinging times for the 100% cotton and the 50/50 cotton/polyester fabrics, but decreased the clinging time for 100% polyester. These trends can also be explained by the moisture regain data. The electrostatic clinging test appears to be very sensitive to small changes in amounts of water on fibers. For instance, the clinging times of unfinished 100% cotton, acrylic finished cotton and cotton finished with DMDHEU are 1, 28 and 152 seconds, which correlates with their respective moisture regains of 3.9, 3.3 and 3.2%. An efficiency index was defined in order to compare the performance of DSDMAB in reducing clinging times of the test fabrics. These values are listed in Table 3 and were calculated using the following formula:

$$\text{Efficiency Index} = (T_0 - T_1) / C \qquad [2]$$

where T_0 is the clinging time of the fabric with no DSDMAB treatment, T_1 is the clinging time of the fabric with DSDMAB treatment and C is the concentration of DSDMAB on the fabric expressed as % WOF. The surfactant was most efficient in reducing the clinging time of unfinished 100% polyester. Although the effect of DSDMAB was measurable by both electrical resistivity and electrostatic clinging test methods, relative humidity played the greater role in modifying these electrical properties.

Moisture regain. The presence of small amounts of water on fiber surfaces is believed to contribute to electrical charge dissipation, thus preventing static electricity build-up (21). The water vapor sorption of a textile may be influenced by the presence of a cationic surfactant (6). Therefore, moisture regain values for untreated fabric samples and those treated with 0.0034 and 0.01 wt/v% DSDMAB were compared at relative humidities of 24.1, 39.7 and 67.8%. No significant differences at the 95% confidence level existed due to DSDMAB treatment, with the exception of the 100% polyester fabric finished with acrylic acid. At 67.8%

TABLE 3

Effect of Cationic Surfactant (DSDMAB) on Clinging Time of Test Fabrics

		Clinging time (sec)			
Fiber content	Finish	No treatment (T_0)[a]	DSDMAB treatment (T_1)[a]	DSDMAB on fabric (% WOF) (C)[a]	Efficiency index
100% Cotton	None	1 ± 1	0 ± 0	0.235	4
100% Cotton	DMDHEU	152 ± 2	53 ± 17	0.182	544
100% Cotton	Acrylic	28 ± 3	0 ± 0	0.334	84
50/50 Cotton/polyester	None	23 ± 4	20 ± 6	0.204	15
50/50 Cotton/polyester	DMDHEU	167 ± 44	33 ± 8	0.150	893
50/50 Cotton/polyester	Acrylic	59 ± 2	3 ± 1	0.310	181
100% Polyester	None	>600	30 ± 4	0.080	>7,125
100% Polyester	Acrylic	134 ± 9	50 ± 17	0.278	302

[a] See equation [2].

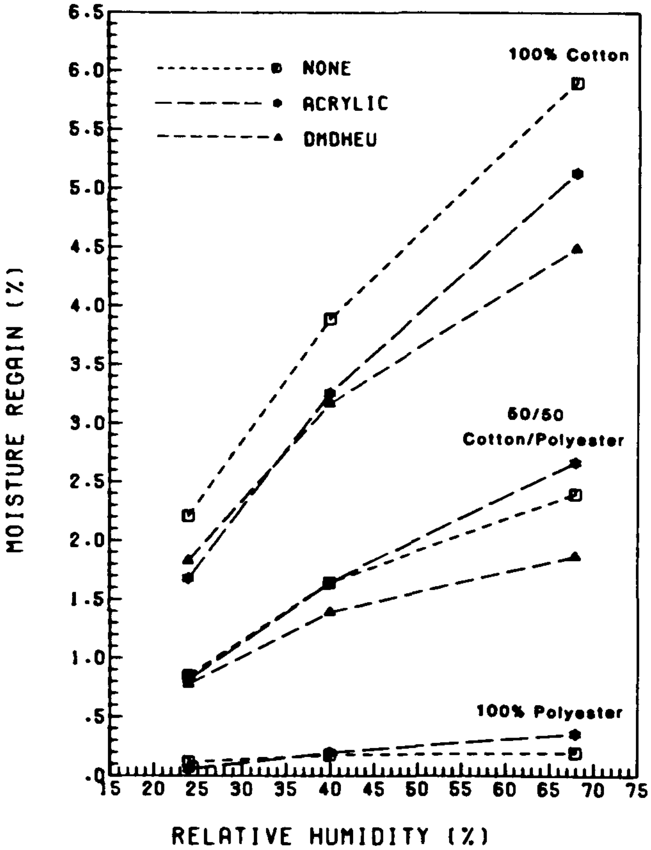

FIG. 6. Moisture regain of test fabrics.

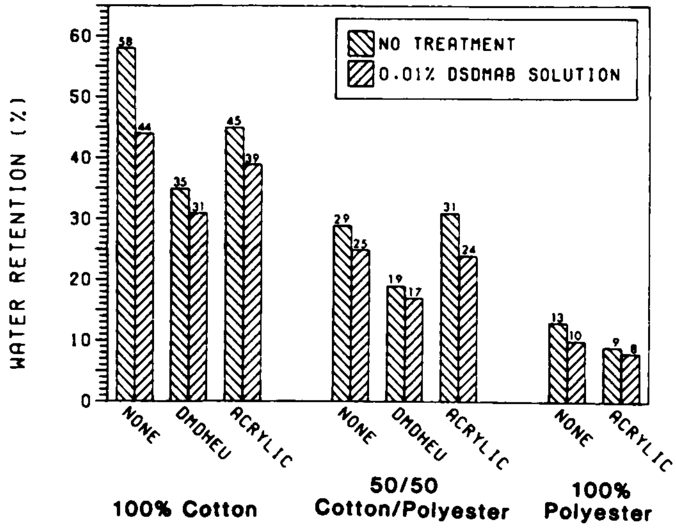

FIG. 7. Water retention of test fabrics with and without cationic surfactant (DSDMAB) treatment at a *g*-factor of 312.

RH, both surfactant treatments significantly lowered the moisture regain of the acrylic acid finished polyester by roughly 28%. This suggests that ionic sorption sites are effectively blocked and not available for hydration. The moisture regain values are reported in Figure 6 and were calculated by averaging data from treated and untreated samples (i.e., each value is the average of nine measurements) since the DSDMAB treatment effect was not significant for most fabrics. However, only the average regain of untreated samples is reported for 100% polyester finished with acrylic acid.

Figure 6 clearly illustrates the differences in moisture regain due to relative humidity and fabric fiber composition. Regain decreases with increasing polyester content. This trend is consistent with the literature. Differences due to fabric finish become apparent at 67.8% RH. The fabrics finished with the durable press agent, DMDHEU, had lower regain values than the unfinished fabrics. DMDHEU is a cellulose crosslinking agent which reduces the number of hydroxyl groups available for water sorption. Acrylic acid finished fabrics containing polyester showed higher moisture regain than their respective unfinished fabrics. This can be expected since the finish introduces polar functional groups on the fabric surface. This trend was not observed for 100% cotton. One possible explanation may be that the topical finish limits access to sorption sites within the hydrophilic fiber. Overall, small deposits of the cationic surfactant, DSDMAB, did not significantly alter moisture regain of the fabrics as measured by this procedure.

Water retention. Water retained by a textile after wetting can be divided into three categories: loosely held surface water and that in the yarn interstices, water held by capillary action between fibers within the yarns, and water held within the fiber itself (22). The water in the first two categories is largely removed by centrifuging as in home laundering, while the water contained within the fiber morphology is usually removed thermally by the dryer. Therefore, the more water that is extracted by centrifuging, the less energy is needed for drying. Levins (22) listed several factors affecting water extraction in home laundering, including washing machine and fabric variables. Spin speed is the dominant washing machine variable in reducing water retention, but beyond a specific threshold it is costly and leads to excessive fabric wrinkling. Levins (22) states that most conventional top loading machines made in the United States spin within a range of 500 to 1,000 rpm. Assuming a basket diameter of 13.5 in. (23), this would give *g*-factors ranging between 96 and 384. For this study, a constant *g*-factor of 312 was selected to simulate household conditions.

Figure 7 shows the water retention values at a *g*-factor of 312. The effect of fabric type on water retention was significant, with 100% cotton retaining 58% water, the 50/50 cotton/polyester 29% water and 100% polyester 13% water. The effect of finishing was to significantly lower water retention, except in the case of acrylic finished 50/50 cotton/polyester. These findings were consistent with the moisture regains of the test fabrics at 67.8% RH, with the exception of acrylic finished polyester.

The results of the 0.01 wt/v% DSDMAB treatment are also given in Figure 7. This treatment lowered the water retention of all fabrics. The differences were statistically significant for all fabrics except the

TABLE 4

Energy Savings Due to Cationic Surfactant (DSDMAB) Treatment

Fiber content	Finish	% Decrease in water retention	Estimated energy savings (BTU)
100% Cotton	None	24	3,276
100% Cotton	DMDHEU	11	936
100% Cotton	Acrylic	13	1,404
50/50 Cotton/polyester	None	14	936
50/50 Cotton/polyester	DMDHEU	11	468
50/50 Cotton/polyester	Acrylic	23	1,638
100% Polyester	None	23	702
100% Polyester	Acrylic	11	234

durable press 50/50 cotton/polyester and the acrylic finished polyester. It appears that the sorption of DSDMAB changes the water/fabric interaction (contact angle) so that water drainage is facilitated during extraction.

Evans (2) raised the question of energy savings through reduced drying times due to rinse cycle fabric softening. Although he implied that energy savings of up to 25% can be realized if fabric softeners are used, he did not publish experimental data. The lowering of water retention caused by the cationic surfactant implies that less water has to be removed during the drying cycle, which may lead to energy savings. Table 4 contains a summary of the water retention decreases for all the test fabrics due to DSDMAB treatment. These decreases are expressed in percent, based on the water retention values for untreated fabrics. From this data, estimated energy savings due to DSDMAB treatments can be derived. The last column shows estimated energy savings for drying fabrics in a 12 lb home dryer load which requires 1,950 BTU to evaporate 1 lb of water (22). The results clearly demonstrate that DSDMAB treatment leads to energy savings during drying. The magnitude of this savings depends on the fiber content and finish of the fabric. Clearly, fiber dependent energy savings are much more significant than those realized by the surfactant treatment. Other researchers have documented energy savings due to fiber content (24).

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