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Transparency Measurement of Plastic Sheet and Film

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Synopsis

Available methods for testing the transparency of plastic sheet and film have been found inadequate as regards the correlation between measurement and visual observation. A newly developed procedure, based on the determination of light transmission within a very small angle, gives good correlation. The application of the method and its limitations, due to the difference in optical effect of small-angle and large-angle scattering, are discussed. A description is given of the instrument, a special feature of which is that it gives direct readings of optical density and transparency.

INTRODUCTION

Light-transmission characteristics of plastic sheet and film are difficult to define and measure. Current terminology comprises terms like clarity, transparency, total transmittance, diffuse transmittance, see-through, resolution distance, haze, turbidity, opacity, translucency, hiding power, etc., none of which is well-defined. In addition, several types of measurement have been proposed. Some of them record that part of the transmitted light which is scattered in a forward direction outside a certain angle with respect to the normal incident beam.[1-3] Other methods determine a quantity characterizing the resolution in an image formed of a specific object, with the sheet or film placed between object and image.[4,5] In fact, only a plot of scattered-light intensity versus scattering angle would completely describe the optical properties of the material for transmitted light. This would, however, be a cumbersome test method and the results would be hard to interpret.

ASTM D-1003, which is probably the method most widely used, defines "haze" as "that percentage of transmitted light which, in passing through the specimen, deviates from the incident beam by forward scattering more than 2.5° on the average." However, as has been recognized by several authors,[2-4,6] this haze value bears little relation to the visibility of distant objects seen through the specimen. Furthermore, during our search for nucleating agents for polypropylene having a strong clarifying effect on sheets of this polymer, determination of the haze value sometimes indicated the absence of any effect or even a reversal of order compared with what was observed visually.

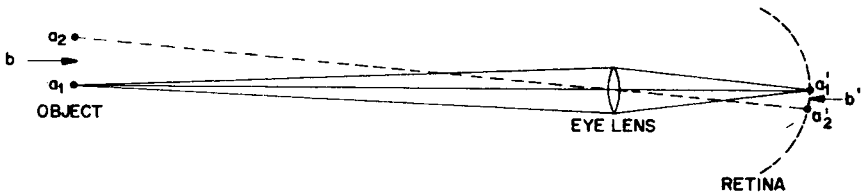

Fig. 1. Image formation in the human eye.

This prompted us to look for a test method which would be more in line with visual assessment. This paper deals with the development of such a method and with the design of a suitable apparatus. The results are compared with those of existing methods; differences in results are discussed with the object of evaluating the various methods and finding an adequate way of describing the optical properties of polymer sheet or film.

PRINCIPLES

Definition of Transparency

In everyday language, transparency is the effect of a sheet or film on the visibility of an object full of contrast, the specimen being interposed at a considerable distance from the object. Contrary to what might be thought, transparency is not generally the opposite of haziness. Certain hazy specimens are, in fact, more transparent than less hazy ones (see Results and Discussion).

According to the above definition, the degree of transparency depends on image formation through the specimen.

Image Formation in the Human Eye

The human eye can still discern two small light sources of equal brightness (a_1 and a_1 in Fig. 1) if their angular distance with respect to the eye is about $4'$ of arc. This is true only if the brightness of area b between a_1 and a_2 differs sufficiently from that of a_1 and a_2.

If, however, due to scattering of light, e.g., by a plastic sheet (Fig. 2),* the intensity distribution on the retina is different from that on the object, the limit of resolution changes. Under such conditions two sources a_1 and a_2 (Fig. 3a) may on the retina generate an intensity distribution as drawn in Figure 3b. According to the frequently employed Rayleigh criterion for resolving power, the image points a_1' and a_2' are seen separately if the minimum in the intensity distribution (at b') is less than 0.8 times the value of the local maxima. Therefore, the limit of resolution in this situation may be much larger than $4'$. It is mainly small-angle scattering

* We assume that no rough surface irregularities are present to cause prismatic diffraction of light.

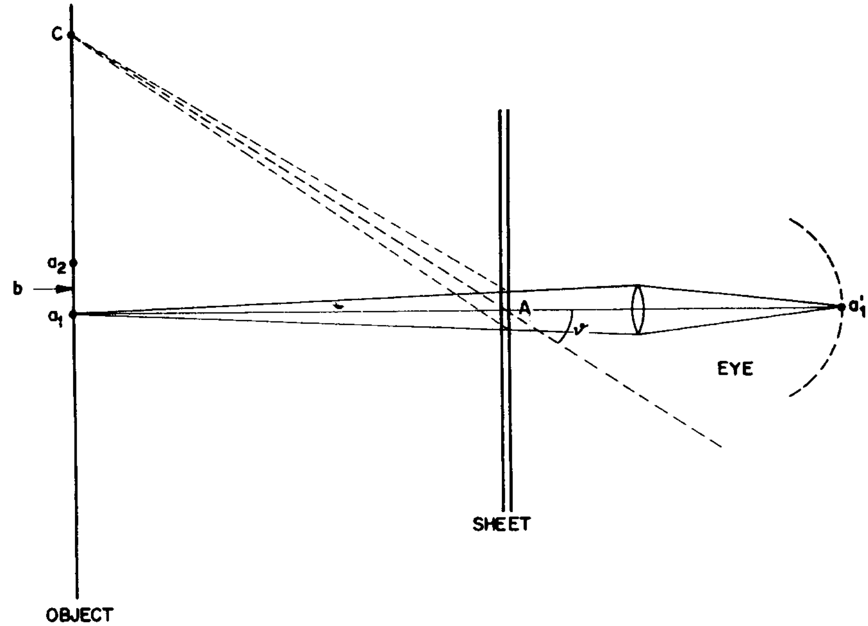

Fig. 2. Image formation in the human eye with plastic sheet between object and eye.

that causes the intensity distribution of the image of a point source to flatten and thereby the resolution to decrease.

Actually, the object (or its background) will be much larger than a_1 and a_2 and will contain many points c of considerable brightness (Fig. 2). Let A be the area of the sample through which the beam passes that forms the image a_1' of a_1. Some light coming from a point c and going through A will be deviated through an angle ϑ and coincide with the beam forming the image of a_1. Such large-angle scattering increases the intensity both at a_1' and at b' (Fig. 3c), so that the relative contrast diminishes and the resolution angle increases. This is the cause of haziness. Large-angle scattering also affects transparency, although to a lesser extent than small-angle scattering.

Thus, there is a difference in effect between small-angle scattering (blurring) and large-angle scattering (haziness) on image formation through the specimen. Nevertheless, as will be shown below, both types of scattering can together be expressed in one number.

Let the bright points c be homogeneously distributed over the object. Then per unit solid angle the area A of the specimen receives light of the same mean intensity I_t from any direction. From an annulus on the object, of which the inner and outer radii subtend angles of ϑ and $\vartheta + d\vartheta$, respectively, viewed from A, area A receives a radiant flux of intensity

$$I_t 2\pi \sin \vartheta d\vartheta$$

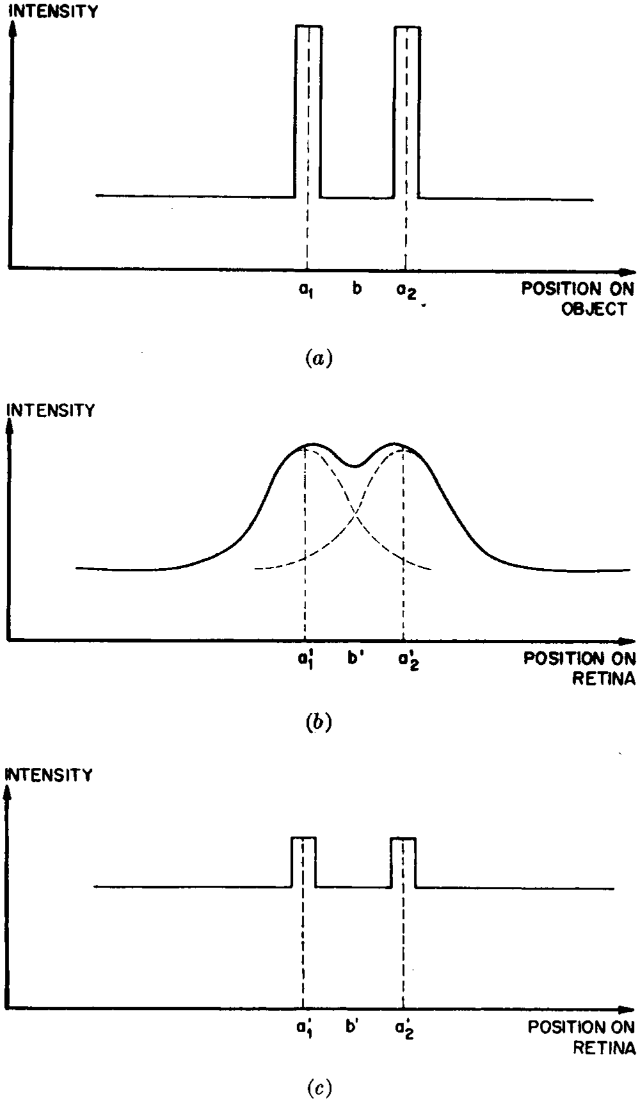

Fig. 3. (*a*) Intensity distribution in part of the object; (*b*) effect of small-angle scattering; (*c*) effect of large-angle scattering.

Of this flux a fraction $p_\vartheta \beta$ is deviated in the direction of a_1', where p_ϑ is the portion of the total flux scattered per unit solid angle and β is the solid angle at which the area around a_1, which corresponds with the area around a_1', is seen by the eye. (The specimen is assumed to be much nearer to the eye than the object.) So the total scattered-light intensity at a_1' is

$$I_{sc} = \int_{\alpha}^{\pi/2} I_i p_\vartheta \beta 2\pi \sin \vartheta d\vartheta \tag{1}$$

in which α is the angular arc subtending the same circular area as solid angle β.

The intensity of the flux received at A from the area around a_1 corresponding with β is $I_t\beta$, of which

$$I_{st} = I_t\beta p_{\vartheta=0} \tag{2}$$

is transmitted straight to a_1'. Another part is scattered in a forward direction, with $\vartheta > \alpha$. This part is $\int_{\alpha}^{\pi/2} I_t\beta p_\vartheta 2\pi \sin \vartheta d\vartheta$, which again is equal to I_{sc} [see eq. (1)].

Therefore, we can determine how much light comes from the area outside a_1 and b and is scattered by A in the direction of a_1 and b', by measuring the light coming from a_1 and scattered by A outside $a_1'a{\cdot}d\ b'$. Thus, for a_1 we can employ a point source and avoid the use of a large object, which would be difficult to define.

A third part, I_{asb}, is lost by absorption, reflection, and back-scattering. Let

$$I_t\beta = I_0$$

Then

$$I_0 - I_{abs} = I_{st} + I_{sc} \tag{3}$$

where I_{st} and I_{sc} determine image quality and so the transparency of the specimen, because the intensity at a_1' is now $I_{st} + I_{sc}$ [sum of eqs. (1) and (2)] if a_1 is a luminous point, and the intensity at b' is I_{sc} if b is a completely dark area. It is then the ratio

$$I_s = [I_{sc}/(I_{st} + I_{sc})]\ 100\% \tag{4}$$

that determines the loss of image contrast and therefore

$$I_r = 100 - I_s = [I_{st}/(I_{st} + I_{sc})]100\% \tag{5}$$

characterizes the transparency of the specimen.

Contrary to what has been said elsewhere,[3] pupil size has little influence on image formation through a light-scattering specimen. It is proportional to area A, which in turn is proportional to I_t. Since in the ratio I_r [eq. (5)] both the numerator and denominator are proportional to I_t, I_r is independent of the size of the pupil.

The visual difference in clarity between specimens with $I_r = 1\%$ and 2% is about the same as that between specimens having $I_r = 10\%$ and 20%. So the I_r scale is not adequate to characterize optical properties. Besides, the human eye discerns the differences in intensity in a logarithmic rather than in an absolute way. These facts suggest the use of a logarithmic scale: $\log I_r$ or some function of $\log I_r$. Obviously, an I_s scale would be just as unsuitable as an I_r scale and a $\log I_s$ scale would be even worse.

The ratio I_r can be measured directly by an apparatus reversing the

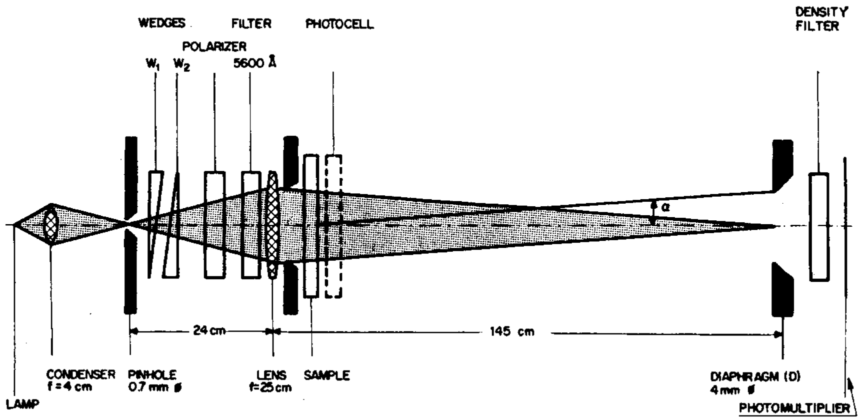

Fig. 4. Optical arrangement of transparency meter.

situation shown in Figure 2: a point source replaces the retina and the light-sensing devices are at the location of the object (Fig. 4).

EXPERIMENTAL

Apparatus

Considerations Underlying the Optical Layout. A transparency meter was designed according to the principles outlined in the previous section. The basic optical arrangement is shown in Figure 4. A light source is focussed on a pinhole. The pinhole itself is focussed via the lens on diaphragm D. A photomultiplier behind the diaphragm measures the total light passing through D. The sample will be placed just behind the lens. The light will thus traverse a large surface area of the sample, and so local irregularities will be averaged.

From the middle of the sample, light rays coincident within α with the incident beam will pass through diaphragm D. On an average the photomultiplier thus measures the light (transmitted from all parts of the sample) which is coincident within α with the direction of the incident light rays. We have thus realized the experimental conditions to measure I_r. For α a value of $2'$ of arc should be chosen.

With a pinhole of 0.7 mm. diameter, which can still be drilled with good accuracy, all the dimensions are fixed once the diameter of diaphragm D has been chosen. To match the size of D with that of the image of the pinhole, the diaphragm should be made adjustable. Thus the minimum aperture diameter will be about 4 mm. for a magnification of about 6×. For $\alpha = 2'$ the apparatus would have to be about 5 m. long. Constructing an instrument of this size will be justified only when the object has details that will strain the eye to its lowest limit of resolution. Since this is rarely the case we took $\alpha = 5'$. This enabled us to build a more compact instrument without deviating too much from the basic principles.

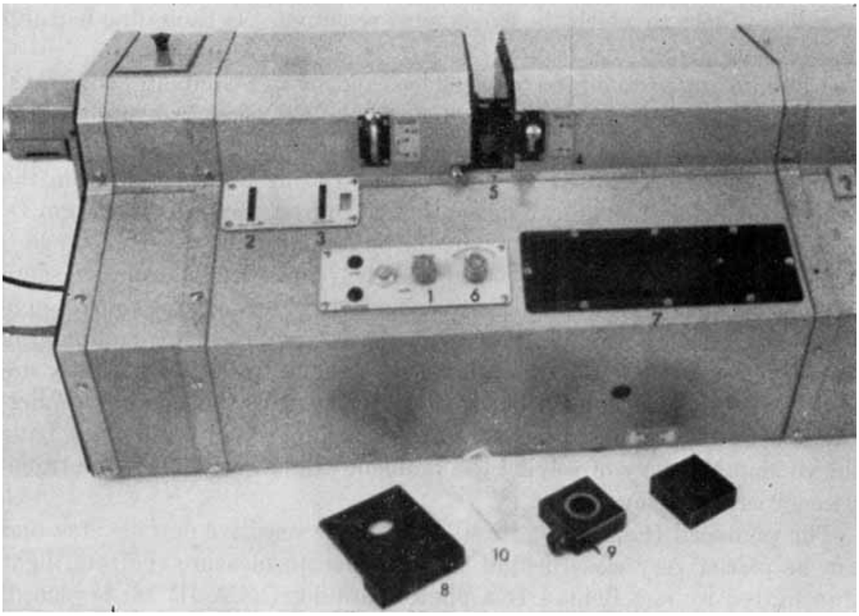

Fig. 5. Control panel of transparency meter: (*1*) on-off switch; (*2*) adjustment of light source; (*3*) absorption of specimen (variable density wedges); (*4*) photocell positioner; (*5*) location of specimen; (*6*) selector and range switch; (*7*) galvanometer scale; (*8*) sheet-specimen holder; (*9*) vacuum film-specimen holder; (*10*) Pyrex cell.

Design. The apparatus we constructed (Fig. 5) gives direct readings not only of the value of I_r but also of the light absorbed by the specimen. The latter is also used as a quality criterion, although it seldom affects image quality of an object viewed through the specimen. No additional calculations are necessary for either.

A lamp-condenser (f = 4 cm.) system illuminates the pinhole (diameter 0.7 mm.). Behind this pinhole two circular variable-density wedges are placed. The first wedge, W_1, is used for adjustment purposes, for instance to cope with long-term variations in the light source. The second wedge, W_2, is used to measure the optical density of the sample. To ensure a nearly uniform illumination of the sample surface, increasing density of the wedges has been made to correspond with rotation in opposite directions.

Optionally a polarizer with snap action (horizontal or vertical plane of polarization) can be placed in the optical path. We preferred this arrangement to a continuously variable polarizer because the instrument is used mainly for measuring oriented samples in directions transverse or parallel to the direction of orientation. Naturally, the sample must then be so placed as to match the polarizer positions.

An interference filter with maximum transmission at 5500 A. and a width of 100 A. at 50% of peak transmission was inserted to restrict the wavelengths to those to which the eye is most sensitive. It caused no harmful depolarization.

A 25 mm. aperture placed between lens and sample eliminates edge rays. A sample surface of 25 mm. diameter reduces the spread in results for a single sheet considerably, because local irregularities are averaged.

As described previously, all light rays deviating less than 5′ from the axis of the incident beam can be considered to pass through diaphragm D, the total intensity being measured by the photomultiplier.

Sheets whose surfaces are not perfectly plane-parallel cause a small prismatic deflection of the "directly transmitted" beam, which would give a gross error in the result. In order to avoid this difficulty, diaphragm D can be opened to twice the image of the pinhole, so that the slightly deflected directly transmitted beam is still caught by the photomultiplier. Tests with slightly distorted sheets of blank poly(vinyl chloride) have shown that this way of solving the problem will scarcely affect the transparency as here defined.

The photocell (Eel Corporation) has a large sensitive surface area and can be placed very close behind the specimen to measure the total light transmitted by it. Behind D a photomultiplier (RCA IP 28) is placed, which has good linearity over a wide range. By using density filters the illumination level on the photocathode is reduced to avoid saturation effects.

A galvanometer is used to measure the electrical signals originating both from the photocell and from the photomultiplier. Together with the necessary power supplies it has been mounted on the optical bench.

Principles of Measuring Procedure. The photomultiplier measures the undeviated portion of the total flux transmitted, the photocell the total transmitted light. First, by means of wedge W_1 and with no sample in the path of the beam, the photomultiplier is made to give a deflection of 100 units. This radiant flux is then measured with the photocell, which gives a reference reading R.

With a sample in the optical path the photocell will give a lower reading due to absorption losses in the sample. By rotating wedge W_2 the total transmitted flux impinging on the photocell is then increased to give the same reference reading R. The photocell has been checked for linearity and uniform sensitivity, so that the total transmitted light measured is indeed equivalent to the light flux which would give a full-scale reading (100) on the photomultiplier. The photomultiplier only measures the directly transmitted light when a sample is present. Therefore the signal of the photomultiplier will automatically be equivalent to the desired ratio I_r.

To compensate for absorption losses ($a = I_{abs}/I_0$) in the sample, the incident flux is increased from I_0 to $I_0(1 - a)$ by reducing the attenuation due to wedge W_2. This wedge is provided with a scale indicating the optical density of the sample equivalent to the attenuation reduction $1/(1 - a)$.

The long-term consistency of the results should be good, because they are dependent only on the linearity of the photomultiplier. The photocell is used as a short-term reference only, but substituting this reference reading for the photomultiplier reading is no longer permissible once the photocell has lost its uniform sensitivity. Overall performance, however, can be checked by using, for example an etched glass plate as a semistandard.

The speed of the measurements renders this procedure very suitable for routine work. Both values of interest can be read from the instrument once the proper settings have been made.

Measurements

As completely opalescent specimens have I_r = about 0.1%, the log I_r scale has somewhat strange boundary values: −1 and +2. By defining the transparency number, T, as:

$$T = (10/3)(1 + \log I_r) \qquad (6)$$

a scale of 0 to 10 is obtained, in which perfect transparency is indicated by $T = 10$, while $T \leqq 0$ means complete turbidity. A table for converting I_r into T is kept on the desk of the apparatus.

For comparison, we have also determined the haze values of several samples in the Eel hazemeter according to ASTM D-1003 and in a laboratory-built hazemeter. The former measures transmitted light deviating more than about 2°30′ on an average. The latter does the same for an average angle of 1°30′ and measures total transmitted light up to an angle of 45° on an average.

To elucidate differences in results obtained by the various methods, the angular dependence of light scattering has been recorded for a few samples. A light-scattering meter was used in which the primary beam of an angular aperture of less than 15′ produced an illuminated spot in the sample of $^1/_2$ mm. diameter (see Fig. 6). This spot was the center of rotation of a swing arm carrying a photomultiplier fitted with a $^1/_4$-mm. diameter pinhole. Thus the intensity measured at $\vartheta = {}^1/_2°$ (without specimen) was less than 1% of the intensity measured at $\vartheta = 0°$.

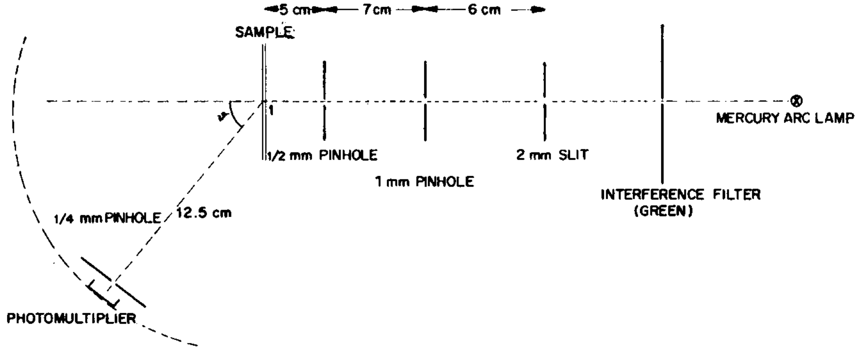

Fig. 6. Light-scattering meter.

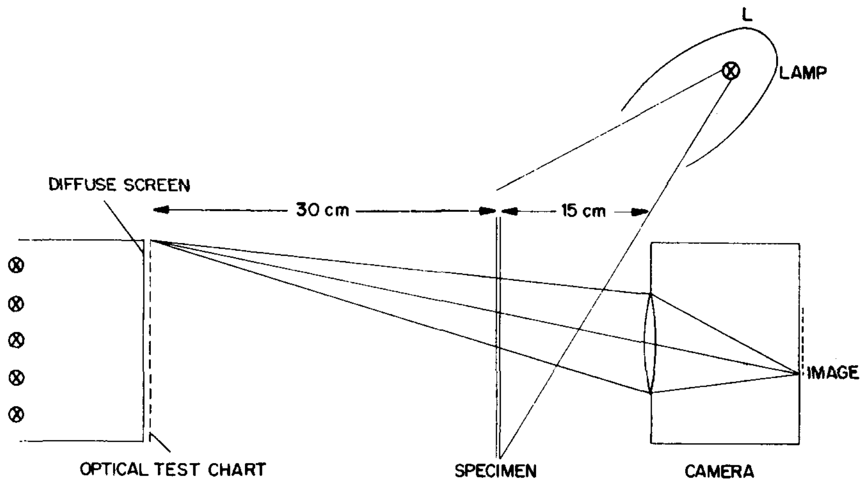

Fig. 7. Arrangement for photography through scattering specimen.

Also, photographs (obtained with an Exacta Varex IIb 35 mm. camera) of a luminous optical test chart were taken through a few specimens, first in a dark room, then while a strong lamp illuminated the specimen (see Fig. 7), in order to illustrate the effect of light scattering at large angles.

Samples

Since for the present purpose the material of which specimens are made hardly matters, the specimens will here only be characterized by their optical properties. Variations between specimens taken from the same batch will also be considered.

RESULTS AND DISCUSSION

Results of measurements on a few samples (polyethylene or polypropylene sheets), each representing an optical class, are presented in Table I in order of increasing transparency.

Table I shows that the transparency number correlates well with actual transparency, but that, on the other hand, the hazemeters fail to discriminate clearly between complete turbidity and low and moderate levels of transparency. Thus, these meters proved unsuitable for the evaluation of nucleating agents for polypropylene, the C and D sheets being compression-molded polypropylene containing low concentrations of nucleating agent (0.1 phr or less). The Eel hazemeter even gave a considerably lower haze value for a milky sheet (A) than for slightly transparent sheets. But then, it is recommended for haze values below 30% only.

Sheets E_1 and E_2 merit separate discussion. They showed no visible differences, as is also indicated by their transparency numbers. Haze values, though indicating a high level of transparency, differed widely.

TABLE I
Transparency Measurements on Nine Different Sheets

Optical quality of sheets	Haze, % (ASTM D-1003, Eel hazemeter)	Haze, % (laboratory hazemeter)	Transparency number T
Milky			
A	73	95	−0.35
Nearly opalescent			
B_1	89	94	2.01
B_2	90	95	2.19
Slightly transparent			
C_1	96	92	4.01
C_2	92	92	4.65
Moderately transparent			
D_1	90	87	5.65
D_2	89	90	6.05
Nicely transparent, only slightly hazy			
E_1	28	27	8.25
E_2	43	35	8.31

Light-scattering curves explain this phenomenon qualitatively (Fig. 8). Sheet E_1 shows a stronger dependence of intensity on scattering angle than E_2. Since according to the transparency numbers the integrated scattered intensity outside $\vartheta = 5'$ is the same for both sheets, the integrated scattered intensity outside a larger cone must be higher for E_2 than for E_1. This is reflected in the haze values, but not in the visual appearance. These facts suggest that the limit of applicability of ASTM D-1003 is even below 30% haze.

For measuring the transparency of sheets the method described in this paper would therefore seem to be preferable.

The transparency number, owing to its logarithmic nature, is little influenced by variations in thickness of 10% or less. Specimens prepared in the same way from one batch of polymer, although virtually equal in thickness, showed some scatter in transparency number. Therefore the transparency number is rounded off to the first decimal for values below 9.0. For reasons to be discussed below the second decimal is included for T values higher than 9.0.

With films, and probably also with sheets of very clear amorphous plastics, such as straight polystyrene, slight surface irregularities markedly affect optical properties. Just as a coarse crystallization morphology, they may cause considerable scattering at angles of less than 1°. Consequently, a fine-structured object will produce a very blurred image on the retina, owing to overlap of the diffraction patterns of adjacent image points (Fig. 3*b*). An object with a coarse structure, on the other hand, may then still give little loss in definition.

Large-angle scattering (i.e., a more uniform scattering in all directions),

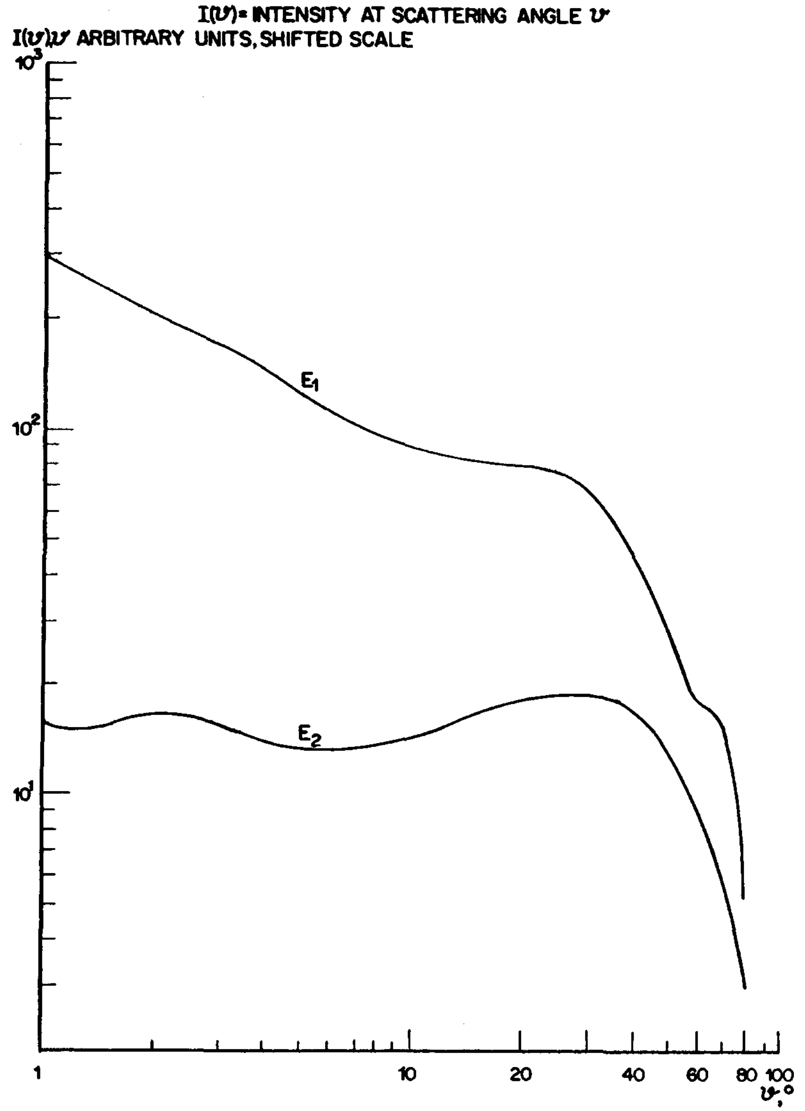

Fig. 8. Light-scattering curves for sheets E_1 and E_2.

often caused by a fine crystallization pattern, hardly affects image formation itself, but gives rise to a slight haze. Here, it is environmental light that raises background intensity and thus causes loss of contrast. This slight haze may be important enough, because in judging optical quality, one not only looks at some object, but also observes the film itself.

A few measurements on films are presented in Table II.

A haze value of 11 (sample Q_1), for instance, would be commercially unacceptable for several applications, although an object may still be clearly seen through the specimen.

TABLE II
Transparency Measurements on Films

Films	Appearance	Haze, % ASTM D-1003	Transparency number T
P	No haze, many surface irregularities of 20–100 μ	3.8	9.16
Q_1	Slight haze, due to fine crystallization morphology	11	9.56
Q_2		6.5	9.59
R	No haze, no surface irregularities	1.1	9.86

The difference in optical effect between scattering at small and at large angles is demonstrated by photographs of a distant luminous object taken through the specimen (Figs. 7, 9). To bring out the effects more clearly a slightly frosted glass plate and a thin sheet were used instead of films. Small-angle scattering is seen to cause considerable blurring, whether the room is dark or not. Large-angle scattering causes hardly any blurring, and here environmental light gives a loss of contrast rather than of definition.

Thus, for films other than translucent ones, two unconnected transmittance properties have to be determined, viz., small-angle scattering (for which we prefer the method here described) and large-angle scattering (which can be determined by ASTM D-1003). For sheets, generally, it is difficult to distinguish clearly between small-angle and large-angle scattering properties, most sheets scattering considerably in both angular areas. Therefore optical characterization of sheets by one number, relating to total scattering, is sufficient.

As small optical differences between thin specimens (films) are more striking than those between thick specimens, it is necessary to record the transparency number for films in two decimals.

CONCLUSIONS

The ASTM D-1003 method is inadequate for measuring the transparency of plastic sheet and film.

The apparatus described in this paper is based on the principles of image formation in the human eye. It measures light transmission within an angle of 5′ of arc.

A transparency number T is defined, which is a logarithmic function of transmission within an angle of 5′. This number correlates well with visible transparency.

Small-angle and large-angle scattering have different effects on image formation and affect the appearance of the sample in different ways. Therefore, transparency and haze are not opposite quantities. Haze de-

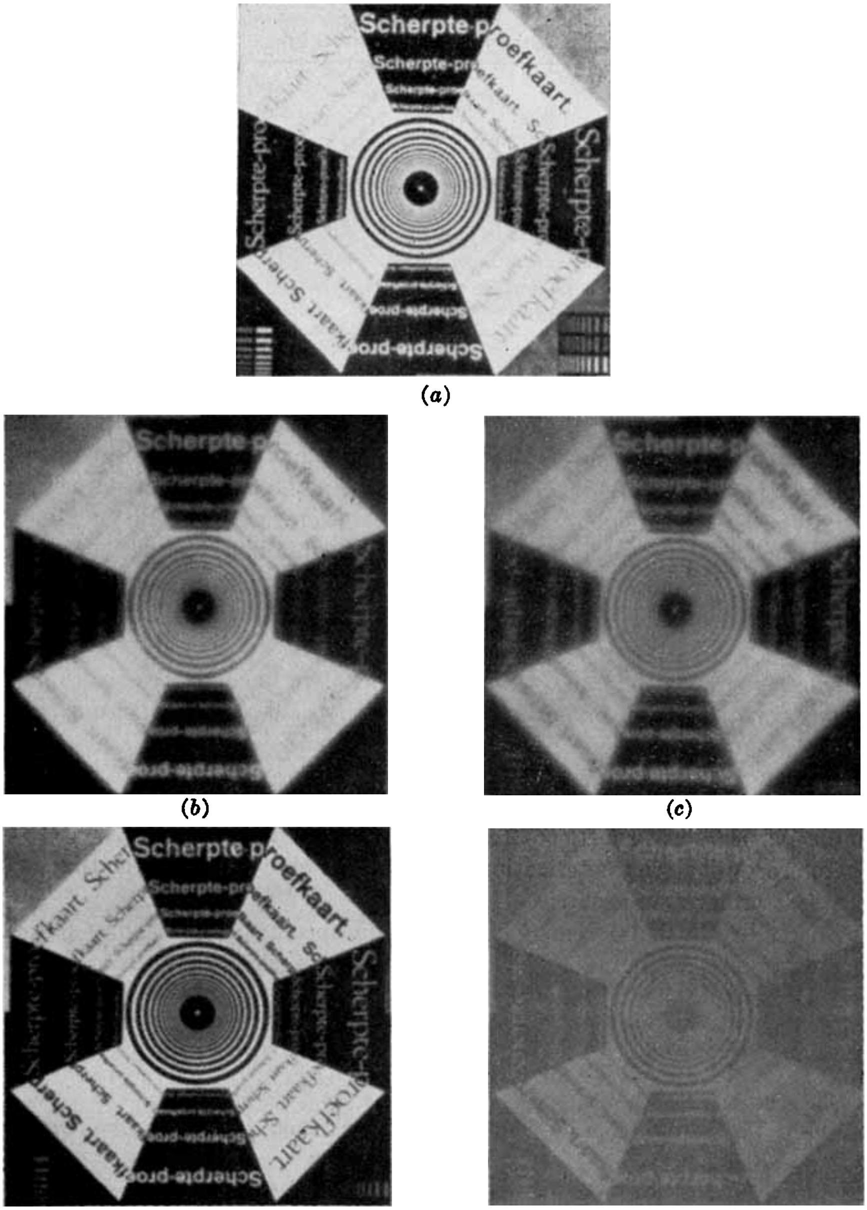

Fig. 9. Test chart for optical resolution photographed through scattering specimens: (*a*) no sheet present; (*b*) small-angle scattering, specimen in dark room; (*c*) same as *b*, but with environmental light; (*d*) large-angle scattering, sheet in dark room; (*e*) same as *d*, but with environmental light.

pends on large-angle scattering only, whereas transparency depends on both.

The diameter of the pupil of the eye has little influence on the visible transparency of the specimen.

The transparency number and the absorption by the specimen can be read direct from the apparatus. If desired, polarized light can be used.

For sheets the transparency number alone seems sufficient to characterize the optical properties. For films both transparency number and haze (e.g., according to ASTM D-1003) have to be determined.

Samples should be free of coarse surface irregularities, which may cause prismatic diffraction; otherwise they must be immersed in an optical cell containing a liquid of the same refractive index.

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Résumé

Les méthodes disponibles pour mesurer la transparence de feuilles ou films de plastiques ont été trouvées inadéquates en ce qui concerne la corrélation entre les mesures et l'observation visuelle. Un procédé nouvellement développé, basé sur la détermination de la transmission lumineuse sous très petits angles, donne une bonne corrélation. L'application de la méthode et des limitations dues à la différence de l'effet optique de la diffusion à petit et à grand angle sont discutées. Une description de l'instrument est donnée; une caractéristique particulière de celui-ci consiste dans la lecture directe de la densité optique et de la transparence.

Zusammenfassung

Die vorhandenen Methoden zur Prüfung der Transparenz von plastikfolien und -filmen erwiesen sich zur Korrelierung zwischen den Messwerten und der visuellen Beobachtung als unzureichend. Ein neu entwickeltes, auf der Bestimmung der Lichtdurchlässigkeit innerhalb eines sehr kleinen Winkels beruhendes Verfahren liefert eine gute Korrelation. Die Anwendung der Methode und ihre, durch den Unterschied des optischen Effekts bei Kleinwinkel- und Weitwinkelstreuung bedingten Beschränkungen werden diskutiert. Eine Beschreibung des Instruments, dessen Besonderheit in der direkten Ablesbarkeit der optischen Dichte und Transparenz besteht, wird gegeben.

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