FIBER-YARN-FABRIC RELATIONSHIPS IN COTTON/DYNEEMA FABRICS

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Introduction

100% cotton fabrics have been commonly used for out door tent applications because cotton has many natural advantages, such as good breathability, high wet strength, pore space reduction in wet condition due to natural swelling, and ability to provide additional functional performance such as fire retardance through chemical treatments. One known drawback, however, is its high weight-to-strength ratio. To address this drawback, researchers at USDA (Sawhney, et al 1989, Sawhney, et al 1991, Harper and Ruppenicker, 1987, Radhakrishnaiah and Sawhney, 1996, and Ruppenicker et al, 1989) suggested blending of small percentages of synthetic fibers. In particular, it has been shown that blending of Dyneema (a low density polyethylene fiber) with cotton offers many advantages. The yarns and fabrics containing small percentages of Dyneema were shown to offer superior durability properties (Sawhney, et al 1989). The present work focuses on the influence of Dyneema content on nondurability properties such as airpermeability, water vapor transmission, thermal energy dissipation, etc. It also attempts to develop empirical relationships to predict selected yarn and fabric performance properties from blend composition. Other specific objectives of this work are:

1. Understand the influence of Dyneema content on stiffness, and breathability.
2. Develop regression equations to predict durability properties of fabrics representing different Dyneema contents.
3. Study the inter-relationships between air permeability and water vapor diffusion resistance.
4. Understand the influence of within yarn fiber arrangement and yarn structural parameters on the yarn physical and mechanical properties.
5. Understand the influence of fiber arrangement and yarn structure on the durability, breathability, stiffness, and thermal properties of the fabrics.
6. Establish relationships between yarn and fabric tensile properties.

Materials and Methods

Six different fabrics were used in this work, and they represented four different blend compositions and two different fiber arrangements in the yarn (intimate blend and core-sheath fiber arrangement). The yarn and fabric particulars are given in Table 1 and Table 2.

Table 1. Yarn particulars.

		Count (tex)	
Yarn Type	**Composition**	**warp**	**filling**
A	70C/30D intimate blend	42	39
B	80C/20D intimate blend	42	39
C	90C/10D intimate blend	42	39
D	100% cotton	42	39
E	80C/20D core-wrap	42	39
F	90C/10D core-wrap	42	39

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Table 2. Fabric particulars.

Fabric Type	Composition	EPI x PPI
A	70C/30D intimate blend	52 x 34
B	80C/20D intimate blend	52 x 34
C	90C/10D intimate blend	52 x 34
D	100% Cotton	52 x 34
E	80C/20D Core-Wrap	52 x 34
F	90C/10D Core-Wrap	52 x 34

Preparation of all the fabrics for finishing included desizing and scouring. A simple boil-off was used for desizing, and the scouring was done with a 2.0% caustic solution. The scoured fabrics were treated for flame retardancy with a standard chemical formulation used for 100% cotton fabrics.

Yarn Evaluation

Strength and Elongation. Yarn breaking strength and elongation at break were measured on a Uster single-strand strength tester following the ASTM D2256 procedures

Fabric Evaluation

Tensile Strength. Fabric breaking strength and elongation were determined by the cut strip method on an Instron Tester (5567) according to ASTM D5035.

Air Permeability. The air permeability of the fabrics was measured on the Frazier Air Permeability Tester in both dry and wet states. To measure the dry and wet air permeabilities at exactly the same spots on the fabric samples, circular marks with waterproof ink were made on the face of the fabric. After measuring the dry air permeabilities in the marked spots, the fabric samples were soaked in distilled water for 10 minutes. Each wet sample was then removed from water and placed in the middle of a stack of absorbent tissue paper. A standard weight was also placed on the top of the stack to help absorb the loose water from the wet fabric specimen. The specimen was removed from the stack after five minutes, and the squeezed specimen was weighed immediately after it was removed from the stack. The difference between the wet and dry weights of the specimen gave the weight of water contained by the specimen at the time of measuring its wet air permeability. Eight trials were made for each sample in both dry and wet states.

Water Vapor Transmission. The resistance to water vapor diffusion was measured on the Shirley Water Vapor Permeability Tester. Diffusion resistance is expressed as the height in millimeters of a still air column presenting an equivalent resistance to water vapor diffusion as that of the fabric.

Thermal Energy Dissipation. The Kawabata thermal tester "Thermolabo-II" was used to measure the thermal energy dissipated through the fabric in a unit time. The instrument contains a constant temperature hot plate (BT-Box) and it is used to measure the heat energy dissipated through the fabric. The energy dissipation through fabric was determined by the difference in the electrical power required to maintain the hot plate at the body temperature with and without the test specimen placed on the tester. The energy dissipation values were obtained for both dry and wet conditions, at both normal fan speed and high fan speed. The energy dissipation values were also measured when the fabric was directly placed on the surface of the hot plate, and when the fabric was placed on the top of an elevated hood, i.e. with a substantial air gap maintained between the fabric and the hot plate. Twelve trials were made for each sample in each condition.

Statistical Analysis

Minitab for Windows (Release 12) was used to conduct statistical analysis. Regression analysis and hypothesis tests were performed for fabric properties.

Results and Discussion

Influence of Dyneema Content on Durability Properties

Yarn Breaking Strength and Elongation. Table 3 gives the measured tensile properties of the experimental yarns . It can be seen that Dyneema exerts a dramatic influence on both strength and elongation properties. 10% Dyneema in an intimate blended yarn accounts for a 50% improvement in yarn breaking strength, while the same amount of fiber in a core-wrap yarn accounts for a 33% improvement in yarn strength. A 30% Dyneema content improves yarn strength by approximately 130%. If we compare the tensile properties of the two fibers, we find that Dyneema is roughly 15 times stronger than cotton and that its breaking elongation is less than 50% of that of cotton. Thus in terms of tensile behavior, Dyneema is compatible with cotton. In a blend yarn, Dyneema fiber can be expected to break ahead of the cotton fibers, thus contributing to yarn strength to the maximum possible extent. The major contribution extended by Dyneema to yarn strength, therefore, is not surprising.

Table 3. Yarn tensile properties.

		Breaking Strength				Breaking Elongation			
		(g / tex)		CV%		(%)		CV%	
Yarn Type		warp	weft	warp	weft	warp	weft	warp	weft
A	70C/30D-I	34.5	36.8	14.6	11.2	6.7	6.4	10.0	8.9
B	80C/20D-I	27.6	27.6	11.4	12.5	6.7	6.4	11.4	9.6
C	90C/10D-I	23.3	23.6	10.8	10.2	5.7	5.8	8.6	10.2
D	100%C	15.3	14.8	8.1	10.7	5.0	4.7	8.8	9.2
E	80C/20D-CW	22.3	22.2	12.8	15.1	5.7	5.6	8.8	10.3
F	90C/10D-CW	20.1	19.2	9.5	9.8	5.5	5.3	8.4	7.4

Although the core-wrap yarns are considerably stronger than the 100% cotton yarns, they are slightly weaker than the corresponding intimate blend yarns. Previous work (Sawhney, et al 1991, Harper and Ruppenicker, 1987, Radhakrishnaiah and Sawhney, 1996, and Ruppenicker et al, 1989) has shown that with a strong fiber incorporated in the core, the core-wrap yarn tends to be stronger than the corresponding intimate blend yarn. This behavior is to be expected when core fiber slippage is completely eliminated. With no slippage, the relatively straight core fibers extend greater strength contribution to the yarn than their twisted and continuously migrating counterparts in an intimate blend yarn. Clearly, results obtained on the cotton/Dyneema yarns fail to agree with this finding. In the previous work (Sawhney, et al 1991, Harper and Ruppenicker, 1987, Radhakrishnaiah and Sawhney, 1996, and Ruppenicker et al, 1989) the investigators used either 100% polyester or 100% nylon fibers in the core. In the present work, the core portion of the core-wrap yarn comprised a blend of cotton and Dyneema fibers, and not 100% Dyneema fibers. The fact that cotton fibers are shorter than the Dyneema fibers and that their surface frictional properties are substantially different from that of Dyneema fibers, appears to have influenced the sliding behavior of the core fibers.

Examination of the ruptured tails of core-wrap and intimate blend yarns under a microscope, did indeed reveal that there are some unbroken Dyneema fibers left in the core yarn tails and almost no long Dyneema fibers left in the tails of the intimate blend yarns. Thus, excessive slippage of the core fibers in the core-wrap yarn appears to be responsible for the lower strength of the core-wrap yarn.

Predicted and Measured Yarn Tenacities. Assuming all the fibers in the yarn contribute to yarn strength, breaking tenacity (g/tex) is calculated for the different blend compositions based on the rule of mixtures. Table 3A compares the predicted values with the measured values. It can be seen that the percentage difference between the calculated and the measured values is the least for 100% cotton yarn and that the difference between the two increases as the composition of Dyneema in the blend increases.

Table 3A. Calculated and measured yarn tenacities (g/tex).

		Tenacity (predicted)	Tenacity(measured)	
Yarn Type		Warp & Filling	Warp	Filling
A	70C/30D-I	101.5	34.5	36.8
B	80C/30D-I	71.0	27.6	27.6
C	90C/10D-I	40.5	23.3	23.6
D	100% C	22.0	15.3	14.8
E	80C/20D-CW	71.0	22.3	22.2
F	90C/10D-CW	40.5	20.1	19.2

Fabric Strength and Elongation. Fabric breaking strength and breaking elongation are shown in Table 4. It can be seen that the breaking strength of the blend fabrics is much greater than that of 100% cotton fabric. The fabric representing 30% Dyneema content is roughly twice as strong as the 100% cotton fabric. The breaking elongation of blend fabrics is also greater than that of 100% cotton fabric. The results also show that fabrics made from core-wrap yarns have lower tensile strength and elongation compared to fabrics made from random blend yarns.

In general, fabric strength in both warp and filling directions shows a direct association with Dyneema content. Also the strength improvements shown by the blend fabrics are comparable to the strength improvements of the corresponding yarns, thus indicating very good association between yarn and fabric strengths.

Table 4. Results of fabric tensile strength and elongation.

		Tensile Strength (kgf)		Elongation (%)	
Fabric Type		warp	weft	warp	weft
A	70C/30D-I	135.07	101.25	35.96	22.48
B	80C/20D-I	131.46	82.80	24.00	13.60
C	90C/10D-I	107.58	75.86	21.00	14.04
D	100%C	71.15	53.13	19.00	10.40
E	80C/20D-CW	115.20	86.02	23.20	14.28
F	90C/10D-CW	101.07	67.67	19.84	11.20

Comparing the yarn and fabric strengths for core-wrap arrangement, it can be seen that the strength of the core-wrap yarns representing 10% and 20% Dyneema composition in the yarn were 19% and 24% less than that of the corresponding intimate blend yarns. The tensile strengths of the fabrics representing 10% and 20% Dyneema composition core-wrap yarns are only 8% and 7% less than that of the fabrics representing the corresponding intimate blend yarns. It must be inferred that fabric interlacements have permitted better fiber strength utilization in the fabrics made from core-wrap yarns.

Regression analysis was performed separately for fabric strength in both warp and filling directions, and for fabrics made from intimate blend yarns and core-wrap yarns. The regression equations listed below are the ones associated with the highest R-square values.

Strength Prediction Equations.

1. Warp Way Strength (fabric made from intimate blend yarn). The regression equation is Y' = 2.18701 + 2.18E-02X – 4.17E-04X**2 (R^2= 0.967) Where Y' = Log Y= Log (warp way strength), and X =% percentage of Dyneema fiber)
2. Filling Way Strength (fabric made from intimate blend yarn) The Regression model is Y' = 2.08517 + 8.59E -03X (R^2 = 0.757) Where Y' = Log Y= Log (filling way strength), and X = % percentage of Dyneema fiber)
3. Warp Way Strength (fabric made from core-wrap yarn). The data showed a curvilinear trend with a scatter wider than that of the intimate blend fabric. The regression equation is, Y' = 2.18612 + 1.96E-02X - 4.64E-04X**2 (R^2 = 80.7) Where Y' = Log Y= Log (warp way strength), and X = % percentage of Dyneema fiber)

4. Filling Way Strength (fabric made from core-wrap yarn) The regression equation is $Y' = 2.06 + 0.0104\ X$ ($R^2 = 94.7$) Where Y' = Log Y= Log (filling way strength), and X = % percentage of Dyneema fiber)

Air Permeability. The dry and wet air permeabilities are presented in Table 5. It can be seen that the blend fabrics show lower air permeability in both dry and wet states. It can also be seen that the air flow rate of the fabrics containing core-wrap yarns is lower than that of the fabrics containing random blend yarns for both dry and wet measurements. This is due to the higher cover factor of fabrics made from core-wrap yarns. The density of Dyneema fiber is less than that of cotton, and this explains the lower air permeability of the cotton/Dyneema fabrics.

A 10% addition of Dyneema reduces dry air permeability by 27% for the intimate blend fabric, and by 40% for the core-wrap fabric. Also the same 10% Dyneema content in the fabric leads to a 32% reduction in wet air permeability for the intimate blend fabric, and 64% reduction in wet air permeability for the core-wrap fabric. It is clear that fiber density interacts with yarn structure in controlling the dry and wet air permeabilities. Any future attempts at engineering optimal cotton/Dyneema fabrics for tenting applications should carefully consider the implications of Dyneema content on fabric air permeability.

Regression analysis was employed to relate dry and wet air permeabilities to the Dyneema content. A comparison of the regression plots for dry and wet air permeabilities shows that the dry air permeability continues to decrease with increasing Dyneema content but wet air permeability, on the other hand, drops initially and then shows a slowly increasing trend with increasing Dyneema content. It appears that the wet fabrics containing a higher percentage of Dyneema may be allowing moisture to escape with the air-stream because of the lower affinity of Dyneema to water. The higher rate of loss of water vapor from the fabric may be responsible for the slight reversing trend seen in wet air permeability.

Table 5. Results of airpermeability.

		Rate of Air Flow (cubic feet per sqare foot, per minute)			Weight Change
	Fabric Type	**Dry**	**Wet**	**D/W Ratio**	**(g)**
A	70C/30D-I	19.733	5.933	3.326	6.364
B	80C/20D-I	20.369	5.887	3.460	6.508
C	90C/10D-I	27.557	8.437	3.266	6.498
D	100%C	37.904	12.507	3.031	5.939
E	80C/20D-CW	19.521	4.677	4.174	6.112
F	90C/10D-CW	22.579	4.474	5.047	6.975

Water Vapor Diffusion. In a typical tenting application, the rate at which the tenting fabric permits water vapor diffusion influences the comfort feeling of the inhabitants, because diffusion rate tends to regulate the temperature and humidity of the still air enclosed by the tent. Both outside-to-inside and inside-to-outside diffusions are important. While low diffusion rates from inside to outside are desirable for cold weather conditions, high diffusion rates from inside to outside are desirable for hot and humid conditions. Thus fabric selection from the diffusion point of view depends on the predominant weather conditions of the location, where the tent is to be erected.

Figure 1 shows the water vapor diffusion resistance of the six fabrics. It can be seen that the 100% cotton fabric shows the least resistance to water vapor diffusion and that the diffusion resistance increase as the Dyneema content is increased. The fabrics made from core-wrap yarns show slightly higher resistance to water vapor diffusion than that of the corresponding fabrics made from intimate blend yarns.

In general one would expect a higher diffusion resistance from tightly constructed fabrics. In other words, one would expect an inverse relationship between the measured values of air permeability and water vapor diffusion. As expected, the regression plot shows an inverse relationship between the two variables. The parameters of the regression plot suggest that the diffusion resistance can be predicted from air permeability with a reasonable accuracy. Measurement of water vapor diffusion is somewhat complicated and lot more time consuming compared to air permeability measurement. The regression equation developed in this work can be used to predict diffusion resistance from the air permeability values.

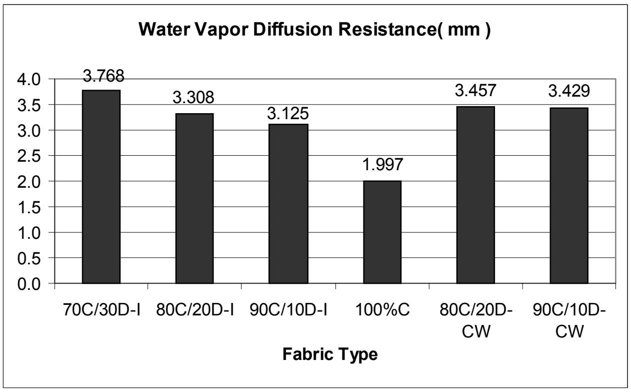

Figure 1. Results of water vapor diffusion resistance.

Thermal Energy Dissipation . Thermal energy dissipation through the fabric has a significance somewhat similar to that of water vapor diffusion. For a tenting application, a fabric with lower thermal energy dissipation (higher thermal insulation) may be beneficial because such a fabric may permit less heat dissipation through the fabric. Reduced heat dissipation through the fabric can enhance the comfort of the inhabitants in winter. Reduced heat dissipation may also be beneficial in summer in that the fabric may serve as a heat shield, thus extending protection from high ambient temperatures.

Significance tests carried out between dry and wet energy dissipations show that the wet dissipations are significantly higher than dry dissipations. This is true for all six fabrics and also for the contact and non-contact conditions of measurement. However, significance tests on the individual energy dissipations suggest that the energy dissipated through the different fabrics is not statistically different. This again is true for both wet and dry energy dissipations and for high and normal fan speeds (airflow rates). It can thus be concluded that the addition of Dyneema to the extent of 30% in the blend does not lead to any significant difference in the heat energy dissipation through the fabric.

Major Observations/Conclusions

Following are some important facts supported by the test results:

1. Fabric strength followed the trend of yarn strength. Higher Dyneema composition resulted in higher tensile strength for the fabric.
2. Core-wrap yarns in general showed lower strength and elongation compared to random blend yarns.
3. Dyneema composition influenced both dry and wet air permeabilities of the fabric. In general, increasing Dyneema composition resulted in lower air permeability. However, dry and wet air permeabilities showed a slightly different trend with increasing Dyneema content. While the dry air permeability showed a continuous drop with Dyneema

content, wet air permeability appeared to increase beyond a certain level of Dyneema content.

4. Fabrics made from core-wrap yarns showed lower air permeability in the wet state.
5. Fabrics made from core-wrap yarns showed a greater reduction in air permeability in the wet state.
6. 100% cotton fabric showed the least resistance to water vapor diffusion. Resistance to water vapor diffusion increased with increasing Dyneema content in the fabric.
7. Water vapor diffusion resistance showed an inverse relationship with air permeability in both day and wet states.
8. Dyneema content did not show a major influence on the heat energy dissipated though the fabric. This is true for both dry and wet energy dissipations. This is also true for dissipations occurring under contact and non-contact conditions.

Recommendations for Future Work

Based on the results obtained for the different yarns and fabrics, and the experience gained in processing the yarns and fabrics, we believe that there is scope for additional work. Following are some specific suggestions for additional work:

1. Since yarns and fabrics can be produced at higher production rates using the processing parameters (speeds, settings, twist levels, machine efficiencies, etc.) applicable for 100% cotton when the composition of Dyneema is less than 6%, it is worthwhile to produce yarns and fabrics containing less than 10% Dyneema, and compare their properties with that of other yarns/fabrics.
2. Dyneema can be incorporated in the yarn in the form of a core filament at the ring spinning stage, virtually eliminating all the processing problems. Properties of the filament-cored yarns and fabrics can be compared with that of staple fiber yarns and fabrics.
3. The stress-strain behavior of the Dyneema fiber/filament can be modified to match that of cotton to achieve even better compatibility in the mechanical behavior of the two components, and hence even better durability properties.

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