Theoretical and Practical Analysis of Fiber Blend Model in Gray Spun Yarn

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ABSTRACT
The final color of blend yarns is dependent on the proportion of the various colored fibers used in colored spun yarns. How to scientifically and effectively quantify the relationship between the proportion of different colored fibers and the color of the yarn is a major problem hindering the development of color spinning technology. This paper suggests three methods for analyzing and comparing the color of gray spun yarns. A color match software, Datacolor Match, was used to calculate a recipe simulating the match of dyes; the a predicting formula based on color mixing model of Kubelka-Munk (K-M) double-constant theory for fiber blends was established. Finally, the colored fiber formula based on the known reflectance curve was calculated according to the relationship between the reflectance value of gray spun yarn and proportion of colored fiber present. This work provides an understanding of colored spun yarn fabrication.

Keywords: gray spun yarn; fiber; blend; match; model

INTRODUCTION
A predictive formula for matching a given color standard by blending colored fibers would have considerable importance in the textile industry. At present, most yarn manufacturers, especially small and medium enterprises using traditional artificial color match methods and no color match equipment have low production efficiency.

Generally, existing color mixing theories include three theories– the Stearns-Noechel model, the Friele model and the Kubelka-Munk theory. The first two models have derived functions of reflectance which have an approximately linear relationship with fiber mass in a blend. In both cases, however, numerical constants must be empirically fitted for the fiber system being used [1, 2, 3, 4]. In this paper, the relationship between reflectance and colored fiber mass proportion in a blend will be employed once again. In 1931, Kubelka and Munk proposed the first thorough mathematical treatment of a system simultaneously absorbing and scattering light, known as the Kubelka-Munk theory [5]. Burlone reported that the double-constant Kubelka-Munk theory was sufficiently accurate for color prediction of blends and mixing pigments in the paint industry [6, 7]. Later Walowit et al published work dealing with the determination of the Kubelka-Munk absorption and scattering coefficients for fibers on the basis of a least-squares algorithm [8]. Burlone found that the best color-matching accuracy was obtained using a double-constant Kubelka-Munk procedure whose formula color differences averaged 1.6 CIELAB units. Formula color matches averaged 2.4 CIELAB units using the Stearns-Noechel method and 2.7 CIELAB units for the Friele method [9]. Allen limited the number of colored fibers to four for the double-constant theory. This was improved by S. H. Amirshahi by applying the pseudoinverse algorithm [10]. Thus, K-M theory is chosen to give a formula contrast. In addition, the mixed rule method is studied using theoretical and experimental methods.

MATERIALS AND METHODS
Materials
Four types of non-fluorescent fibers were used in the experiments- black viscose fiber A, black viscose fiber B, white viscose fiber C and white polyester fiber D. The colorimetric coordinates of the fibers are shown in the *Table I*.

TABLE I. Colorimetric coordinates of the four kinds of colored fibers used in the experiment.

	*L**	*a**	*b**	*C**	*h°*
A	12.992	0.018	-0.133	0.135	277.6
B	13.115	-0.003	-2.532	2.532	269.9
C	93.23	0.229	3.049	3.057	85.7
D	92.22	-0.236	2.391	2.402	95.6

Samples prepared for this study were in the state of loose fibers. The samples containing fiber A or fiber C were named single-component gray spun yarns; the sample containing fiber B and D was called double-component gray spun yarn.

Spinning Process for Colored Spun Yarns

The black and white fibers were opened, cleared, and then blended manually to desired proportions. Then the blended fiber tufts were fed into a carding frame. The carding process was repeated three times to insure uniform fiber mixing. Slow speed, strong carding, tight gauge, and low feed rates were used in the carding process. Next, the fibers were pulled into a sliver using drawing frame. A breaker-drawing step and finisher drawing step were used to blend the fiber further and change the wound state of the fibers. Finally, the drawn slivers went through roving and spinning processes to yield final gray spun yarns.

Color Measurement

Before color measurement, the yarn was uniformly wound on a piece of cardboard using a yarn examining machine. On one hand, spun yarns can reflect the color of the colored spun yarn better than the fiber layer or sliver. On the other hand, yarn measurement reduces the workload of weaving fabric- weaving structure, thickness, fabric tightness and other parameters can affect the color values. A Datacolor SF600 spectrophotometer, with large aperture (30mm), bright luster, 100% UV (filters off), and D65, 10 Degrees, was used to measure the reflectance values (R) of each sample at wavelengths between 360 and 700nm using 10nm intervals at room temperature. Each sample was measured at least 8 times in different directions (horizontal and vertical) and positions. Color differences were expressed in 1976 CIELAB units and CMC (2:1) units [11].

Reflectance Values of Samples

The reflectance values of gray spun yarns containing different mass proportions of black fibers are shown in *Table II* and *Table III*, *Figure 1* and *Figure 2*.

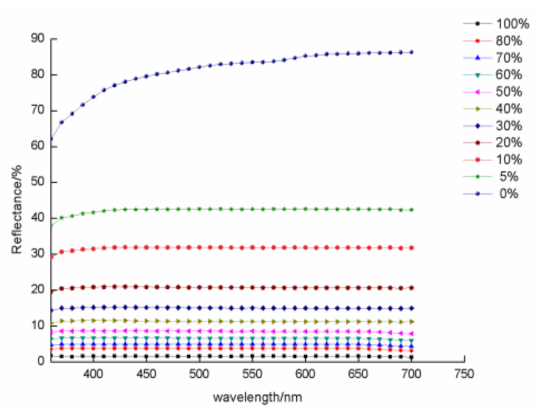

FIGURE 1. Comparison of Reflectance curves for single-component gray spun yarn with different proportion of black fiber.

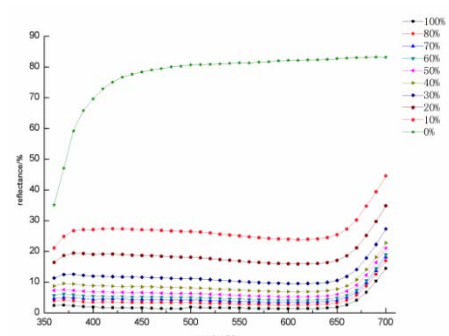

FIGURE 2. Comparison of Reflectance curves for double-component gray spun yarn with different proportion of black fiber.

TABLE II. Reflectance (%) value for single-component gray spun yarn with different proportion of black fiber.

Black fiber proportion C/%	Wavelength/nm						
	400	450	500	550	600	650	700
0	73.85	79.57	82.16	83.52	85.26	85.95	86.28
10	31.53	31.91	31.93	31.87	31.88	31.85	31.79
20	20.86	20.87	20.78	20.7	20.68	20.66	20.61
30	15.19	15.16	15.07	15.01	14.99	14.97	14.93
40	11.52	11.41	11.33	11.25	11.22	11.21	11.17
50	8.66	8.61	8.57	8.54	8.5	8.5	7.9
60	6.64	6.64	6.6	6.59	6.57	6.56	5.95
70	4.94	4.94	4.93	4.93	4.9	4.9	4.29
80	3.69	3.71	3.71	3.72	3.7	3.7	3.09
100	1.57	1.55	1.59	1.57	1.55	1.57	1.35

TABLE III. Reflectance (%) value for double-component gray spun yarn with different proportion of black fiber.

Black fiber proportion C/%	Wavelength/nm						
	400	450	500	550	600	650	700
0	69.58	78.33	80.64	81.3	82.12	82.67	83.13
5	39.23	39.99	39.55	38.07	36.92	38.5	56.81
10	27.06	27.04	26.46	25.04	23.94	25.41	44.53
20	19.02	18.67	18.09	16.87	15.95	17.07	34.83
30	11.94	11.56	11.12	10.22	9.54	10.54	27.28
40	8.82	8.47	8.12	7.41	6.87	7.69	22.75
50	6.83	6.53	6.28	5.68	5.23	5.98	21.08
60	5.37	5.14	4.93	4.44	4.06	4.75	18.94
70	4.38	4.34	4.21	3.75	3.41	4.07	18.07
80	3.39	3.37	3.26	2.86	2.59	3.2	16.93
100	1.81	1.54	1.81	1.54	1.34	1.88	14.46

Color Matching

Datacolor MATCH software was used for this purpose.

RESULTS AND DISCUSSION

Good color-matching accuracy was obtained, as shown in *Table IV*, but as shown in the *Figure 3*, the color difference values in the sixth column of *Table IV* were obviously larger than those in the third column of *Table IV.* This can be explained by the fact that that the data used in the original software calculation would get better final matching results. The algorithm of dye mixing can be used in color matching of fiber blends to a certain extent, so color mechanisms of blended colored fibers and mixing pigments in the paint industry should be based on the K-M double-constant theory.

In *Table III*, those groups in which the black fiber mass proportions in the first column were saved and calculated by the match software, the others were not.

TABLE IV. Prediction formula based on data color match of single-component colored spun yarn.

Blend composition (black/%)	Prediction formula (%)	Color difference (CMC(2:1) units)	Blend composition (black/%)	Prediction formula (%)	Color difference (CMC(2:1) units)
10	10.0154	0.01	5	5.0020	0.00
20	20.0000	0.00	15	15.8098	0.33
30	30.0101	0.00	25	25.5466	0.18
40	39.9952	0.00	35	33.6997	0.38
50	49.9890	0.00	45	45.6313	0.17
60	60.0042	0.00	55	57.1442	0.55
70	69.9999	0.00	65	63.3655	0.44
80	79.9997	0.01	75	76.8087	0.53
90	89.9739	0.01	85	84.1261	0.30

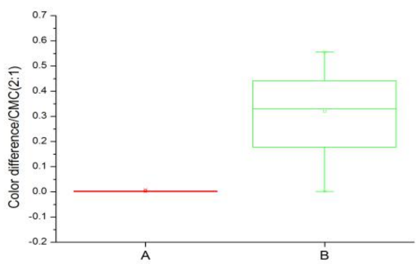

FIGURE 3. The range of the color differences with different proportion of black fiber.

In *Figure 3,* A refers to the data in the third column of *Table IV and* B refers to the data in the sixth column of *Table IV.*

COLOR MATCHING BASED ON K-M DOUBLE CONSTANT THEORY

Kubelka and Munk carried out a simplified analysis of the interaction of incoming light with a layer of material such as a layer of paint. The material is assumed to be uniform, isotropic, non-fluorescent, non-glossy and the sample has to be illuminated by diffuse light. As the basic theory for color mixing in intensely light-scattering materials, the Kubelka–Munk single-constant and double-constant theories have played an important role in color science and technology. The former is mainly used for dye color matching but it does not yield good results when applied to fiber blends [12]. The double-constant theory demonstrated much better results when applied to fiber blends [13]. Therefore, this paper adopted double-constant theory to study fiber blends. A detailed description of the K-M theory can be found in the literature [14, 15]. The equations from the K-M theories were used in this paper as listed below.

According to the K-M theory, the relationship between the absorption and scattering of incident light by a turbid material can be expressed as

$$K/S = \frac{(1-R)^2}{2R} \quad (1)$$

In Eq. (1), R is the reflectance of a sample at different wavelengths from 360nm to 700nm; K is the K-M absorption coefficient (cm^{-1}) of the material at different wavelengths; S is the K-M scattering coefficient (cm^{-1}) of the material at different wavelengths. Thus, the K-M theory and Eq. (1) build a bridge between the reflectance R and K/S value of yarn using the two constants, K and S of each fiber. According to the K-M double-constant theory, the following relationship was established：

$$(K/S)_m = \sum_{i=1}^{n} C_i K_i / \sum_{i=1}^{n} C_i S_i \quad (2)$$

Where $(K/S)_m$ is the ratio of blend's absorption and scattering coefficients. This can also be obtained through Eq.(1). C_i is the ith fiber mass proportion; K_i is ith fiber absorption coefficient; S_i is the ith fiber scattering coefficient; n is the number of types of colored fibers.

If two kinds of fibers were mixed, then,

$$(K/S)_m = (C_1K_1 + C_2K_2)/(C_1S_1 + C_2S_2) \quad (3)$$

Further

$$-C_1K_1 - C_2K_2 + C_1(K/S)_m S_1 + C_2(K/S)_m S_2 = 0 \quad (4)$$

There are four variables of K_1, K_2, S_1, S_2 in Eq. (4). In theory, as few as four equations can be used to obtain the solution. For accurate results, more than four equations were used in this study, and the least-squares algorithm can yield the approximate solution of the equation. There are many factors that may influence the K value and S value substantially, such as the number of equations and the chosen proportion of colored fibers in the equation [16]. It was found that more equations and a wider range of colored fiber proportions yielded more accurate solutions. Thus in the experiments, white and black fibers were mixed in different proportions. Black fiber addition levels of 0, 5, 10, 20, 30, 40, 50, 60, 70, 80 and 100 percent were used. Using the measured reflectance values of the yarns, the K/S values can be obtained according to Eq. (1). According to Eq. (4), the monochrome fiber absorption and scattering coefficients under different wavelengths can be obtained.

DATA ANALYSIS

The experimental results are shown in *Table V,* in and the third and sixth columns are plotted in *Figure 4.* In *Table IV*, those groups with black fiber mass proportions in the first column were saved and calculated by the match software, the others were not.

TABLE V. The formula based on k-m double-constant theory and least-squares algorithm of single-component colored spun yarn.

Blend composition (black/%)	Prediction formula (%)	Color difference (CMC (2:1) units)	Blend composition (black/%)	Prediction formula (%)	Color difference (CMC (2:1) units)
10	10.0312	0.02	5	4.6403	0.24
20	20.7832	0.28	15	16.3214	0.53
30	30.6439	0.19	25	26.2026	0.39
40	40.3941	0.11	35	34.2041	0.23
50	50.5509	0.14	45	45.9829	0.26
60	59.9107	0.02	55	56.7607	0.46
70	70.1138	0.03	65	64.4019	0.16
80	79.2816	0.22	75	75.6121	0.18
90	90.1131	0.04	85	84.4419	0.19

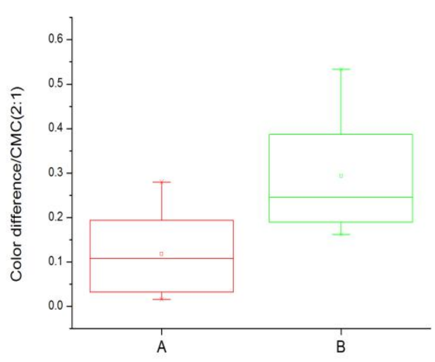

FIGURE 4. The range of the color differences with different proportion of black fiber.

In *Figure 4*, A refers to the data in the third column of *Table V* and B refers to the data in the sixth column of *Table V.*

RESULTS AND DISCUSSION

The data in *Table V* showed for single-component fiber blending that when the actual black fiber mass proportion was 15 percent, the method yielded a predicted level of 16.32 percent, the maximum error obtained. To assess the color difference between the two, samples with black fiber add levels of 15 percent and 16.32 percent were generated and analyzed using the Datacolor Tools software. Color difference of 0.65 ClELAB units between the two samples resulted. This relatively small difference in the two results is encouraging. On the whole, good color matching accuracy was obtained using a K-M double-constant theory.

From the plot in *Figure 5*, there is a good curve relationship between K/S value and fiber proportion when the colored fiber proportion are low (less than 30 percent) at different wavelengths.

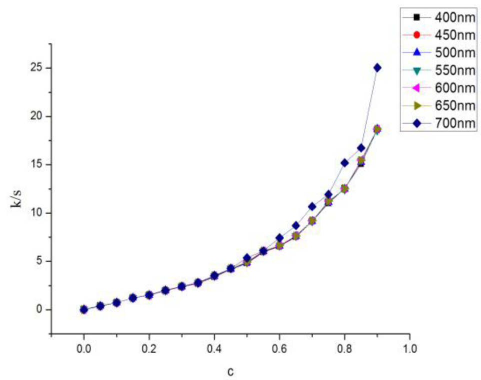

FIGURE 5. Relationship between K/S value and black fiber proportion at different wavelengths.

This relationship does not exist when the colored fiber proportion was high. The seven correlation coefficients were 0.99717, 0.99704, 0.99732, 0.9927, 0.99631, 0.99715, 0.99271. It provided a convenient and efficient matching basis for small-proportion colored spun yarn spun from blends of two fibers.

COLOR MATCHING BASED ON REFLECTANCE-COLORED FIBER MASS PROPORTION FITTING

There is a well-known relationship between concentration of dyes in fabrics and the reflectance of the dyed sample. A similar relationship was expected to exist between the reflectance of colored spun yarns and the proportion of colored fiber in the yarns. It was found that at a given wavelength the reflectance of yarn and the proportion of the colored fiber are related with a correlation coefficient from 0.99 to 1.

The index of the relationship was expressed as:

$$C(\lambda) = m_1 e^{m_2 R(\lambda)} + m_3 e^{m_4 R(\lambda)} \tag{5}$$

$$R(\lambda) = m_1 e^{m_2 C(\lambda)} + m_3 e^{m_4 C(\lambda)} \tag{6}$$

In the Eq. (5) and Eq. (6), the *R(λ)* is the reflectance value of a blend at λ wavelength; *C(λ)* is the proportion of the colored fiber of the blend at λ wavelength; and m_i is a coefficient obtained using the inline function in MATLAB.

When the actual R values from 400nm to 700nm (10nm intervals) of a blend are obtained, the fitting proportions *C(λ)* can be computed using Eq. (5).

Because there are 31 real *R(λ)* values from 400nm to 700nm (10nm intervals), the fitting *C(λ)* also will be 31, so the final fitting proportion C of the colored fiber can be obtained using the equation following:

$$C = \frac{\sum_{\lambda=400}^{700} C(\lambda)}{31} \tag{7}$$

When the fitting *C(λ)* from 400nm to 700nm (10nm interval) are known, the fitting *R(λ)* from 400nm to 700nm (10nm interval) can be calculated with Eq. (6).

The color difference, ΔL, ΔC, ΔH, and other data between the real R and fitting R also can be obtained using the color difference equation in MATLAB.

Some of the fitting curves between *R(λ)* and *C(λ)* obtained with the Eq. (5) are shown in the *Figure 6*, Some of the fitting curves between *C(λ)* and *R(λ)* obtained with the Eq. (6) are shown in the *Figure 7*.

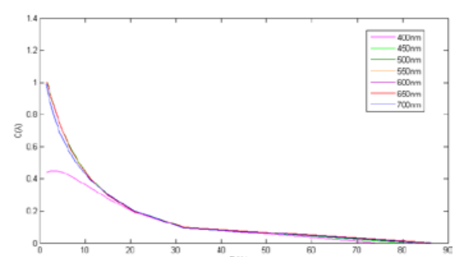

FIGURE 6. Relationship between reflectance values *R(λ)* and the black fiber proportions *C(λ)* at different wavelengths.

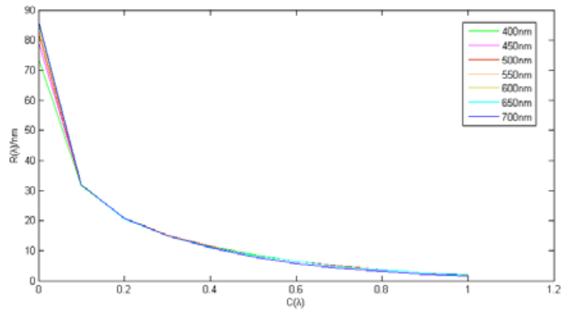

FIGURE 7. Relationship between the black fiber proportions *C(λ)* and reflectance values *R(λ)* at different wavelengths.

DATA ANALYSIS

According to the above method, using the fitting formulas in *Table V*, the range of the color differences are shown in *Figure 7*. From *Table VI*, black fiber mass proportions in the first column were saved and calculated by the match software, the others were not.

In *Figure 7*, A refers to the data of the third column of the *Table VI*, B refers to the data of the sixth column of the *Table V.I*

TABLE VI. The formula based on reflectance-colored fiber proportion fit of single-component colored spun yarn.

Blend composition (black/%)	Prediction formula (%)	Color difference (CMC(2:1) units)	Blend composition (black/%)	Prediction formula (%)	Color difference (CMC(2:1) units)
10	9.84	0.78	5	5.1	0.93
20	20.12	0.73	15	16.42	0.83
30	29.95	0.37	25	25.5	0.56
40	39.86	0.18	35	33.55	0.24
50	50.26	0.09	45	45.61	0.14
60	59.89	0.09	55	56.75	0.06
70	70.32	0.21	65	64.49	0.15
80	79.54	0.29	75	76.06	0.25
90	90.09	0.29	85	84.93	0.29

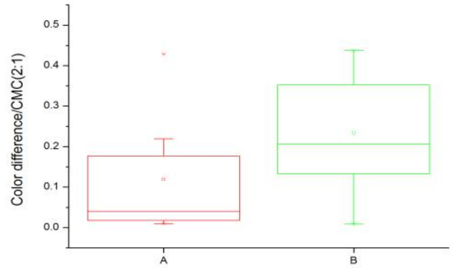

FIGURE 7. The range of the color differences with different proportion of black fiber.

RESULTS AND DISCUSSION

This method based on reflectance-proportion of black fiber fitting yields satisfactory results when the fitting correlation coefficients between reflectance values R and black fiber mass proportions C are higher (0.9~1). Similar drawbacks associated with the previous two methods remained for the following reasons:

(1) Fiber mixing uniformity in the spinning process of yarns with small colored fiber proportion;
(2) Fibers of black and white loss unevenness in the spinning process;
(3) Three kinds of yarn unevenness, such as uneven twist, uneven fineness, and uneven weight. All these factors would increase error in the data..

In general, the matching results were within acceptable limits.

COLOR MATCHING FOR DOUBLE-COMPONENT COLORED SPUN YARN

Using the method described above, black viscose fiber B and white polyester fiber D were mixed to verify the effectiveness of the three methods for double-component colored spun yarn. Results of the formula predictions for the standards were shown in *Table VII* and *Figure 8*. *Figure 9* shows the color difference range between the single-component formula predictions and the three methods above.

In *Table VII*, the data used in the fitting process of the three methods were the black fiber blend compositions of 10% to 90% (10% interval); the blend compositions of 5% to 85% (10% interval) were not used.

TABLE VII. Formula predictions using three methods for double-component colored spun yarn.

Blend composition (black/%)	Software matching formula(%)	Color difference (CMC (2:1) units)	Formula based on K-M theory and least-square method(%)	Color difference (CMC (2:1) units)	Formula based on reflectance-proportion of black fiber fitting(%)	Color difference (CMC(2:1) units)
5	5.1064	0.09	4.1713	0.78	5.3	0.26
15	16.763	0.85	16.4106	0.63	15.9031	0.43
25	26.7632	0.89	23.2089	0.86	24.4527	0.18
35	33.913	0.4	35.6123	0.44	33.5164	0.68
45	47.1721	0.94	46.8281	0.94	45.7564	0.3
55	53.4608	0.63	54.3157	0.62	56.7517	0.9
65	64.0458	0.66	66.5921	0.75	63.0217	0.84
75	75.921	0.48	76.1829	0.55	76.9118	0.85
85	84.3619	0.49	84.9137	0.15	84.2069	0.58

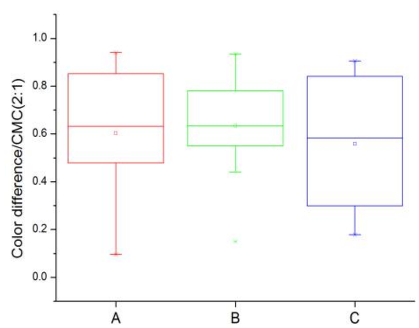

FIGURE 8. The range of the color differences between the R and fitting R' based on different methods.

In *Figure 8*, A refers to the data in the third column of the *Table VII*, B refers to the data of the fifth column of the *Table VII*, *C* refers to the data in the seventh column of the *Table VII.*

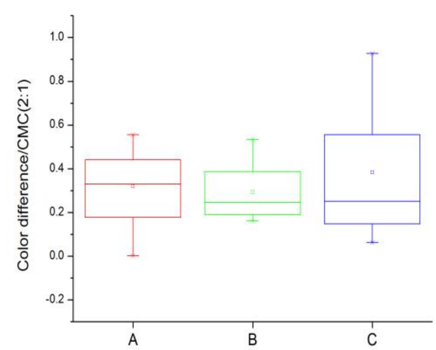

FIGURE 9. The range of the color differences between the R and fitting R' based on different methods.

In *Figure 9*, A refers to the data in the sixth column of the *Table IV,* B refers to the data of the sixth column of the *Table V*, *C* refers to the data in the sixth column of the *Table VI.*

According to *Figure 8* and *Figure 9*, the formula predictions for double-component color spun yarn had almost equally satisfactory but slightly worse results compared to single-component colored spun yarn, due to the differences in fineness, fiber length, fiber crimping and so on between the mixed fibers. These differences caused the fibers arrange differently than the single-component colored spun yarn, resulting in larger formula differences.

In *Table VII*, there were three groups of samples with the highest error. They were the blends with actual black fiber levels of 45, 45 and 55 percent. Mixtures of the black polyester and white viscose were prepared using the predicted levels of 47.1721 percent, 46.8281 percent and 56.7517 percent. Color measurement software gave the color differences between the two. As shown in *Table VIII*.

TABLE VIII. Color differences between different yarns containing different black fiber proportion.

Black fiber proportion (%)	Black fiber proportion (%)	Color difference (CIELAB units)	Color difference (CMC (2：1) units)
45	47.1721	1.43	0.61
45	46.8281	0.82	0.5
55	56.7517	1.57	0.85

THE COMPARISION OF COLOR MATCHING RESULTS AMONG THE THREE METHODS

To compare the differences between the three types of color matching methods (Datacolor MATCH software, K-M double constant theory and reflectance-colored fiber mass proportion fitting) single factor anova analysis was used.

The ‘color matching method’ is the ‘single factor’, the ‘CMC (2:1) values of the blends’ is the subsample. There are 18 CMC (2:1) values for the combined single-component samples from 0.05 to 0.9 (0.05 interval) and 9 CMC (2:1) values for the combined double-component samples from 0.05 to 0.85 (0.10 interval). A summary of the combined single-component and double-component results is shown in the *Table IX*, and the analysis results with the significance level α equals 0.01 were shown in the *Table X*.

TABLE IX. The summary of the combined single-component and double-component.

	Single-component samples				Double-component samples			
Groups	Count	Sum	Average	Variance	Count	Sum	Average	Variance
Software matching	9	2.88	0.32	0.033	9	5.43	0.603	0.074
K-M theory LSF	9	2.64	0.293	0.018	9	5.72	0.636	0.057
Reflectance-proportion	9	3.45	0.383	0.099	9	5.02	0.558	0.076

TABLE X. The analysis results of the combined single-component and double-component.

	Single-component samples						Double-component samples					
Source of Variation	SS	df	MS	F	P-value	F crit	SS	df	MS	F	P-value	F crit
Between Groups	0.04	2	0.02	0.39	0.684	3.4	0.03	2	0.01	0.2	0.82	5.61
Within Groups	1.2	24	0.05				1.66	24	0.07			
Total	1.24	26					1.69	26				

In *Table X*, the P-values of the single-component double-component samples are 0.684 and 0.82 respectively. These are both greater than the significance level α 0.01, indicating no significant difference between the average CMC (2:1) values of single-component samples and double-component samples for the three methods.

CONCLUSION

In terms of gray spun yarn, whether single-component or double-component blends, three methods can be used for color matching with no significant differences between the average CMC (2:1) values. However, these methods have their own limitations. For example reflectance-colored fiber proportion fitting can only apply to two colored fiber blends where fitting correlation coefficients between reflectance values R and the black fiber mass proportions C are higher (the higher the correlation coefficients are, the better the fitting results are). The least-squares method based on the K-M theory can calculate the absolute absorption coefficient and scattering coefficient values of single fiber, a variety of selective formulas of one colored spun yarn sample will be obtained and the best one taking everything into consideration would be chosen.

ACKNOWLEDGEMENT

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