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〈Research Paper〉

A study on the Modification of Fastness Formulae and the Measurement of Staining Fastness by CCM

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Abstract— A new fastness formula based on the CIEDE2000 color-difference formula was developed by B. Rigg and his coworkers. It is much simpler to calculate the staining fastness grade than the ISO 105-A04 fastness formula based on the CIELAB color-difference formula. Sample pair sets, which cover a wide color space range were accumulated from the NCS(Natural Color System) color book. For those sample pair sets, a visual measurement experiment and an instrumental measurement experiment of fastness grade were carried out. Each performance of the ISO 105-A43 fastness formula and newly developed fastness formula was compared through degree of agreement for visual measurement results. The newly developed fastness formula indicated improved performance for measuring fastness grade as it was confirmed that the performance of the current ISO fastness formula ISO 105-A04 for assessing staining, was inadequate for measuring fastness grade. Then the fastness formulae were examined more closely according to the particular color spaces and the correlation of hue, lightness and chroma for measuring staining fastness grade was also considered to recommend more improved fastness formula. By modifying the weighting functions of CIEDE2000, which is a basis of new fastness formula developed by B. Rigg, a modified fastness formula is proposed in this study.

Keywords : *fastness formula, color-difference formula, gray-scale, CIELAB, the new fastness formula developed from the CIEDE2000*

1. Introduction

Fastness is an important property for textile·dying materials. It is typically evaluated via visual measurements by experienced operators against the gray-scale. Two types of grey-scale method are recommended by the International Standards Organization(ISO) to assess fastness grade, which are the ISO 105-A02(for change of color) and the ISO 105-A03(for staining)[1,2]. But this measurement method is highly subjective, because each personal opinion for color-difference tolerance is different. So, many troubles have been generated in the case of measuring color qualities of textile·dying products such as repeatability and color-difference as well as fastness grade and so on[3,4].

The ISO TC38/SC1 committee conducted many experiments and tests to develop more objective and accurate methods for assessing fastness in the 1980s. This committee established reliable data sets, and then added two new instrumental measurement methods to the standard series as alternatives to the corresponding visual methods (ISO 105-A02[5]) and A03[6]): the ISO 105-A04[7]) (fastness formula for assessing staining degree), and ISO 105-A05[8])(fastness formula assessing

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change in color). Both these methods(ISO fastness formulae) are based upon modifications to CIELAB color space and CIELAB color-difference formula and applied to instrumental color assessment methods such as spectrophotometer or the CCM (computer Color Matching) system. Therefore, it is possible to measure the fastness grade through numerical calculations. However, these methods have not been widely used, because of the limitations of spectrophotometers, such as difficulties in measuring very small-sized test samples. This is particularly the case for the multi-fiber test strips used for assessing staining specimens1). More importantly the problems of the ISO fastness formulae have been confirmed, as color control systems such as CCM are used widely and generalized for systematical analysis of color and accurate color matching. The CIELAB color-difference formula which is the basis of ISO fastness formulae has been proven to have many disagreements with visual measurements results. Particularly, for dark color space(low lightness area and low chroma area), this color-difference formula brings about large errors compared to visual measurements[9-11]. Although ISO fastness formula is developed by considering the effects of hue, lightness and chroma from various angles, textile·dyeing industries have complained that there are large errors when these methods are applied to assess fastness grade.

So, in this study, this type of staining assessment method(ISO 105-A04fastness formula) is considered. Also, this study introduces a new fastness formula[12,13] developed by B. Rigg and his coworkers based on the CIEDE2000 Color-difference Formula [14,15]. The performances of these two fastness formulae(ISO 105-A04 fastness formula, new fastness formula by B. Rigg) were compared against visual measurement results. By confirming each fastness formula's error range for hue angle, chroma, as well as lightness in CIELAB color space, the methods such as modifying the exiting fastness formula were considered. A modified staining fastness formula is proposed in this study to develop a more accurate fastness formula.

2. Experimental

2.1. Preparation of sample pair sets

The NCS color system[16], which is used widely as color standard along with the Munsell color system[16], was used to prepare sample pair sets to diminish the error within samples. If the sample pair sets are produced from an actual dyeing process, they might have errors inter-samples. These lead to lots of differences in instrumental color assessment and the measurement of fastness grade. The color standards of the NCS color book (Natural Color System, Scandinavian Color Institute AB, Stockholm, Sweden 2004) were assessed by the CCM (X-Rite8200, U.S.) and sample pairs were selected by using $\triangle E$ values of instrumental color-difference measurement results.

As mentioned above, by using the NCS color standards as experimental sample pairs, big errors during the actual dyeing process could be avoided. The objective sample pair sets, which cover a wide color space and have interrelations for lightness, hue and chroma respectively, could be accumulated.

2.2. Instrumental assessment conditions

The optical characteristics of the CCM (X-Rite8200, US), which was used in this study, were as follows :

Repeatability (white) : 0.02 $\triangle E^*$
  Illumination : Pulsed Xenon lamp
  Illumination spot size : 7.5/12.7/25.4 mm
  Spectral range : 360 nm to 740 nm
  Wavelength interval : 10 nm
Aperture
  Small Area of View 4.0 mm
  Medium Area of View 8.0 mm
  Large Area of View 19.0 mm
Geometry : Diffuse/8°(illumination/measurement),
Specular Component : Included/Excluded

An instrumental measurements were carried out with the following conditions : D65 standard illuminant; 10 ° standard colorimetric observer; medium aperture; SCI(Specular Component included) and UV included. Under these conditions, the gray-scale(ISO 105-A02) and 1,949 color standards of the NCS color book were measured. then, 180 sample pair sets were selected from the NCS color standards by using these instrumental color assessment results : 60 sample pair sets having a fastness grade difference by lightness difference only; 60 sample pair sets having a fastness grade difference by hue difference only; 60 sample pair sets having a fastness grade difference by chroma difference only. The instrumental color assessment results of each selected sample pairs were accumulated.

2.3. Measurement of staining fastness grade according to fastness formulae

The accumulated instrumental color assessment results were applied to fastness formulae and used to measure the fastness grade of each sample pair set.

2.3.1 ISO 105-A04 fastness formula

As given in Equations (1) and (2), the ISO 105-A04 fastness formula is based on the CIELAB color difference formula[3]. This fastness formula makes it possible to numerically calculate the fastness grade by setting up the color-difference tolerance for each fastness grade of gray-scale indicating staining fastness for

$$SSR_{ISO} = 6.1 - 1.45\ \mathrm{In}(\triangle E_{GS}) \quad \text{if) } SSR = 4 \qquad (1)$$

$$SSR_{ISO} = 5.0 - 0.23\ \mathrm{In}(\triangle E_{GS}) \quad \text{if) } SSR > 4 \qquad (2)$$

$$\text{Where, } \triangle E_{ab} = \triangle E^{*}_{GS} - 0.4\ [(\triangle E^{*}_{ab})^2 - (\triangle L^{*})^2\ ]^{1/2}$$

The accumulated instrumental color assessment results(color-difference : $\triangle E_{CIELAB}$, lightness difference : $\triangle L^{*}$, chroma difference : $\triangle C^{*}_{ab}$ and hue difference : $\triangle H^{*}_{ab}$) for each selected sample pair were applied to this ISO 105-A04 fastness formula and instrumental measurement data of the staining fastness grade could be acquired.

$$\triangle E_{ab} = [(\triangle L^*)^2 + (\triangle a^*)^2 + (\triangle b^*)^2]$$
$$L' = L^*$$
$$a' = (1+G)a^*$$
$$b' = b^*$$
$$C' = \sqrt{a'^2 + b'^2}$$
$$h' = \tan^{-1}(b'/a')$$

$$\triangle E_{ab} = \left[(\triangle L^*)^2 + (\triangle a^*)^2 + (\triangle b^*)^2\right]^{1/2}$$
$$L' = L^*$$
$$a' = (1+G)a^*$$
$$b' = b^*$$
$$C' = \sqrt{a'^2 + b'^2}$$
$$h' = \tan^{-1}(b'/a')$$
$$\triangle L' = L'_B - L'_S$$
$$\triangle C' = C'_b - C'_s$$
$$\triangle H' = 2\sqrt{C_b \cdot C_s}\,\sin\frac{\triangle h'}{2}$$

$$\text{where, } G = 0.5\left(1-\sqrt{\frac{\overline{C^*_{ab}}^7}{\overline{C^*_{ab}}^7 + 25^7}}\right)$$

$\overline{C^*_{ab}}$: average of sample pair' C^*_{ab}

$$\text{where, } \triangle h' = h'_b - h'_s$$

$$E_{00} = \sqrt{(\triangle L'/K_L S_L)^2 + (\triangle C'/K_C S_C)^2 + (\triangle H'/K_H S_H)^2 + R_T(\triangle C'/K_C S_C)(\triangle H'/K_H S_H)}$$

where,

$$S_L = 1 + 0.015(\overline{L'} - 50)^2 / \sqrt{20 + (\overline{L'} - 50)^2} \qquad (3)$$
$$S_C = 1 + 0.045\overline{C'}$$
$$S_H = 1 + 0.015\overline{C'}T$$

2.3.2 CIEDE2000color difference formula and New fastness formula developed by B. Rigg and etc.

New fastness formula is based on the CIEDE 2000 color-difference formula(Equ.3) developed by modifying the measurement error of CIELAB color-difference formula. This color-difference formula includes not only lightness, chroma, and hue weighting functions, but also an interactive term between chroma and hue differences for improving the performance.

The instrumental color assessment results ($\triangle E_{00}$, $\triangle L_{00}$) from CIEDE2000 color-difference formula were also applied to the new fastness formula. (Equ.4) Thus, the other instrumental measurement data of the fastness grade for staining were acquired.

$$\triangle E_{GS} = \triangle E - 0.423\sqrt{\triangle E^2 - \triangle L^2} \qquad (4)$$
$$SSR = -0.061\triangle E_{GS} + 2.474(1 + e^{-0.191\triangle E_{GS}})$$

2.3.3 visual measurement conditions

Visual measurements was also conducted for selected sample pairs in the Light Box(The Judge II, Macbeth, U.S.) and the conditions were as follows : D65 standard illuminant; 10 ° standard colorimetric observer; 0 °/45 ° (illumination/viewing) geometry. Under these conditions, visual measurement results were accumulated from 13 observers who were very sensitive to color.

And then, these visual measurement data for the selected sample pairs was compared with instrumental measurement data of the staining fastness grade.

2.3.4 RMS(Root Mean Square) value

ll differences between measurement data of the fastness grade for color change were expressed in terms of root mean square error(RMS), as given in Equation(5) which shows the disagreement between the two measurement data of fastness grade [1].

$$RMS = \sqrt{\frac{\sum_{i=1}^{n}(X_i - Y_i)^2}{n}} \qquad (5)$$

Where X_i and Y_i are the two sets of values for the fastness grade unit for sample i. For perfect agreement, RMS should be zero. An RMS value of 0.5 indicates a typical disagreement of a half grade, which corresponds to the acceptable tolerance in practice. For example, if the pass/fail tolerance is 3.5 for a particular type of goods, a sample with a grange of 3.0 will be rejected.

3. Results and Discussions

3.1. Measurement errors

Inter-observer errors of visual measurement data and errors of instrumental measurement were evaluated to confirm the reliability of accumulated measurement data. The RMS value was used to indicate agreement between two sets of data.

The inter-observer agreement was calculated by comparing assessments of one observer with those for every other observer. The mean value of inter-observer errors was 0.59, with values ranging from 0.00 to 1.54.

Instrumental color assessment was conducted 5 times for each samples pair. These color assessment results were converted to ISO SSR grades, using Eqn. 1 or 2, and rounded to the nearest half grade. For each sample pair, the mean and RMS of the ISO SSR grades were calculated. The RMS values ranged from 0.00 to 0.76, with a mean of 0.31. Since these values are much lower than the comparable values for the inter-observer errors (mean 0.59), it was concluded that the instrumental performance was satisfactory for assessing staining.

3.2. Instrumental measurement of gray-scale grades for staining by fastness formulae

It is necessary to confirm the instrumental fastness measurement result of fastness formulae for each grade of gray-scale(ISO 105-A03) because the agreement degree with the gray-scale grade standardized to the fastness grade can be the basis of developing a more accurate fastness formula. Instrumental color assessments of each gray-scale (ISO 105-A03) grade for staining were conducted, and ISO SSR grades and SSR grades of the new fastness formula were calculated by using those instrumental color assessment results. These calculated ISO SSR grades and SSR grades from new fastness formula were compared with each grade of the gray-scale for staining are given in fig. 1. It can be seen that the measurement results calculated from the IS0 105-A04 fastness formula(ISO GSR grade) give an almost perfect fit to each gray-scale grade, but the measurement results calculated from the new fastness formula (SSR grade from new fastness formula) slightly disagree with each gray-scale grade(RMS value = 0.097). However, because the ISO 105-A05 fastness formula was developed by setting up the color difference tolerance for each fastness grade ofgray-scale indicating fastness for color change, it was already predicted that the calculated ISO SSR grade almost perfectly agrees with each gray-scale grade for staining. From the point of view that an RMS value of 0.5 indicates a typical disa greement of a half grade which corresponds to the acceptable tolerance in practice. It needed to be noted that the RMS mean value between calculated SSR grades from new fastness and gray-scale grades had a very low numerical value of 0.097. Thus, it was confirmed that both performances of the ISO 105-A04 fastness formula and the new fastness formula developed by B. Rigg have satisfactory agreement for staining gray-scale.

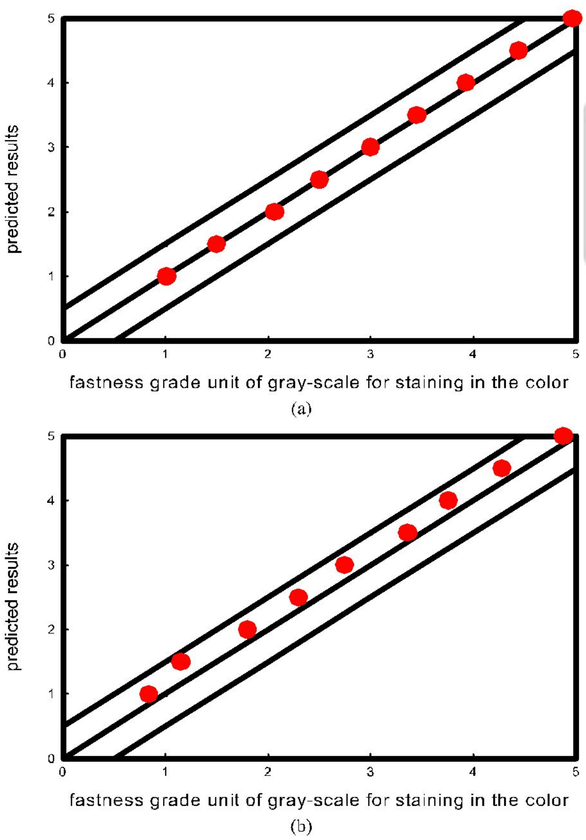


Fig. 1. Predictions of fastness formula plotted against fastness grade of gray-scale for staining.
(a) ISO 105-A0 fastness formula(b) new fastness formula developed by B. Rigg (For a perpect agreement between the instrumental prediction and visual result, all points should fall on the 45 °dashed line. Points outside the two solid-lines gave predictions disagreeing by over 0.5 of the grade)

3.3. Fastness measurement of fastness formulae for selected sample pairs

3.3.1 For sample pair sets having only lightness difference

The instrumental measurement result by the fastness formulae and the visual measurement result from the 13 observers for the sample pair sets having fastness difference only lightness difference are shown in fig. 2. As shown in the figure, the RMS value between the measurement result of the ISO 105-A04 fastness formula and the visual measurement result is a very high numerical value, 1.1360. The RMS value with the measurement result of the new fastness formula developed from the CIEDE2000 is lower than that, 0.1347.(Table 1.). It can be confirmed that the new fastness formula shows improved performance of fastness measurement compared to the RMS values of the ISO 105-A04 fastness formula. From the point of view that a 0.5 RMS value is the tolerance limitation indicating agreement between the two data sets, the measurement result of the new fastness formula is also very satisfactory result. One remarkable point acquired from these data is that the fastness measurement performance is improved by the new fastness formula for the sample set of dark color space having large error due to the disagreement between visual measurements and existing color-difference formulae such as CIELAB. It can be predicted that the disagreement of the existing color-difference formula is improved by the recently recommended CIEDE2000 color-difference formula.

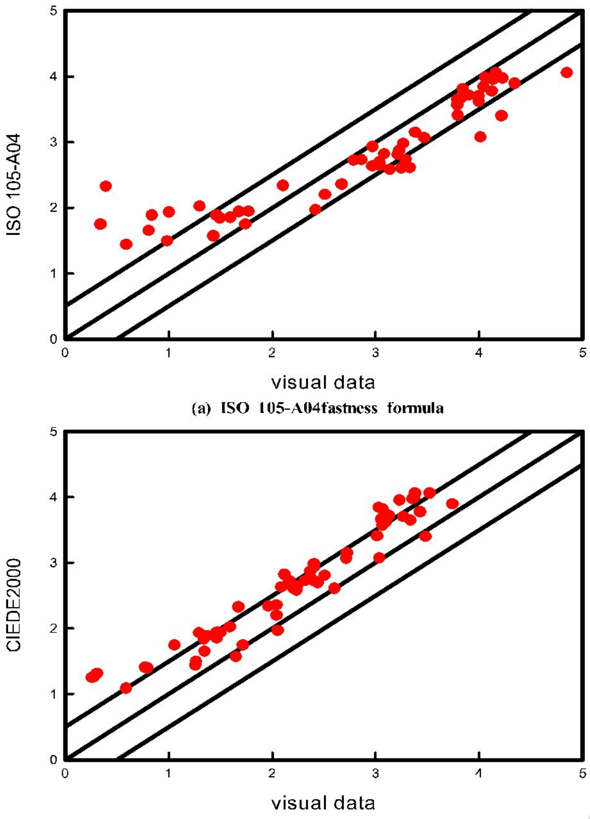


Fig. 2. Predictions of fastness formula plotted against visual data sets according to the lightness difference (a) ISO 105-A04 fastness formula (b) New fastness formula developed from the CIEDE2000

3.3.2 For sample pair sets having only chroma difference

Instrumental measurement results from the fastness formula and visual measurement results for sample pair sets having a fastness difference from only chroma difference are shown in fig. 3. The RMS value of the ISO SSR grade against the visual measurement result is 0.9576 and the RMS value with the measurement result of new fastness formula developed from the CIEDE2000 is 0.0146. (Table 1)

Table 1. RMS values between visual results and Instrumental results by the fastness formula

Sample pairs \ Fastness formula	ISO 105-A04	New Fastness formula
Gray-scale	0.3014	0.0976
Lightness difference	1.1360	0.1347
Chroma difference	0.9576	0.0146
Hue difference	0.7265	0.1026
Total	0.9548	0.5234

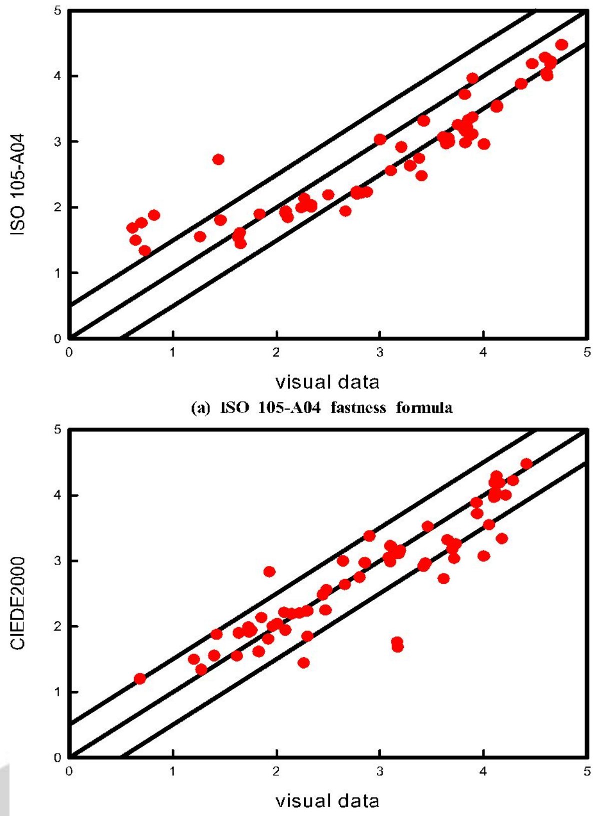
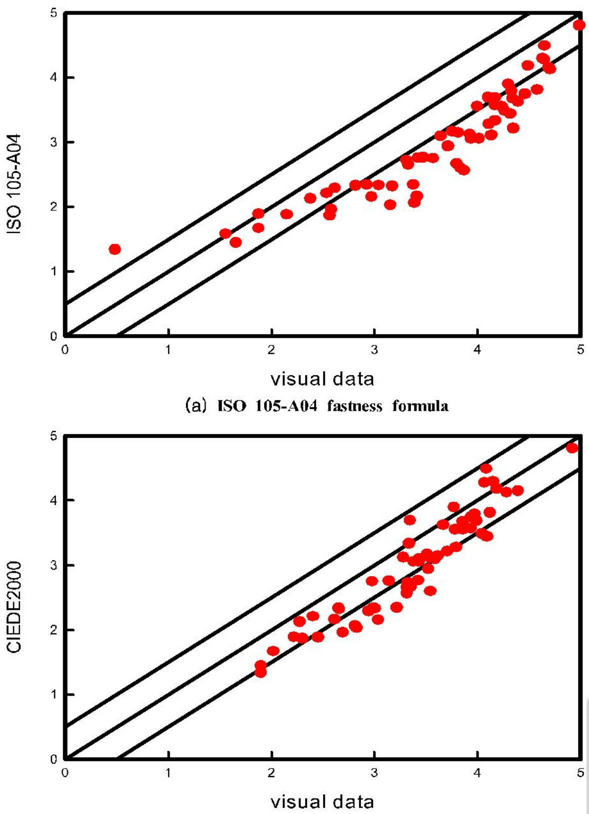


Fig. 3. Predictions of fastness formula plotted against visual data sets according to the chroma difference (a) ISO 105-A04 fastness formula (b) New fastness formula developed from the CIEDE2000

As shown by the RMS values, the new fastness formula developed from the CIEDE2000 performs better than the ISO 105-A04 fastness formula to measure the fastness grade. Also as mentioned above, for dark color sample pair of low chroma having large errors, the new formula shows improved performance for measuring fastness grade.

3.3.3 For sample pair sets having only hue difference

Instrumental measurement results of the fastness formula for sample pair sets having fastness difference from only hue difference are shown in fig. 4 against visual measurement results. The new fastness formula also shows improved fastness measurement performance compared to the ISO 105-A04 fastness formula for the sample pairs having a fastness grade difference by only hue difference. The RMS value of the ISO 105-A04 is 0.7265 and the RMS value of the new fastness formula developed from the CIEDE2000 is 0.1026 against visual measurement result.



(b) New fastness formula developed from the CIEDE2000

Fig. 4. Predictions of fastness formula plotted against visual data sets according to the chroma difference (a) ISO 105-A04 fastness formula (b) New fastness formula developed from the CIEDE2000

3.4 Modification of new fastness formula.

As shown in figure 2~4, new fastness formula shows improved performance tp fastness measurement.

But, It was not necessarily so that the new fastness formula has satisfactory agreement and shows improved fastness measurement performance for all selected sample pair sets. So, by revised each Lightness, chroma, and hue weighting functions (S_L, S_C, S_H) of CIEDE2000 color-difference formula, which is a basis of new fastness formula, more accurate modified fastness formula is proposed in this study.

The RMS values between visual assessment result and assessment result of modified new fastness from the revised S_L, S_C, S_H coefficient (A~E) of CIEDE2000 color-difference formula are compared in Table 2. From the RMS values according to each weighting function in Table 2, it is confirmed that when the coefficient of S_L, S_C, S_H equation was revised to 0.51 : 0.99 : 1, the modified fastness formula shows optimum performance.

Table 2. RMS values according to revised weighting functions of CIEDE2000 color-difference formula.

	S_L : S_C : S_H	hue	lightness	chroma
A	0.51 : 0.99 : 1	0.0130	0.1301	0.0120
B	0.52 : 0.98 : 1	0.1681	0.3666	0.0145
eC	0.55 : 0.5 : 1	0.1045	0.1141	0.1072
D	0.55 : 1 : 1	0.1046	0.1141	0.0111
E	0.57 : 1 : 1	0.1053	0.1073	0.0108

4. Conclusions

A study on the staining fastness formula was carried out and the following conclusions have been reached.

1. From the figure 1, it is confirmed that the fastness measurement results calculated from ISO 105-A04 fastness formula give an almost perfect fit to each gray-scale grades, and new fastness formula developed from CIEDE2000 color-difference formula also has satisfactory agreement with gray-scale grades.
2. The disagreement degree between instrumental measurement results calculated by the fastness formula and visual measurement results and selected sample pairs according to hue, lightness and chroma are shown in table 2 and figure 2-4. From the RMS value of table 2, it is confirmed that the new fastness formula developed from the CIEDE2000 has satisfactory agreement and shows significantly improved fastness measure - ment performance compared to the ISO 105-A04 fastness formula.
3. New fastness formula developed from the CIEDE2000 color-difference formula having factors of weighting function with regard to hue, lightness, chroma is used by the base formula. From the RMS values according to each weighting function in table 2, when the coefficient of S_L, S_C, S_H equation was revised to

0.51:0.99:1, the modified fastness formula showed optimum performance. Although this modified fastness formula does not performs perfectly in Lightness and Chroma, it shows significantly improved fastness measurement performance in Hue. It also showed satisfactory agreement with visual assessments in Lightness and Chroma. (From the RMS values according to the weighting functions in table 2, the RMS value of A in Lightness and Chroma was satis factory level and had lower value or an approximate value compared with the RMS values of the other weighting functions.)

So, this modified fastness formula is proposed by fitting this data set and it appears better performance than other formulae.

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