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Friele Model of Rotor Spun Multi-Primary-Colour-Blended Yarn

Abstract

Multi-channel rotor spinning equipment can produce multi-colour mixed yarn by changing the feed speeds of three primary coloured slivers separately. The method realises the mixing of colour fibres during the spinning process, and has the characteristics of high production flexibility, simplicity and quickness. The colour mixing effect and colour blending ratio prediction are important conditions for industrial production. In this paper, two-component and three-component samples were spun with rovings of red, yellow and blue with different blending ratios. A colour model of the rotor spun multi-primary-colour-blended yarn was established based on Friele theory by determining the σ value, which is the model parameter determined by experiments. Two methods were employed to calculate the σ value to improve the accuracy of the model: 1. under the condition of all wavelengths and 2. at various wavelengths. The results showed that the model parameters calculated at various wavelengths could better predict the colour of multi-channel rotor spun colour-blended yarn.

Key words: *rotor spun, colour blended yarn, Friele model.*

Introduction

Fabrics and yarns are usually dyed or printed to obtain a colour or pattern. The process will cause water pollution and electricity loss, affecting the ecology of the environment. The production process of multi-channel rotor spun yarn can reduce the above-mentioned problems [1-3]. Colour matching is one of the key technical problems of coloured spun yarn in the textile industry. It is one of the necessary conditions to realise intelligent computer colour matching in the process of colour blended spinning with different ratios of coloured fibre. Several methods have been introduced to describe the colour blending of pre-colored fibres, such as the Kubelka-Munk theory [4-6], Friele equation [7-9] and Stearns-Noechel model [10-12], among which the Friele model is a theo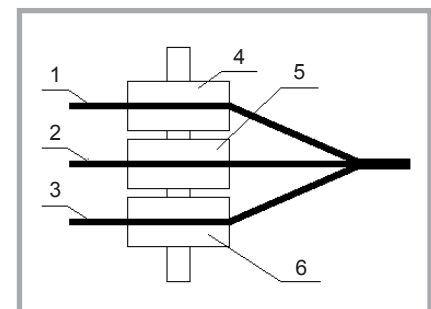retical colour-prediction model proposed by Friele for mixed coloured fibres [7]. Philips et al. extended the application of the model to cotton fibres [8]. Shen et al. applied the models to the spectral colour matching of yarn spun from coloured cotton and coloured wool, respectively [9]. All the researches above were conducted based on blending fibres during the drafting process or open-cleaning process or by hand [13-15]. However, in the textile industry, blending methods have a great influence on the colours of blended fibres [16-17].

In this study, the Friele model was extended to yarns by blending three primary coloured cotton fibres just during the multi-channel rotor spun process. The σ value is the main parameter to determine the Friele model, which is calculated from experiments. Two methods were employed to calculate the σ value to determine the model: 1) under the condition of all wavelengths and 2) at various wavelengths. The blended colour and blending ratios were calculated and compared, which provided a theoretical basis for further research on the three-colour blending model of smart rotor spun yarn and intelligent computer colour matching.

Research material and methods

Spinning method: multi-channel rotor spinning

The feeding mechanism of multi-channel rotor spinning contains three combined feeding rollers: 4, 5 and 6, which rotate around the same axis, as shown in *Figure 1*. The feeding speed of each feeding roller is controlled by a separate servo motor drive independently (the feeding speeds can be the same or different and can be changed on-line), thus the blending ratio of slivers 1, 2 and 3 can be varied. Hence, three primary coloured fibres can be blended in suitable proportions to obtain as many target colours as possible.

Different components of the slivers are fed by feeding rollers separately, which rotate to feed the sliver to the carding area. The slivers are opened, stripped, carded separately and mixed by the carding roller, which rotates at a high speed in the carding area, so that the sliver becomes single fibres, which are separated and arranged parallel to each other. Single fibres then enter into the fibre transport channel. Under the action of air flow, the fibres flow into the rotor through the fibre transport channel. With the centrifugal force of the rapidly rotating rotor, the fibres in the collection groove are further piled up and mixed, and then the fibres are jointed with the mother-yarn and twisted by a navel to form a yarn.

Figure 1. *Feeding part of three-channel rotor spinning machine: 1, 2, 3 – slivers, 4, 5, 6 – combined feed rollers.*

Material	Cotton
Colour of fibres	Red, Yellow, Blue
Dyeing method	Exhaust dyeing
Fibre length	32 mm
Fibre fineness	1.72 dtex
Roving count	400 tex
Yarn count	44.85 tex
Twist factor	402
Winding angle	33°
Navel type	KN4 smooth
Rotor speed	23000r/min
Winding speed	20m/min
Temperature	252 °C
Room humidity	502%

In the process of spinning, the servo driving system is controlled by a computer program to feed three slivers asynchronously to the carding area by means of the feeding roller at three freedom degrees. By controlling the feeding amount and feeding ratio of the three feeding rollers online, it is possible to dynamically configure the final yarn density of the rotor spinning and the blending ratio of the three components to produce segment-colour yarn, gradient colour yarn, segment-colour slub yarn, slub yarn and mélange yarn, shown by *Figure 2-6*. Then yarns can be woven into fabric without dyeing. By combining the fabric texture with the length of the colour change and/or the slub cycle, a fabric pattern can be obtained. The method has high flexibility and adaptability and is an effective method for producing colour yarns to reduce environmental pollution. Its production is environmentally friendly, small-scale and multi-style. Fabric woven with this kind of yarn presents a unique color effect – harmony, and a soft and rich hazy three-dimensional effect and texture [1].

Materials

In this paper, colored yarns were produced by multi-channel rotor spinning with various blending ratios of the same linear density. *Table 1* shows the specification of the raw material and test conditions. 66 types of colour yarns were produced with three basic coloured slivers (Red, Yellow and Blue), fed at different rates by changing the feeding speed of each sliver. Codes and components of the yarns are given in *Table 2*.

The dyes were C.I. Reactive Red 239 (Reactive Red 3BSN), C.I. Reactive blue 19 (Reactive blue KN-R) and C.I. Reactive Yellow 176 (Reactive Yellow
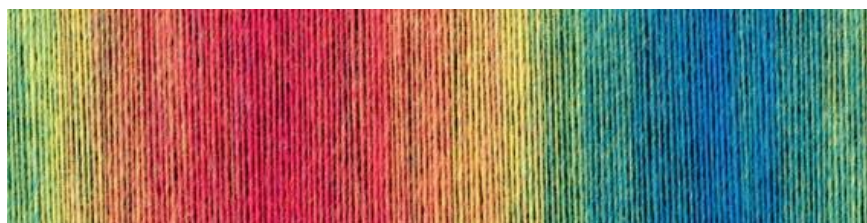

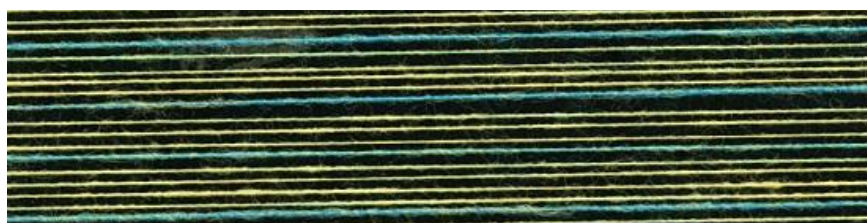*Figure 2.* *Segment colour yarn.*

Figure 3. *Gradient colour yarn.*
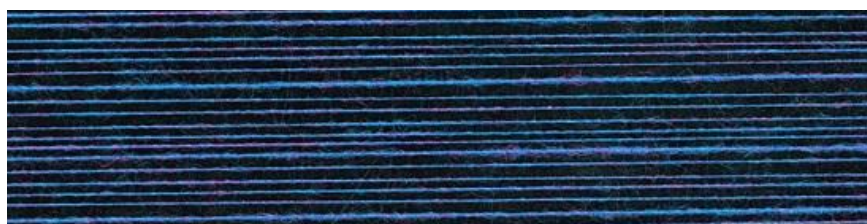

Figure 4. *Segment-colour slub yarn.*

Figure 5. *Slub yarn.*
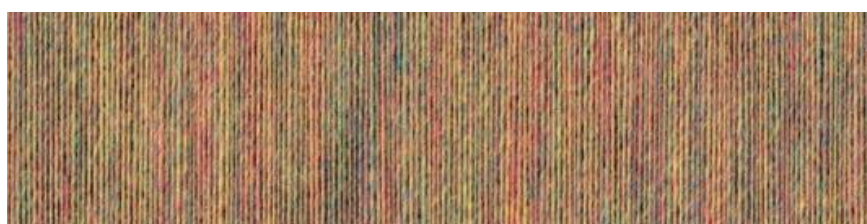
Figure 6. *Mélange yarn.*

Table 2. *Colour matching scheme.*

No.	R:Y:B	No.	R:Y:B	No.	R:Y:B	No.	R:Y:B	No.	R:Y:B	No.	R:Y:B	No.	R:Y:B
#1	1:0:0	#12	9:1:0	#23	0:2:8	#34	5:1:4	#45	1:2:7	#56	1:4:5
#2	0:1:0	#13	1:0:9	#24	0:3:7	#35	4:1:5	#46	6:3:1	#57	4:5:1
#3	0:0:1	#14	2:0:8	#25	0:4:6	#36	3:1:6	#47	5:3:2	#58	3:5:2
#4	1:9:0	#15	3:0:7	#26	0:5:5	#37	2:1:7	#48	4:3:3	#59	2:5:3
#5	2:8:0	#16	4:0:6	#27	0:6:4	#38	1:1:8	#49	3:3:4	#60	1:5:4
#6	3:7:0	#17	5:0:5	#28	0:7:3	#39	7:2:1	#50	2:3:5	#61	3:6:1
#7	4:6:0	#18	6:0:4	#29	0:8:2	#40	6:2:2	#51	1:3:6	#62	2:6:2
#8	5:5:0	#19	7:0:3	#30	0:9:1	#41	5:2:3	#52	5:4:1	#63	1:6:3
#9	6:4:0	#20	8:0:2	#31	8:1:1	#42	4:2:4	#53	4:4:2	#64	2:7:1
#10	7:3:0	#21	9:0:1	#32	7:1:2	#43	3:2:5	#54	3:4:3	#65	1:7:2
#11	8:2:0	#22	0:1:9	#33	6:1:3	#44	2:2:6	#55	2:4:4	#66	1:8:1
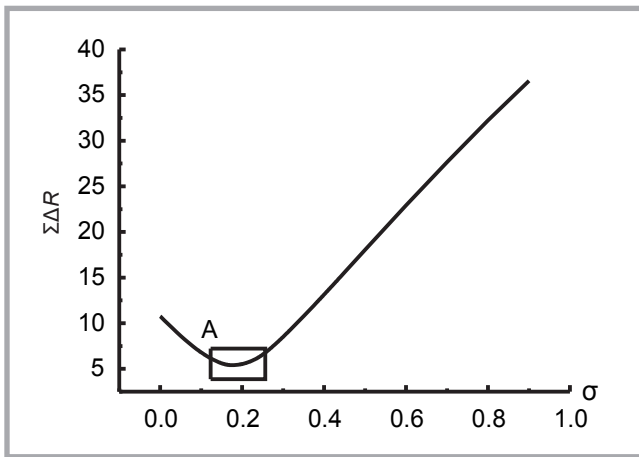
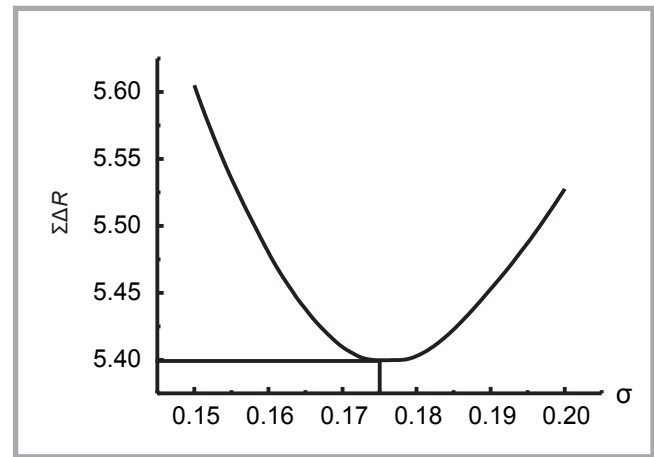**Figure 7.** *ΣΔR of two-component samples.*
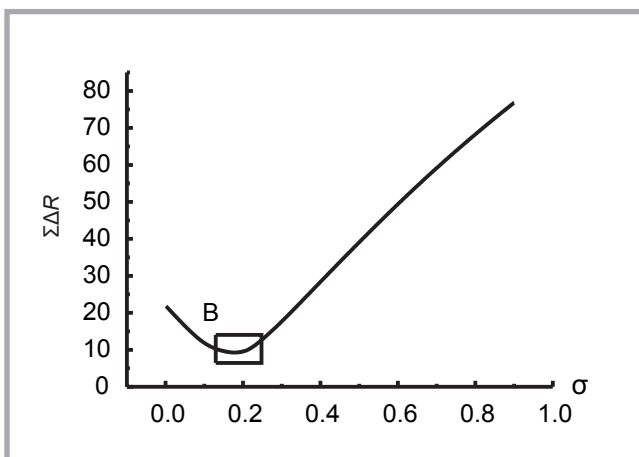

Figure 8. *Enlarged A position.*

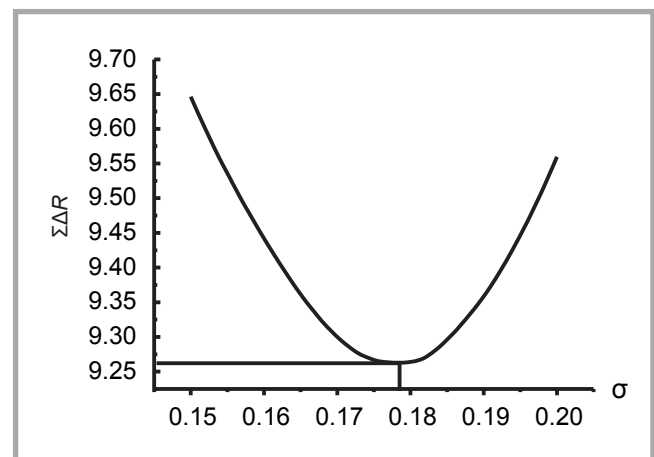**Figure 9.** *ΣΔR of three-component sample.*

Figure 10. *Enlarged B position.*

3RS), purchased from Lonsen Ltd.(Zhejiang, China), and the dyeing machine was a WXS250. Knitted fabrics were produced with three-channel rotor spun yarns. The sample was 20 cm x 20 cm, and the fabric had a density of 120 coils/ cm^2 (15 * 8), produced by a TF-S3F4. Colour characteristics of the fabrics were tested by Datacolor 650, which mainly measures the spectral reflectance at a specific wavelength of the fabric, ranging from 360 nm to 700 nm, at a wavelength interval of 10 nm. The measurement results are used as basic data for subsequent models. During colour testing, the knitted samples were folded into 4 layers to ensure opacity, and a 30 mm aperture was selected. In each sample, the colours at different locations were measured. All tests were conducted under standard conditions (22 ± 2 °C and 65 ± 2% RH). An vverage colour difference less than a 0.2 CIELAB colour unit was taken as the final result.

Friele models

The predictive method developed by Friele is based on the principle of an addi-tive formula, that is, their hypothesis is made assuming that [7-9]

$$f\left[R_{blend\,(\lambda)}\right] = \sum_{i=1}^{n} x_i \, f\left[R_{i(\lambda)}\right] \quad (1)$$

$$\mathrm{f}[R(\lambda)] = e^{-\sigma[1-R(\lambda)]^2/2R(\lambda)} \quad (2)$$

where, R_{blend} (λ) denotes the reflectance of the blend at wavelength λ, R_i (λ) the reflectance of the ith component of the blend at the same wavelength, x_i, the mass proportion of the ith component that has been introduced in the blend, f, the additive function provided by the authors; and σ is a dimensionless constant. And the following condition must be fulfilled:

$$\sum_{i=1}^{n} x_i = 1 \quad (3)$$

Model parameter σ is experimentally determined. The classical algorithm is to deduce the σ value using *Equations (1) and (2)* in the case of mixing several monochromatic colours at a certain mass ratio with known monochromatic proportions and monochromatic reflectance; the σ value is then substituted to calculate the reflectivity and obtain the difference between all the calculated values of the sample and the actual sample colour. σ, corresponding to the minimum colour difference is chosen as the model parameter.

▪ Results and discussion

σ based on assignment method (σ_1 and σ_2)

In this experiment, the colour-mixed fabric of two-component and three-component rotor spun yarns, respectively, were used to assign σ according to the Friele model in the range of 0 to 1 in 0.001 increments. The spectral reflectances of all the samples are predicted for each value of σ at a visible wavelength of 360-720 nm. All samples here refer to all two-component samples or all three-component samples. The sum of the absolute values of the spectral reflectance difference between the predicted and actual value is calculated, expressed by ΣΔR, reflecting the overall prediction capability of the model. For the smaller of the spectral

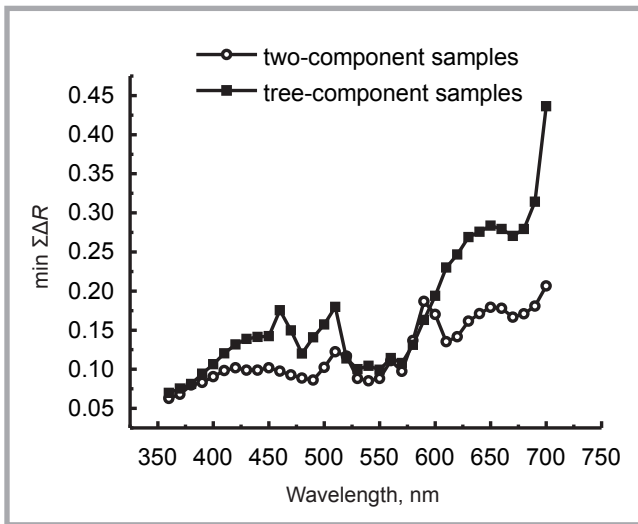**Figure 11.** *Min ΣΔR at each wavelength.*

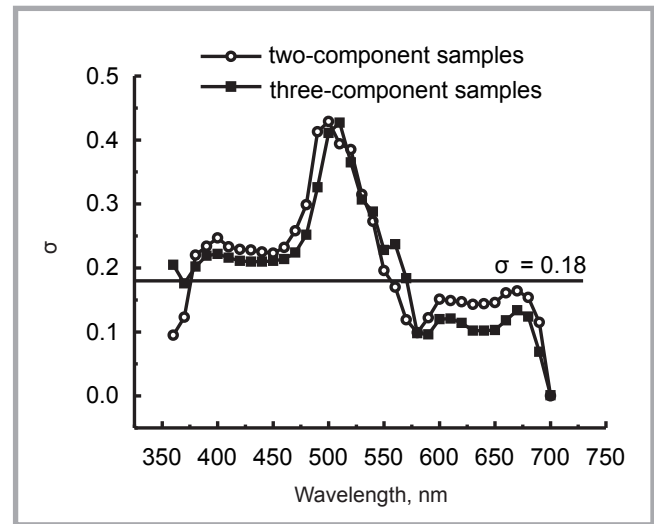**Figure 12.** *σ value corresponding to min ΣΔR.*

reflectance errors, the predicted value is closer to the spectral reflectance of the sample.

The calculated ΣΔR against each σ of all samples are shown in **Figures 7-10**.

From **Figures 7** and **9**, it can be seen that the value of ΣΔR decreases first and then increases with an increase in σ, for both two-component and three-component samples. When σ is around 0.2, ΣΔR is smaller. As can be seen from the enlarged view of part A in **Figure 7** and part B in **Figure 9**, ΣΔR is the smallest for two-component and three-component samples, with σ values of 0.175 and 0.178, respectively. That is, when σ = 0.175, denoted as σ₁, the Friele model has the best prediction effect for two-component samples, and when σ = 0.178, denoted as σ₂, the prediction effect of the three components is the best.

σ depends on wavelength (σ₃ and σ₄)

The ΣΔR against each σ of all samples at different wavelengths was calculated, with the σ value also in the range of 0 to 1 in 0.001 increments. The wavelength range is 360-720 nm, with 10 nm as the wavelength interval. The relationship between ΣΔR of the σ value and the wavelength is demonstrated by **Figure 11**.

The optimal model parameter σ which can achieve the smallest colour difference (Min ΣΔR) at each wavelength is determined, as σ₃s and σ₄s, for two-component and three-component samples, respectively. The results are shown in **Figure 12**. The trend of the model parameters σ at different wavelengths is the same for both the two-component and three-component samples, but the values are slightly different. The optimised model parameters change rapidly with wavelength at about 500 nm. At 500 nm, the model parameters σ corresponding to min ΣΔR are larger, 0.429 and 0.419, for two-component and three-component samples, respectively. They are more stable around 425 nm and 625 nm, close to 0.18.

Colour difference calculation and prediction

The parameters of the Friele model obtained by the above-mentioned methods, previously recommended by other researches, are used to predict the colour of the sample. The colour difference is compared and analysed. The CMC (l: c) colour difference formula is employed to calculate the colour difference, as shown in **Equation (4)** [8-9].

$$\Delta E_{CMC} = \left[\left(\frac{\Delta L}{l S_L} \right)^2 + \left(\frac{\Delta C}{c S_C} \right)^2 + \left(\frac{\Delta H}{S_H} \right)^2 \right]^{1/2} \quad (4)$$

Where, ΔL, ΔC and ΔH are the brightness difference, saturation difference and hue difference, respectively; S_L, S_C and S_H are the weight coefficients of ΔL, ΔC and ΔH; l, respectively, and c is used for judging the colour difference acceptability among samples, taking 2 or 1, respectively.

Four kinds of Friele model parameters are calculated in this article. When the wavelength factor is not considered, the model parameters are $\sigma_1 = 0.175$ and $\sigma_2 = 0.178$ for two-component and three-component mixed yarns, respectively. When the wavelength factor is considered, the model parameters of the two-component mixed yarn at each wavelength are assumed to be σ_3 and for three-component

Table 3. *Colour difference between the actual and predicted two-component samples.*

σ	Color difference	Pass percentage		
		<1	<2	<3
σ₁	0.98	66.7%	92.6%	100%
σ₃	0.78	74.1%	100%	100%
σ₅	1.16	51.2%	88.9%	100%
σ₆	1.12	48.1%	81.5%	100%

Table 4. *Colour difference between the actual and predicted for three-component samples.*

σ	Colour difference	Pass percentage		
		<1	<2	<3
σ₂	1.62	25%	75%	97.2%
σ₄	1.10	58.3%	86.1%	94.4%
σ₅	2.38	8.3%	44.4%	75%
σ₆	1.63	8.3%	83.3%	97.2%

yarn $-\sigma_4$. Model parameters recommend by other researchers are $\sigma_5 = 0.245$ and $\sigma_6 = 0.128$ [8-9]. The parameters are respectively substituted into the Friele model to predict the reflectivity of the samples. The colour differences between predicted and actual samples under the above-mentioned model parameters are shown in **Tables 3** and **4**.

From **Tables 2** and **3**, we can see that when the wavelength factor is not considered, the mean value of the colour difference of two-component samples with σ_1 is 0.98, and that of three-component samples with σ_2 is 1.62. And for the two-component and three-component samples, respectively, those with a colour difference less than 3 account for 100% and 97.2% of the total 92.6% and 75% with a colour difference less than 2, and 66.7% and 25% with colour difference less than 1, respectively.

Considering the wavelength, the mean values of the colour difference of two-component samples and three-component samples, whose model parameters are σ_3 and σ_4, respectively, are 0.78 and 1.10, respectively. And those with a colour difference less than 3 account for 100% and 94.4% of the total, 100% and 86.1% with a colour difference less than 2, and 74.1% and 58.3% with colour difference less than 1, respectively.

Compared with σ_1, the average value of the colour difference of σ_3 decreases by 0.2, and that of σ_4 decreases by 0.52 compared with σ_2. When the tolerance range is as small as 1, the sample passing rates of σ_3 and σ_1 are all 100%, and σ_4 is 2.8% higher than σ_2.

It can be seen that model parameters σ_3 and σ_4 obtained at different wavelengths have better prediction ability compared with σ_1 and σ_2, respectively. And no matter the average value of the colour difference or the pass rate of different tolerance ranges, the prediction results of two-component samples are better than those of three-component samples. It shows that the Friele model has different predicting ability for samples with various monochromatic quantities. The fewer components there are, the stronger the prediction ability of the model is.

σ_5 and σ_6 are recommended by other researchers [8-9]. The mean values of the colour difference of all samples are larger than those of the parameters calculated in this experiment. When the tolerance range is smaller, the pass rate of the sample is smaller, and the forecasting result is not satisfactory. As, the colour blending method of traditional colour spinning is different from that of multi-channel rotor spinning yarn, it can be concluded that the applicability of the Friele model changes with the fibre blending method.

■ Conclusions

In this paper, multi-primary-colour-blended yarn was produced by a three-channel rotor spinning machine, which is a smart and sustainable spinning method for colorful textiles. The Friele model was used to predict the colour of the yarns. The results show that although model parameter σ calculated without considering the wavelength factor is better than that of parameters recommended by other researchers, the colour of rotor-spun multi-primary-colour-blended yarn cannot be predicted well. Considering the wavelength factor to optimise the model parameters, the predictive capability of the model is greatly improved. The model has higher prediction ability for samples with fewer monochromatic quantities. Friele colour matching model parameter σ based on multi-channel rotor spinning can be used as a reference for the development of colour matching software, which can promote the production and development of this process. Besides, it is of great significance to improve the efficiency of colour spinning enterprises.

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