A New Apparatus for Measuring Various Properties of Plastics Using C Specimens

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Synopsis

A new apparatus for measuring various properties of plastics is proposed. Using a split circular ring-type specimen (C specimen), displacement L, tension P, and fringe order N are measured by means of a differential transformer, a load cell, and a polarizer-analyzer. The Young's modulus and photoelastic sensitivity of samples can be estimated from L, P, and N. Experiments are carried out in the environments of air, water, oils, and chemical reagents under-temperature controlled conditions. Typical data are, presented showing the applications of this apparatus to the determination of the heat distortion temperature and the effect of temperature on the rigidity and photoelastic properties, to the simultaneous measurement of stress relaxation and birefringence and of creep and birefringence, and to the continuous measurement of resistance to chemical reagents and ultraviolet rays.

INTRODUCTION

In the previous paper[1], a new specimen type named C specimen having the following merits was proposed:

1. It is deformed easily, so it is suitable for examination of the effect of deformation on degradation.
2. As photoelastic fringes caused by deformation are parallel to the center of the specimen, the fringe number counted is convertible into birefringence and photoelastic sensitivity.
3. The variation of the restoring force of the specimen with deformation is convertible into Young's modulus or apparent stiffness.
4. The specimen can be immersed into a liquid medium without dipping of the specimen chucks.
5. As the shape is circular, specimen preparation by machining is comparatively easy.

In the previous paper[1] a new method for evaluating durability intermittently by means of a photoelastic scale was proposed, and in this paper, a new apparatus for evaluating durability continuously by employing the same specimen shape is proposed.

PRINCIPLE

In the case of C specimens, shown in the Physical Consideration section of the previous paper,[1] the Young's modulus E of samples is proportional to $P/(L_n - L_p)$ as far as the theory of elasticity is applicable where P is the restoring force (or tension) per unit thickness, and L_n and L_p are the slit distances in the natural and deformed positions, respectively.

While L_p is smaller than L_n in the previous method, as the specimen is deflected toward its inside, in this method L_p is larger than L_n as the specimen is stretched toward the outside.

Equation (12) of the previous paper[1] is useful in this method, as follows:

$$E = \frac{K_2 P}{(L_p - L_n)} \tag{1}$$

The value of K_2 was calculated to be 1.37×10^3 in the case of a specimen of 60-mm outside diameter and 40-mm inside diameter.

On the other hand, from the derivation in the previous paper, the principal stress difference $\Delta\sigma$ in the center of a C specimen is proportional to P:

$$\Delta\sigma = K_1 P. \tag{2}$$

Since the photoelastic sensitivity α is defined as $\alpha = N/t\Delta\sigma$ in terms of photoelastic fringe order N, $\Delta\sigma$, and specimen thickness t, α can be expressed using relation (2) as follows:

$$\alpha = \frac{N}{tK_1 P} = \frac{K_3 N_{in}}{M} \tag{3}$$

where N_{in} is the photoelastic fringe order for inside of zero fringe, K_3 is the specimen size constant, and M is the loading weight, where $M = P \times t$. The value of K_3 was calculated to be 0.30 mm, using the eq. (8) of the previous paper.

Birefringence Δn is expressed as follows:

$$\Delta n = \frac{\lambda N}{t} \tag{4}$$

where λ is the wavelength of the light source, being 5461 Å.

According to eqs. (1), (3), and (4) in this paper, we can determine the changes of E, α, and Δn by measuring the changes of L, P, and N in principle as follows:

$$\frac{E_0}{E} = \frac{\Delta L}{\Delta L_0}, \tag{5}$$

$$\frac{E_0}{E} = \frac{P}{P_0} \tag{6}$$

$$\frac{\alpha}{\alpha_0} = \frac{\Delta n}{\Delta n_0} = \frac{N}{N_0} \tag{7}$$

where $\Delta L = L_p - L_n$, suffix zero indicating the value at reference time.

In practice, considering that the changes in specimen size occur by cracking, swelling, and resolution P/P_0, $\Delta L/\Delta L_0$, and N/N_0 can be used as appropriate measures for the degree of degradation.

APPARATUS AND PROCEDURE

A general view of this apparatus is shown in Figure 1.   Mainly this consists of a sample chamber with a temperature control, a differential transformer-type displacement meter, a strain gauge-type load cell, a weight loading mechanism, and a polarizer-analyzer with mercury lamp.
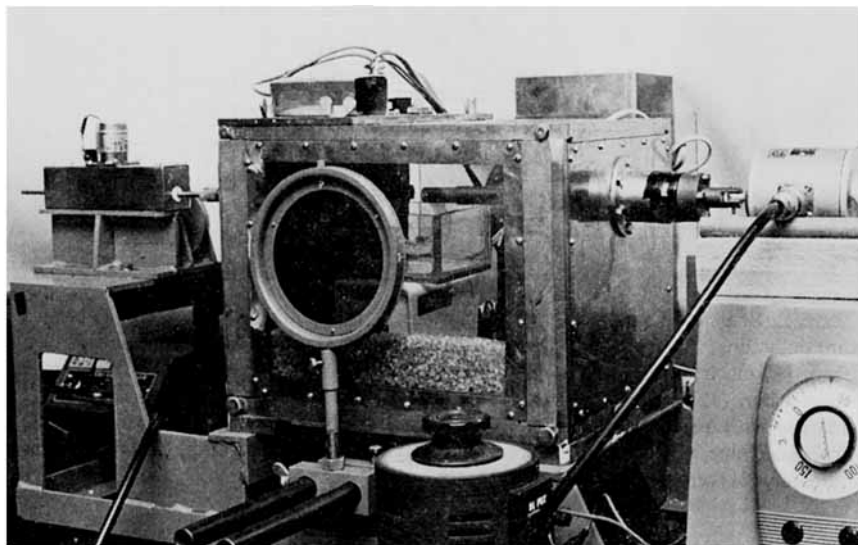
Fig. 1. Photograph of testing apparatus.

The mechanism of this apparatus is shown schematically in Figure 2. The C specimen (1) is pivotally fixed to the shaft (9) with two pins in the chamber (8).   The chamber is made of brass and glass and is equipped with a heater (2) for controlling the temperature of the chamber, a small-size fan (7) with a motor, and an ultraviolet irradiating lamp (6) (Toshiba GL-6, 6W, 254 nm); in the case of liquid medium, a rectangular glass beaker (4) is placed on the magnetic stirrer (5) with a heater (2) and a thermistor-type temperature detector (3).   In addition, simplified equipment for measuring photoelastic properties is placed on the side position of the specimen, that is, a mercury arc lamp (Toshiba SHL-100UV) with a green filter (λ = 5461 Å), and a pair of polymeric polarizer and analyzer (15) (Shimadzu PV-4) with a quarter-wave plate.

Experiments in this method are based on the following three procedures:

1.   For following thermal deformation and creep properties, the slit distance L_p under the constant load is recorded continuously in the recorder (21), and N_{in} is counted intermittently.

2. To evaluate degradation, the tension P, when the displacement is fixed, is recorded continuously by means of the load cell (13) (Toyo Meas. Inst. TCLB-2Kg), the strain gauge amplifier (17–18) (Tokyo Sokki Kenkyujo TS-1B), and the recorder (21), and N_{in} is counted intermittently.
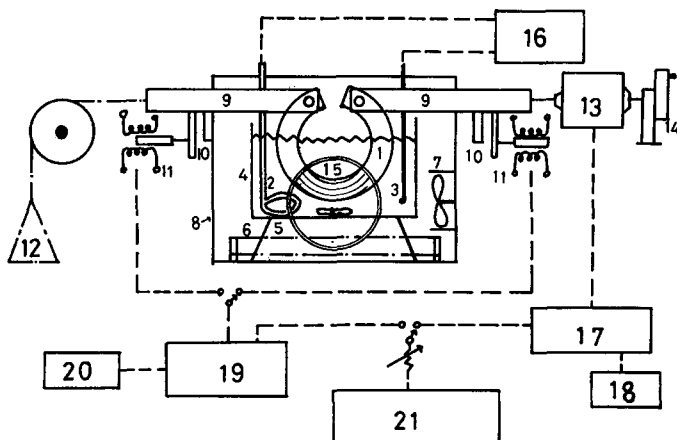

Fig. 2. Schematic view of testing apparatus: (1) specimen, (2) heater, (3) temperature detector, (4) rectangular beaker, (5) magnetic stirrer, (6) ultraviolet irradiating lamp, (7) electric fan, (8) chamber, (9) shaft, (10) stopper, (11A) (11B) differential transformer, (12) weight, (13) load cell, (14) handle for stretching the specimen, (15) polarizer with quarter-wave plate, (16) temperature control, (17) strain gauge amp, (18) strain indicator, (19) differential transformer-type displacement amp, (20) displacement indicator, (21) one-pen recorder.

3. To estimate the values of E and α, when the predetermined weight (12) is hung, the slit displacement ΔL is measured by means of the differential transformer (11A) (Hoshidenki DTD-101A) and the displacement indicator (19–20) (Hoshidenki DEM-1); at the same time, the photoelastic fringe order N_{in} which appears on the specimen is counted by eye or a magnifying glass through the polarizer-analyzer (15).

EXPERIMENTAL RESULTS

Several results will now be given to illustrate the use of this apparatus.

Displacement and Fringe Order as a Function of Load

Typical examples are shown in Figure 3. Photoelastic fringe bands appear on both sides of the zero fringe line on the surface of the specimen. The inside fringe order N_{in} is greater than the outside fringe order N_{out}, because $\Delta\sigma_{in}$ is greater than $\Delta\sigma_{out}$, therefore we adopted N_{in}.

Figure 3 shows that the ΔL values are proportional to the loading weight M for three materials, but N_{in} is not linear for the weight M of PC_u and UP.
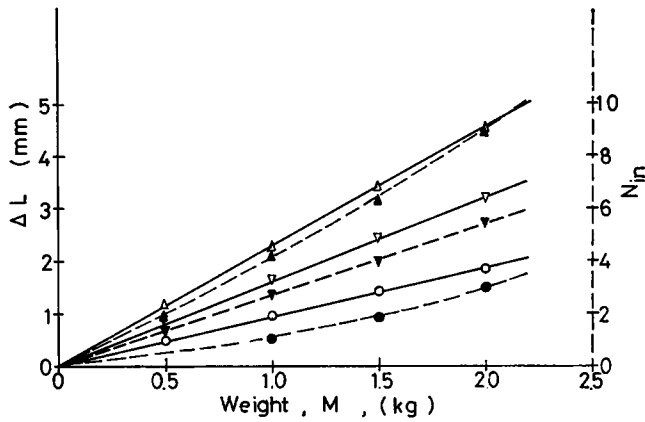
Fig. 3. Displacement and fringe order as function of weight at room temperature: (△) (▲) PCu; (▽) (▼) EP; (○)(●) UP.

Young's Modulus and Photoelastic Sensitivity of Several Plastics

Though the purpose of developing this apparatus is not for measuring the absolute value of Young's modulus and photoelastic sensitivity, but for tracing the relative change of these values caused by degradation, the values of E and α estimated from the experiments using eqs. (1) and (3) are shown in Table I.

TABLE I
Young's Modulus and Photoelastic Sensitivity
(at Room Temperature)

Material	L/P, mm^2/kg	E^a, kg/mm^2	N_{in}/M, kg^{-1}	α, mm/kg
Polycarbonate (PCu)[b]	6.0	228	4.5	1.34
Polycarbonate (PC$_a$)[c]	6.6	208 (210–250)	4.5	1.34
Unsaturated polyester (UP)	4.94	277	0.95	0.28
Epoxide (EP)	4.8	285 (260)[d] (274)[e]	2.7	0.81 (0.8–1.0)[d] 0.92[e]
Acrylonitrile–styrene copolymer (AS)	5.55	247	0.38	0.11
Polystyrene (PS)	5.58	245	0.88	0.26

[a] $E = 1.37 \times 10^3 P/\Delta L$, $\alpha = 0.30 N_{in}/M$ (suppose $\nu = 0.3$).
[b] Specimen thickness 3.0 mm.
[c] Specimen thickness 4.4 mm.
[d] From catalog of sheet supplier.
[e] Values measured by standard photoelastic equipment using a rectangular-type specimen, with wire strain gauges, prepared from the same sheet of EP.

Heat Distortion Curve

Some standard testing methods for measuring heat distortion have been adopted, for example, ASTM D648-56, D1637-61, and D1043-61T.

With this apparatus, heat distortion curves are drawn easily under various environments. Figure 4 shows an example for poly(vinyl chloride) under 1 kg loading in air. The deformation temperature was affected by the rate of temperature increase.
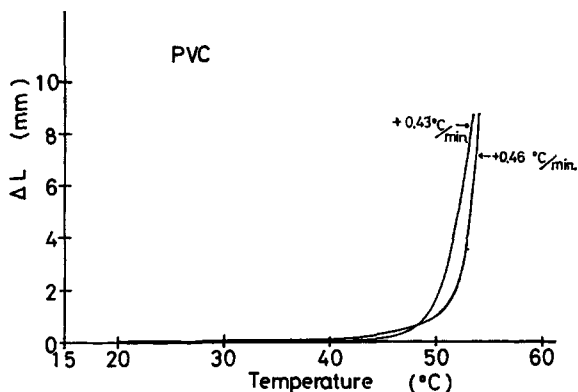

Fig. 4. Heat distortion curve of poly(vinyl chloride) under load (1.0 kg).

Effect of Temperature on Modulus and Photoelastic Sensitivity

The temperature dependence of Young's modulus is well known, and the photoelastic sensitivities at various temperatures were studied[2] for epoxide, phenolic, and diallyl phthalate.
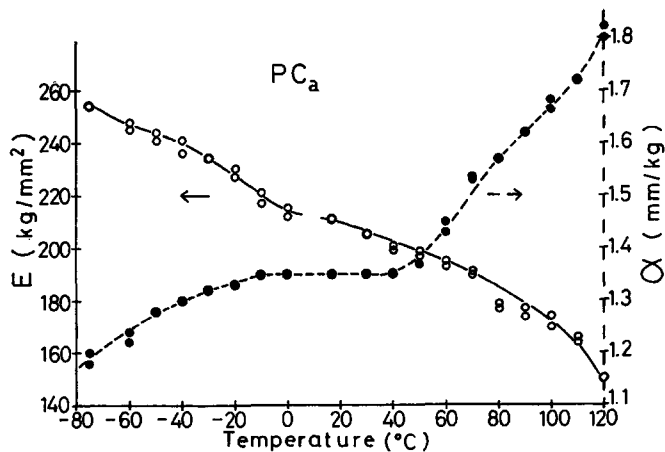

Fig. 5. Effect of temperature on Young's modulus (O) and photoelastic sensitivity (●) of polycarbonate (PCₐ), in ethanol and Dry Ice below room temperature and in silicone oil above room temperature.
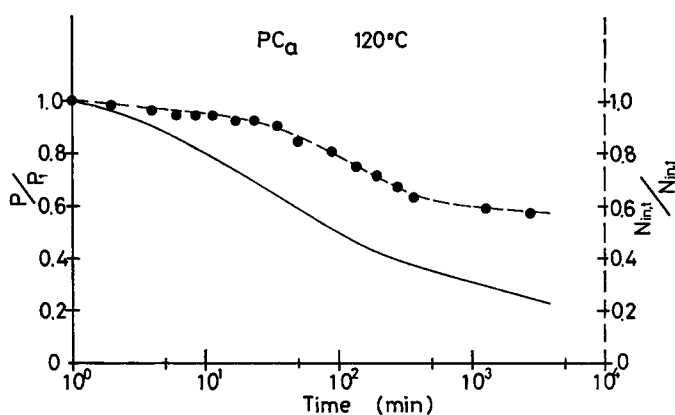
Fig. 6. Stress relaxation and birefringence of polycarbonate (PC$_a$) at 120°C in silicone oil.

A typical example of the use of this apparatus is shown in Figure 5. Both E and α were calculated from $\Delta L/P$ and N_{in}/M measured intermittently at predetermined temperatures.

The decrease in E with temperature increase is considered as thermal softening; on the other hand, the increase in E at low temperatures indicates brittleness due to low temperature.

Simultaneous Measurement of Stress Relaxation and Birefringence

Measuring stress relaxation and birefringence is important for investigating polymeric materials, because the information gained is valuable for studing chemo-rheological process.[3]   Accordingly, several apparatus for measuring them simultaneously have been developed.[4-6]   In these apparatus, a flat strip specimen was used under stretching, and a Babinet- or
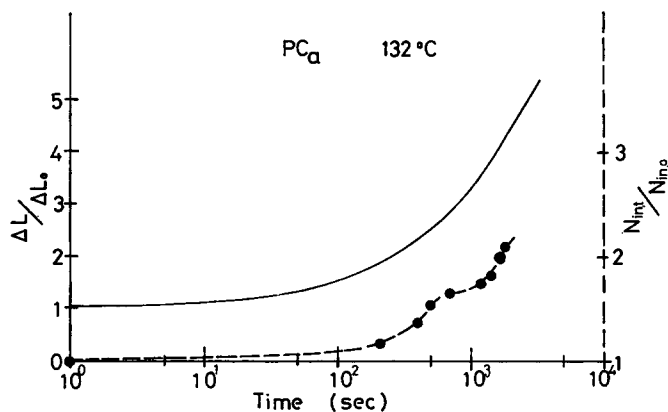

Fig. 7. Creep and birefringence of polycarbonate (PC$_a$) at 132°C (1.7 kg).

Senarmount-type compensator was necessary. In the present apparatus, a C specimen is used, and no compensator is necessary.

Typical data with this apparatus are shown in Figure 6.

Simultaneous Measurement of Creep and Birefringence

Creep curves are drawn by recording ΔL under load at predetermined temperatures; additionally, the fringe order is counted as shown in Figure 7. The reason for the increase in fringe order, in spite of constant load, is considered to be the contribution of the residual fringe by permanent deformation of the specimen.

Evaluation of Resistance to Chemical Reagents

Some standard testing methods for measuring chemical resistance have been adopted, for example, ASTM D543-67; however, this method of evaluation is not satisfactory. The apparatus here described made it possible to examine degradation caused by chemical reagents continuously as well as quantitatively. Typical data obtained with this apparatus are shown in Figure 8.
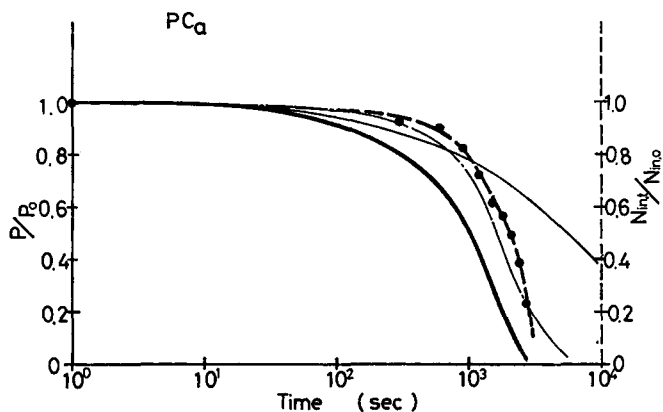

Fig. 8. Evaluation of chemical resistance of polycarbonate (PC_a) by stress relaxation and birefringence: (—) (—·—) in CH_2Cl_2; (—) in $CHCl:CCl_2$; (-··-) in CCl_4.

Polycarbonate is resolved by methylene chloride, swelled by trichloroethylene, and cracked by carbon tetrachloride. In this case, the change of tension is not convertible to Young's modulus, because the specimen size is changed during degradation.

Evaluation of Resistance to Ultraviolet Rays

For long-time degradation, the method described in the previous paper[1] is proper; but for continuous measurement of short-time degradation, this apparatus is more useful. Typical data obtained using this apparatus are
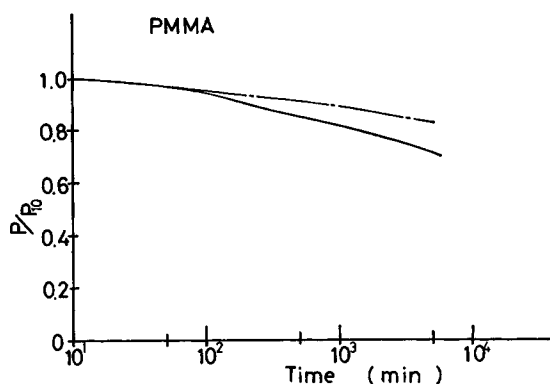
Fig. 9. Evaluation of light resistance of poly(methyl methacrylate) by stress relaxation (UV rays: 254 nm, 6 W mercury lamp, 70 mm away from specimen), at 35°C: (—) with UV irradiation;   (-·-) without UV irradiation.

shown in Figure 9.   The effect of ultraviolet irradiation on stress relaxation is clear from this figure.

CONCLUSIONS

A new apparatus for measuring various properties of plastics using C specimens was designed and tried.   Displacement L, tension P, and photoelastic fringe order N are measured by means of a differential transformer, a load cell, and a polarizer-analyzer, respectively.   These can be good measures for the evaluation of performances of plastics.   The absolute values of Young's modulus and photoelastic sensitivity can be obtained from L, P, and N in principle, but this is not recommended, because, strictly speaking, the derived equations are valid while all the physical relations remain linear, supporting the theory of elasticity.

According to the experimental results, the apparatus has wide applications for such purposes as determination of heat distortion temperature, effect of temperature on rigidity and photoelastic properties, simultaneous measurement of stress relaxation and birefringence, simultaneous measurement of creep and birefringence, and continuous measurement of resistance to chemical reagents and ultraviolet rays.

Materials which can be investigated with this apparatus are general plastics; rigid plastics are made into thin specimens while flexible ones are made into thick specimens.   In the case of opaque or photoelastically insensitive samples, photoelastic fringes do not appear, so the fringe order N cannot be used as a measure of degradation.   For long-time degradation, the method described in the previous paper[1] is better than the present method.

References

1. F. Ohishi, *J. Appl. Polym. Sci.*, **14**, 2225 (1970).
2. K. Kawada and J. Tsuji, *Kagaku Kenkyu-Jo Hokoku*, **29**, 1 (1953).
3. R. S. Stein and A. V. Tobolsky, *J. Polym. Sci.*, **18**, 201, 302 (1948).
4. R. S. Stein, F. H. Holmes, and A. V. Tobolsky, *J. Polym. Sci.*, **14**, 443 (1953).
5. E. F. Gurnee, L. T. Patterson, and R. D. Andrews, *J. Appl. Phys.*, **26**, 1106 (1955).
6. M. Horio and T. Chikado, *J. Jap. Soc. Testing Materials*, **6**, 256 (1957).