Classifications of Decorative Paper using Differential Reflection Spectrophotometry Coupled with Soft Independent Modeling of Class Analogy

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With the rapid development of the decorative papers industry on a worldwide scale, the aesthetic assessment of decorative papers has evolved as one of the major fields for industrial production. This study was performed to investigate the ability of visible spectroscopy and NIR spectroscopy coupled with the soft independent modeling of class analogy (SIMCA) to reflect the surface characteristics of decorative paper and to classify decorative papers with different visual characteristics. The results showed that visible spectroscopy has a higher relationship with the surface characteristics of decorative papers than the NIR data during PCA analysis due to larger variations. Additionally, when using visible spectroscopy (400 to 780 nm), the classification accuracy reached 94% to 100%, a more accurate result than could be achieved based on color data. In the results of the NIR spectroscopy (780 to 2500 nm), the classification accuracy decreased to the range 1% to 56%, except for a value of 95% for the samples that were grained with a slightly dark color, and a greater number of samples were assigned to more than one class. There were significant differences in the performance of the models built with visible spectroscopy and NIR spectroscopy, so it can be concluded that visible spectroscopy coupled with SIMCA is more useful to classify the different types of decorative papers than NIR spectroscopy.

Keywords: Decorative papers; Classification; Colorimetric parameters; Visible spectroscopy; NIR spectroscopy; SIMCA

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INTRODUCTION

As a fast-developing industry, the wood-based panel industry is one of great significance for the economy and for the saving and recycling of wood resources. The global output has reached approximately 300 million m^3 in 2010, with an average annual growth rate of 7% since 2000 (Qian 2011). With decorative paper being an important material for wood-based panels, the decorative paper industry has achieved rapid development and become a booming field. Decorative paper is a specialty grade of paper that is affixed to the surface of a suitable substrate at elevated temperature after the base papers are printed and impregnated with resin (Nemli 2008). For the purpose of decoration and protection, decorative paper has taken up 70% of the market for decorative materials for manufactured boards (O'Carroll 2004). In Europe, the birthplace of decorative paper, the production capacity of base papers has already reached 494,200 tons (approximately 61.9 million m^2 on a per weight of unit area basis: 80g/m^2) in 2010. The widespread use of decorative paper, especially for papers printed with wood grain, has increasingly taken the place of natural wood veneer, serving as a way to conserve natural wood resources (Kandelbauer and Teischinger 2010).

The visual color always determines the acceptability of the decorative paper to its seller and ultimately to the consumer. Customers very much look forward to seeing the same color every time they purchase the same product, whether it is days or months between purchases. But with the rapid development of the decorative paper industry, the quality of decorative paper products has increasingly been a matter of concern, with the most obvious quality problem being color differences manifested on the surface of decorative papers, which should have a more attractive appearance (Cai and Xu 2006). Traditional evaluation methods for color difference have included humans' visual evaluation, as well as colorimetric instrumental measurement based on the CIELAB color scale. The former method is simple and fast, but it demands the worker's proficiency, and the efficiency and accuracy of the method may be low due to eye fatigue, working environment, and subjective factors (Dharavath 2007). Instruments are capable of seeing pure values of the colorimetric coordinates CIELAB L^*, a^*, and b^*, and the theory underlying the CIELAB system presumes that there are three dimensions including a red-to-green color dimension, a yellow-to-blue dimension, and a non-linear function of lightness (Lee 2005). And this method is being used in many industries including paper (Harold 2001), wood (Moya and Calvo-Alvarado 2012), and others. But there also exist some disadvantages: the measurement of color data is a complex process, and there are more stringent requirements for the samples (Shi 2006). Thus, it is of great importance to find a new method that has the following advantages: small size, simple operation, high efficiency, a high degree of on-line quality control, *etc*.

Visible and near-infrared (NIR) spectroscopy have been widely used as a convenient, nondestructive, fast, and high-efficiency inspection technology in many fields, such as agriculture (Hamaoka *et al.* 2011; Cozzolino *et al.* 2007), food (Yao *et al.* 2003; Fernandes *et al.* 2013), forestry (Kobori *et al.* 2008; Yang *et al.* 2013), *etc*. This method mainly includes the visible region (350 to 780 nm) and NIR region (780 to 2500 nm). The method provides surface information about color, gloss, and roughness in the visible region. In addition, mechanical and chemical information might be reflected using NIR spectroscopy. Although the evaluation of color difference is included in many studies (Chen and Wang 2003; Lee 2005; Moya *et al*. 2012), very few studies specially train the panelists to do an evaluation of decorative paper using visible spectroscopy and near-infrared spectroscopy.

In the present study, the objective was to study and analyze spectroscopic data collected from the surface of decorative paper; to evaluate the ability of visible and NIR spectroscopy to assess the color difference of decorative papers; and to compare the accuracy of these two methods for the classification of decorative paper in order to find the most effective technique.

EXPERIMENTAL

More than 200 decorative papers in the market were observed. From them, 120 decorative papers of equal size (140 mm×110 mm) were randomly selected and divided into six categories according to their appearance features (grain and the depth of color) for our research. To verify the validity and reliability of classification, 30 people, whose color discrimination was normal, were invited to observe and estimate again using the colour assessment cabinet. The observation conditions are detailed as follows: fluorescent lamp light (at a level of 200-300 lux) was perpendicular to the surface of the paper and visual direction is at a 45 degree angle with an observation distance of 35 mm. All of them expressed agreement with the classification of samples. The six types of decorative papers being used for the color measurement and spectral collection were: samples with grained and dark color (GD); samples with grained and slightly dark color (GM); samples with grained and light color (GL); samples with solid color and dark color (SD); samples with solid color and slightly dark color (SM); and samples with solid color and light color (SL). Twenty decorative papers were selected for each type.

Colorimetric data were conducted on a CM-2600d spectrophotometer (Konica Minolta, Japan). L^*, a^*, and b^* are measured and recorded, where L^*, a^*, and b^* are the CIELAB metric lightness, index of (red-green opponent) axis, and index of (yellow-blue opponent) axis. The light source of D65, the illumination area of 8 mm and the observer of 10° were selected with the mode of SCI (specular component included) during the measurement. Five measuring spots were measured per a decorative paper.

The visible and NIR spectra measurements were collected with an ASD Field Spec Pro FR (Analytical Spectral Devices, Boulder, CO, USA) spectrometer in the diffuse reflectance mode at 1 nm intervals between 400 and 2500 nm. The reference material was a piece of commercial microporous Teflon. A fiber-optic probe positioned 8 mm above the sample was oriented perpendicular to the sample, and the spot diameter was 7 mm. Five scanning points were selected for each sample, and thirty scans were accumulated and averaged for each of the scanning points. A total of 600 spectra were taken from all the samples.

Unscrambler® (version 9.2, CAMO, Corvallis, OR, USA) software was employed for principal component analysis (PCA) computing, partial least squares (PLS), and soft independent modeling of class analogy (SIMCA) analysis. The PLS regression is one of the most common statistic methods, and it builds a linear regression model by projecting the predicted variables and the observable variables to a new space. The main principle of SIMCA is to make a separate PCA model for each type of sample and to classify the samples by comparing the distance between the samples and models, then calculate the shortest distance and classify the sample into the corresponding model (Wold 1976).

RESULTS AND DISCUSSION

Surface Visual Characteristics of Samples

Table 1 shows the surface characteristics of different types of decorative papers by displaying the L^*, a^* and b^* values measured by the instrument. It can be seen from Table 1 that a great difference in surface characteristics existed among different types of decorative paper. The samples from GL and SL exhibited high color lightness, as evidenced by a mean value greater than 90. The samples from GD showed the lowest lightness value of 36.05, and the remaining samples fell somewhere in the middle. The samples from GM and SD displayed similar color lightness. The presence of red in the decorative papers increased from dark colors to light colors. By comparing the mean value of b^* from different types of samples, it was observed that the samples from GM and SM were the strongest in yellow. There was little variance detected among the samples from GD and SD due to the large standard deviation. To more accurately understand whether there exists difference among six types of decorative papers, the

ANOVA analysis was performed at the 5% significance level. And the overall F test is significant (F=6.58; p <0.05), which indicated that that there are differences among the six types of decorative papers. The above results are consistent with evaluation by the visual assessment of the human subjects, which could illustrate that the previous artificial classification has a certain rationality and feasibility.

Table 1. Results for the Colorimetric Parameters of the Surface of the Decorative Papers

Sample types	L^*				a^*				b^*			
	Max	Min	Mean	Stdev	Max	Min	Mean	Stdev	Max	Min	Mean	Stdev
GD	46.54	28.49	36.05	4.64	35.03	7.01	20.14	7.01	35.57	7.36	20.74	7.72
GM	77.37	58.32	69.23	4.54	21.15	2.97	12.29	3.78	41.84	14.88	28.13	5.72
GL	93.39	88.07	90.90	1.29	3.42	-1.11	0.61	1.17	18.52	2.21	10.15	2.96
SD	76.07	54.89	64.70	7.71	24.87	11.58	20.00	4.16	29.95	13.79	21.32	5.62
SM	86.06	81.18	85.01	1.18	8.88	4.92	5.72	0.91	31.42	26.08	27.60	1.33
SL	96.93	95.87	96.26	0.19	-0.19	-1.07	-0.58	0.17	5.19	2.46	3.53	0.46

Visible Spectroscopy and Near Infrared Spectroscopy Analysis

The mean NIR spectroscopy pretreated with baseline shift from the six types of samples between 400 and 2500 nm are presented in Fig. 1. In the visible region (400 to 780 nm), the spectra showed great variability in shape and absorption. The samples from GD had the highest absorption peak, followed by SD, GM, SM, GL, and SL. The visible spectra showed differences in overall chemical and physical properties of decorative papers. The spectra in the region of 780 to 2500 nm were very similar, other than the GD grouping. There were pronounced peaks located at approximately 1470 and 2089 nm, which were attributable to O-H stretching and C-H deformation of cellulose and hemicellulose (Schwanninger *et al.* 2011). Bands near 1922 nm were related to a combination of O-H stretching and O-H deformation vibrations in water (Hageman *et al.* 2005). A visual inspection of the NIR spectra seemed to be unhelpful for the classification of decorative papers because only GD paper could be separated from other types.

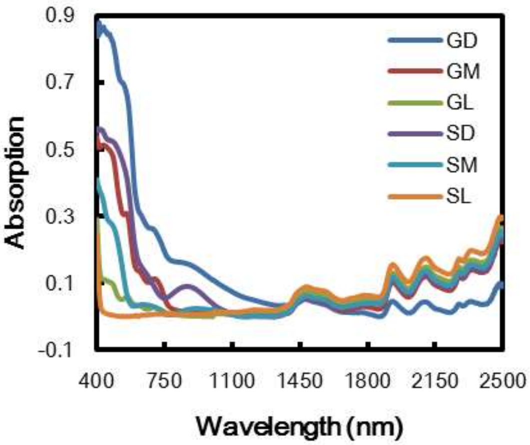

Fig. 1. Visible and near infrared spectra absorption of different types of decorative papers

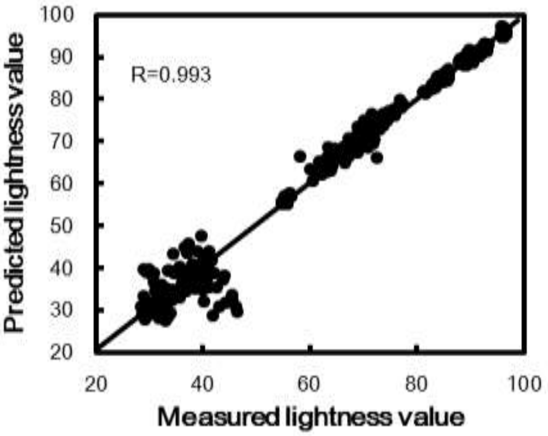

Fig. 2. Relationship between visual spectroscopy (400-800 nm) and lightness values on the surface of decorative papers

To investigate the relationship between the color data and spectroscopy from the surface of decorative papers, a PLS regression was performed on the spectral range of 400 to 780 and 780 to 2500 nm separately before PCA analysis. The PLS model based on color data and NIR spectroscopy had a high R value of 0.767 to 0.976, and the PLS model based on color data and visible spectroscopy exhibited a higher R value of 0.949 to 0.993. Thus, the majority of information about L^*, $a^*$and b^* of decorative papers was obtained in the spectroscopy range of 400 to 780 and 780 to 2500 nm. The PLS regression model based on lightness values and visible spectroscopy of 400 to 780 nm is shown in Fig. 2.

PCA Analysis

The previous results confirmed that there existed a great relationship between L^*, $a^*$and b^* and spectroscopy of 400 to 2500 nm on the surface of decorative papers, while it is still not clear which spectral range between 400 to 780 or 780 to 2500 nm played a leading role. Thus, the data of L^*, $a^*$and b^*, the visible spectroscopy (400 to 780 nm) and NIR spectroscopy (780 to 2500 nm) from six types of samples were selected and then submitted to PCA analysis. The PC1 versus PC2 score plots are shown in Fig. 3 (a, b, and c). The first PC explained 83%, and the second PC 14% for the color data, and 96%, 98% (PC1) and 3%, 2% (PC2) for the visible spectroscopy and NIR spectroscopy, respectively.

It can be seen that the distribution and tendency in Fig. 3 (a) and (b) were nearly similar, and six clusters of decorative papers were clearly separated along the first two PCs except that the samples from SD were close to the samples from GM. The spread of the samples from SM, GL, and SL was rather small, while for some classes (GD, GM, and SD) there was a larger spread. Notably, the samples from SD seemed to be inhomogeneous and contained sub-clusters. From Fig. 3 (c), the samples from classes of GM, SD, SM, GL, and SL were severely overlapped. The samples from GD were greatly scattered, the results of which were completely different from the results in Fig. 3 (a) and (b). Therefore, it seems to be that the visible spectroscopy was highly influenced by the surface characters of decorative papers, while the NIR data showed a larger variation.

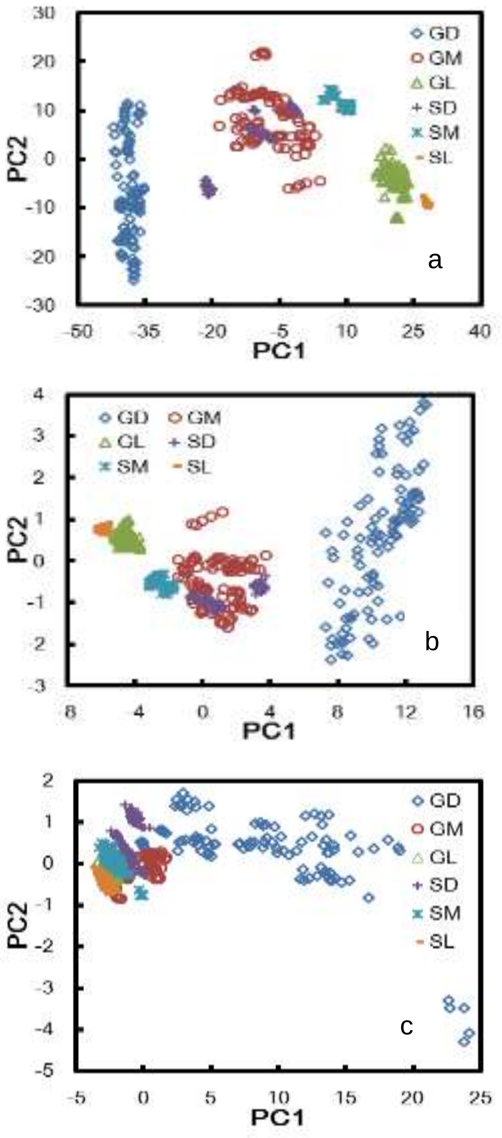

Fig. 3. The PC1 vs. PC2 score plots of color data (a), visible spectroscopy (b), and near-infrared spectroscopy (c) of six types of samples

SIMCA Classification

After PCA analysis, separate PCA models for each type of sample were built using the color data, visible spectroscopy, and NIR spectra. Then, the same samples were classified using the established PCA models based on the cross-validation. Table 2 shows the summary of validation of classification models developed over color data and spectroscopy wavelength region of 400 to 780 and 780 to 2500 nm at the 5% significance level. When the data of L^*, a^*, and b^*were used, the classification accuracy reached 79 to 96%. 13% of the GM samples and 15% of the SD samples were assigned to more than one class, and there were many samples that could not be assigned to any class. Only 2% of GM and 1% of SM samples were wrongly assigned.

When spectroscopy of the wavelength region of 400 to 780 nm was used, the accuracy of classification increased significantly. The samples were almost assigned correctly, other than a few samples from GL, SD, SM, and SL that could not be assigned to any class. However, only one class's classification accuracy was up to 95%, with more samples assigned to more than one class. For the classes of GL and SL, only a single sample was assigned correctly. The classification result based on the NIR spectroscopy was poor, but it seemed to be reasonable because it was consistent with the visual inspection of the NIR spectra and the result of PCA analysis. The above results indicate that it is feasible to use the visible spectroscopy (400 to 780 nm) to reflect the surface characteristics of decorative papers and to classify different types of decorative papers, while that is not the case for the NIR spectroscopy (780 to 2500 nm).

Table 2. Classification Results of Different Types of Decorative Paper using Color Data, Spectroscopy Wavelength Region of 400 to 780 and 780 to 2500 nm

Analysis methods	Sample types	PCs	Model distances	Classification (% of totally classified samples)			
				More	Wrong	No	Right
Colorimetric parameters (L^*, a^*, and b^*)	GD	2	1	0	0	4	96
	GM	2	378	13	2	6	79
	GL	2	3307	0	0	7	93
	SD	2	830	15	0	0	85
	SM	2	2901	0	1	15	84
	SL	2	9277	0	0	8	92
Visible spectroscopy (400 to 780 nm)	GD	3	1	0	0	0	100
	GM	4	12	0	0	0	100
	GL	4	57	0	0	3	97
	SD	2	128	0	0	1	99
	SM	2	63	0	0	6	94
	SL	3	57	0	0	2	98
Near infrared spectroscopy (780 to 2500 nm)	GD	2	1	0	0	5	95
	GM	2	10	44	0	0	56
	GL	2	14	96	2	1	1
	SD	3	36	90	0	0	10
	SM	3	10	86	0	4	10
	SL	2	28	99	0	0	1

PCs: principal components; Model distances: the distance between models; More: samples were assigned to more than one class; Wrong: samples were wrongly classified; Right: samples were assigned correctly; No: samples were not assigned to any class.

CONCLUSIONS

This study applied colorimetric parameters, visible spectroscopy, and NIR spectroscopy coupled with SIMCA to the classification of different types of decorative papers. There were clear distinctions in the performance of classifications when compared to the models developed using the visible spectra region of 400 to 780 nm and the NIR spectra region of 780 to 2500 nm. The classification accuracy of the samples reached up to 94% to 100% when using the visible spectra region of 400 to 780 nm at the 5% significance level, a much higher precision than that of the result based on the color data. While the classification accuracy of the samples was only 1% to 95%, and there still existed great variances within the NIR spectra region of 780 to 2500 nm, the findings of this study suggest that visible spectroscopy in combination with SIMCA can be used to classify different types of decorative papers, and visible spectroscopy has a great potential to be a better technology than both colorimetric parameters and NIR technology in the classification of decorative paper. Visible spectroscopy provides a rapid, low-cost, and accurate analysis when used in the quality control of decorative papers. In addition, this study was only preliminary and there are only six classes of decorative papers were used. More classes of decorative papers would be selected to research in the future.

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