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Determining Tolerance Values of Instrumentally Measured Color Differences to Evaluate Black Filament Yarns

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ABSTRACT

There are many factors affecting the tolerance values of instrumentally measured color differences, including variety of industries, type of products to be matched with the original samples, the need of customers, etc. Regarding the insufficiency of various color difference formulae to deal with the acceptability of color matching of reproduced samples with the target, some researchers tried to present an instrumental color tolerance limit in accordance with the results of visual assessment experiments. Considering the specific colorimetric attributes of achromatic samples (with low lightness and chroma values), it was tried to set an instrumental tolerance limit based on the measured and visually perceived color differences between 20 filament black yarns and the reference one. The results showed that determining the color tolerance value based on various color difference formulae, i.e. ΔEa^*b^*, CIE94, CIE2000 and CMC (2:1), results in different instrumental wrong decisions, while the ΔE^*_{ab} color difference equation with the color tolerance value of 0.5 for filament black yarns showed the minimum number of wrong decisions. Prog. Color Colorants Coat. 13 (2020), 187-197© Institute for Color Science and Technology.

1. Introduction

There are many industries such as textile, paper, printing, paint, automotive, ink and plastic concerning with color matching problem to quality control their colored products. The colorimetric attributes of reproduced products are controlled in two different ways; visual and instrumental [1-3]. In the case of visual color matching, the color quality control is determined by the perceived color difference between the reproduced sample and the original one [4]. There are many factors affecting the results of visual assessment experiment, including age, nationality, gender, sample size, texture, intensity and spectral quality of the light, angular size of the light source, incident angle, viewing angle, background and surround, separation and juxtaposition, interference from adjacent colors, etc. All the parameters are categorized in three main groups; i.e., observers situation, lightening conditions and objects' properties [2, 4, 5]. Due to the subjective concept of visual assessment experiments, achieving repeatable outcomes is not simply possible. Regarding the need of different industries to quality control the color matching of reproduced batches with the target, it seems necessary to develop objective-based evaluation methods. In other words, developing an index to instrumentally evaluate the color difference values and confirm the results of visual assessment experiments leads to more reliable results [6]. In this way, various color difference equations have been employed to quantify the visually perceived color differences [7-10]. Noticeably, to pass or fail the color appearance of reproduced objects as the metameric pairs of the target, it is very important to determine an instrumental color tolerance while applying color difference formula [6, 11, 12]. Regarding the diversity of the industries, the

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variety of applied color difference equations and the customer need, the mentioned color tolerance limits are not constant and defined as arbitrary and variable values [13, 14]. On the other hand, it seems that even for a specific industry, such as textile, the other colorimetric attributes, in this case “hue”, may affect the determination of color tolerance values. It means that for the specific reproduced products in an individual industry, the samples with various hues may benefit from different color tolerance values [14, 15]. Performing the color evaluation and color acceptability process for high requested dark achromatic objects like blacks, to be reproduced and matched in textile industries is subject to many variables and proved to be difficult [15].

In contrary to ideal achromatic definition (samples with the lightness and chroma values equal to zero), actual blacks, whites and grays show low lightness and chroma properties. Regarding the tint attribute of real achromatic samples, it is not possible to suitably describe them in one-dimensional space [16-18]. Besides, the observers evaluate the color differences of real achromatic objects based on their perceived lightness and tint attribute differences [19-22]. Meanwhile, it was found that for the blackness/ whiteness perception, observers decide based on their hue preferences [23-27]. While the black objects are used in different industries, i.e., textile, printing, paints, automotive, cosmetics, and so on, there are limited researches on their spectral and colorimetric properties [28-32]. Regarding the color matching of black shades one research concerned with the objective evaluation of black textile samples (both glossy and matt) in accordance with physiological experience. The results showed that the estimation of black objects’ matching cannot be occurred based on the color difference values obtained from CIELAB and CMC(l:c) color difference equations and some other criteria such as a*/b* value and the lightness level should be concerned [15]. On the other hand, considering the insufficiency of developed color difference equations to set a manufacturing color tolerance in accordance with the visual assessment results, it was tried to derive an instrumental tolerance from the instrumental and visual dataset [4, 6]. According to this method, the ΔE^*_{94} value that minimized the number of instrumental wrong decisions was considered as the final color tolerance value for a specific set of data.

In this paper, it is tried to drive an instrumental color tolerance value for the black yarns based on the measured and perceived color differences. In order to avoid the effect of tint attribute, the selected samples benefit from the same tint effect in the first quarter of hue area.

2. Experimental

2.1. Sample preparation

In order to achieve an instrumental color tolerance limit based on the measured and visual perceived color differences for the black yarns, 20 filament black samples were randomly selected from different reproduced batches. Besides, the black yarn sample requested by the customer was considered as the reference. In order to prepare the opaque specimens for the instrumental measurement, 21 filament black yarns were winded closely and parallel on the uniform and neutral color cards without fluorescing agents through commercial card winders to ensure consistent tension and a constant number of 6 windings.

2.2. Sample measurements

The reflectance spectra of filament black yarns were measured using Color-Eye 7000A spectrophotometer (Gretag Macbeth Company) over the visible wavelength range (400 to 700 nm) by 10 nm intervals. Regarding the glossy appearance of black yarns, the specular component of the reflectance was included during the spectral measurements. The colorimetric attributes of samples in CIELAB and CIELCH color order systems were calculated under D65 standard illuminant and CIE1964 standard observer. Finally, the colorimetric differences between 20 reproduced black yarns and the reference sample were computed based on various color difference formulae; i.e. ΔEa^*b^*, CIE2000, CIE94 and CMC(2:1).

2.3. Visual assessments

In order to achieve the results of perceived color differences between the reference sample and 20 filament black yarns, the samples were evaluated under VeriVide light booth and D65 standard illuminant as pairs. 10 mature staffs, including 5 males and 5 females aged from 26 to 35 years old with an average of 30 years, evaluated the samples. The CIE1964 standard observer and the illumination/observation geometry of 0/45 were employed during the visual assessment experiments. The observers were asked to assess the perceived color differences between the reproduced samples and the reference one as pairs and present their evaluation results by words "pass/fail"; the word "pass" means that the visually perceived color difference between the reproduced black yarns and the reference specimen is very small and acceptable within the commercial terms, while the word "fail" means that the evaluated color difference between two samples of a pair is not visually acceptable.

3. Results and Discussion

Figure 1 shows the reflectance spectra of 21 black yarns over the visible wavelength range from 400 to 700 nm. The reflectance behavior of the reference sample is shown by the line with (*) marker. Table 1 shows the colorimetric properties of black yarns in both CIELAB and CIELCH color spaces. The first row in Table 1 indicates the colorimetric specifications of the reference sample.

Figures 2 and 3 show the scatter plots of filament black yarns in CIELAB and CIELCH color order systems, respectively. According to Table 1 and Figure 2, all black yarns are located in the first quarter of hue area and benefit from the positive a* and b* values. In other words, there are some black yarns with yellowish to reddish tint attributes. The reference black yarn is shown by (■) marker.

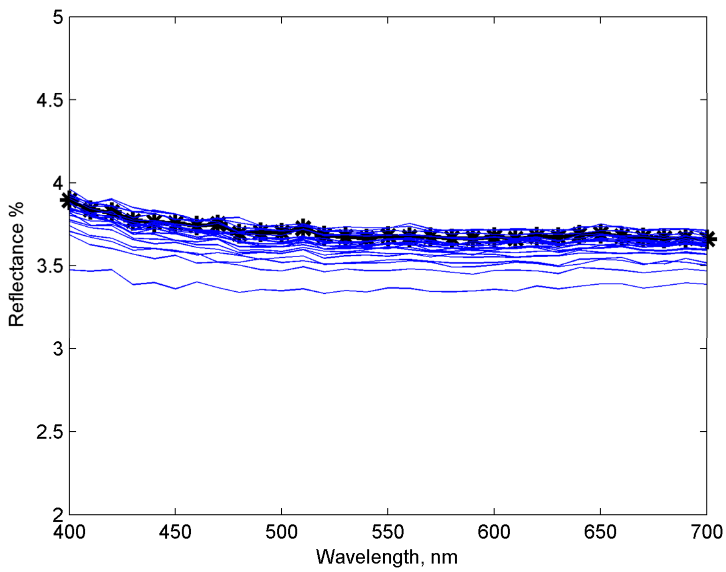

Figure 1: The reflectance spectra of 21 black yarns. The (*) marker indicates the reference sample.

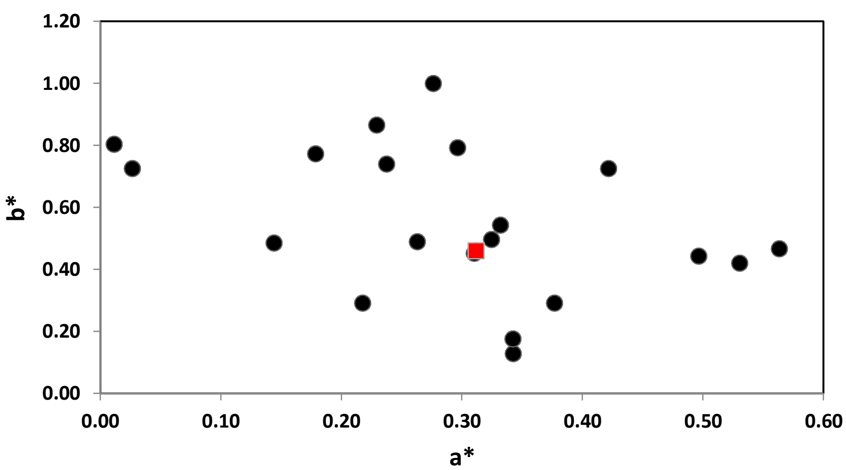

Figure 2: Distribution of 21 black yarns over a*b* diagram in CIELAB color order system. The reference sample is shown by (■) marker.

Table 1: The colorimetric attributes of 21 black yarns.

Sample #	L*	a*	b*	C*	h°
Ref: d9	20.83	0.31	0.46	0.56	55.90
d3	20.43	0.26	0.49	0.56	61.70
d84	20.46	0.23	0.87	0.90	75.15
d71	20.25	0.24	0.74	0.78	72.19
d2	20.23	0.18	0.77	0.79	76.96
d16	20.81	0.01	0.80	0.80	89.16
d17	20.32	0.28	1.00	1.04	74.54
d14	20.78	0.03	0.73	0.73	87.89
d23	20.20	0.50	0.44	0.67	41.74
d22	20.57	0.34	0.13	0.37	20.60
d24	20.28	0.33	0.54	0.64	58.57
d21	20.45	0.32	0.50	0.59	56.84
d26	20.64	0.22	0.29	0.36	53.21
d25	20.16	0.34	0.18	0.39	27.22
d30	20.32	0.56	0.47	0.73	39.64
d20	20.92	0.31	0.45	0.55	55.51
d19	20.14	0.53	0.42	0.68	38.41
d28	20.36	0.38	0.29	0.48	37.67
d31	20.73	0.14	0.49	0.51	73.46
d27	20.25	0.42	0.72	0.84	59.81
d29	20.20	0.30	0.79	0.85	69.46

Figure 3 shows the C*L* scatter plot of 21 black yarns in CIELCH color order system. The reference black yarn is shown by (■) marker in Figure 3. According to Table 1 and Figure 3, 21 black samples benefit from low lightness and chroma values, as it is expected, while L* values change from 20.14 to 20.92 and C* values vary from 0.36 to 1.04.

Table 2 shows the results obtained from the visual assessment experiments. The second column in this table shows the number of observers who have visually accepted or rejected the samples of a pair. According to Table 2, the perceived color differences between the reproduced filament black yarns and the reference sample are presented by words “pass” or “fail” under D65 standard illuminant. The word “pass” means that the majority of observers (at least 70%) did not perceive very significant color differences between the samples and the target. In fact, the perceived color differences were acceptable. On the other hand, “fail” means that at least 40% of observers have rejected the color matching between the reproduced black yarns and the target.

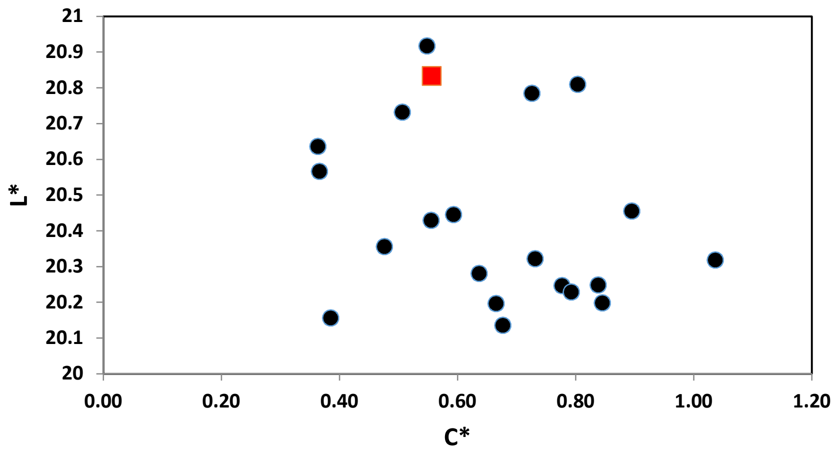

Figure 3: Distribution of 21 black yarns over C*L* diagram in CIELCH color order system. The reference sample is shown by (■) marker.

Table 2: The result of visual assessment experiments.

Sample	# of observers	Acceptance under D65 standard illuminant
d9 (ref.)	-	-
d3	4	Fail
d84	8	Pass
d71	7	Pass
d2	9	Fail
d16	10	Pass
d17	8	Fail
d14	10	Pass
d23	9	Fail
d22	8	Pass
d24	7	Fail
d21	9	Pass
d26	9	Pass
d25	10	Fail
d30	5	Fail
d20	10	Pass
d19	10	Fail
d28	5	Fail
d31	10	Pass
d27	7	Fail
d29	9	Fail

Tables 3 and 4 show the lightness differences (ΔL*) as well as the visual and instrumental color differences between the 20 reproduced filament black yarns and the reference sample by using various color difference equations, i.e., ΔEa*b*, CIE94, CIE2000 and CMC (2:1). The first column of these tables indicates the numbers of samples that have been passed or failed in the visual assessment experiments (derived from Table 2). Table 3 shows all reproduced black yarns that have been visually accepted to have color matching with the reference sample. Table 4 indicates the reproduced black yarns that have been visually rejected.

Considering Tables 3 and 4, it is not possible to determine an instrumental color tolerance based on the employed color difference equations.

Table 3: The instrumental color difference values of black yarns which were visually accepted to have color matching with the reference sample.

Pass (i #)	Sample	DEa*b*	DE94	DE2000	CMC (2:1)	ΔL*
1	d20	0.08	0.04	0.06	0.07	0.08
2	d31	0.20	0.18	0.26	0.27	-0.10
3	d26	0.28	0.21	0.26	0.33	-0.20
4	d21	0.39	0.20	0.27	0.32	-0.39
5	d14	0.39	0.39	0.50	0.58	-0.05
6	d22	0.43	0.35	0.38	0.54	-0.27
7	d16	0.46	0.45	0.56	0.68	-0.02
8	d84	0.56	0.45	0.49	0.68	-0.38
9	d71	0.65	0.41	0.50	0.64	-0.59

Table 4: The instrumental color difference values of black yarns which were visually rejected to have color matching with the reference sample.

Fail (i #)	Sample	DE a*b*	DE 94	DE2000	CMC (2:1)	ΔL*
1	d3	0.41	0.21	0.29	0.33	-0.40
2	d28	0.51	0.30	0.38	0.47	-0.48
3	d24	0.56	0.29	0.39	0.46	-0.55
4	d30	0.57	0.36	0.51	0.56	-0.51
5	d27	0.65	0.40	0.51	0.63	-0.58
6	d23	0.66	0.37	0.52	0.58	-0.64
7	d2	0.69	0.45	0.56	0.70	-0.60
8	d29	0.72	0.45	0.79	0.71	-0.63
9	d19	0.73	0.41	0.58	0.65	-0.70
10	d25	0.74	0.44	0.55	0.69	-0.68
11	d17	0.75	0.59	0.64	0.90	-0.51

Samples in Tables 3 and 4 have been sorted into “pass” and “fail” and placed in ascending order based on their instrumental DEa*b* with the reference sample. Similar tables were designed for other employed color differences; DE94, DE2000 and DE CMC (2:1), while they were not shown here. Then, the cumulative percentages of each group of “passed” or “failed” pairs were calculated based on Equations 1 and 2 [4].

$$Cumulative_{pass,i} = 100(i/n_{pass}) \tag{1}$$

$$Cumulative_{fail,i} = 100\text{-}100(i/n_{fail}) \tag{2}$$

where n_{pass} and n_{fail} represent the number of black yarns passed or failed, respectively, to be matched with the reference sample, and i refers to black yarns 1, 2, …, n_{pass}/n_{fail}.

In order to determine an instrumental color tolerance value for black filament yarns, the ascending ordered color difference values are shown in Table 5 with their corresponding cumulative percentages [4]. The left side of Table 5 shows the cumulative percentages corresponding to the ordered color difference values of passed samples. The cumulative percentages corresponding to the ordered color difference values of failed samples are shown in the right side of Table 5.

The computed cumulative percentages were plotted against the ordered color difference values. Figures 4 to 7 show various color difference versus their corresponding cumulative percentages for two groups of data (“pass/fail”). In all the figures, the optimized tolerance value is defined by the intersection point of two data sets.

According to the intersection point shown in Figure 4, the color difference value that minimizes the number of instrumental wrong decisions is 0.5 for DEa*b*. Based on the achieved tolerance value of (0.5 DEa*b*), the number of instrumental wrong decisions is 3 for these data.

Table 5: The cumulative percentages of the ascending ordered color difference values

Pass Cumulative%	DE a*b*	DE94	DE2000	CMC2:1	Fail Cumulative %	DE a*b*	DE94	DE2000	CMC2:1
11.1	0.08	0.04	0.06	0.07	90.9	0.41	0.21	0.29	0.33
22.2	0.20	0.18	0.26	0.27	81.8	0.51	0.29	0.38	0.46
33.3	0.28	0.20	0.26	0.32	72.7	0.56	0.3	0.39	0.47
44.4	0.39	0.21	0.27	0.33	63.6	0.57	0.36	0.51	0.56
55.5	0.39	0.35	0.38	0.54	54.5	0.65	0.37	0.51	0.58
66.7	0.43	0.39	0.49	0.58	45.4	0.66	0.4	0.52	0.63
77.8	0.46	0.41	0.50	0.64	36.4	0.69	0.41	0.55	0.65
88.9	0.56	0.45	0.50	0.68	27.3	0.72	0.44	0.56	0.69
100	0.65	0.45	0.56	0.68	18.2	0.73	0.45	0.58	0.70
-	-	-	-	-	9.1	0.74	0.45	0.64	0.71
-	-	-	-	-	0	0.75	0.59	0.79	0.90

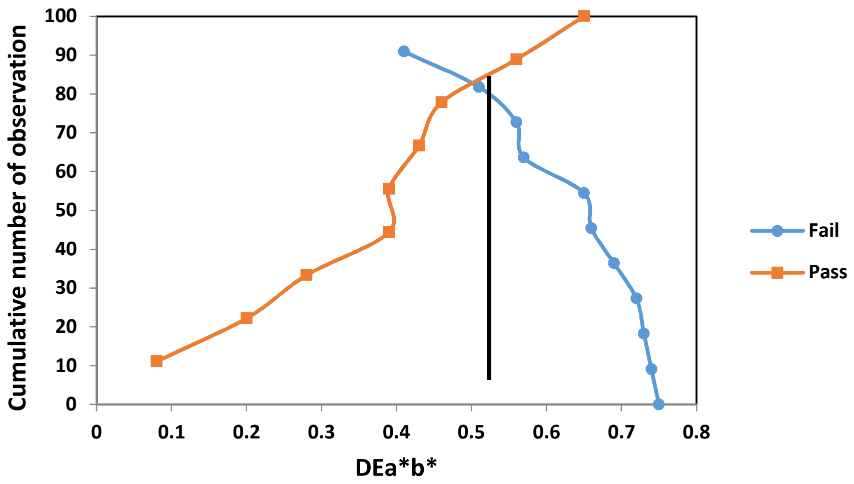

Figure 4: The cumulative percentages corresponding to ordered DE a*b* color difference values.

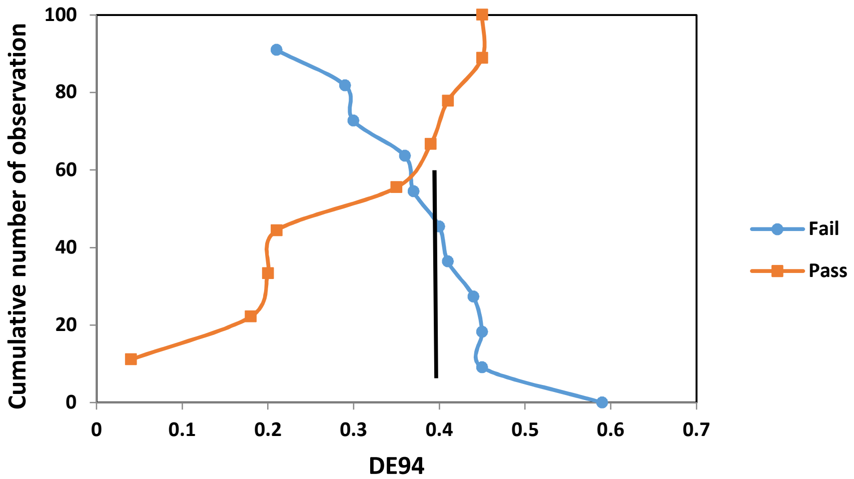

Figure 5: The cumulative percentages corresponding to ordered DE94 color difference values.

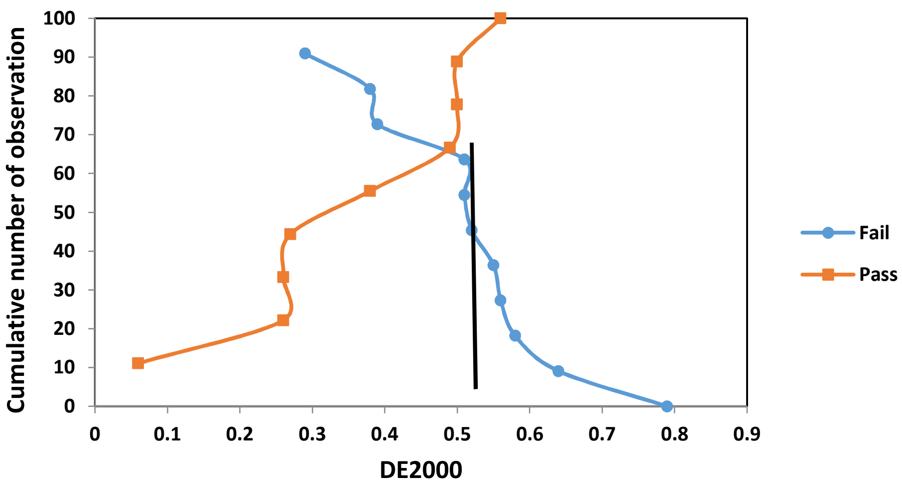

Figure 6: The cumulative percentages corresponding to ordered DE2000 color difference values.

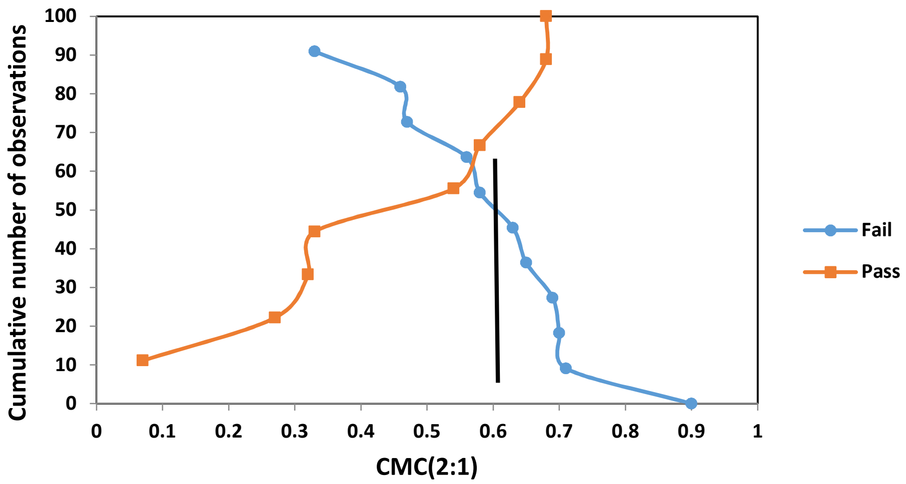

Figure 7: The cumulative percentages corresponding to ordered DECMC 2:1 color difference values.

Table 6: The number of instrumental wrong decisions as well as the achieved tolerance limits corresponding to the applied color difference formulae.

Color difference formula	Tolerance value	# Instrumental wrong decisions
DEa*b*	0.5	3
DE94	0.37	8
DE2000	0.49	6
DECMC(2:1)	0.57	8

Table 6 summarizes the results achieved from Figures 4 to 7 based on the achieved tolerance values corresponding to the applied color difference formulae. Although the scale of CIELAB color difference formula is not the same as the visual perception of color differences, according to Table 6, the DEa*b* color difference equations with the tolerance value of 0.5 result in the minimum number of instrumental wrong decisions (3) among all applied color difference formulae. Besides, the DE94 and CMC (2:1) with the maximum number of instrumental wrong decisions (8) represent the tolerance values of (0.37) and (0.57), respectively.

The acquired color tolerance values could be considered for the final agreement between the clients and the suppliers of black textile products. It is noticeable that although the CIELAB color difference formula was found as the best, the achieved results are based on the judgment of perceived color differences between 20 samples and a single target. Regarding the mentioned limitation and the number of observers, some further work and research should be done for achieving more reliable results.

4. Conclusion

At the present study, deriving an instrumental color tolerance limit was investigated for filament black yarns using a set of color difference formulae. In this way, the subjective and objective color evaluations were performed between 20 reproduced filament black yarns and a target. 10 mature observers subjectively assessed the color matching of samples as pairs. Besides, four color difference formulae, i.e., DEa*b*, DE94, DE2000 and CMC(2:1), were employed to objectively evaluate the color differences. The results showed that DEa*b* color difference formula with the tolerance value of 0.5 results in the minimum number of instrumental wrong decisions among all applied color difference equations. This limit value facilitates the management of product color appearance and can be used to control the acceptance of the color differences achieved between the sample and the target.

5. References

1. T. F. Chong, Instrumental measurement and control of colour, *Color. Technol.*, 18(1988), 47-55.
2. J. Park, Instrumental colour formulation: a practical guide, SDC, Bradford, 1993, 22-26.
3. O. Gomez, E. Perales, E. Chorro, V. Viqueira, F. M. Martinez-Verdu, Visual and instrumental assessments of color differences in automotive coatings, *Appl. Opt.*, 55(2016), 6458-6463.
4. R. S. Berns, Billmeyer and Saltzman's principles of color technology, 3th Edition, John Wiley & Sons, INC., NewYork, 2000, Chapter 3.
5. L. Tao, Impact of blackness preference and perception on product design, PhD thesis, University of Leeds, England, 2013.
6. R. S. Berns, Deriving instrumental tolerances from Pass-Fail and colorimetric data, *J. Color Res. Appl.*, 21(1996), 459-472.
7. R. McDonald, Color physics for industry, 2th Ed, Dyers company publication trust, Bradford, 1997, Chapter 4.
8. M. R. Luo, Development of colour-difference formulae, *Rev. Prog. Color*., 32(2002), 28-39.
9. H. Wang, G. Cui, M. R. Luo, H. Xu, Evaluation of colour-difference formulae for different colour-difference magnitudes, *J. Color Res. Appl.*, 37(2012), 316-325.
10. M. Habekost, Which color differencing equation should be used?, *IC Journal.,* 6(2013), 20-33.
11. Standard test methods for Establishing Color and Gloss Tolerances, Annual Book of ASTM Standard, ASTM Standard, D3134 - 97, 2008.
12. Standard test methods for Calculation of Color Tolerances and Color Differences from Instrumentally Measured Color Coordinates, Annual Book of ASTM Standard, ASTM Standard, D2244 - 07, 2008.
13. Standard test methods for Instrumental Color Difference Measurement for Exterior Finishes, Textiles and Colored Trim, SAE INTERNATIONAL, 2014.
14. G. A. Klein, Industrial color physics, Springer, New York, 2010.
15. M. I. Glogar, D. Parac-Osterman, Black hues matching problem in clothes designing, in Proceeding of the 22nd International IFATCC Conference, Stresa, Italy, (2010).
16. R. Jafari, S. H. Amirshahi, S. A. Hosseini Ravandi, Spectral analysis of blacks, *J. Color Res. Appl.*, 37(2012), 176-185.
17. R. Jafari, S. H. Amirshahi, S. A. Hosseini Ravandi, Determination of spectral dimensions of Munsell neutral samples, in Proceeding of AIC 2011 midterm meeting, Zurich, Switzerland, (2011), 447-450.
18. R. Jafari, S. H. Amirshahi, Spectral reconstruction of blacks and whites by using the statistical colorants, *Prog. Color Colorants Coat.,* 8(2015), 135-144.
19. J. R. Clonts Haslup, R. Shamey, D. Hinks, The effect of hue on the perception of blackness using Munsell samples, *J. Color Res. Appl.*, 38(2013), 423–428.
20. L. Tao, S. Westland, V. Cheung, Blackness: preference and perception (Hue), in Proceeding of the 19th IS&T/SID Color and Imaging Conference, San Jose, Norway, (2011), 270-275.
21. L. Tao, S. Westland, V. Cheung, Blackness: preference and perception (value and chroma), in Proceeding of the 6th European Conference on Colour in Graphics, Imaging, and Vision, Amsterdam, Netherland, (2012), 253-258.
22. R. Jafari, S. H. Amirshahi, S. A. Hosseini Ravandi, Effect of lightness on blackness preference of black fabrics, *Prog. Color Colorants Coat.,* 8(2015), 11-24.
23. R. Jafari, S. H. Amirshahi, A comparison of the CIE and Uchida whiteness formulae as predictor of average visual whiteness evaluation of textiles, *Text. Res. J.*, 77(2007), 756-763.
24. R. Jafari, S. H. Amirshahi, Variation in the decisions of observers regarding the ordering of white samples, *Color. Technol*., 124(2008), 127–131.
25. H. Uchida, A new whiteness formula, *J. Color Res. Appl.*, 23(1998), 202-209.
26. S. Westland, T. L. V. Cheung, O. R. Lozman, A metric for predicting perceptual blackness, in Proceeding of the 14th Color Imaging Conference Final Program and Proceedings, Society for Imaging Science and Technology, Arizona, USA, (2006),14-17.
27. R. Jafari, S. H. Amirshahi, S. A. Hosseini Ravandi, Colorimetric analysis of black coated fabrics, *J. Coat. Technol. Res.,* 13(2016), 871-882.
28. R. Jafari, F. Ameri, N. Khalili, Effect of the type of illumination on perceived blackness of automotive finishes, *J. Coat. Technol. Res.,* 13(2016), 133-141.
29. L. Tao, S. Westland, V. Cheung, Black, in Proceeding of the CREATE: Colour in art, Science, Design, Conservation, Research, Printmaking, Digital Technologies, Textiles Conference, Gjovik, Norway, (2010).
30. R. Jafari, The Dependency of colorimetric characteristics of black fabrics to the whiteness attribute of substrate. *Prog. Color Colorants Coat.*, 11(2018), 113-122.

31. J. R. Clonts, R. Shamey, D. Hinks, Effect of colorimetric attributes on perceived blackness of materials, in Proceeding of the 4th European Conference on Colour in Graphics, Imaging, and Vision, Finland, (2010).

32. R. Jafari, S. H. Amirshahi, S .A. Hosseini Ravandi, Blacks colorimetric boundaries based on the perceived blackness, in Proceeding of the 12th Congress of the International Color Association, AIC Color 2013, Newcastle, United Kingdom, (2013), 503-506.

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