Assessing total differences for effective samples having variations in color, coarseness, and glint

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Effect coatings have the unique property of large change of appearance under different viewing conditions. This results in quality control problems of related products. In this letter, samples of metallic panels with effect coatings are visually assessed and measured. Based on experimental results, we propose formulae to predict precisely the total differences of effective samples in terms of variations in color, coarseness, and glint. Under diffused illumination, the total difference formula includes color difference and coarseness difference. Under directional illumination, the total difference formula includes color difference and glint difference.

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Effect coatings have been generally adopted in industries, such as the finishing of vehicles, printing, cell phones, etc., to achieve amazing appearance and draw the attention of customers. Due to the complexity of describing their unique properties, the quality control for this kind of coating has lagged behind in spite of decades of research. Further studies have become necessary in the light of the growing percentage of cars with effect coatings and the increasing amount of exotic effect pigments produced by pigment manufacturers[1−3].

Aside from color, effective pigments have affected another aspect of coating appearance, namely, the visual texture. Visual texture has been defined as the perceived small-scale non-uniformity of the color of the effective pigment when observed within a distance of a meter or less. It has been regarded as an important property because of its contribution to the appearance of effective pigment. It can be added as a new dimension when characterizing effective pigments. Generally, coarseness and glint have been considered two of the most important attributes influencing the overall appearance of effective pigments. Coarseness is the perceived contrast in the light/dark irregular pattern exhibited by effect coatings. The perceived value of coarseness depends on the lightness difference between the light and dark regions, and on the size of the pattern. Glint, also called bright sparkle, is the tiny spot that is strikingly brighter than its surrounding. It is only visible under directional illumination conditions. The glint is expected to switch on and off when the observation geometry is changed. Thus, it is angle-dependent. Glint value is defined by the local contrast between bright sparkle and its surrounding, and the amount of the sparkle[4−6].

Metallic coatings, the most common effect coatings, have been used in modern industries. Traditional methods of their characterization include multi-angle or multi-geometry measurement. These methods, however, have failed to take into account texture properties. For example, two samples with large variation in texture and little difference in color cannot be distinguished. For this reason, a method that could assess effective samples in terms of color, coarseness, and glint is proposed in this letter.

The BYK mac (BYK-mac CM-6397, BYK-Gardner, Germany) is an instrument developed recently to measure multi-angle reflectance, coarseness, and glint level of metallic samples separately under the geometries. As illustrated in Fig. 1, the incident light at the angle of 45° with respect to the sample surface was reflected by the surface of the sample. Reflected light was received and measured at six points with aspecular angles of –15°, 15°, 25°, 45°, 75°, and 110°. Before the visual experiment, all 556 samples produced by Akzo Nobel were measured using the BYK mac. Among them, a set of 44 pairs consisting of 50 metallic-coating panels, some of which were utilized in more than one pair, were used as testing samples in this experiment. The set included 4 pairs of gray, 10 pairs of purple, 5 pairs of yellow, 5 pairs of red, 10 pairs of green, and 10 pairs of blue samples. Based on the measurement by the BYK mac with aspecular angle of 45°, the following criteria were used in choosing the test samples. Firstly, the color of each sample pair should be located around a single color center. Secondly, the color difference within each individual sample pair should be within 3–8 ΔE^*_{ab}. Finally, coarseness and glint difference should be larger than 2 units to ensure that their coarseness and glint differences could facilitate observable perception. To check intra-observer repeatability,

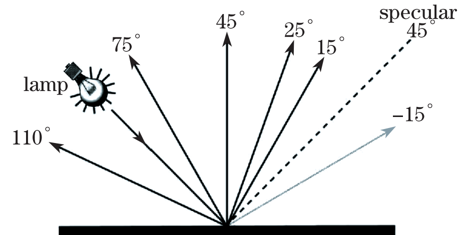

Fig. 1. Six-angle reflectance measuring geometry of the BYK mac.

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16 pairs were selected as repeat test samples, including 2 pairs of gray, 3 pairs of purple, 2 pairs of yellow, 2 pairs of red, 3 pairs of green, and 4 pairs of blue samples.

A panel of 10 observers (4 females and 6 males) participated in the visual assessment. The observers were either students or members of the staff of the University of Leeds who passed the Ishihara visual test, thus with normal color vision. The geometries employed in this visual experiment are illustrated in Fig. 2(a). The sizes of the samples were 15 × 10 (cm), and the distance between the viewing point and the samples was 50 cm. Thus, the CIE 1964 standard observer was utilized. Two kinds of light sources were adopted: a daylight simulator incorporated in the GretagMacbeth SpectraLight II Cabinet serving as the diffused illumination with measured luminance level of 370 cd/m^2 on the panel, and a tungsten halogen lamp for the directional illumination with measured luminance level of 4110 cd/m^2 on the sample surface. In the first two sessions of the visual experiment under diffused illumination, the geometries of the maximum coarseness difference and the maximum total difference within each individual sample pair that could be detected by observers were θ of 27° and 31°, respectively. In the third session, under directional illumination, the viewing geometry was fixed at the geometry of θ at 58° such that the observers could perceive the maximum glint impression according to the research of Kitaguchi[6]. After finalizing the viewing condition, the observers were then asked to scale the total difference against a gray scale, as shown in Fig. 2(b). The scale, which consisted of 9 pairs of samples representing 9 levels of visual difference, is listed in Table 1. It should be noted that these 9 pairs of reference samples are made of paper and have no difference in texture except in the gray level. Based on the above-mentioned procedures, the observers were then asked to give a number representing the total difference of a sample pair. In the case of diffused daylight source, observers were instructed to give two other numbers representing percentages for color and coarseness differences in relation to the total difference. For the spot light source, the observers were asked to give three other numbers representing the percentages for color, coarseness, and glint differences in relation to the total difference. In all visual experiments, 60 pairs (44 testing pairs + 16 repeat pairs) × 3 viewing sessions (θ being 27°, 31°, and 58°) × 10 observers =1800 assessments were conducted.

For each source, scale values representing the total difference of each sample pair were transformed into visual differences in terms of CIEDE2000 color difference using the corresponding spectral power distribution (SPD) measured by a Minolta tele-spectroradiometer (TSR) (CS1000, Konica Minolta Sensing, Japan). Based on the percentages given by the observers, each individual difference in color, coarseness, and glint was obtained. Thus, intra-observer repeatability and inter-observer variation for total difference, as well as color difference, coarseness difference, and glint difference, were evaluated. Finally, with the total difference obtained from the visual experiments, and with color, coarseness, and glint differences measured by the BYK mac, the total difference formulae were developed.

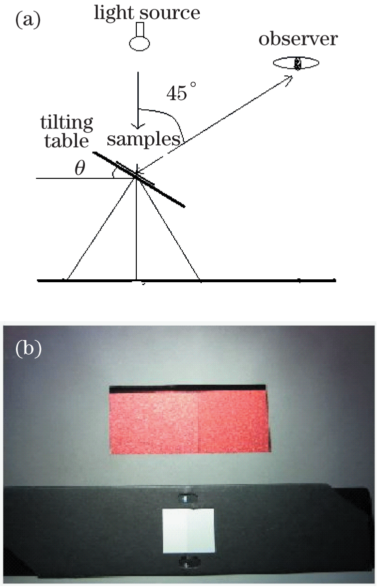

Fig. 2. Experimental setup and indication of the visual assessment. (a) Overall geometry for visual assessment and (b) sample pair against the gray scale.

The statistics of measurements and visual data were evaluated in terms of standardized residual sum of squares (STRESS)[7], which is calculated by

$$\text{STRESS} = \left[\frac{\sum(\Delta E_i - F\Delta V_i)^2}{\sum F^2 \Delta V_i^2}\right]^{1/2} \times 100, \quad (1)$$

where the subscript i is the index, ΔE_i and ΔV_i are two groups of data, and F equals 1 since ΔE_i and ΔV_i have the same scale in this experiment. Evidently, the STRESS value will be 0 if the two groups of data are exactly the same. The STRESS will increase with the increase of the difference between the two groups.

The observer accuracy was estimated via intra-observer repeatability and inter-observer variation. For each term, the total difference, as well as for color difference and coarseness difference, was evaluated under diffused illumination. Intra-observer repeatability was derived from comparison within one observer; STRESS values were calculated for the 16 pairs of the repeated samples. Inter-observer variation was derived from the comparison between each observer and the mean of the 10 observers; STRESS values were calculated for the 44 pairs of samples. The results of intra-observer repeatability and inter-observer variation test for the two geometries

Table 1. Color Differences of the Gray Scale in Terms of CIEDE2000 under Two Light Sources

Scale Value	5.0	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0
Directional	0.05	5.71	5.93	6.18	7.44	8.24	11.08	16.04	23.15
Diffused	0.05	1.94	3.22	4.37	6.38	8.18	11.18	16.45	23.55

Table 2. Observer Accuracy under Diffused Illumination in Terms of STRESS

Viewing Geometry	Color Difference		Coarseness Difference		Total Difference	
	Intra-	Inter-	Intra-	Inter-	Intra-	Inter-
Maximum Coarseness Difference	36	50	50	53	31	41
Maximum Total Difference	38	54	56	50	33	46

under diffused illumination (with θ being 27° and 31° from the observers for perceived maximum coarseness difference and maximum total difference, respectively) are given in Table 2. The STRESS values at the geometry of maximum coarseness difference were smaller than that at the geometry of maximum total difference, except that of the inter-observer variation for coarseness difference. This indicates better performance for observers viewing the geometry for maximum coarseness difference. As expected, the inter-observer variations of the two geometries were greater than that of the intra-observer repeatability, except that of coarseness difference for the maximum total difference. Among the three attributes, total difference results were most reliable, followed by the color difference, while the coarseness difference was the most difficult to assess.

Since the two viewing geometries under diffused illumination showed minimal difference, they were regarded as one ($\theta = 29°$) when establishing the total difference formula. The total difference of each sample pair was expected to correlate with the instrument measurement, shown as

$$\Delta T = \sqrt{\sum_{i=1}^{6} c_i(\Delta E^*{}_i)^2 + c_7(\Delta \text{Coarseness})^2}, \qquad (2)$$

where i is the ith measuring geometry corresponding to the aspecular angles of –15°, 15°, 25°, 45°, 75°, and 110° with i=1, 2, 3, 4, 5, 6; c_i is the constant to be developed; ΔE_i^* is the CIEDE2000 color difference[8,9] under the ith measuring geometry; ΔCoarseness is the coarseness difference measured by the BYK mac; and ΔT is the visual total difference. To optimize Eq. (2), the STRESS value of the visual total difference and the corresponding $\sqrt{\sum_{i=1}^{6} c_i(\Delta E^*{}_i)^2 + c_7(\Delta \text{Coarseness})^2}$ for all sample pairs were minimized by changing the values of c_i. Results are given in Table 3. The aspecular angles with the three largest constants of color difference were 25°, 45°, and 15° in descending order. This suggests that the geometries at such aspecular angles were the most important in determining the color differences of metallic-coating samples under diffused illumination. The STRESS value of 20 implies that the total difference obtained from the instrument measurement by using the formula could effectively predict what the observers perceived[10].

Table 3. Constants c_i of the Total Difference Formula and the Corresponding STRESS Value under Diffused Illumination

	Coarseness Only
c_1	0.00
c_2	0.02
c_3	0.34
c_4	0.26
c_5	0.00
c_6	0.00
c_7	0.24
STRESS	20

Table 4. Observer Accuracy under Directional Illumination in Terms of STRESS

Difference	Intra-	Inter-
Color	31	32
Coarseness	56	55
Glint	40	42
Total	17	22

Observer accuracy under directional illumination was similarly evaluated (Table 4). As expected, the mean STRESS values of inter-observer variation test were larger than those of intra-observer repeatability. However, the values were smaller compared with that of coarseness difference. The results for total difference for both intra-observer repeatability and inter-observer variation were of the best values. The observers directly provided the total difference, while the values of the other three attributes were given. However, the STRESS values of color difference were less than those of the coarseness difference and glint difference, which suggested that the observers assessed the color difference more easily than the two others. The STRESS values of coarseness difference were the largest of all variables. This implies that the coarseness difference for the observer was the most difficult attribute for precise assessment. In addition, results of coarseness difference were considered the most unreliable because the coarseness difference partly influenced total difference. The STRESS value of the total difference for inter-observer variation was 22, which was typical in color appearance studies[11]. Therefore, the visual data of this experiment were considered acceptable.

The coarseness difference was measured using the BYK mac under diffused illumination. This rendered its use in establishing the formula under directional illumination inappropriate. On the other hand, coarseness difference partly influenced total difference according to visual results from observers; thus, it could be eliminated. In addition, coarseness was never before measured under directional illumination[1,6]. Thus, the total difference formula under directional illumination only included color and glint differences.

Since the aspecular angle of 45° was the closest viewing condition at which visual assessment was taken, the measured results of 45° geometry were adopted to develop the total difference formula under the directional illumination. They were linked with the visual result from

$$\Delta T = \sqrt{c_1(c_2\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}) + c_3\Delta \mathrm{Glint}^2}, \quad (3)$$

where c_1, c_2, and c_3 are the constants to be optimized; ΔL^*, Δa^*, Δb^*, and ΔGlint are the measured results of BYK mac for the geometry of aspecular angle of 45°; and ΔT is the visual total difference. For the optimization of Eq. (3), STRESS values for the total difference of all sample pairs and corresponding $\sqrt{c_1(\Delta c_2\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}) + c_3\Delta \mathrm{Glint}^2}$ were minimized by changing the values of c_i. The resulting constants c_i and the corresponding STRESS value are listed in Table 5. The constant c_2 (1.09) is very close to 1, which suggests that chroma and lightness were of similar importance in the total difference. Based on the two attributes of color and glint differences, the STRESS value of 21 showed that this proposed formula could accurately predict the total difference under directional illumination[10].

In conclusion, the total difference between effective samples with variations in color, coarseness, and glint can be visually assessed by observers. Visual results can be linked with instrumental measurements. Under diffused illumination, the geometry of θ equal to 29° is confirmed as the viewing angle where the total difference is easily perceived by observers. Two formulae are developed to predict the visual total difference within each sample pair from the measured color, coarseness, and glint differences under diffused and directional illumination. The STRESS values (20 and 21) indicate their satisfactory prediction performance.

Table 5. Constants c_i of the Total Difference Formula and the Corresponding STRESS Value under Directional Illumination

c_1	c_2	c_3	STRESS
0.92	1.09	0.76	21

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