RP555

THE FLEXOMETER, AN INSTRUMENT FOR EVALUATING THE FLEXURAL PROPERTIES OF CLOTH AND SIMILAR MATERIALS

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ABSTRACT

An instrument is described with which the flexural work, flexural resilience, and flexural hysteresis of cloth, paper, sheet rubber, and similar materials can be evaluated. A pair of test specimens of standard dimensions are mounted in opposite angles formed by two vertical intersecting plates one of which is fixed and the other movable on a spindle. The work done in folding the specimens to various angles between the plates, the work recovered when they are allowed to unfold, and the work lost are measured. These quantities are a measure, respectively, of flexural work, flexural resilience, and flexural hysteresis of the specimens. They are related to the stiffness and creaseability of cloth and affect the sensations which contribute to the psychological qualities of "handle" or "feel" and the "drape" of fabrics. Typical results are given..

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I. INTRODUCTION

The "handle" or "feel" and the "drape" of fabrics are of great importance to the user of textiles in clothing and home furnishings, as well as to the textile designer and the textile finishing mill. They are psychological qualities and are commonly expressed only in the vaguest of terms.[1] Obviously the first step in the development of means for evaluating them is to provide adequate methods for evaluating the physical attributes of cloth that affect the sensations which contribute to "handle" and "drape." The purpose of this paper is to describe an instrument, the flexometer, for evaluating three of these attributes—flexural work, flexural resilience, and flexural hysteresis. Flexural work, flexural resilience, and flexural hysteresis are significant in other materials, such as paper, sheet rubber, patent leather, and varnish film. Typical results obtained with the flexometer for silk and cotton fabrics and for paper and sheet rubber are shown and discussed.

Other investigators have devised methods and instruments for measuring some physical characteristics of cloth that affect the sen-

[1] William D. Appel and the author are attempting to enumerate and define what may be called the kinaesthetic and tactile characteristics of cloth and the related physical properties.

sations which contribute to "handle" and "drape." Among the recent contributions may be mentioned a paper by Peirce on the handle of cloth as a measurable quantity.[2] Peirce measured thickness, weight, and the angle to which a specimen of definite dimensions droops under its own weight. He also discussed the relationship of these quantities to drape, feel, harshness, compactness, fullness, thinness, and paperiness. Peterson and Dantzig have developed a quantitative method for evaluating the stiffness of starched fabrics and have studied the effect of different starches.[3] McNicholas and Hedrick have described a method for measuring the resistance to bending and the elastic recovery under flexure of cloth and applied it to the evaluation of parachute cloth.[4] Mercier has published a method for determining the coefficient of friction of fabrics.[5] Schiefer has described a method for evaluating the thickness, compressibility, and compressional resilience of textiles.[6]

The general idea of the instrument to be described was suggested to the author by McNicholas as an improvement over the one described by McNicholas and Hedrick.[7] It is more sensitive than the instrument devised by Peterson and Dantzig and therefore can be used for delicate silk fabrics as well as for stiff cotton ones. Unlike the methods used by Peterson and Dantzig and by Peirce, the method to be described gives a measure of the amount of work done on the specimen in folding it through a definite angle. This value, the flexural work, is closely related to the stiffness of the specimen as appreciated by the fingers when the specimen is folded by them.[8]

The amount of work recovered when the specimen is allowed to unfold is also obtained. When expressed as a percentage of the work done in folding the specimen, this quantity is a measure of the flexural resilience of the specimen. So far as the author is aware, entirely satisfactory means of evaluating this characteristic have not previously been provided.

The difference between the work done in folding and the work recovered when the specimen is allowed to unfold—that is, the work lost—is partially expended in deforming or creasing the specimen. This amount of work when expressed as a percentage of the work done in folding the specimen, called flexural hysteresis, is closely related to the creaseability of the specimen. The angular crease in the specimen and the amount of work which must be done to bring the specimen back to its initial position, which are measured with the flexometer, are quantities also related to the creaseability of the specimen.

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[2] F. T. Peirce, The Handle of Cloth as a Measurable Quantity. J. Textile Inst., vol. 21, p. 9, September 1930.

[3] E. C. Peterson and T. Dantzig, Stiffness in Fabrics Produced by Different Starches and Starch Mixtures, and a Quantitative Method for Evaluating Stiffness, U.S. Department of Agriculture, Tech. Bull. No. 108, 1929.

[4] H. J. McNicholas and A. F. Hedrick, The Structure and Properties of Parachute Cloths. National Advisory Committee for Aeronautics Tech. Note, No. 335, 33 pp., 1930.

[5] A. A. Mercier, Coefficient of Friction of Fabrics, B.S. Jour. Research, vol. 5 (RP 196), pp. 243–246, 1930.

[6] H. F. Schiefer, The Compressometer, An Instrument for Evaluating the Thickness, Compressibility and Compressional Resilience of Textiles, B.S. Jour. Research. (Will appear in June Journal.)

[7] See footnote 4. In their method a strip of fabric 3 by 9 inches in size is folded back upon itself and the height of the fold is measured when the fold is compressed by various loads. Similar measurements are made during unloading.

[8] Peirce assumed that the flexural rigidity, G, of the specimen is a measure of the stiffness as appreciated by the fingers. He computes it from the weight of the fabric per unit area, w, and from the angle, θ, to which a specimen of definite length, l, droops under its own weight, by the formula

$$G=\frac{wl^3 \cos \theta/2}{8 \tan \theta}$$

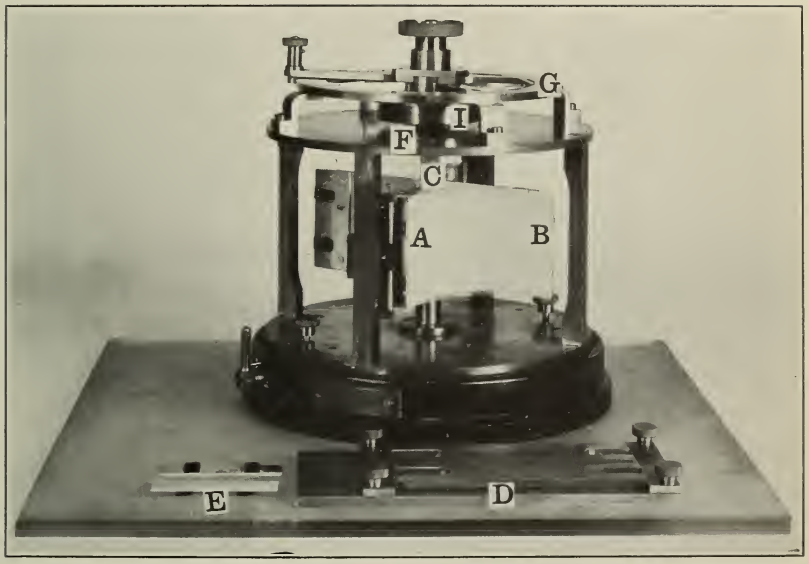

FIGURE 1.—*The flexometer.*

In this photograph the spiral spring was used to measure the torque. The spiral spring is mounted in the casing I.

II. FLEXOMETER [9]

1. DESCRIPTION AND TEST PROCEDURE

The flexometer with samples inserted ready for test is shown in figure 1. Two fixed plates, *A*, 2 inches wide and 2½ inches long, are attached to two diametrically opposite posts. A movable plate, *B*, 2 inches wide and 5⁵⁄₁₆ inches long, is mounted on a spindle, *C*, which rotates freely on a small steel ball. The specimen to be tested, 1¾ inches wide and 6 inches long, is placed carefully in the mounting clamp *D*. The two small clamps, *E*, are given a thin coat of canadian balsam dissolved in benzol. They are then pressed against the specimen and stick to it. The excess material at each end of the specimen is cut off making the test specimen 4 inches long. The small clamps slip on the end of the fixed and movable plate as shown at *A* and *B*. The test specimen is tangent to each plate when mounted and will fold in the angle formed by the two plates when the angle between the plates is decreased by rotating the movable plate on the spindle.[10] As the specimen is folded between the plates, its resistance to folding or bending exerts a torque on the movable plate. For symmetry and to increase the torque exerted, a pair of specimens is tested simultaneously in opposite angles. The torque exerted by the specimens on the movable plate when they are folded to a certain angle between the plates is measured by the deflection of a calibrated spring which is attached to the spindle. The work done in folding the specimens through any small angle is given by the product of this small angle measured in radians and the average torque. If the torque is plotted against the angle between the plates, then the area under the curve bounded by any two angles is equal to the work done on the specimens in folding them from the larger to the smaller angle. The work recovered in unfolding is obtained in a similar manner.

2. CALIBRATED SPRINGS

Calibrated spiral or cantilever steel springs may be used with the instrument to measure the torque exerted on the movable plate by a pair of test specimens. Both types have been used and found to be satisfactory. If cantilever springs are used, then several springs of different capacities may be mounted permanently. With a set of six springs whose capacities bear a ratio of 1 to 2, specimens whose resistance to bending vary in a ratio of 1 to 32 may be tested by merely changing a spring-deflecting pin from one deflecting spoke to another. The springs are conveniently fastened to a hub at the top of the movable plate at an angular spacing of 60°. Another hub with six spokes is fastened to a knob at the top. By placing the deflecting pin in any spoke at a constant distance from the center, the spring directly below it may be deflected. The angle through which the spring hub or movable plate is rotated is indicated by a pointer, *F*, on a scale graduated in degrees. The spring deflection is obtained from the reading of a second pointer, *G*, on a similar scale.

In figure 2 is shown a typical calibration curve for one of the cantilever springs. The spring deflection in degrees is plotted as abscissa

[9] William D. Appel gave a brief description of the flexometer before Committee D-13, American Society for Testing Materials, on Mar. 13, 1930. This was published in Textile World, vol. 77, no. 13, p. 61, Mar. 29, 1930.

[10] For paper and starched fabric the specimens may be mounted so that they will fold outside of the angle formed by the plates. This should be done whenever no crease or set is desired in the specimens.

and the torque in ergs per degree is plotted as ordinate. The combined friction in the spindle bearings of the movable plate, in the

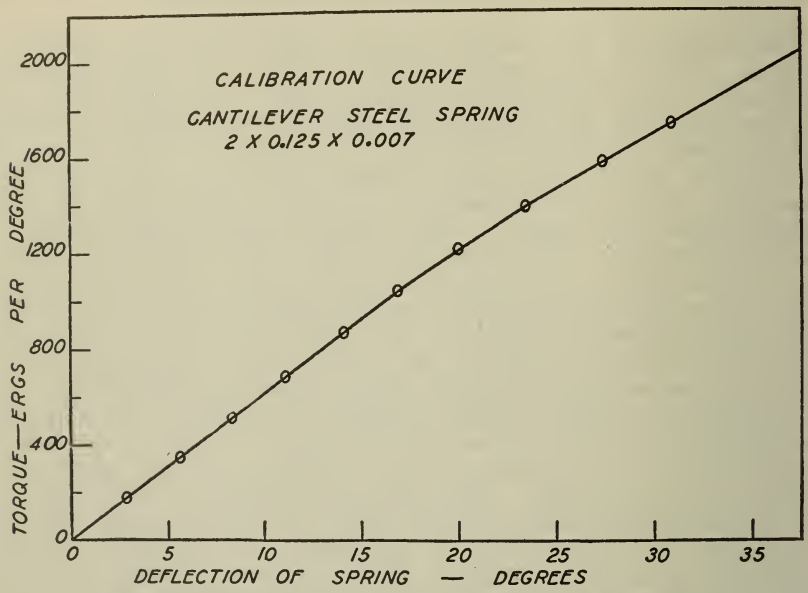

FIGURE 2.—*Calibration curve of a cantilever steel spring.*

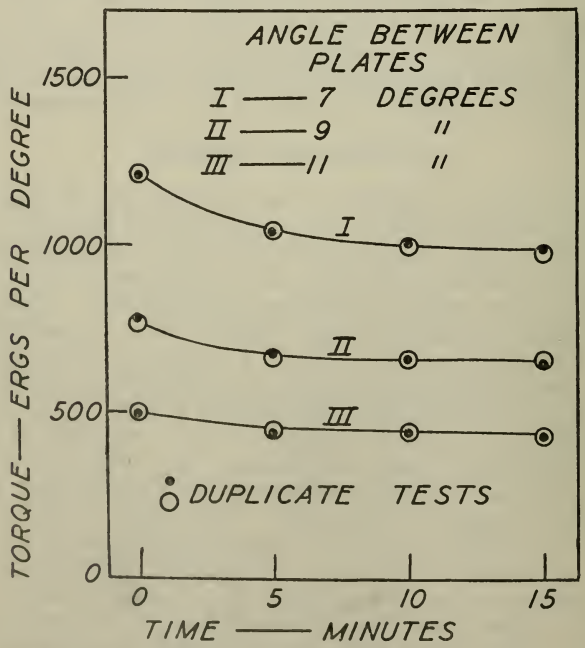

FIGURE 3.—*Curves showing effect of time and angle between plates on the torque developed by pairs of test specimens of a silk fabric.*

bearings of the calibration pulleys, and at the contact of the deflecting pin and spring amounts to approximately 3 percent of the torque at

maximum spring deflection. The effect of friction was eliminated in the tests by the method adopted for testing.

The calibration curve for a spiral spring is similar to that of a cantilever spring. However, for a given torque the deflection of a spiral spring may be 10 to 20 times that of a cantilever spring.

If many specimens are tested with one spring, then a calibration table will facilitate the computations greatly and save much time.

III. ILLUSTRATIVE DATA

In figures 3, 4, and 5 are shown typical curves obtained with the flexometer for different materials and under different methods of

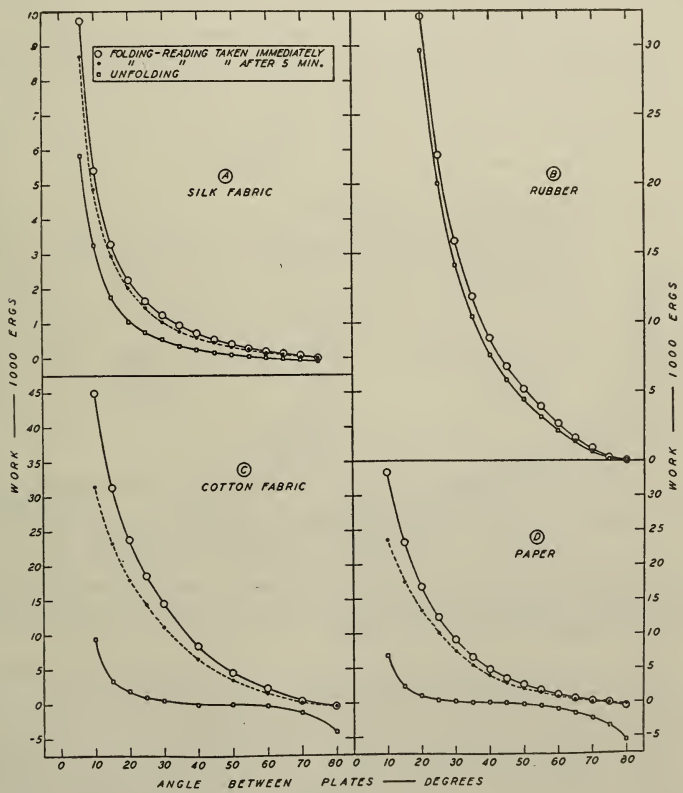

FIGURE 4.—*Typical curves for the folding and the unfolding of test specimens.*

testing. The curves in figures 3 and 4 were obtained by using a spiral spring, and those in figure 5 by using a cantilever spring. All tests were made on specimens in equilibrium with an atmosphere of 65 percent relative humidity at a temperature of 70° F.

In folding a specimen in the angle between the plates of the flexometer the spring deflection was determined when a given angle between the plates was approached from opposite directions; that is, when a specimen was folded to an angle of say 30° between the plates, the spring deflection was read as the angle was decreased to 30°. Immediately thereafter the angle was decreased 0.5° and the spring deflection was again read as the angle was increased to 30°. The

same procedure was followed at the other angles during folding. The data given in this paper for folding are based upon the first of these two readings. In unfolding the specimen a similar procedure was followed, namely, when the specimen was allowed to unfold to an angle of say 30° between the plates, the spring deflection was read as the angle was increased to 30°. Immediately thereafter the angle was increased 0.5° and the spring deflection was again read as the angle was decreased to 30°. The same procedure was followed at the other angles during unfolding. The data given in this paper for unfolding are based upon the last of these two readings. In other words, the data given in this paper are based upon the spring deflections obtained when the movable plate was rotated clockwise. This method of testing was adopted to eliminate the effect of friction.

To show the effect of time and angle between the plates on the torque developed by test specimens when folded, the following tests were made: Six pairs of specimens were cut from a silk fabric with

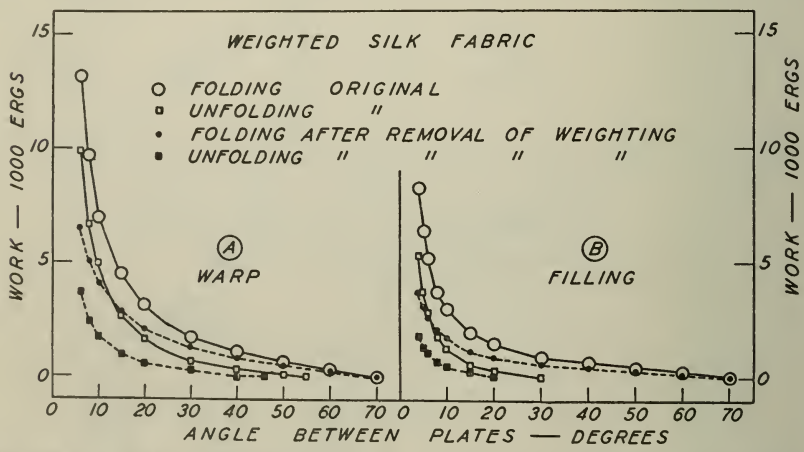

FIGURE 5.—*Curves showing the difference between a weighted silk fabric and the same silk from which the weighting has been removed chemically and the difference between the behavior of warp and filling.*

warp threads in lengthwise direction. Two pairs were folded to an angle of 7° between the plates. The spring deflection was noted immediately and after 5, 10, and 15 minutes, respectively. Two other pairs were folded to an angle of 9° and the spring deflections were noted as above. The remaining two pairs were folded to an angle of 11° and the spring deflections were again noted as above. The torques corresponding to these spring deflections were obtained from the calibration table. The results are shown graphically in figure 3. The torque is plotted as the ordinate. It is expressed in ergs per degree; that is, the work, in ergs, that would be done if the torque acted through one degree. The variation in duplicate determinations is shown by the solid and open circles.

The curves in figure 3 show how the torque decreases with time when a pair of specimens of a silk fabric are folded to given angles between the plates. The greatest decrease in the torque occurs during the first 5 minutes and at the smaller angle. Only a small additional decrease in torque would be expected after 15 minutes.

Similar measurements indicate that the decrease in torque is more pronounced for cotton fabric and paper, while no measurable decrease is observed for rubber. This is brought out in figure 4, where the work done on the test specimens in folding them to a given angle between the plates is plotted as ordinate and the angle as abscissa. The torque developed at any angle is equal therefore to the slope of the curve at that angle.

The curves *A*, figure 4, are for a silk fabric in which the warp threads were folded. A pair of specimens was folded to a given angle between the plates and the spring deflection was noted. The specimens were kept folded at this angle and the spring deflection was again noted at the end of 5 minutes. The angle between the plates was decreased 5° at a time and the spring deflections were noted as above. The results are shown by the curves through the circles and solid circles, respectively. The spring deflections were also obtained at the same angles during unfolding and the results are shown by the curve through the squares where the ordinate at any angle indicates the work recovered in unfolding. The decrease in spring deflection (torque) during the 5 minutes indicates that the specimen is being creased. The difference between the work done in folding and that recovered in unfolding expressed as a percentage of the work done in folding is related to the creaseability of the test specimen.

The curves, *B*, figure 4, are for folding and unfolding a specimen of sheet rubber. The spring deflections did not decrease by a measurable amount when the specimen was kept folded at each angle for 5 minutes. The curve for unfolding is slightly below the curve for folding, 92 percent of the work done in folding being recovered in unfolding.

The curves *C* and *D*, figure 4, are for cotton fabric and paper, respectively. They were obtained in the same manner as the curves for a silk fabric shown in 4, *A*, and for sheet rubber in 4, *B*. The spring deflections decrease a greater amount when specimens of these materials are kept folded at each angle for 5 minutes. The curves for unfolding are greatly below the curves for folding, indicating that these materials are more easily creased. Approximately 25 percent of the work done in folding is recovered in unfolding. The specimens unfold only to approximately 45° instead of to the initial angle of 80°. The crease in the cotton fabric and the paper specimens is not readily removed. To completely unfold these specimens to 80°, work must be done which is shown as negative work recovered in their curves for unfolding. The permanent crease and the amount of work necessary to unfold the specimens to the initial position are related to the creaseability of the specimens.

The curves *A*, *C*, and *D*, figure 4, show that the torque developed by the specimens of these materials when folded to a given angle between the plates decreases with the length of time the specimens are kept folded at that angle.

The curves in figure 5 show the difference between a weighted silk fabric and the same silk from which the weighting has been removed. The difference between the behavior of warp and filling is also shown. Specimens for test were taken from a tin-weighted silk, weighing 4.7 ounces per square yard and containing approximately 50 percent weighting material, and from the same fabric after the weighting materials had been removed chemically. The results for the warp

and filling are shown in *A* and *B*, respectively. The curve through the circles shows the amount of work in ergs done in folding a pair of specimens to various angles between the plates. The curve through the squares shows the amount of work recovered during unfolding. The dotted curves through the solid circles and squares are for the folding and unfolding of a pair of specimens taken from the same fabric after the weighting materials had been removed chemically.

IV. DISCUSSION

In order to assign numerical values to the flexural work, flexural resilience, and flexural hysteresis of different kinds of cloth or other materials to which the method is applicable, the dimensions of the test specimen and the minimum angle to which the specimen is folded between the plates of the flexometer must be specified. The dimensions specified, 4 inches long and 1¾ inches wide, were chosen simply because of their convenience. The angle to which the specimen is folded may not be chosen arbitrarily for it depends upon the thickness of the specimen. Thus a thick specimen cannot be folded in the flexometer to so acute an angle as a thin one and the angle which gives satisfactorily measurable results for a thick specimen may not be acute enough to give accurate results for a thin specimen.

In order to determine the angle to which a given specimen shall be folded, the assumption can be made that this angle is proportional to the thickness of the specimen. That this assumption is acceptable would be difficult to demonstrate for textile fabrics because of their complicated heterogeneous structure. However, it can be shown that the assumption is a good approximation for specimens of homogeneous isotropic material when the minimum angle between the plates is between 4° and 12°. For, if a thin specimen of homogenoeus isotropic material is bent in a principal plane by forces applied at the ends only, then the shape of the plane curve of the central line is an inflexional elastica, whereas if it is bent in a principal plane by couples applied at the ends only, then the plane curve of the central line is an arc of a circle.[11] Rigorous and approximate formulas for the inflexional elastica and for the circular arc are given below. For each case it is assumed that the results obtained are comparable when specimens of the same material but of different thicknesses are bent until the maximum tensile stresses are equal. The last assumption simply imposes the condition that the specimens of different thicknesses, h, are bent until the minimum radius of curvature, ρ_m, of the neutral surface [12] is equal to some constant, n, times the thickness h, or $\rho_m = nh$.

Let O in figure 6 be the center of the spindle, OM the movable plate, and OF the fixed plate. The angle between these two plates at any instant is denoted by β. Let $N\ P\ H^1\ P^1\ N^1$ be the central line of the specimen when it assumes the shape of the inflexional elastica, and let $N\ P\ H\ P^1\ N^1$ be the central line of the specimen when it assumes the shape of a circular arc. Let h be the thickness, $2\ P\ Q$, of the specimen, S_e the arc $P\ H^1\ P^1$ of the specimen for the inflexional elastica, and ρ_m the minimum radius of curvature. Let S_c be the arc $P\ H\ P^1$ of the specimen for the circular arc of radius r. Then it follows that

[11] The Mathematical Theory of Elasticity, by Love, 4th ed., pp. 399–404.

[12] By neutral surface of a bent specimen is meant that surface in which the elements suffer no deformation in the direction of length. For a homogeneous specimen it is midway between the two external surfaces.

$$r=\frac{L-l-\frac{h}{2}\tan\alpha}{\tan\alpha-\alpha}$$

$S_c=2\alpha r$ for the circular arc and

$$\rho_m=\frac{(L-l-\frac{h}{2}\tan\alpha)\cos\alpha}{2\sin{}^{\alpha}/2\,[2E\text{ am }K-(1+\cos\alpha)\,K]}$$

$S_e=4\rho_m\,K\sin{}^{\alpha}/2$ for the arc of the inflexional elastica where E and K denote the elliptic integrals of the second and first kind with

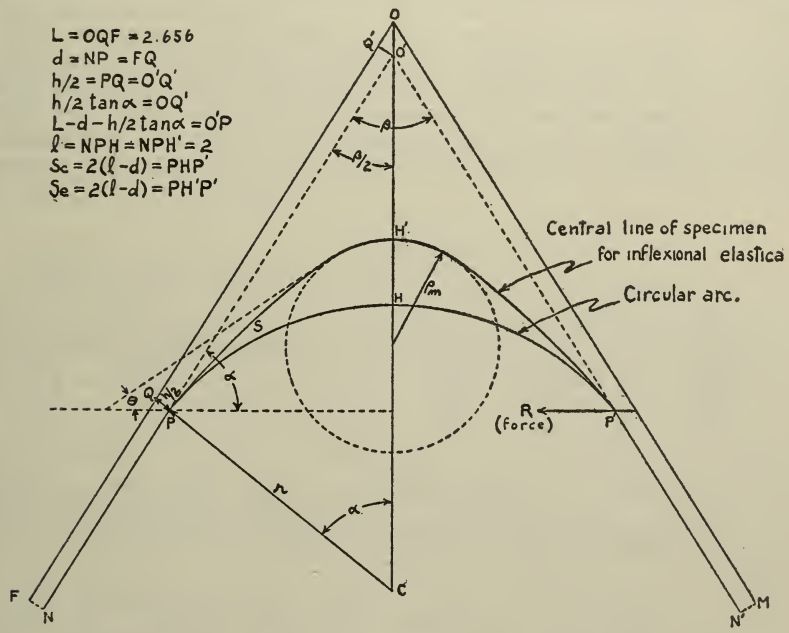

FIGURE 6.—*Schematic diagram of test specimen and intersecting plates.*

modulus k given by the equation $k=\sin{}^{\alpha}/2$.[13] The symbols L and l are constants, L being one half the length of the movable plate, or 2.656 inches, and l one half the length of the specimen, or 2 inches. The angle α is the complement of $^{\beta}/2$.

The formula $\rho=2\,h$ represents r within ± 6 percent for all values of β between 4° and 12° and the formula $S=6.2\,h$ represents S_c within ± 8 percent for all values of β between 4° and 20° provided $\beta=400\,h$. The formula $\rho=2\,h$ represents ρ_m within ± 6 percent for all values of β between 4° and 12° and $S=10\,h$ represents S_e within $\pm$ 6 percent for all values of β between 4° and 16° provided $\beta=460\,h$. The angle β, $2(90-\alpha)$, is measured in degrees, and the thickness h is measured in inches.

Similar approximate formulas may be obtained when ρ is taken equal to some other constant times h. The value 2 was chosen for

[13] See footnote 11, p. 654.

the constant n because for this value the magnitudes of the quantities measured for very thin specimens were such as to be easily measured and reproduced.

The results given above justify the assumption that the minimum angle between the plates should be proportional to the thickness of the specimen regardless of whether we assume the shape of the bent specimen to be circular or that of the inflexional elastica.

As previously mentioned, textile fabrics have a complicated heterogeneous structure. The arc of the bent specimen probably assumes a shape which lies somewhere between that of the inflexional elastica and the circle. Since $\rho=2\ h$ represents very closely the radius of the circular arc when $\beta=400\ h$ and represents very closely the minimum radius of curvature of the inflexional elastica when $\beta=460\ h$, it is assumed that $\rho=2\ h$ represents the minimum radius of curvature of the arc of the bent specimen when $\beta=430\ h$. The arc of the bent specimen may then be represented by the formula $S=8.6\ h$. To show the variations of the circular arc and of the inflexional elastica from the assumed shape, data for β, ρ, and S are given in table 1 for various values of h and the percentage variations of r and ρ_m from ρ, and of S_c and S_e from S, are given for these values of h.

TABLE 1.—*Values of β, ρ, and S for various values of h*

h	$\beta=430\ h$	$\rho=2\ h$	$S=8.6\ h$	$\frac{(r-\rho)100}{\rho}$	$\frac{(\rho_m-\rho)100}{\rho}$	$\frac{(S_c-S)100}{S}$	$\frac{(S_e-S)100}{S}$
Inch	°	*Inch*	*Inch*	*Percent*	*Percent*	*Percent*	*Percent*
0.0093	4	0.0186	0.08	4	−13	−26	3
.0186	8	.0372	.16	10	−8	−23	7
.0279	12	.0558	.24	17	−2	−20	10
.0372	16	.0744	.32	24	4	−18	14
.0465	20	.0930	.40	32	11	−15	19

The thickness [14] of a textile fabric may vary several percent from place to place in the same fabric. It is therefore suggested that it is not worth while to measure the angle β closer than to the nearest half degree.

The arc given by the formula $S=8.6\ h$ probably represents the arc of the bent specimen fairly closely. The area, volume, and weight of the arc of the bent specimen are therefore known with the same degree of approximation. The work done on the arc, S, of the bent specimen may thus be expressed in terms of unit width, unit cross section, unit arc, unit area, unit volume, or weight per unit area.

The following definitions based on the foregoing discussion may now be proposed for the standardization of numerical expression of three physical attributes of fabrics.

The flexural work of a fabric shall be the amount of work in ergs done in folding a specimen 4 inches long by 1¾ inches wide to an angle β, measured in degrees, which is determined by the thickness of the specimen, h, measured in inches, according to the equation $\beta=430\ h$.

The flexural resilience of a fabric shall be the amount of work recovered when the specimen which is folded as described above is allowed to unfold, expressed as a percentage of the work done in folding the specimen.

[14] Thickness shall be measured according to the standard method. See footnote 6, p. 648.

The flexural hysteresis of a fabric shall be the amount of work lost when the specimen is folded and allowed to unfold as described above, expressed as a percentage of the work done in folding the specimen.

It is evidently necessary in applying these definitions to specify the time consumed in folding and unfolding the specimen and the time it is allowed to remain folded. The previous history of the area included in the specimen is important. Imperfections of weave, creases, and other deformities may be expected to affect the result. A specimen taken from a small roll of cloth or from a folded area will not be representative of other portions that may have been kept flat. It is assumed that tests made with the flexometer will be carried out on specimens that are in equilibrium with an atmosphere of 65 percent relative humidity at a temperature of 70° F., the standard conditions for textile testing.

The flexometer should find use in the specification of the properties of fabrics required for given purposes. Mills which modify the flexural properties by sizing, weighting, and finishing operations may find in the flexometer a useful tool for the control of processes and standardization of products. The flexometer should make possible quantitative studies of effect of variations in processes upon the flexural properties of the products.

V. SUMMARY

An instrument called the flexometer with which the flexural work, flexural resilience, and flexural hysteresis of fabrics, paper, sheet rubber, and similar materials can be evaluated is described. Typical results in the form of curves showing the flexural characteristics of cotton and silk fabrics, paper, and sheet rubber are given.

The angle to which specimens must be folded to obtain comparable results depends upon the thickness of the specimens. An equation for determining the minimum angle for any given thickness of specimen has been developed.

Drawings of the flexometer showing the details of construction may be obtained from the textile section of the Bureau of Standards.

WASHINGTON, March 13, 1933.