Studying the Mechanical Properties of Blended Fibrous Structures Using a Simple Model

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Textile Research Journal 2000; 70; 502
DOI: 10.1177/004051750007000606

Studying the Mechanical Properties of Blended Fibrous Structures Using a Simple Model

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ABSTRACT

A simple theoretical model is proposed for studying the properties of blended fibrous structures. The model is verified using experimental results from blended yarns. The effect on a blended system's properties due to interactions of the different constituents in the blended structure is analyzed, and the parameters influencing these interactions are revealed and discussed. A systematic dimensionless analysis is carried out, and the applicability of the model to predict the relationship between the optimal twist factor and the blend ratio for a blended yarn is also examined.

Fiber blending has been a common practice in the textile industry for a long time, stimulated to a great degree by the availability of an ever-increasing number of man-made fibers. Fiber blending can achieve quality products that cannot be realized using one fiber type alone, and it can also reduce the cost by substituting a less expensive fiber for a more costly one.

Research on blended textiles has focused mainly on blended yarns [1, 2, 3, 6, 8, 10, 11]. One interesting observation in these investigations is the effect caused by the interactions of the different fiber types in these structures. For example, Kemp and Owen [3] studied the strength and mechanical behavior of nylon/cotton blended yarns, and they found that a dependence exists between the behavior of the two fiber types: the cotton fibers in the blended yarn break at strains considerably less than the breaking strain of an all-cotton yarn. In earlier work (Monego and Backer [6] and Pan *et al.* [9]), we developed a series of experiments and computer models to explore the reinforcing mechanism of fiber blending, and the effect of twist-generated interactions of the different constituent fibers on the strength and fracture behavior of the blended yarns. Pan and Postle [10] recently completed a theoretical analysis of interfiber interactions and their effects on the strength of blended yarns.

Predicting the properties of blended or mixed materials has a theoretical and practical significance that is not limited just to the textile field. In general, if a material is a mixture of more than one constituent component, the overall properties of the blended system are obviously related to the relative proportion and corresponding properties of each component. Also, if the mixture is not uniform, the distribution or local concentration of each constituent plays an important role in determining some aspects of the system's behavior. The remaining factor has to do with the interactions of the components themselves, which complicate an otherwise much simpler relationship between the blend system and its component properties.

Therefore, if we can find a general model that is simple but contains all the factors listed above, *i.e.*, the relative proportions and properties of the components and their interactions, we will then be able to study the blend system's properties and avoid the complex mathematical and mechanistic analysis normally required for modeling the mechanical behavior of a blended material. The work presented in this paper is just such an attempt. Although we use blended yarns as examples, the technique and some of the conclusions should also be applicable to other blended products or systems.

A Prediction Model

Many properties of a material mixed or blended from two or more different components can be calculated

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  0040-5175/$2.00

using the simple rule of mixtures (ROM); such properties include the elastic moduli, electrical and thermal conductivities, dielectric constant, and thermal expansion coefficient [7]. However, there are other properties of a material, like its overall strength or electric lifetime, which are influenced by the interactions of the different components in the system and therefore cannot be accurately predicted by the simple ROM; thus a more sophisticated model is needed. According to Nielsen [7], if we have a mixture of two different constituents, types 1 and 2 in general, the system property X_s can be calculated by a generalized ROM:

$$\begin{aligned} X_s &= X_1 W_1 + X_2 W_2 + I W_1 W_2 \\ &= X_1 W_1 + X_2(1 - W_1) + I W_1(1 - W_1) \quad , \end{aligned} \tag{1}$$

where X_i and W_i are the corresponding property and the fraction (it can be weight, volume, or other fractions depending on the problem, but in this study, we use volume fraction because the results are good) of the constituent $i = 1$ and 2, and I is a coefficient representing the intensity of the interactions of the two constituents. There are three cases based on the value of I: for $I > 0$, the interactions of constituents 1 and 2 will enhance the overall system property and lead to a synergetic effect, $I < 0$ represents a case where the interactions actually reduce the system property, and $I = 0$ means that the interactions do not exist so that Equation 1 degenerates into the simple ROM. One expression for I can be written as

$$\begin{aligned} I &= 4X_{50\%} - 2(X_1 + X_2) = 4[X_{50\%} - 0.5(X_1 + X_2)] \\ &= 4[X_{50\%} - \langle x \rangle] = 4\Delta X \quad , \end{aligned} \tag{2}$$

where $X_{50\%}$ is the actual system property X_s when $W_1 = W_2 = 0.5$, and $\langle X \rangle = 0.5X_1 + 0.5X_2$ is the arithmetic mean of the property for homogeneous constituents composed of X_1 and X_2 alone. That is, if there are no interactions of the two constituents, there will be $X_{50\%} = \langle X \rangle$, so that $\Delta X = 0$ and $I = 0$. Otherwise, we will see either the synergetic or reduced overall result due to the interactions.

There is another way to specify this alternation of the system's overall properties caused by the interactions of the different constituents by using the concept of the hybrid effect. One definition of the hybrid effect is given by Marom *et al.* [4] as the deviation of behavior of a hybrid structure from the ROM. A positive hybrid effect means the synergetic case, and the actual property is above the ROM prediction, whereas a negative hybrid effect means the property is below the prediction. Therefore, numerically, the value of ΔX can be used to indicate the hybrid effect and can be written from Equation 2 as

$$\Delta X = X_{50\%} - \langle X \rangle = X_{50\%} - (0.5X_1 + 0.5X_2) \quad . \tag{3}$$

Experimental Verifications of the Model

We have obtained data to verify this model from two sets of yarn samples in this study. The first set was made from polyamide 66 (nylon 66) and polypropylene (PP) filaments whose properties are shown in Table I ; both were supplied by BASF. Each yarn sample consists of ten filaments. By altering the numbers of nylon 66 and PP filaments, we could adjust the blend ratio of each yarn. The yarns were twisted to different degrees according to experimental design. The extent of twisting on a yarn depends on two variables, *i.e.*, the number of twists per length and the thickness of the yarn. We used the yarn twist factor (TF) here to reflect the joint effect of the two variables, *i.e.*,

$$TF = \frac{\text{twist}}{\text{cm}} \sqrt{\text{tex}} \quad . \tag{4}$$

The yarn samples were tested on an Instron tester according to ASTM D2256-80, and each data point was a result averaged over at least eight tests.

TABLE I. Fiber properties.

	Thickness, tex	Initial modulus E_f, GPa	Tenacity σ_b, GPa	Breaking strain ϵ_b, %
Nylon 66	0.24	4.84	0.55	30.66
PP	0.43	4.46	0.36	17.72
PET	7.78	5.74	0.38	24.10
Cotton	7.44	2.12	0.25	7.34

The second data set came from our earlier experimental work [5, 6]. Each yarn sample consisted of 91 components, either cotton yarns or polyester (PET) filament yarns, drawn from independent packages in a creel and twisted carefully with negligible radial migration. The properties of both PET and cotton components can also be seen in Table I. The 91 components were distributed in five helical layers about a central or core yarn. A range of such yarns varied from 0% to 100% for cotton composition (100% to 0% for polyester) with a twist factor ranging from about 5.0 to 45.0.

For the first data set, we chose the nylon 66 fiber as the reinforcing fiber, and its volume fraction was therefore designated as W_1. For the second set, the PET component was the reinforcement.

TABLE II. Testing results for the first set of blended yarns $\left(\frac{g}{tex}\right)$.

	Twist factor						
	0.0	5.0	10.0	12.5	15.0	17.5	20.0
Ny66 = 100%	45.50	45.70	47.80	48.00	49.40	50.20	50.40
80%	42.20	43.30	45.00	44.10	46.60	45.90	47.50
60%	39.60	40.90	43.30	44.10	44.20	44.20	42.90
40%	38.00	38.60	41.00	40.40	41.30	41.70	38.00
20%	37.50	38.80	38.80	41.70	39.40	38.80	35.50
PP = 100%	31.10	32.30	37.50	37.20	35.80	35.30	34.90
$X_{50\%}$[a]	38.80	39.75	42.15	42.25	42.75	42.95	40.45
$\langle X \rangle$	38.30	39.00	42.650	42.60	42.60	42.75	42.65
ΔX	0.5	0.75	−0.5	−0.35	0.15	0.2	−0.2

[a] Estimated from interpolation.

THE TENSILE STRENGTH INVESTIGATION

We could focus on either tensile modulus, or tenacity or breaking strain of the yarns as the system property for our study, and we chose yarn tenacity or strength for easy determination. The strengths of the yarn samples at different twist factors and blend ratios are provided in Tables II and III for the two sets of yarns. In the tables, the values of ΔX defined in Equation 3 are also included.

TABLE III. Testing results for the second set in $\frac{g}{tex}$.

	Twist factor				
	5.17	10.34	20.77	31.10	41.53
PET = 100%	42.02	44.56	44.56	43.47	42.75
98.9%	42.35	41.98	41.98	40.54	40.17
97.8%	41.73	41.95	41.58	41.95	41.95
89%	38.42	38.78	39.49	38.06	37.70
78%	34.16	35.23	34.88	33.95	32.03
67%	29.49	29.63	29.77	30.34	27.87
56%	25.53	25.88	27.00	27.98	26.79
44%	22.17	23.91	25.36	25.98	23.91
33%	20.27	22.12	23.70	23.36	20.95
11%	19.25	20.94	21.96	24.15	22.97
Cotton = 100%	17.82	20.10	22.11	23.45	23.45
$X_{50\%}$[a]	23.85	24.90	26.18	26.98	25.85
$\langle X \rangle$	29.92	32.33	33.34	33.46	33.10
ΔX	−6.07	−7.43	−7.16	−6.48	−7.25

[a] Estimated from interpolation.

To illustrate the relationship between yarn strength and fiber blend ratio, Figure 1 is plotted using the data in Table II at $TF = 10$, for which the value of ΔX is negative. As stated above, a negative ΔX means that the interactions of the two fiber types cause a reduction in the system property. There are two curves in addition to the experimental data in Figure 1: one is based on Equation 1 in our model and the other is based on the simple ROM. Therefore, corresponding to a negative ΔX, the predic-

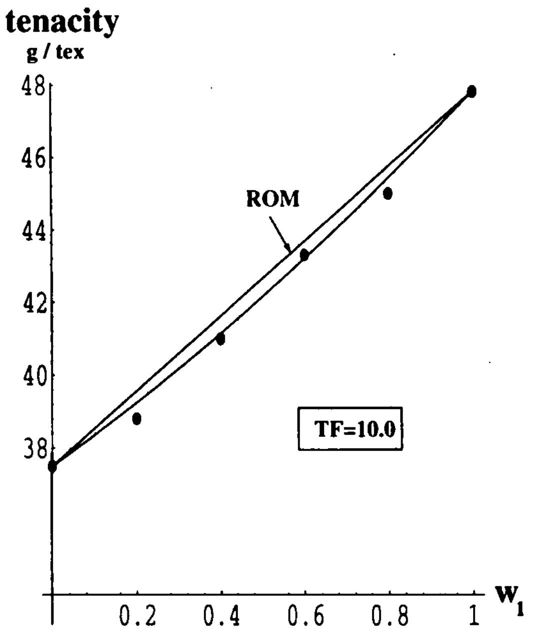

FIGURE 1. Tenacity versus blend ratio W_1 for the first set of yarns. Comparison of predictions by our model and by the ROM and the experiments for 10.0 twist factor.

tions from our model will be below the ROM results. In general, based on the figure we can conclude that our overall predictions are closer to the experiments than the results from the ROM. Also, for this set of yarns, the hybrid effects we observed, as reflected by the ΔX values in Table II, are not substantial.

The results from the second set of yarn samples are different. Table III shows that all the values of ΔX are negative with greater magnitudes than those in Table II. We first plotted Figure 2 with the data from Table III at $TF = 5.17$. Again, our model yielded better predictions than the ROM shown in the figure, and the fit with the experiments was also very good. Because of the greater magnitude of ΔX in this case, there was a much bigger

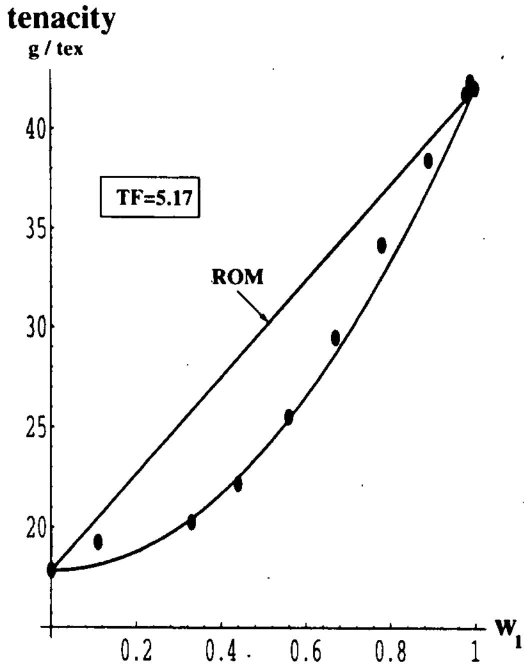

FIGURE 2. Tenacity versus blend ratio W_1 for the second set of yarns. Comparison of predictions by our model and by the ROM and the experiments for 5.17 twist factor.

gap between the two curves from our model and from the ROM. In other words, considerable hybrid effects exist in the data. We should mention that the original unit for the data in Table III was breaking load in pounds. When we used the same data before converting the unit into g/tex, the fit between the predictions and the experimental data was not good at a W_1 range from 0.6 to 0.9. A likely explanation for the better fit in g/tex is that when determining W_1, we have taken fiber thickness in tex into account. So by converting the strength unit into g/tex, we have made all the units in Equation 1 consistent.

To further analyze the data, we normalized the results in two ways. First, we divided all the data by the strength X_2 of the yarn of 100% weaker fiber type, *i.e.*, the PP fiber for the first set and the cotton component for the second set of yarns. This way, results actually represent the net increase in yarn strength when the reinforcing fiber is incorporated. Equation 1 thus changes to

$$X_{sn} = \frac{X_s}{X_2} = \frac{X_1}{X_2} W_1 + (1 - W_1) + \frac{I}{X_2} W_1(1 - W_1) \quad . \quad (5)$$

Figure 3 is generated using the new data calculated from Table III for the second set of yarns at three different twist levels. Each curve in the figure depicts the relationship between the strength reinforcing effect and the composition of the reinforcing fiber type at a given twist level. Because of the way the data are normalized, one would think the effect of twist, as represented by X_2, has been more or less eliminated from the data. Still, the three curves in Figure 3 have quite different paths, corresponding to different twist levels. To overcome that, we then tried another way by normalizing all data with respect to $X_{50\%}$. We thus obtained another result for the relative system property:

$$X_{sn\%} = \frac{X_s}{X_{50\%}} = \frac{X_1}{X_{50\%}} W_1 + \frac{X_2}{X_{50\%}} (1 - W_1) + \frac{I}{X_{50\%}} W_1(1 - W_1) \quad . \quad (6)$$

Since the data $X_{50\%}$ include the effects of both twisting and interactions, these effects will be largely removed from the new results. Therefore, we will expect more agreement between the curves at different twist levels. Figure 4 confirms that: with the same set of yarns, the curves corresponding to different twist levels are now much closer to each other. This implies that Equation 5 could be used to predict the properties (tensile strength in this case) of blend yarns made from the same fiber types regardless of their twist levels. A comparison of Figures 3 and 4 reveals the importance of interfiber interactions reflected by $X_{50\%}$ in determining yarn strength.

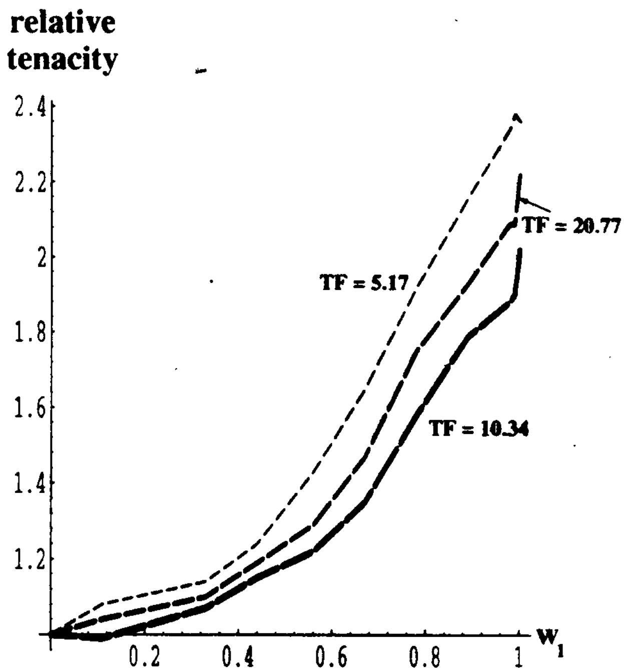

FIGURE 3. Relative tenacity (normalized by X_2) versus blend ratio W_1 for the second set of yarns. Comparison of experiments at three twist levels, TF = 5.17, 10.34, and 20.77.

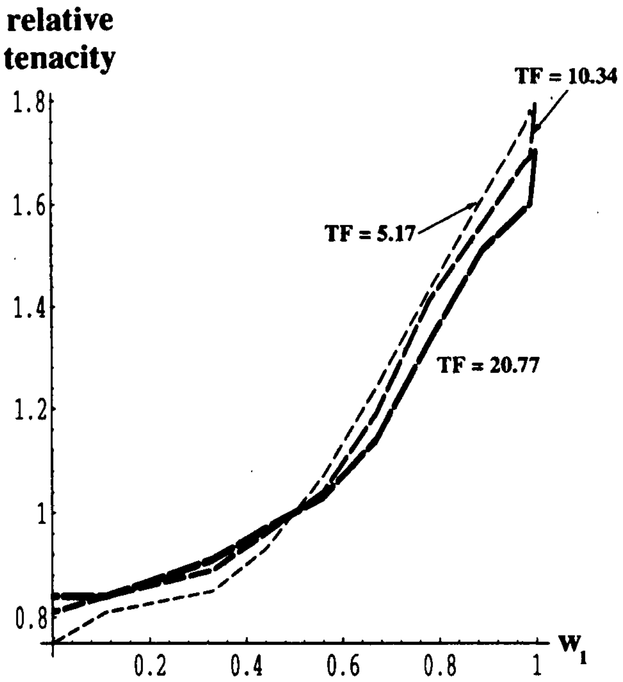

FIGURE 4. Relative tenacity (normalized by $X_{50\%}$) versus blend ratio W_1 for the second set of yarns. Comparison of experiments at three twist levels, TF = 5.17, 10.34, and 20.77.

MORE ON THE HYBRID EFFECTS

As seen above, the two sets of yarns tested in this study have demonstrated different behaviors in terms of ΔX values or hybrid effects. For the first group, the hybrid effects are much smaller than those for the second group. To explain the differences, we turn to an earlier publication (Pan and Postle [10]). In that paper, they predicted that increasing the tensile modulus ratio $\frac{E_{f1}}{E_{f2}}$ of the two fiber types in a blended yarn would lead to a more significant hybrid effect. If we check the fiber data in Table I, we see that the ratio $\frac{E_{f1}}{E_{f2}} = 1.09$ for the first set of yarns is lower than $\frac{E_{f1}}{E_{f2}} = 2.71$ for the second set. This accounts for the difference in the hybrid effects of the two groups of yarns.

THE OPTIMAL TWIST FACTOR

It is well known that there is an optimal twist level at which yarn strength will reach its maximum. What we were interested in was the effect of fiber blending on this optimal twist level. In other words, we would like to see if the original optimal twist level will be altered by adding another fiber type into the yarn structure. Furthermore, if fiber blending does indeed change the optimal twist, is the new optimal twist, like yarn strength, a function of the blending ratio and is it possible for us to predict this relationship using Equation 1? For this purpose, we constructed Tables IV and V as well as Figure 5 from our experimental results showing the relationship between blend ratio and optimal twist factor for the blend yarns. It is clear from both curves, however, that there is no definite trend in the changes of the optimal twist factor as we alter the blend ratio W_1, and what the data show is just a random pattern. Obviously this relationship between blend ratio and optimal twist factor cannot be predicted by Equation 1. This may reflect interactions within the blended yarns, including load sharing and dynamics that impact on the system fracture.

TABLE IV. Blend ratio and optimal twist factor TF_{opt} for the first yarn set.

	TF_{opt}
Ny66 = 100%	25.0
80%	30.0
60%	17.5
40%	17.5
20%	12.5
PP = 100%	30.0

TABLE V. Blend ratio and optimal twist factor TF_{opt} for the second yarn set.

	TF_{opt}
PET = 100%	20.77
98.9%	5.17
97.8%	41.53
89%	39.49
78%	10.34
67%	31.10
56%	31.10
44%	31.10
33%	20.77
11%	31.10
Cotton = 100%	41.53

This change of optimal twist factor with blend ratio has its practical significance. If we intend to increase yarn strength by adding reinforcing fibers, yarn strength may not increase as much as we expect at the original optimal twist factor; it may take much less or much more twist to reach the new optimal level, as indicated by the data in the tables.

Note, though, that when we change the blend ratio by increasing the composition of another fiber type, we may more or less alter the thickness of the yarn as well, possibly leading to changes in the optimal twist factor, which might contribute to irregularities in the relationship. However, we do not have any reported evidence

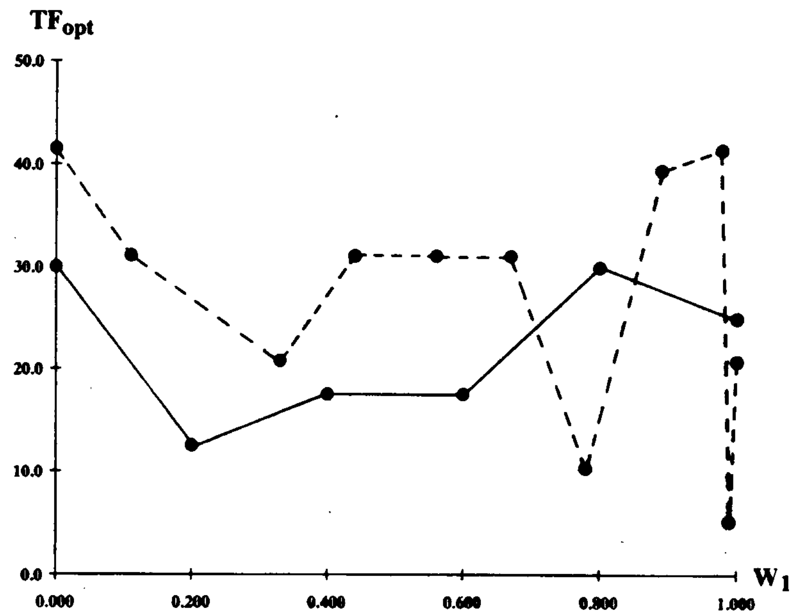

FIGURE 5. Optimal twist factor versus blend ratio W_1 for the two sets of yarns. Solid line = yarn set 1, dotted line = yarn set 2.

that changing the thickness of a yarn changes its optimal twist factor.

Finally, note that Equation 1 is probably more useful for studying the interactions in a blended system than for predicting the system's properties, although the latter can be readily done when all required information is available, as is the case in our work.

Conclusions

We have demonstrated in this work that Equation 1 is a simple and useful tool for investigating the effects of interactions of different constituents in a blended system. Our study has also yielded several interesting findings. Depending on the nature of these interactions of the different fiber types in blended yarns, the mechanical behavior of the structures can be classified into three groups, *i.e.*, those with positive, negative, or zero hybrid effects, respectively. The nature and results of the interactions of different fiber types are determined by their properties, such as the tensile modulus. For each group, a generalized dimensionless equation can be used for relative property prediction, regardless of the twist levels. The optimal twist factor changes at different blend ratio levels, but there is no definite trend between the two variables.

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Manuscript received December 11, 1998; accepted April 9, 1999.