Evaluation and Control of Coated Paper Stiffness

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For coated paper, Young's modulus of the coating layer affects the stiffness of the whole coated paper considerably because the external layer undergoes a larger strain during bending than the internal layer. A method to calculate Young's modulus of coating of a one-side coated sheet according to fundamental material mechanics is presented here. An interpretation of the Clark stiffness formula allows us to calculate Young's modulus of the coating layer from Clark stiffness of the whole coated paper. To achieve this, coating on an impervious film is required for avoiding swelling and roughening problems. Pure bending stiffness meriting constant curvature along the span was also applied. A well-known fact that the introduction of starch into a latex bound coating increases its stiffness is verified. Application of a starch-rich coating to the outside is found to be advantageous. Small-sized plastic pigment provides a level of stiffness close to that of calcium carbonate.

La rigidité est une propriété importante du papier. Dans le cas du papier couché, le module d'élasticité de Young de la couche a un effet considérable sur la rigidité de l'ensemble du papier couché, parce que la couche externe subit un stress plus important que la couche interne lors du pliage. Nous présentons ici une méthode permettant de calculer le module d'élasticité de la couche d'une feuille couchée une face selon la mécanique matérielle fondamentale. Une interprétation de la formule de rigidité Clark permet de calculer le module de Young de la couche à partir de la rigidité Clark de l'ensemble du papier couché. Pour ce faire, il faut appliquer une sauce de couchage imperméable pour le calcul, parce que le papier supportgonfle et devient rugueux lorsqu'il est mouillé avec de l'eau, ce qui produit des valeurs incorrectes d'élasticité. La rigidité pure au pliage peut aussi être utilisée pour obtenir les couches de sauce du module de Young. Selon cette méthode, une bande de papier couché est pliée avec la même courbure mais seulement en mode traction, et non mêlée à un mode compression comme pour l'essai de rigidité Clark. Il est bien connu que l'introduction d'amidon dans une sauce de couchage au latex accroît sa rigidité. Pour améliorer la rigidité de la feuille couchée à un poids de couchage constant, l'application en surface d'une sauce de couchage riche en amidon a donné des effets avantageux. Les petits pigments de plastique fournissent un degré de rigidité presque similaire à celui du carbonate de calcium.

INTRODUCTION

In the field of coating science, emphasis has been put mainly on printability of coated paper and fluid dynamics of coating colour. Less research has been conducted regarding coated paper physics. Knowing the physical properties of coated paper would help in the examination of the bending and compressive deformation that coated paper undergoes in a printing press, e.g. feeding problems on copy machines, on optical character recognition machines and in sheet-fed printing presses with papers that are too flexible.

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A clearly definite physical value, "stiffness" is used in general analyses of materials during bending. The definition is the product of Young's modulus E and second moment of area I. How smoothly paper sheets are fed is often predicted by a sensory subjective stiffness. Kazumori et al. [1] examined these sensed properties ("sensory stiffness" refers to this concept thereafter) to correlate it to physical "stiffness". The authors reported that, at the same stiffness EI, the higher the Young's modulus E, the "stiffer" the paper was sensed. They concluded that the criterion of sensory stiffness was resistant to a snap and slow flip under its own weight, its thickness and the ease of recovery from a bend as much as the resistance to an external bending force.

Physical parameters related to stiffness are summarized in Table I. "Clark stiffness" is the bending resistance of a paper strip bending under its own weight. "Pure bending stiffness" [2,3] is stiffness divided by the sample width when a paper strip is bent with the same curvature along the whole span (while the closer to the support, the higher the curvature in the Clark test). So, pure bending stiffness is considered to relate to the action of turning pages of a book.

"Liveliness" originally indicates the speed at which a textile recovers from a given curvature. Naito and Abe [4] applied this to paper and defined the liveliness of paper to be "the reciprocal of recovery time squared" so that this immediate recovery property would relate to stiffness. Liveliness and Clark stiffness may be more suitable to analyze paper behaviour on an offset press feeding sheets with suction pads because how fast the paper sheet recovers from bending under its own weight and the moment of inertia of the paper are relatively important.

TABLE I
TERMINOLOGY RELATED TO STIFFNESS

Physical value	Equation	Concept
Stiffness	S, EI	Resistance to a bend
Clark stiffness (Handling stiffness)	$\frac{L^3}{100}, \propto \frac{EI}{bW}, \frac{ET^3}{12W}$	Resistance to a bend due to the weight of its own
Flexing resistance	$\frac{L^3W}{100}, \propto \frac{EI}{b}$	Stiffness divided by sample width
Pure bending stiffness	$\frac{EI}{b}$	Stiffness divided by sample width when bent with the same curvature along the whole span
Liveliness	$\frac{1}{t^2}$	Inverse of squared time of recovery from certain curvature
Sensory stiffness		Stiffness subjectively estimated by people
Young's modulus	$E, \frac{\sigma}{\varepsilon}$	Longitudinal elastic modulus
Second moment of area	$I, \frac{bT^3}{12}$	Integral of squared distance from neutral axis
Bending moment	$M, \frac{EI}{r}$	Force times distance

Note: L is overhung length (cm), W is basis weight (g/m^2), t is time (s), T is thickness, b is sample width, σ is stress, ε is strain and r is radius of curvature.

There has been a lot of research regarding stiffness of uncoated paper, but little regarding that of coated paper. Naito et al. [5] measured stiffness of coated paper by several methods and compared them to uncoated paper, then concluded that pure bending stiffness is more correlated to sensory stiffness than Clark stiffness. Nagai and Matsuda [6] calculated the Young's modulus of the coating layer of symmetrically two-side coated paper from Gurley stiffness, but this cannot be applied to one-side coated paper.

Base paper property dominates most mechanical properties of the whole coated paper. However, particularly with regard to bending stiffness, a coating layer has considerable effect [7,8]. This is because the strain that the outer coated layer undergoes is much larger than that of the inner base paper layer. However, because the density of the coating is about twice that of base paper, Clark stiffness would decrease with increasing coat weight even if the Young's modulus of the two layers were equal.

Considering coated paper as a composite material consisting of two layers, i.e. coating and base paper, this work aims at the estimation of how much the coating layer contributes to the total stiffness of the coated paper. For this purpose, we assumed that determination of Young's modulus of a coating layer would be the best approach, because it is independent of the coat weight and thickness, but is dependent only on the coating composition and its structure. In the beginning, theoretical and empirical methods were established to determine Young's modulus of coatings. Then, the effect of starch on coating Young's modulus was examined to confirm the general knowledge that starch-containing coatings have higher stiffnesses than starch-free ones. Finally, double coating with coatings having different formulations and the addition of plastic pigment were evaluated with a view to improve the stiffness of the coated paper.

THEORY

It is assumed that coated paper is a laminate made of two parallel layers of uniform and homogeneous substance glued together. Nagai and Matsuda [6] gave an equation to calculate Young's modulus of the coating layers for two-side coated paper of the same coat weight on each side. However, it is practically difficult to coat a sheet to meet this requirement on a laboratory scale. Therefore, another equation for one-side coated paper was developed as below.

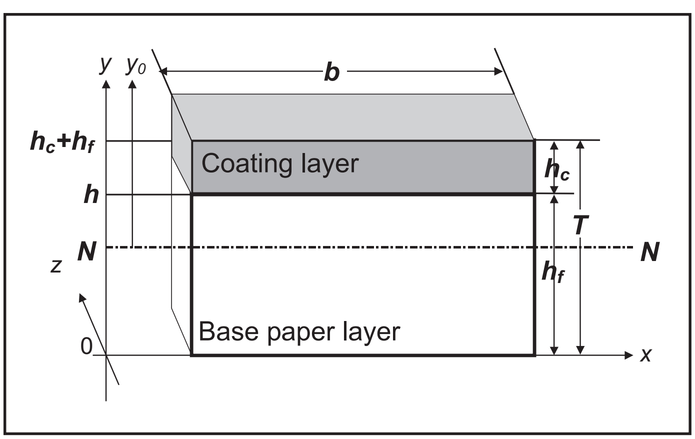

Fig. 1. Schematic cross-section of coated paper for calculating second moment of area.

The stiffness of the whole coated paper R_a is the average Young's modulus E_a times the second moment of area I_a of the whole coated paper (see Fig. 1).

$$R_a = E_a \times I_a = E_a \frac{bT^3}{12} \tag{1}$$

where T and b are the coated paper thickness and width, respectively.

The second moment of area of the coated layer I_c, its Young's modulus E_c, the second moment of area of the base paper layer I_f and its Young's modulus E_f give Eq. (2).

$$R_a = E_c \times I_c + E_f \times I_f \tag{2}$$

Then, the reference axis (x axis) is taken at the bottom of the cross-section to determine the coordinate of the neutral axis N-N, where no strain occurs. Bending stress develops only in z axis and the integration of the stress with regard to y_0 axis (y-N) is 0. Consequently, Eq. (3) is obtained.

$$E_f \int_f y_0 \mathrm{d}A_f + E_c \int_c y_0 \mathrm{d}A_c = 0 \tag{3}$$

where A_f and A_c are the cross-sectional areas of the base paper and the coating layer, respectively. Substituting $y_0 = y - N$ into Eq. (3) leads to Eq. (4).

$$E_f \int_f (y - N)\mathrm{d}A_f + E_c \int_c (y - N)\mathrm{d}A_c = 0 \tag{4}$$

If this is solved with regard to N, Eq. (5) is obtained.

$$N = \frac{E_f \int_f y\mathrm{d}A_f + E_c \int_c y\mathrm{d}A}{E_f \int_f \mathrm{d}A_f + E_c \int_c \mathrm{d}A} = \frac{E_f \int_0^{h_f} yb\mathrm{d}y + E_c \int_{h_f}^{h_f+h_c} yb\mathrm{d}y}{E_f bh_f + E_c bh_c} = \frac{E_f h_f^2 + E_c\left(2h_f h_c + h_c^2\right)}{2E_f h_f + 2E_c h_c} \tag{5}$$

where h_f and h_c are thickness of the base paper and coating layer, respectively. Equations (2) and (5) give Young's modulus of the coating layer E_c as shown in Eq. (6). Therefore, E_c can be calculated if one measures stiffness of coated paper R_a.

$$E_c = \frac{R_a - E_f \int_{-N}^{h_f - N} y^2 \mathrm{d}y}{\int_{h_f - N}^{h_f + h_c - N} y^2 \mathrm{d}y} = \frac{3R_a - E_f (h_f - N)^3 - E_f N^3}{(h_f + h_c - N)^3 - (h_f - N)^3} \tag{6}$$

Clark stiffness has been known as a standard method to measure stiffness of paper or textile for a long period. Following is how to calculate Young's modulus of a coating layer from Clark stiffness. First, Clark stiffness is defined this way. A long paper strip is held at

TABLE II
YOUNG'S MODULUS OF POLYETHYLENETELEPHTHALATE (PET) FILM

Method and equation	Clark $\frac{L^3}{100}=\frac{EI}{bW}$	Clark $\frac{L^3}{203}=\frac{EI}{bW}$	Ultrasound velocity	Bending mode at 23°C [14]
Modulus, GPa	12.8	6.3	7.2	2.41 – 3.10

one end and supported upright. As the holder rotates, the strip flops suddenly from the bending side to the other at a certain angle. The total angle on either side where flopping occurs was measured. The overhung part is then extended until the total angle reached 90º. The satisfactory overhung length L cubed divided by 100 is the Clark stiffness. In Clark's publication [9] and JIS Standard P8 143-1996 [10], L is measured in cm, but in mm in TAPPI Test Method T 451 cm-84 [11]. The reason why the cubed length is used is expressed in Eq. (7), as shown by Oda et al. [12].

$$\frac{L^3}{100} \propto \frac{EI}{bW}\left(=\frac{ET^3}{12W}\right) \tag{7}$$

According to their work, the overhung length L (cm), Young's modulus E (dyne/cm^2), thickness T (cm) and basis weight W (g/m^2) empirically satisfy the equation where the two terms are equal (not only proportional) on the condition that those variables are expressed in the units specified in parentheses.

Theoretically, as shown by Takadera et al. [13], this action is represented by the equation of a beam with one end fixed (Eq. 8).

$$\frac{d^2\theta}{dq^2} = q\sin\theta \tag{8}$$

Boundary condition: $q = 0$ at $\theta = \alpha$
and

$$q = K = \sqrt[3]{\frac{b(W\times10^{-4})G}{EI}}L \text{ at } \theta = \beta \tag{9}$$

where q, θ, α, β are the distance from the free end, the angle from the downward vertical direction at q, the angle at the free end, and the angle of the holder at the fixed end, respectively. If the nip angle is symmetrical on the right and left sides, β is equal to 225°. All the other variables are equal to that of Eq. (7). The authors calculated that a paper strip flops at this angle at a condition, $K = 2.71$. K is correspondent to a kind of absolute overhung length that has no unit and is independent of Young's modulus and thickness of the material. Practically, since basis weight acts as a load to bend a paper strip, it must be multiplied by the gravitational constant G. Thus, Eq. (10) is obtained by substituting K = 2.71 into Eq. (9).

$$\frac{L^3}{2.71^3} = \frac{ET^3}{12G(W\times10^{-4})}$$

$$\frac{L^3}{203} = \frac{EI}{bW} = \frac{ET^3}{12W} \tag{10}$$

In the first version of Eq. (10), all units are the same as that of Eq. (7). To adjust every variable to the cgs system of units, basis weight was corrected as $W\times10^{-4}$ (g/cm^2). In addition, $G = 981$ (cm/s^2). In the second version, the units, basis weight in g/m^2, length and thickness in cm and Young's modulus in dyne/cm^2 can be used. Actually, air currents and the vibration of the paper strip may prompt it to flop earlier than it would otherwise. Thus, L measured may be less than the true L.

Developing a general empirical equation is very difficult because the coefficient varies depending on the method in which Young's modulus and thickness are measured, as Oda et al. [12] discussed. In our preliminary experiment to check where this equation is applicable, polyethylenetelephthalate (PET) film having a uniform thickness was used rather than paper for the Young's modulus calculation because thickness of paper varies depending on the measurement method as well as from location to location. Table II shows that Young's modulus calculated based on theoretical Eq. (10) came close to the dynamic Young's modulus measured by the ultrasound velocity method, but is about twice as large as that in the reference. In contrast, Young's modulus calculated based on the empirical equation (both sides assumed to be equal in Eq. 7) was considerably larger than the dynamic Young's modulus. Hereafter, Eq. (10) was used first to determine R_a(=EI). Then, Eqs. (4) and (5) were used to calculate Young's modulus of a coating layer.

EXPERIMENTAL

Determination of Young's Modulus of Coatings

Table III shows the coating colour formulation used. Calcium carbonate (Brilliant-15, Shiraishi Industry, Hyogo, Japan), starch (Ace-A, Oji Cornstarch, Tokyo, Japan), SB-latex (TO-135, Mitsui Chemicals, Tokyo, Japan) and dispersant (Aron T-40, Toa Gosei Chemicals, Tokyo, Japan) were used. The latex was for web offset with a glass transition temperature of 3°C. Basestock was commercial wood-free paper (25 s Stöckigt sizing degree and 64 g/m^2 basis weight) and impervious PET film 100 μm thick to apply coatings uniformly.

TABLE III
FORMULATION OF COATING COLOUR

Constituent	Parts
Calcium carbonate (0.4 μm mean diameter)	100
SB latex (0.21 μm mean diameter; Tg 3°C)	10
Starch	5
Sodium polyacrylate	0.8
	Solids content = 50%

Hereafter this base paper and PET film will be referred to as just base paper and base film, respectively. Coatings were applied manually with a wire bar, #6, 10 or 16, (Kumagai Riki Kogyo, Tokyo, Japan) and then dried at room temperature. Those were conditioned at 20°C and 65% relative humidity for more than 24 h and subjected to measurements under the same condition.

In the experiment to examine the effect of water penetration on the base paper, distilled water was applied with a wire bar #10 to about 10 g/m^2, followed by drying at room temperature. Pure bending stiffness was measured after the samples were conditioned.

Coated paper and coated film were cut into a 5 mm × 5 mm square with one edge cut sharply at 45° to the bottom plane to prepare specimens for observation in a scanning electron microscope (SEM; S-4000, Hitachi, Tokyo, Japan). Each specimen was adhered on a specimen stub for SEM with two-side conductive tape, then platinum coated for 300 s in an ion spatter (E-1030, Hitachi) and observed.

To produce a coated film with a rough coating/film interface purposely, the base film was hot pressed at 200°C for 1 min together with a sandpaper sheet, Teflon board and steel board sandwiched in this order outward on either side, as illustrated in Fig. 2. Thermal stability of this material was confirmed by a result from thermal gravimetrical analysis which determined that decomposition did not occur below 350°C. The base film was compared to one hot pressed without sandpaper because there was a risk that hot pressing might change Young's modulus of base film. These hot-pressed base film sheets were coated in the same manner with the non-pressed base film.

Clark stiffness was measured according to TAPPI Test Method T 451cm-84 [11]. The sample width was 30 mm. The results were rounded off to three significant figures.

Pure bending tester has a characteristic that a paper strip is bent with the same curvature along its whole span. This tester measures initial stiffness (at the beginning of a bend) and average stiffness through the whole bend. In this work, only the initial stiffness was plotted in every figure. Coated sheets were cut to a 100 mm × 100 mm square after conditioning. The sample was set on a tester with a span of 50 mm in machine direction and with a width of

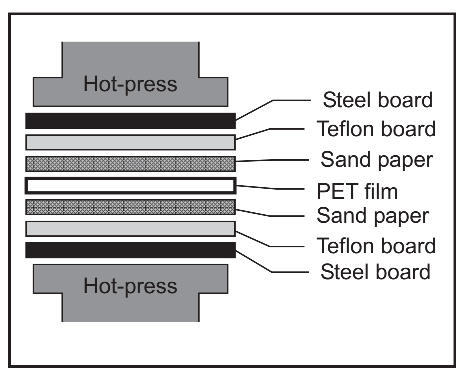

Fig. 2. Order of sheets in hot-press to make a rough film.

100 mm so that the coated side would be subject to only tension. The tester used was pure bending tester JTC-1 (Nihon Seiki, Tokyo, Japan).

Young's modulus of the coating layer was calculated according to Eqs. (5) and (6) from Clark stiffness and according to the equation $S_{PB} = ET^3/12$ from pure bending stiffness. The effect of coating composition was examined.

Verification of Young's Modulus Determination

Binder blend was prepared from starch and SB latex. The blend ratio was of five levels: starch: SB latex = 0:15, 3:12, 5:10, 7:8 and 10:5. These were applied on base film, followed by drying at room temperature. Clark stiffness of the coated film was measured after conditioning.

Plastic pigment (PP) was formulated in place of calcium carbonate of the colour of Table III in the next experiment. The PP used was polystyrene emulsion P-2 and P-4 (Mitsui Chemicals, Tokyo, Japan), with characteristics listed in Table IV. The colour was prepared at 27–33% solids and applied on base film followed by drying at room temperature. Clark stiffness was measured after conditioning.

The PET film, rather than paper, was used to make uniform coatings. Two kinds of colours shown in Table V were used. First, colour SF was applied manually with a wire bar #16 followed by drying at room temperature. Then, colour SC was coated additionally on it in the same way after the first layer was dried completely. Another sample was prepared with the coatings applied in the reversed order. Pure bending stiffness was measured.

RESULTS AND DISCUSSION

Determination of Young's Modulus of Coatings

Figure 3 shows Clark stiffness and pure bending stiffness of the coated film and pure bending stiffness of the coated paper. Clark stiffness has a dimension of stiffness divided by the weight. Consequently, it decreases as coat weight increases because Young's modulus of the coating layer is relatively low for its high relative density. There is scatter in the data because it is difficult to apply coating uniformly by hand and the results depended on whether the thick side or the thin side was held. Pure bending stiffness increased with increasing coat weight because stiffness of the coating layer added to that of the substrate.

Figure 4 shows Young's modulus of the coating layer calculated from the three kinds of stiffness in Fig. 3. Young's modulus of the coating layer on the film was estimated to be about 0.7 GPa from Clark stiffness and 0.5 GPa from pure bending stiffness. These data scattered to some extent for the same reason as before–non-uniform thickness, but did not depend on the coat weight.

On the other hand, the coat weight dependence was found with the coating on paper. Some of them resulted in negative values in the coat weight range below about 17 g/m^2. This presumably stems from the fact that Young's modulus was miscalculated. The possible reasons for this are:

1. Increased thickness and decreased Young's modulus of the base paper due to water penetration.
2. Moisture content change even in the same atmosphere due to water absorption.
3. Pore filling near base paper surface with a coating and a roughened coating/base paper interface due to surface roughening by hydration from a wet coating.
4. Changes in coating composition and structures during consolidation processes and the resultant difference in Young's modulus from a coating on film.

If reason (4) is true, this is special to paper and the evaluation of a coating on film is not applicable to the paper case. However, if reasons (1) to (3) are true, coating on paper is not appropriate to evaluation of Young's modulus of a coating layer. In subsequent experiments, whether those possible reasons were true or not were examined.

Table VI shows changes in physical properties of base paper caused by absorption of distilled water. Water absorption swelled the base paper by 6% in thickness. The basis weight was increased 2% because of the hysteresis in moisture content due to wetting. Then, Young's modulus was reduced by 34%. This suggests that Young's modulus of unwetted base paper cannot be used for the calculation as it leads to miscalculating Young's modulus.

TABLE IV
SPECIFICATION OF PLASTIC PIGMENTS

Plastic pigment	P-2	P-4
Appearance	Milky white	Milky white
Major ingredient	Styrene	Styrene
Structure	Dense (not hollow)	Dense (not hollow)
Involatile ingredients, %	47.9	46.9
pH	8.0	8.1
Viscosity, cps	41	15
Particle diameter, μm	0.23	0.50

TABLE V
FORMULATION OF COATING COLOUR FOR DOUBLE COATING

Colour type	SF	SC
Calcium carbonate	100	100
SB latex	15	10
Starch	0	5
Sodium polyacrylate	0.8	0.8

unit: parts
Solids content = 50%

SF - starch free; SC - starch containing

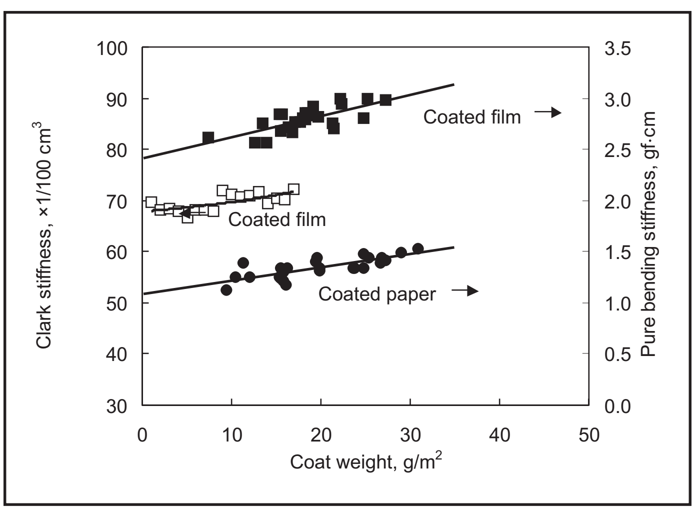

Fig. 3. Clark stiffness and pure-bending stiffness of coated paper and film as a function of coat weight.

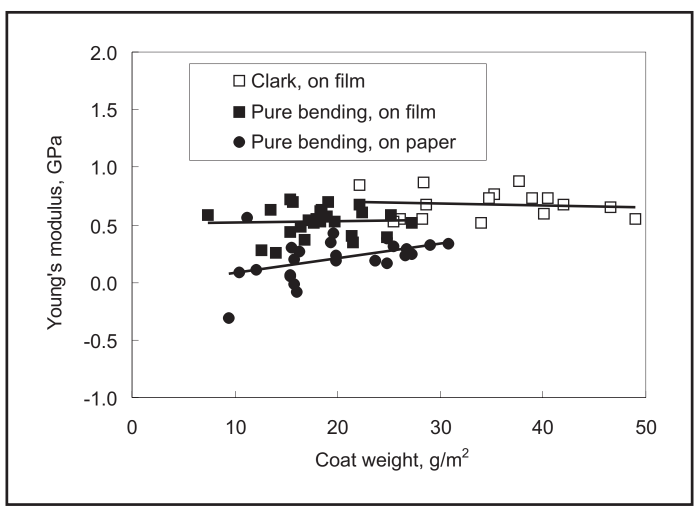

Fig. 4. Calculated Young's modulus of coating on paper or film as a function of coat weight.

Figure 5 shows pure bending stiffness of the coated film with a rough or smooth coating/film interface. Stiffness of the coated film with a smooth interface was larger than that for a rough interface. This means that, the smoother the interface, the larger the coated sheet stiffness, thus implying that Young's modulus of a coating layer would be miscalculated if the coating was applied on base paper due to roughening [15].

The scanning electron micrographs of Figs. 6 and 7 are cross-sections of the coated paper and the coated film, respectively. It was revealed that surface pores of the base paper were filled with the coating and that the interface was rough, while the coating/film interface was very smooth and the thickness was constant. The observed interface roughness confirms that this difference was one of the reasons why the calculated results of Young's modulus were different between paper and film in Fig. 4.

Verification of Young's Modulus Determination

It is difficult to verify that the calculated Young's moduli, ranging between 0.5 and 0.7 GPa, fall in a reasonable range. Another method capable of measuring a coatings' Young's modulus is the ultrasonic method. But, ultrasonic waves are likely to be transmitted through as stiff parts as possible like base paper of ca. 0.5–3.5 GPa. So, the ultrasonic method cannot be exactly applied for this purpose unless a coating is separately present. Figure 8 shows Young's modulus of the blend binder film coated on base film from starch and SB latex. With increased starch ratio, Young's modulus of the blend binder film increased remarkably. This result agreed with the general knowledge that starch-rich coatings have high stiffnesses. In other words, the method of Young's modulus determination proposed here was proved to be appropriate. The ratio 33% corresponds to the binder composition of the colour used in Fig. 4. The Young's modulus of the blend binder film at 33% was 0.60 GPa, being close to the average of Young's modulus (0.66 GPa) of the coating layer of Fig. 4.

Figure 9 shows Young's modulus of the coating layer containing only plastic pigment (PP) in place of calcium carbonate as a function

TABLE VI
CHANGES IN SHEET PROPERTIES OF WOOD-FREE PAPER BY WATER APPLICATION

	No water appl. Average	No water appl. (Std. dev.)	After water appl. Average	After water appl. (Std. dev.)
Thickness, μm	80.2	(0.5)	85.0	(0.8)
Basis weight, g/m²	64.3	(0.6)	65.6	(0.5)
Pure bending stiffness, gf•cm	1.22	(0.06)	0.95	(0.13)
Young's Modulus, GPa	2.77	(0.12)	1.82	(0.24)
PPS roughness, μm	5.27	(0.03)	6.60	(0.07)

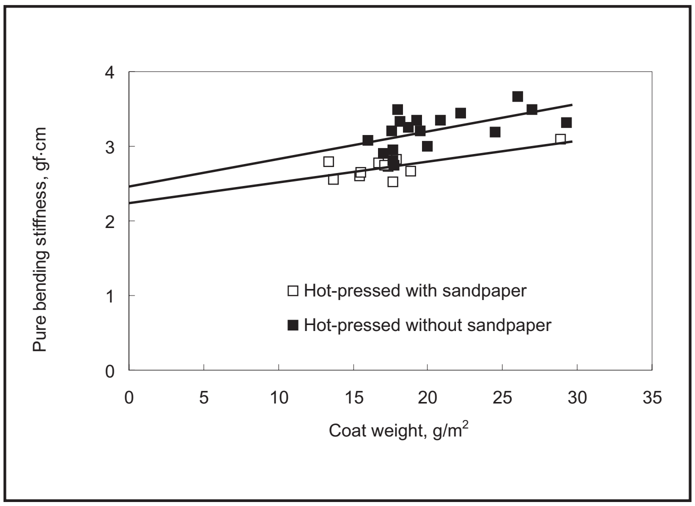

Fig. 5. Influence of interface shape on relationship between basis weight of coated film and pure bending stiffness.

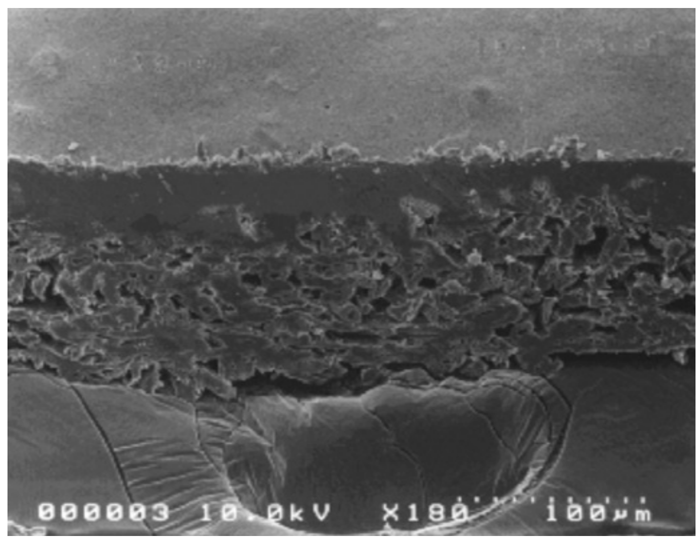

Fig. 6. Cross-section of coated paper.

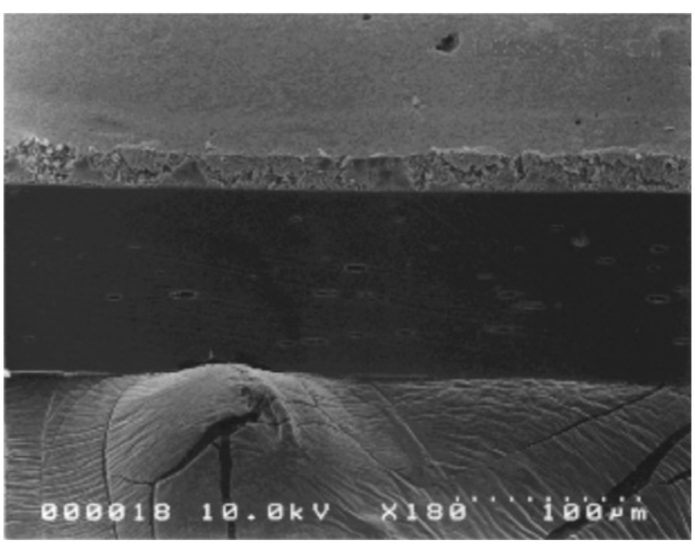

Fig. 7. Cross-section of coated film.

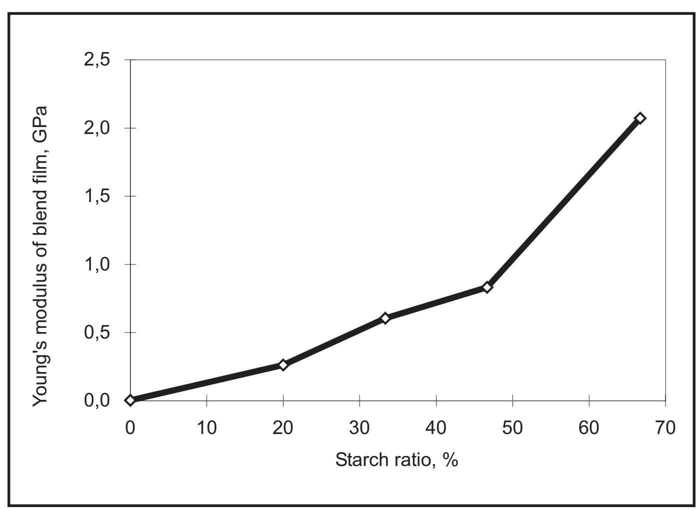

Fig. 8. Starch effect on modulus of latex/starch blend film.

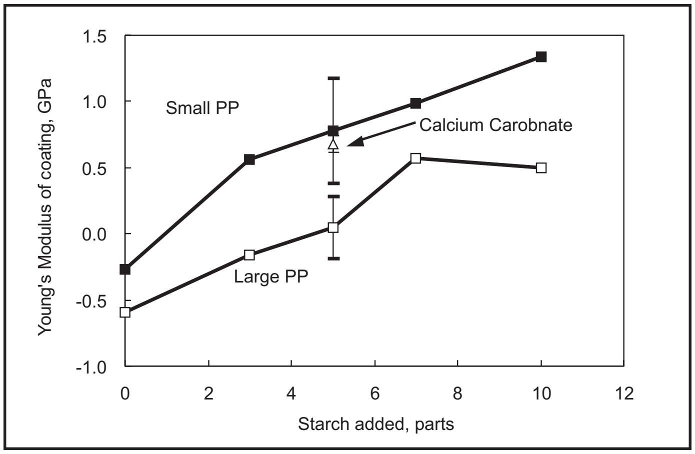

Fig. 9. Starch and plastic pigment (PP) effects on coating modulus.

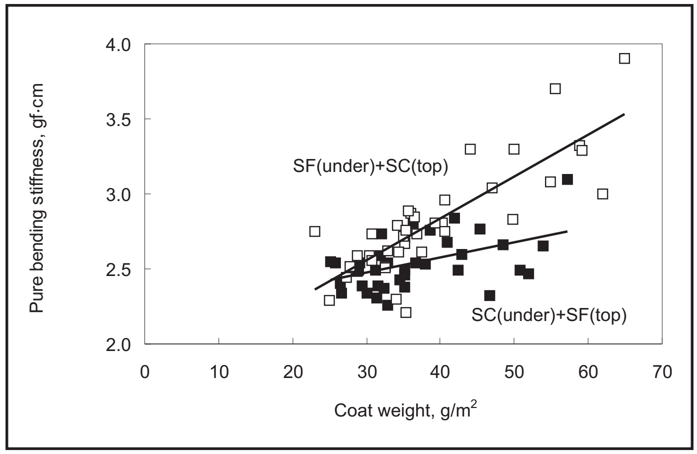

Fig. 10. Effect of double-coating order of starch-containing(SC) and starch-free(SF) colours on pure bending stiffness of coated film.

of formulated parts of starch (the total binder formulated was 15 pph). Remarkable starch effects on Young's modulus were found again with the two PPs, irrespective of the particle diameter (0.23 and 0.50 µm). Some data of Young's modulus were calculated to have negative values, presumably because the nonuniform coating (thick parts locally present) misled the thickness to a larger value than the average.

Control of Coated Sheet Stiffness

Turning to the effects of particle size of PP, the larger the particle diameter of PP, the higher the Young's modulus as shown in Fig. 7. It is probably because the small particle made the structure tighter during consolidation. Young's modulus of the coating containing only calcium carbonate as pigment is also plotted after Fig. 4. Young's modulus of the coating for the smaller PP was close to that for calcium carbonate. However, PP is expected to make Clark stiffness (stiffness against the weight of its own) of the whole coated paper larger than mineral pigments even if Young's modulus of the coating layer is at similar levels because PP has a lower density.

As a trial to improve coated paper stiffness, external coating of high Young's modulus containing a higher ratio of starch was applied and its effect was examined. Figure 10 shows pure bending stiffness of the coated film versus the total coat weight. The coated film with the starch-rich (SR) coating external exhibited higher stiffness than when internal. This suggests that external coating of a color containing stiff components acts to improve the stiffness of the whole coated paper. Practically, too much of starch in the external coating should reduce surface porosity. Consequently, care must be taken in deciding the optimum dose of starch to maintain other properties.

CONCLUSIONS

1. An equation was developed to calculate the Young's modulus of a coating layer from values of stiffness and thickness both of a one-side coated sheet and the base sheet (paper or film). Then, a theoretical interpretation of Clark stiffness established the method by which Young's modulus of a coating layer was calculated from Clark stiffness.
2. Young's modulus of a coating layer on paper was found to be miscalculated. It is because thickness (due to swelling) and basis weight (due to moisture content hysteresis) increased after coating. Therefore, values for unwetted base paper cannot be used in the calculation and an impervious film must be used.
3. Determination of Young's modulus of coatings was verified by the agreement with a general knowledge that starch-rich coatings have high stiffnesses as follows. Young's modulus of the blend binder film made from starch and SB latex increased with increased starch dose. This trend was found with plastic pigment-based colour as well as with calcium carbonate-based colour. External deposit of starch-rich (stiff) coating improved stiffness of the whole coated film.
4. Plastic pigment of the smaller particle diameter made the coating Young's modulus higher, but was close to that of calcium carbonate. With regard to stiffness in a bending mode, a coating layer has considerable effect because the outlying coated layer undergoes a much larger strain than the inner base paper layer.

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