Enomae, T and Kuga, S., "Methodology to use flatbed image scanner for formation analysis of paper", Japan Tappi J., 56(4)97-104(2002)

紙の地合解析のためのフラットベッドイメージスキャナ応用法*

東京大学 大学院農学生命科学研究科　江前敏晴, 空閑重則

Methodology to Use Flatbed Image Scanner for Formation Analysis of Paper

Toshiharu Enomae and Shigenori Kuga

Graduate School of Agricultural and Life Sciences

The University of Tokyo

Abstract

Versatility of a desktop flatbed image scanner with a transparency unit as an image input device for formation analyses is exhibited and discussed. Optical density of scanner output is defined as the logarithm of the ratio of gray level in full transmission with no material to that at a given site (pixel) of a sample. Optical density of the scanner output under satisfied prerequisite conditions showed an excellent agreement with that of Elrepho type reflectometer and the pre-calibrated values noted on a standard film though the proportional constant is reduced from 1 due to aged deterioration of the light source after 1 year, maintaining linearity. For stacked paper sheets, however, there remains distortion in the output characteristics, that is, non-linearity even after the calibration. So, unlike Elrepho type, optical density squared is empirically almost proportional to the basis weight of paper. In application, formation of handsheets loaded with calcium carbonate from softwood and hardwood pulps at different retention times is quantitatively analyzed with the light transmission images obtained by the scanner. The formation index, the standard deviation of optical density squared correlated better with the subjective ranking by 6 panelists than that of optical density or of gray level. Optical density squared divided by the basis weight shows the highest Kendall's coefficient of correlation. In summary, the standard deviation of gray level is found to lack in validity as a formation index except comparison between papers with close gray levels.

Keywords:

Formation index, Gray level, Light transmission image, Optical density, Subjective ranking

---

* Part of this research was presented at the 10th ISWPC －Recent Advances in Paper Science and Technology－, Korea Tappi, Seoul, Korea, June, 1999

1. INTRODUCTION

A lot of work on sheet formation analysis of paper has been performed for over sixty years. Through the period of time, image input devices or scanning devices based on a transmission of light had a wide variety. The representative systems so far were the rotating disc of paper with a light spot[1)], the Alinco tester using a cathode ray tube whose beam sweeps over an area of up to 44×44 mm^2 by raster[2, 3)], the rotating transparent cylinder with a light spot[4)] and video camera systems[5)].

A desktop flatbed image scanner is a useful device to obtain image data to a computer. Nowadays, it is prevalently available to many computer users at low costs. In the department of Biomaterial Sciences of the University of Tokyo, analysis of paper sheet formation is one of the major subjects of the juniors' experimental course. The image scanner combined with a transparency unit has been used since 1995 as an input device of light transmission images in place of a CCD video camera for a formation analysis. Shinozaki[6)] built up an image analysis system mainly for sheet formation, where an image scanner was used as one of input devices. He also obtained light transmission images with a flatbed image scanner for evaluation of paper formation[7)]. However, the author did not discuss how to configure the scanner for reliable images. The purpose of this study is to examine output characteristics of a scanner and to analyze the output images from a viewpoint of formation. The fundamental methodology will be useful for many other possible applications of a scanner for examining paper structure and properties.

2. MATERIALS

2.1 Apparatus

Flatbed image scanner GT-8500WIN and transparency unit GTA4FLU (Epson Inc., Japan) were used in combination. The working mechanism of the scanner is as follows: RGB xenon fluorescent lights (recent scanners use white xenon fluorescent lights, but there is no large difference) irradiate a sample with three colors of rays. Transmitted (or reflected) light was collected by a lens and detected by an in-line CCD sensor. The sensor is assembled with the fluorescent lights, so they move together in working. The direction of the CCD sensor alignment is called the main scan direction; and that of its movement, the sub-scan direction. On the other hand, common CCD video camera systems use a halogen lamp, but uniform illumination is not warranted because a relatively wide area is acquired at one time and external room light may interfere with the destined illumination. A system of a pinpoint beam in combination with a scanning sample stage eliminates this defect, but specific light scattering coefficient depends on basis weight for parallel incidence[8)]. This may create different images from those experienced commonly over diffuse light. Furthermore, it takes long time to scan the whole area in two dimensions and the accuracy of positioning is lower. To interface the image scanner to image analysis software, image input driver (software) Epson ScanII32, 2.00J, 1994 was used. The optical resolution was 256 gray levels.

Image analyzer DA-5000S (Oji Scientific Instruments, Japan) and the original software the authors developed using Visual Basic 5.0 (Microsoft Japan) were used to calculate optical density of every pixel in the images for the formation analysis.

Brightness R_∞ was measured on Elrepho type reflectometer, TD-1800, Tokyo Denshoku, co. ltd., Tokyo, Japan with D65 diffuse illuminant and normal observer. Opacity R_0 was measured with the same configuration but a spectrally different light band on the same reflectometer with a black cavity backing.

2.2 Samples

To ensure the accuracy of the image scanner output, a standard film designed for optical instruments was used. The film was a piece of Density Step Tablet, Fuji Photo Film Co., Ltd., manufactured to measure diffuse visual density. This tablet is a film consisting of portions at several different densities calibrated preliminarily according to Japan Industrial Standard (JIS K 7605).

To compare output characteristics between the scanner and the Elrepho reflectometer, a plastic film 199 μm thick of 178 g/m^2 in basis weight, and tracing paper 41.0 μm thick of 39.3 g/m^2 in basis weight were used. The plastic film was colored blue, but transparent. The tracing paper was of low light scattering for paper, but translucent. Some sheets of them were stacked and loaded slightly by a weight or a scanner cover in measurement.

For an application to formation analysis, handsheets made from softwood or hardwood kraft pulps, loaded with 40 % calcium carbonate to dry pulp, were prepared. Retention time before drainage was 10 (standard-based) or 120 s. Cationic polymer, polyamideamine-epichlorohydrin resin (WS-570, Japan PMC Co., Japan) was added to a half of the samples at 0.4 % to dry pulp. Thus, four kinds (2× 2 conditions) of handsheets each were prepared from softwood and hardwood pulps.

3. METHODS

3.1 Configuration of scanner

It was found that there are some requirements of the scanner configuration. They are;

(1) to cover the rest of the sample area on the document glass stage with an opaque sheet to prevent extra reflected light on the sample surface from coming into the detector,

(2) to make external lighting uniform in the direction of sub-scan because no calibration is made in this direction to compensate for its non-uniformity, and

(3) to set input parameters at proper values so that the whole range of optical density for the sample including full transmission outside the sample area will come within the whole input range.

3.2 Proper input parameters

In the scanner driver, users can set some input parameters to their purposes. For a formation analysis, one need to set γ-value, highlight and shadow at 1(100 % for this driver), 255 or higher in some cases and 0, respectively. γ-value is a characteristic curve to determine gain of output to input levels. This must be linear, namely, 1 for a quantitative analysis. The values of highlight and shadow are a threshold value above which all the levels in input are set at 255 in output, and below which all the levels are set at 0, respectively. So, care must be taken in setting so that the third requirement in the last section is fulfilled. Then, the in-between values are divided into 256 levels at equal intervals.

With the three prerequisites satisfied, the samples were scanned at a resolution of 120 dpi, namely, at ca 0.2 mm intervals. The scanned area was 100 mm×100 mm each, but the calculated area was 60 mm×60 mm (283 pixel×283 pixel) each. The standard film of Density Step Tablet was scanned at the same resolution and the calculated area was 12.7 mm×6.4 mm (60 pixel×30 pixel). For the plastic film and the tracing paper, almost the same area was measured.

3.3 Calculation of optical properties

Optical specification of a sheet, film or any material is likely to be achieved favorably by determining brightness and specific light scattering coefficient. The Kubelka-Munk equation[9] describes the relation between those parameters. According to it, optical density *OD* (refereed also to absorbance) is expressed by the equation:

$$OD = -\log\left(\frac{b}{a\sinh bsW + b\cosh bsW}\right), \qquad \text{.....} \quad (1)$$

where s is the scattering coefficient, W is the basis weight, and sinh and cosh are hyperbolic functions. Likewise, OD of scanner output, that is, gray levels is defined as follows:

$$OD = \log\left(\frac{V_0}{V}\right), \qquad \text{.....} \quad (2)$$

where V and V_0 are the gray level of the considered pixel and the gray level in full transmission with no material, respectively. s can be calculated from R_∞, a and b as follows:

$$s = \frac{1}{bW}\mathrm{Ar\,ctgh}\frac{1-aR_0}{bR_0}, \qquad \text{.....} \quad (3)$$

$$a = \frac{1}{2}\left(\frac{1}{R_\infty} + R_\infty\right) \text{ and } b = \frac{1}{2}\left(\frac{1}{R_\infty} - R_\infty\right), \qquad \text{.....} \quad (4)$$

where R_0 is the reflectance of single sheet with a black cavity backing, R_∞ is the reflectance factor of infinite pile of paper and Ar ctgh is the inverse function of a hyperbolic function, ctgh. But, actually the calculation was made following the modified equation introduced by Hamada[10].

Radiation such as β-ray or soft X-ray used commonly for formation analyses tends to attenuate in relation to the local basis weight of paper or distance of the medium through which it is transmitted. Lambert's law below describes the relationship.

$$\log\left(\frac{I_0}{I}\right) = ad, \qquad \text{.....} \quad (5)$$

where I, I_0, a and d are the intensity of the transmitted radiation, the intensity of the incidental radiation, the linear absorption coefficient and the distance of the medium, respectively. The Kubelka-Munk equation reduces to this law if s equals to zero in the derivative form.

3.4 Subjective ranking

Six panelists made subjective ranking with the 8 handsheets in terms of the degree of inhomogeneity in look-through over diffuse white light. The judgement was made by comparing every pair of the sheets. The better one was given 1 point and the total points were calculated for every sample. The figure of ranking represents the average point given to an individual sheet. The correlation coefficient of each formation index with the subjective ranking was determined according to Kendall's method. This method is as follows: the same order of each pair with the subjective ranking gives 1 point and the reversed order gives –1 point; the correlation coefficient is expressed in terms of the total points divided by the number of every pair, that is, 28 in this case. This correlation method is advantageous in that it correlates to the ranking order, not to the absolute ranking point that is not to scale.

4. RESULTS AND DISCUSSION

4.1 Scanner output characteristics

The standard film was scanned by the scanner. Then, optical density *OD* was calculated. **Figure 1** shows a good agreement of *OD* measured between by the scanner and by the Elrepho reflectometer up to ca 1. This range roughly means that there is a good linear relationship in gray levels ranging from 25 to 250, for example. The values are also consistent with the pre-calibrated ones noted on the standard film. However, the output characteristics change over time. After one year, the same standard film was scanned and *OD* was calculated again. The gradient representing the relationship became much lower, maintaining a good linear relationship (broken line). This may be because the light source had deteriorated. To avoid this possible deterioration, determination of absolute OD values needs calibration as based on a standard film. Scanners of other manufacturers were also confirmed to show a linear relationship.

Figure 2 compares *OD* measured by the Elrepho reflectometer for the two types of materials; the plastic film and the tracing paper. The *OD* values of the plastic film (denoted by filled squares) were exactly proportional to the number of sheets. This relationship can be explained by Lambert's law, equation (5), if the number of sheets is assumed to be the thickness of the material. Lambert's law applies limitedly to the case that the scattering coefficient is negligible. Accordingly, the coefficient was very low (filled triangles). For the tracing paper, *OD* was not proportional to the number of sheets (open squares). This behavior is typical to paper having many fiber-air interfaces that tend to scatter light (open triangles), as taught by the Kubelka-Munk equation.

OD by the scanner was supposed to provide the same relationship if the agreement found in Figure 1 is taken into account. **Figure 3**, however, shows distortion in scanner output. The *OD* is already corrected by the calibration based on the standard film. The gray square plots for the Elrepho output are exactly the same data with in the previous figure. The filled triangle plots for the scanner output curves upward in the middle range. The reason for this is unknown for the present.

Figure 4 shows *OD* as a function of a root of the total basis weight of the tracing paper stacks, which was easily calculated from the basis weight per single sheet times the number of sheets. The relationship for the scanner is almost proportional to the basis weight, while that for the Elrepho have a linear portion but does not pass through the origin. The proportional relationship for the scanner may be coincidental or may be designed so.

4.2 Formation analysis

Figure 5 is the scanner images of the 4 kinds of handsheets each regarding retention time and cationic polymer addition, made from hardwood and softwood pulp, respectively. **Table 1** lists several physical properties of the samples. The result of Figure 4 suggested that the average of OD^2_{ave} would be proportional to Basis weight *W*. But, actually they were not in proportion presumably because softwood pulp has the higher light scattering coefficient *s* and the addition of cationic polymer retained more calcium carbonate, which increased *s*, as both found in Table 1. The proportionality seems to apply limitedly to the same furnish.

There are many formation "inhomogeneity" indices that have been proposed from various standpoints. Apart from frequency analyses[11)] and floc structure analyses[12)], formation has been generally analyzed in terms of the coefficient of variation *CV* of local basis weight[13,14)]. In this study, a variety of formation indices were calculated from the scanner light transmission images. Firstly, *OD* and OD^2 were calculated every pixel. OD^2 was thought to be necessary because it was found to be proportional to basis weight empirically as Figure 4 shows. Secondly, standard deviation *std* of Gray level V_{std}, *OD* and OD^2, and the coefficient of variation *CV* (a ratio of the average to *std*) of OD^2 were calculated. Table 1 summarizes the results as well as the subjective ranking. The eight images in Figure 5 were modified to appear distinctively contrasted at the time of press. So, it may be difficult to connect the images to the statistic results.

Figure 6 shows the validity of the formation indices to relate to the subjective ranking. The formation indices were normalized so that the average of each index would be 3.5. Among the three standard deviations, that is, V_{std}, OD_{std} and OD^2_{std}, OD^2_{std} was found to distinguish the samples with the fewest reversed pairs. This finding implies that human perception is the most sensitive to the amount convertible to basis weight *W*. To be more exact, this conversion applies limitedly to paper with uniform structure in terms of fiber source, density, filler content and so on like the tracing paper stacked to different numbers of sheets as demonstrated in Figure 4. So, the conversion does not apply to the samples in Figure 5. In spite of the actual discordance, human perception has a scale based on

OD^2. However, CV of OD^2 showed a low Kendall's coefficient r. So, it may be difficult to sense the amount of relative variation accurately. The ratio of OD^2_{std} to W, an index where the average of OD^2 was replaced for W in CV of OD^2, shows high validity with r of 0.86. This index distinguished well the eight sheets except HN120. The sheet of HN120 was observed to have many flocs with the order of ca. 5 mm. This order of flocs seems to be striking to visual perception, as Shinozaki[15)] showed that the variation in the range of 5.7 to 6.2 mm in wavelength had a high correlation with a subjective ranking. OD_{std} and, particularly, V_{std} lacked in validity as a formation index. V_{std} is sometimes used to estimate formation, but it must be confined to papers with close gray levels. Kajanto[16)] proposed that normalized *std* (*std* divided by a root of average both on the basis of grammage by β-radiography) fitted the appearance better than the coefficient of variation. The normalized *std*, that is, $(OD^2_{std})/\sqrt{W}$ correlated well but did not function better than $(OD^2_{std})/W$ in this work, as the other possible indices did not.

5. CONCLUSIONS

The desktop flatbed image scanner with a transparency unit was found to function properly as an image input device for formation analysis under satisfied prerequisite conditions if the output is calibrated based on a standard film or by comparison to Elrepho type reflectometer. However, there remained distortion in the output characteristics even after the calibration. So, unlike Elrepho type, optical density squared was almost proportional to the basis weight of paper. The formation index, the standard deviation of optical density squared correlated better with the subjective ranking than that of optical density or of gray level. Optical density squared divided by the basis weight showed the highest Kendall's coefficient of correlation. In summary, the standard deviation of gray level was found to lack in validity as a formation index except comparison between papers with close gray levels.

ACKNOWLEDGMENT

The authors wish to thank the junior students of Biomaterial Sci. Dept. of The Univ. of Tokyo for preparing the handsheets for the formation analysis. The graduate students on Paper science laboratory of The Univ. of Tokyo are thanked for their contribution to the subjective test.

REFERENCES

1) Davis M. N., Roehr W. W. and Malmstroem H. E.: Paper Trade J. 101 (July 25) 35 (1935)

2) Anonymous author: Paper Trade J. 140 (April 16) 61 (1956)

3) Jamison W.: Paper Trade J. 140 (October 8) 30 (1956)

4) Burkhard G., Wrist P. E. and Mounce G. R.: Pulp Paper Mag. Can. 61 (6) T319 (1960)

5) Bergh P. and Luner P. The application of image analysis to evaluate small scale basis weight variations in paper. Trans. of 7th Intl. Fundamental Research Symp (Vol 2), Mech Eng Publ, London, pp 707-722. (1983)

6) Shinozaki M., Tajima Y. and Miyamoto S.: Japanese J of Paper Technology (Kamipa Gitai) 36 (4) 24 (1996)

7) Shinozaki M., Tajima Y. and Miyamoto S.: Sen'i Gakkai-shi 55 (8) 383 (1999)

8) Yuhara T., Nakayama S., Arie Y., Kodaka I. and Okushima S.: Proceedings of Japan Tappi pulp and paper research conference, Tokyo, 1989, p14

9) Kubelka P.: New contribution to the optics of intensely light-scattering materials. Part I. J Optical Soc of America 38 (5) 448 (1947)

10) Hamada H., Enomae T., Onabe F. and Saito Y.: Japan Tappi J., 55(11) 79(2001)

11) Cresson T. and Luner P. The characterization of paper formation analysis. Tappi J. 73 (12) 175 (1990)

12) Dodson C. T. J. and Schaffnit C.: Tappi J. 75 (1) 167 (1990)

13) Norman B. and Wahren D.: Trans. of 5th Intl. Fundamental Research Symp (Vol 1), Tech Sec, Brit Paper Board Ind Fed, London, pp 7-70. (1976)

14) Norman B. and Wahren D.: Svensk Papperstidn 75 (11) 807 (1972)

15) Shinozaki M., Tajima Y. and Miyamoto S.: Sen'i Gakkai Preprints 1998(G), Soc Fiber Sci Tech, Japan, 1998, G-107 (1998)

16) Kajanto I. M., Komppa A. and Ritala R. K.: Nordic Pulp and Paper Res J 4 (3) 219 (1989)

Table 1 Properties and formation analysis results of the handsheets. *r* is Kendall's coefficient of correlation with subjective ranking

Key	HN10	HN120	HP10	HP120	SN10	SN120	SP10	SP120	*r*
Furnish	Hardwood				Softwood				
Cationic polymer	None	None	Added	Added	None	None	Added	Added	
Retention time, s	10	120	10	120	10	120	10	120	
Basis weight (W), g/m^2	63.8	62.4	73.6	76.6	56.4	60.3	68.1	69.1	
$\sqrt{W}$, (g/m^2)$^{1/2}$	7.99	7.90	8.58	8.75	7.51	7.77	8.25	8.31	
Brightness, %	75.5	75.8	74.9	71.6	77.5	77.0	75.8	75.1	
Specific scattering coefficient, m^2/kg	45	44	44	42	32	27	37	36	
Gray level (V)									
Average(V_{ave})	45.3	45.6	34.2	32.2	70.8	71.7	49.9	51.3	
Standard deviation(V_{std})	2.1	2.3	1.7	3.0	4.5	6.7	3.1	5.1	0.36
Optical density (OD)									
Average(OD_{ave})	0.752	0.750	0.875	0.904	0.559	0.554	0.711	0.700	
Standard deviation(OD_{std})	0.020	0.022	0.022	0.040	0.028	0.041	0.027	0.043	0.64
Optical density squared (OD^2)									
Average(OD^2_{ave})	0.567	0.565	0.769	0.822	0.315	0.310	0.508	0.492	
Standard deviation (OD^2_{std})	0.030	0.033	0.038	0.072	0.031	0.045	0.038	0.061	0.79
Coefficient of variation	5.3	5.9	5.0	9.0	9.9	14.7	7.6	12.4	0.43
OD_{std}/W, 10^{-3} m^2/g	0.31	0.35	0.30	0.52	0.49	0.68	40	63	0.50
$(OD_{std})/\sqrt{W}$, 10^{-3} (m^2/g)$^{1/2}$	2.5	2.8	2.5	4.6	3.7	5.3	3.3	5.2	0.57
$(OD^2_{std})/W$, 10^{-3} m^2/g	47	53	52	95	55	75	57	88	0.86
$(OD^2_{std})/\sqrt{W}$, 10^{-3} (m^2/g)$^{1/2}$	3.7	4.2	4.4	8.3	4.1	5.9	4.7	7.3	0.79
Subjective ranking of formation (the lower, the better)	0.0	3.6	1.4	6.4	2.3	5.5	3.0	5.8	

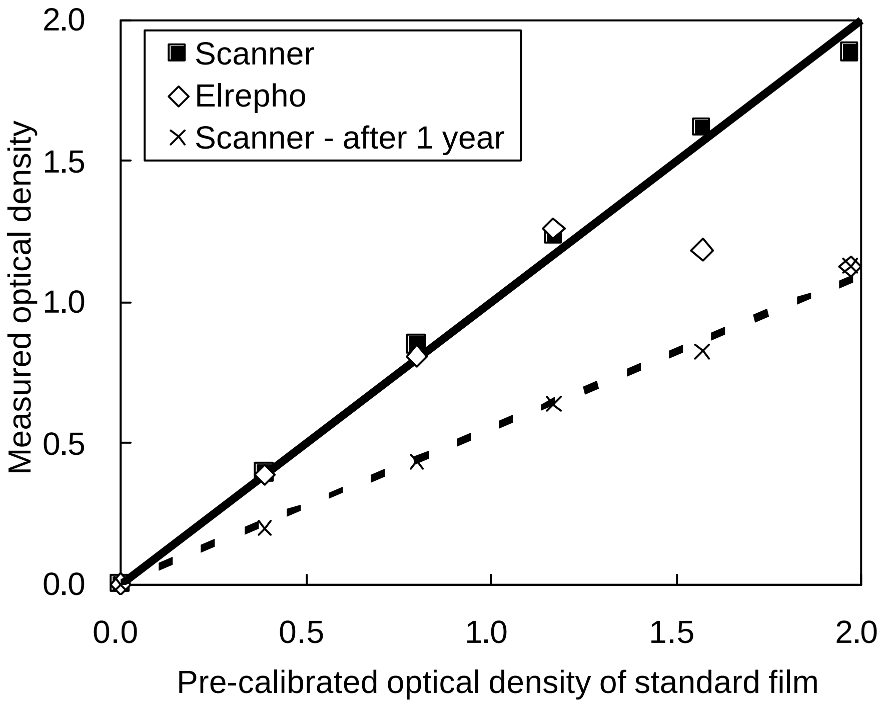

Fig.1 Comparison in optical density of the standard film measured between by scanner and by Elrepho-type reflectometer

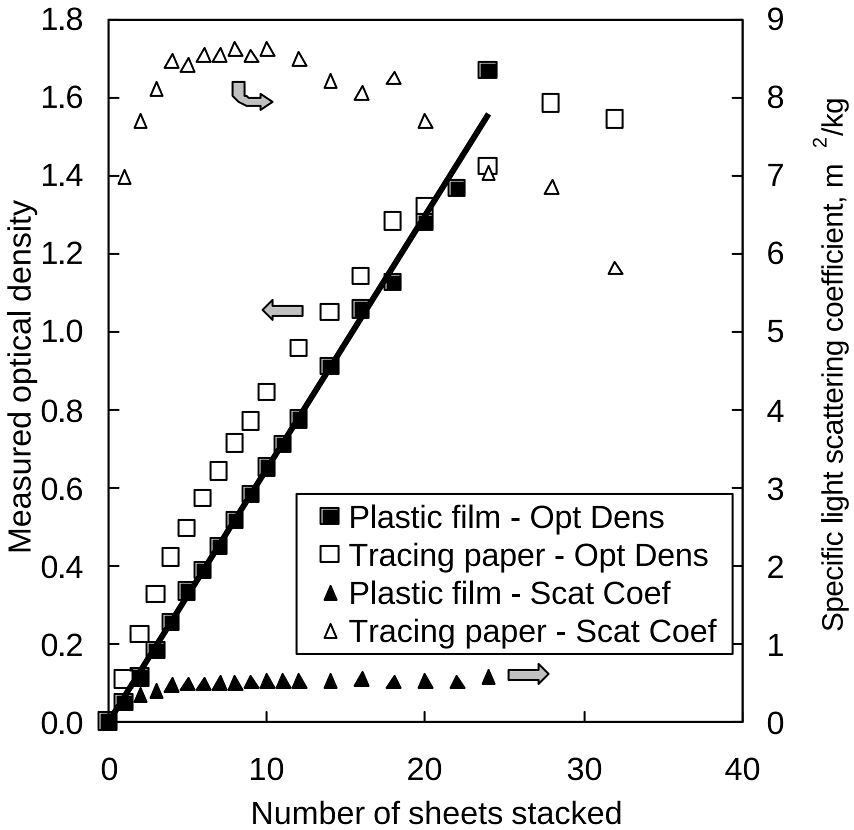

Fig.2 Comparison in optical density measured by Elrepho-type reflectometer between plastic film and tracing paper stacks.

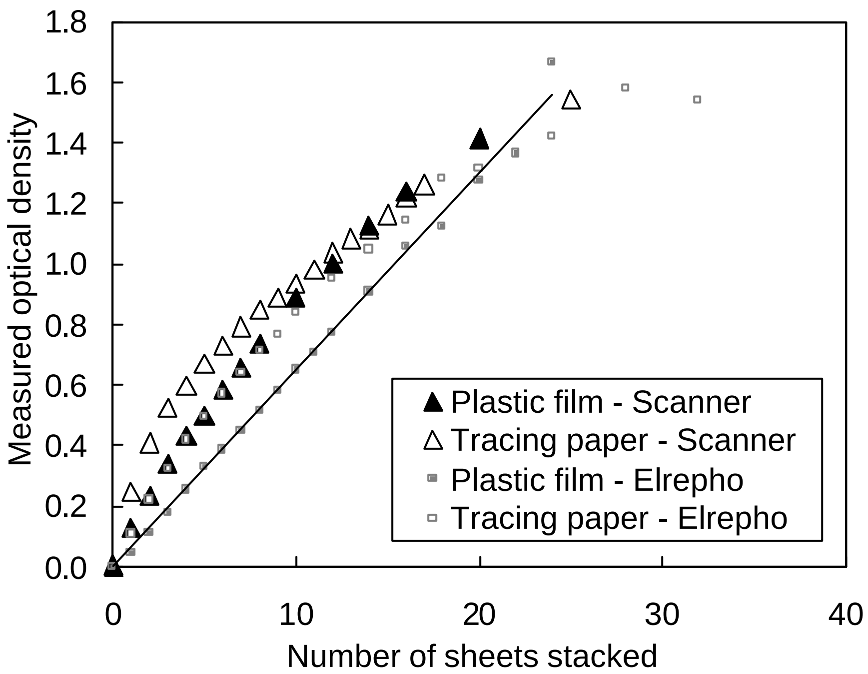

Fig.3 Distortion of scanner output. For the same material stacks, scanner optical density curves upward.

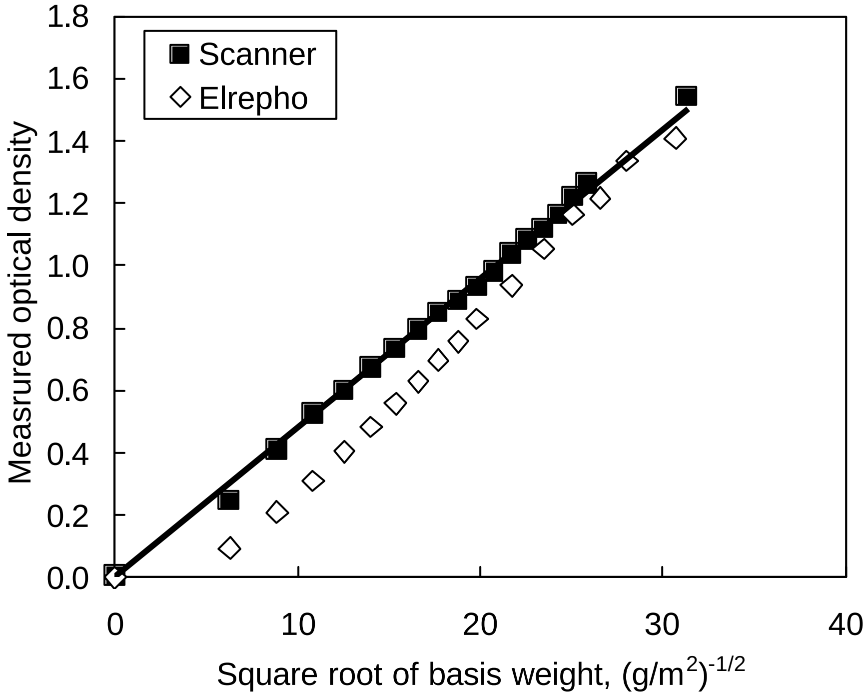

Fig.4 Comparison in optical density of tracing paper stack. The scanner output is proportional to a square root of the total basis weight.

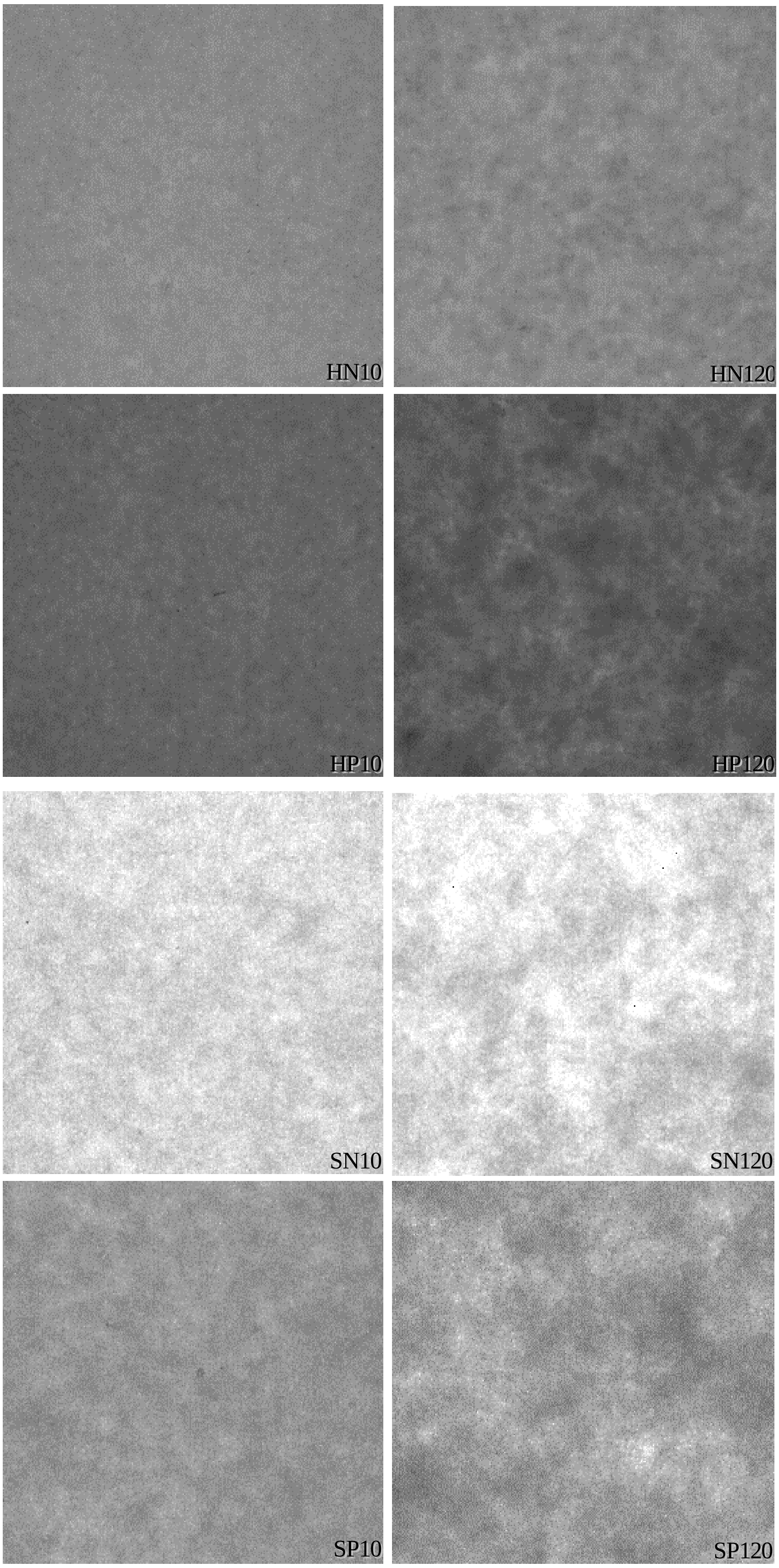

Fig.5 Light transmission images of handsheets made from bleached hardwood kraft pulp. Details are stated in Table 1.

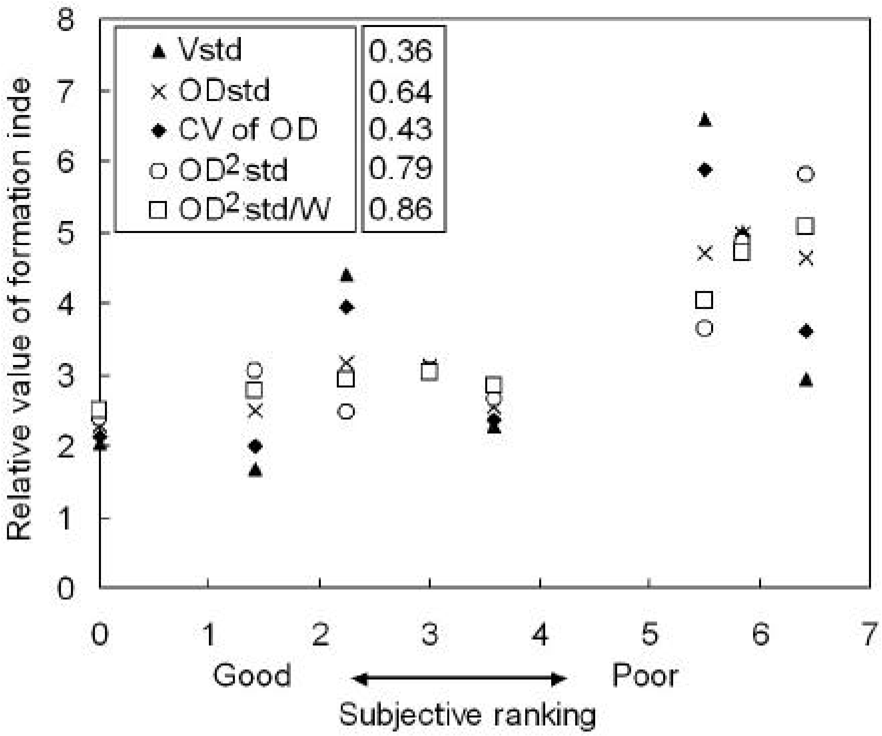

Fig.6 Formation indices and their Kendall's coefficient of correlation. OD^2-based indices show better correlation.