NAL ADVISORY COMMITTEE
FOR AERONAUTICS

APR 21 1923
MAILED

Mr. Truscott

TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

No. 137.

EXPERIMENTS WITH FABRICS FOR COVERING AIRPLANE WINGS.

By A. Pröll.

From Technische Berichte, Vol. 3, No. 3.
(1918)

April, 1923.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

TECHNICAL NOTE NO. 137

EXPERIMENTS WITH FABRICS FOR COVERING AIRPLANE WINGS.*

By A. Pröll.

The following report deals principally with the strength and deformation of the fabric itself, both undoped and doped. In the course of the investigations, it appeared that the doping of the fabric with "Cellon" exercises a predominant influence on the results, according to the nature and number of the coats. It was decided, therefore, to conduct the experiments in such a way that the properties of the fabric when subjected to stresses would be brought out to the best advantage. At the same time, it was endeavored to adapt the degree of doping to actual conditions and to obtain greater uniformity of elongation along warp and filling.

Hence two coats of cellon are applied for all comparative tests. Parallel individual tests were also conducted with the undoped fabric, as likewise with fabric doped three and four times and then painted.

In a general way the figures obtained are not immediately applicable in practice. Still less are they to be taken as standard (with the exception of the results of individual tests with repeated doping). By comparative tests, however, with the usual repeated doping, individual standard figures may be ob-

---

* From Technische Berichte, Vol. 3, No. 3, pp. 57-73 - (1918).

tained from the experiments. These results are disregarded in the present report, it being preferred to initiate further researches with the customary doping and also with various kinds of dope. On the other hand, the research apparatus, methods and instructions are along the same lines as for the previous experiments.

The Strength of the Fabric - General Remarks.

Wing fabrics are never used in the undoped condition, but after being put on the ribs, are always given several coats of dope and then painted over, if a different color is desired. This report, therefore, deals particularly with fabric prepared in this way, and plain fabric is considered only for the purpose of comparison.

The plain fabric is non-isotropic and has two principal directions (warp and filling) along which there is a calculable strength with limited elasticity. In every other direction, the plain fabric is geometrically deformable, and can carry no loads other than those allowed by the mutual friction of the threads. In the doped fabric, the dope creates a state of tension giving the fabric a somewhat flexible stiffness. Its strength in a diagonal direction is, however, very slight, but with a suitable method of attachment at the edges, the fabrics can withstand diagonal stresses, as shown by experiments. The deformations appear either as elongations and contractions in the surface of the fabric, or in the form of wrinkles. The latter occur for the most part only in locally restricted portions of the fabric, showing always that the tension there is far from being uniformly distributed.

In fabrics, as in other materials, there is a definite relation between stress and strain, but it is much more complicated in fabrics and is influenced by many other conditions. In addition to the effect of the weather (temperature and moisture) time plays an important role in this respect, both as a result of protracted elastic tension and of variable loading (residual strain). Different degrees of doping affect the elastic properties of the fabric in different ways, so that a comparison of results is possible only with a knowledge of the actual treatment. It is sufficient, however, for aeronautical science, that a similar treatment be prescribed for all comparative tests, and that the effect of different kinds of dopes be determined by special tests and then given proper consideration. In this connection it is to be noted that, contrary to the case of other materials, the principle of the proportionality of stress and strain is very restricted in application and depends on the method of treatment.

The mutual influence of stresses and strains must first be determined by experiment, the values so found affording a basis for calculation, which is expediently limited to the two principal directions (of warp and filling).

Simple Experiments for Determining Elongation and Tearing Load.

The two directions along the threads are here denoted by 1 for the filling and 2 for the warp. Accordingly, the loads S (kg/m), elongations and contractions ϵ (%) are denoted by

S_1 , ϵ_1 along the filling,
S_2 , ϵ_2 along the warp.

Table I.

Tearing tests.

Direction 1 (Filling)

Fabric W

Test No.	Treatment	Threads per cm.	Threads per in.	Tearing load K_z kg/m*	Tearing load K_z lb/in*	Percent Elongation at tearing ϵ_1
1	Undoped	22	55.9	1310	73.36	11.4
2	Doped once	19	48.3	1030	57.68	9.1
3	Doped once, painted & varnished	22.5	57.2	1000	56.00	--
4	Doped twice, painted & varnished	18	45.7	1020	57.12	6.7
			Fabric	B		
5	Undoped	23	58.4	940	52.64	--
6	Undoped	23.5	59.7	773	43.29	12.9
7	Doped twice	20.8	52.8	1400	78.40	--
8	" "			1330	74.48	--
9	" "	23.5	59.7	1020	60.48	10.3
10	" 3 times	24.0	60.9	1140	63.84	10.1
11	" 4 "	23.5	59.7	1190	66.64	11.0
12	" 2 " painted & varnished	20.0	50.8	845	47.32	12.8
13		20.6	52.3	1115	62.44	--
		20.6	52.3	1130	63.28	--

* Unit of width.

Table II.

~~Tearing test.~~

Direction 2 Warp

Fabric W

Test No.	Treatment	Threads per cm.	Threads per in.	Tearing load K_z kg/m*	Tearing load K_z lb/in*	Percent Elongation at tearing ϵ_1
1	Undoped	21.5	54.6	855	47.88	14.0
2	Doped once	21.0	53.3	1000	56.00	7.5
3	Doped once, painted & varnished	22.0	55.9	1180	66.08	--
4	Doped twice, painted & varnished	21.0	53.3	1280	71.68	4.9
Fabric B						
5	Undoped	19.6	49.8	1000	56.00	--
6	"	--		880	49.28	3.6
7	Doped twice	19.2	48.8	1050	58.80	3.45
8 & 9	" "	20.8	52.8	1060	59.36	--
10	" 3 times	19.2	48.8	1260	70.56	3.3
11	" 4 "	19.6	49.8	1160	64.96	3.3
12	" 3 " painted & varnished	24.0	61.0	910	50.96	7.4
13		24.0	61.0	999	55.94	--
14		19.2	48.8	1020	57.12	--

* Unit of width.

Table III.

Elongation and tearing tests.

Fabric B undoped.

Tension S_1 in direction 1 of filling		Contraction ϵ_2 in direction 2 of warp			Mean	Elongation ϵ_1 in direction 1 of filling			Mean
kg/m*	lb/in*	%	%	%	%	%	%	%	%
40	2.24	0.48	0.23	0.46	0.39	3.60	3.46	3.95	3.7
80	4.48	1.20	1.16	1.63	1.33	5.10	5.10	5.70	5.3
120	6.72	1.68	2.10	2.80	2.19	6.10	6.00	6.60	6.2
160	8.96	2.40	2.90	3.95	3.08	7.10	6.90	7.70	7.2
220	12.32	3.85	4.65	5.30	4.60	8.05	8.15	8.70	8.3
752	42.11	8.90	10.70	12.70	10.70	12.05	11.50	13.80	12.5

Breaking load K_z = 773 kg/m* = 43.29 lb/in* * Unit of width.

Table IV.

Elongation and tearing tests.

Fabric B undoped.

Tension S_2 in direction2 of warp		Contraction ϵ_1 in direction 1 of filling			Mean	Elongation ϵ_2 in direction 2 of warp			Mean
kg/m*	lb/in*	%	%	%	%	%	%	%	%
40	2.24	0.00	0.71	0.24	0.31	0.53	0.32	0.33	0.39
80	4.48	0.47	1.06		0.51	0.92	0.72	0.52	0.72
120	6.72	0.71	1.18		0.63	1.15	0.91	0.81	0.96
160	8.96	0.94	1.41	0.24	0.86	1.20	1.09	0.95	1.08
220	12.32	0.94	1.76	0.46	1.06	1.45	1.19	1.09	1.24
240	13.44	1.18	1.88	0.48	1.18	1.64	1.29	1.19	1.37
Breaking load K_z									
880	49.28	3.5	9.9	9.5	7.6	2.65	3.6	3.57	3.21

* Unit of width.

Table V.

Elongation and tearing tests.

Fabric B, doped twice.

Tension S_1 in direction 1 of filling		Contraction ϵ_2 in direction 2 of warp			Mean	$\sigma_2 10^6$	Elongation ϵ_1 in direction 1 of filling			Mean	$\beta_1 10^6$
kg/m*	lb/in*	%	%	%	%		%	%	%	%	
60	3.36	0.00	0.49	0.12	0.20	34	0.48	0.57	0.57	0.54	90
100	5.60	0.12	0.49	0.49	0.57	37	0.86	0.95	0.95	0.92	92
160	8.96	0.86	0.98	0.74	0.86	53.7	1.95	2.0	2.0	1.98	125
200	11.20	1.48	1.95	1.23	1.55	78	3.3	3.3	3.3	3.3	165
240	13.44	2.21	2.7	2.1	2.33	97.5	4.5	4.57	4.6	4.56	190
1025	57.40	9.2	9.5	9.1	9.3	90	10.0	10.3	10.7	10.3	100
Breaking load K_z											
1080	60.48										

* Unit of width

Table VI.

Elongation and tearing tests.

Fabric B, doped twice.

Tension S_2 in direction 2 of warp		Contraction ϵ_1 in direction 1 of filling			Mean	$\sigma_1 10^6$	Elongation ϵ_2 in direction 2 of warp			Mean	$\beta_2 10^6$
kg/m*	lb/in*	%	%	%	%		%	%	%	%	
60	3.36	0.00	0.36	0.12	0.16	26.7	0.33	0.24	0.38	0.32	53
100	5.60	0.12	0.36	0.24	0.24	24	0.53	0.57	0.52	0.54	54
180	10.08	0.24	0.83	0.24	0.43	23.9	1.0	1.0	0.95	0.98	54.5
240	13.44	0.48	0.83	0.48	0.59	24.6	1.29	1.2	1.14	1.21	50.5
Breaking load K_z											
1050	58.80	2.9	3.2	2.6	2.9	27.6	2.67	3.34	3.57	3.19	30.4

* Unit of width.

Table VII.

Elongation and tearing tests.

Fabric B, doped three times.

Tension S_1 in direction 1 of filling		Contraction ϵ_2 in direction 2 of warp			Mean	Elongation ϵ_1 in direction 1 of filling			Mean
kg/m*	lb/in*	%	%	%	%	%	%	%	%
60	3.36	0.00	0.00	0.12	0.04	0.285	0.39	0.45	0.34
100	5.60	0.00	0.12	0.12	0.08	0.74	0.73	0.93	0.8
160	8.96	0.00	0.12	0.12	0.08	1.58	1.65	1.78	1.67
240	13.44	0.95	0.97	0.97	0.96	3.42	3.58	3.8	3.6
300	16.80	2.1	2.2	2.44	2.25	5.25	5.4	5.6	5.4
952	53.31	--	7.3	--	7.3	9.8**	9.8**	10.2**	9.9
Breaking load K_z									
1140	63.84								

*Unit of width.

** Fracture outside of the measured length. Hence the extension as is too small.

Table VIII.

Elongation and tearing tests.

Fabric B, doped three times.

Tension S_2 in direction 2 of warp		Contraction ϵ_1 in direction 1 of filling			Mean	Elongation ϵ_2 in direction 2 of warp			Mean
kg/m*	lb/in*	%	%	%	%	%	%	%	%
60	3.36	0.00	0.35	0.00	0.11	0.047	0.24	0.335	0.307
100	5.60	0.00	--	0.00	--	0.28	0.48	0.48	0.41
160	8.96	0.12	0.35	0.12	0.19	0.57	0.71	0.77	0.68
240	13.44	0.12	0.35	0.24	0.24	1.00	1.07	1.15	1.07
300	16.80	0.12	0.47	0.36	0.32	1.24	1.43	1.48	1.38
1020	57.12	--	1.42	--	1.42	3.2	3.32	3.5	3.34
Breaking load K_z									
1260	70.58								

* Unit of width.

Table IX.

Elongation and tearing tests.

Fabric B, doped four times.

Tension S_1 in direction 1 of filling		Contraction ϵ_2 in direction 2 of warp			Mean	Elongation ϵ_1 in direction 1 of filling			Mean
kg/m*	lb/in*	%	%	%	%	%	%	%	%
60	3.36	0.132	0.00	0.07	0.06	0.48	0.43	0.38	0.43
100	5.60	0.19	0.07	0.12	0.13	0.91	0.74	0.86	0.84
160	8.96	0.19	0.07	0.12	0.13	1.65	1.51	1.58	1.58
216	12.10	0.244	0.12	0.12	0.16	2.52	2.42	2.39	2.44
272	15.23	0.85	0.61	0.73	0.73	3.92	3.85	3.78	3.85
1104	61.82	--	7.47	--	7.47	11.0	10.9	11.0	11.0
Breaking load K_z									
1190									

* Unit of width.

Table X.

Elongation and tearing tests.

Fabric B, doped four times.

Tension S_2 in direction 2 of warp		Contraction ϵ_1 in direction 1 of filling			Mean	Elongation ϵ_2 in direction 2 of warp			Mean
kg/m*	lb/in*	%	%	%	%	%	%	%	%
60	3.36	0.12	0.12	0.00	0.08	0.4	0.23	0.143	0.26
100	5.60	0.12	0.12	0.12	0.12	0.57	0.475	0.43	0.49
160	8.96	0.12	0.24	0.12	0.16	0.93	0.76	0.72	0.8
240	13.44	0.24	0.36	0.36	0.32	1.38	1.19	1.07	1.21
300	16.80	--	0.48	--	0.48	1.57	1.48	1.43	1.49
1160	64.96	--	2.01	--	2.01	3.31	3.33	3.33	3.32
Breaking load K_z									
1160	64.96								

* Unit of width.

In the calculation of airplane fabrics, the tearing strength must be considered first, and it is determined by the tearing load on strips 5 cm (1.97 in) wide by 30 cm (11.81 in) long, cut in either direction, (See Tables I and II). The elongation and contraction are likewise determined by another series of tests (See Tables III - X). The results of this simple tearing test are:

1. With the plain fabrics tested, a coefficient K_z of a tearing strength of between 770 and 1300, mean 1000 kg/m (43 & 72.8, mean 56 lb/in) in direction 1 (filling) can be relied upon, and between 850 and 1000, mean 900 kg/m (47.6 & 56, mean 50.4 lb/in) in direction 2 (warp).

2. Doping increases the tearing strength coefficient, K_z, substantially; but different fabrics and directions show marked variations (See Fig. 1).

3. Elongation and contraction are diminished after doping (See Tables III - X and Fig. 1). The uniformity of the fabric in the two directions, increases with doping. The curves ϵ_{16c} in Fig. 1 show the percentage elongation in both principal directions with a loading of 160 kg/m (8.96 lb/in).

4. The painting of the doped fabric somewhat diminishes the strength (Table I), and increases the elongation.

5. The coefficients of elongation and contraction given in the table are:

$$\beta = \frac{\text{Elongation}}{\text{Tension}} \qquad \alpha = \frac{\text{(Lateral) Contraction}}{\text{Tension}}$$

or taking them among both warp and filling.

$$\beta_1 = \frac{\epsilon_1}{S_1} \qquad \beta_2 = \frac{\epsilon_2}{S_2}$$

$$c_1 = -\frac{\epsilon_1}{S_2} \qquad c_2 = -\frac{\epsilon_2}{S_1}$$

are, in contrast with the isotropic fabrics of machine construction, markedly dependent on the tension

In Fig. 2 these coefficients are given from a special series of tests on fabric B twice doped without having been previously loaded.* Useful mean values may be applied to a simplified representation of the normal characteristics for limited tension within the range of practical application, up to 150 kg/m (8.4 lb/in.).

In the investigation of wing loadings, one-directional elongation seldom comes into question. The mutual influence of loading along both principal directions must almost always be taken into account.

Normal Characteristics.

The so-called Normal Characteristics (designated hereafter as N.C.) give the best, and at the same time, the simplest representation of these relations which, in themselves, are fairly complicated. There are two sets of curves, which show either elongation or contraction as a function of the loading and, the mutual influence of warp and filling.

---

* The sharp rise of the curves for β_1 and c_1 in the direction of the filling are due to a peculiarity of the fabric which is explained later.

For a given plain or undoped fabric, the strength along warp and filling is very different. Accordingly, two N.C's are required, the one with S_1 (along filling) as abscissa (Fig. 3) and the corresponding elongation ϵ as ordinates, and a family of curves, each for a constant S_2, the other N.C., with the S_2 as abscissa and a family of curves, each for a constant S_1.

It appears for fabrics doped with Cellon-Emaillite and such dopes, that the fabric is distinctly similar in both directions, so that the N.C's, especially for small loads, express substantially the same values. As such fabrics are almost exclusively used, it is sufficient, in the following experiment, to use only one N.C., e.g. the example shown in Fig. 3.

In this figure the full line curves (S_2 = Constant) represent the extension $\left(\frac{\Delta l}{l}\right)_1 = \epsilon_1$, produced by the variable tension S_1 along the filling, the constant tension S_2 acting at the same time. Further, the broken line curves show the elongations $\left(\frac{\Delta l}{l}\right)_2 = \epsilon_2$ which exist simultaneously in the direction of the warp.

This second set of curves really belongs to the second N.C.; but is brought into the same figure for the reasons mentioned.

An arbitrary state of the fabric is thus represented by two points P_0 P_1, where P lies on a full curve, e.g. $S_2 = 100$ kg/m (5.6 lb/in) corresponding to S_1 - 112.5 kg/m (6.3 lb/in) or $\epsilon_1 = +0.76\%$; while P_1 lies on the ordinate through P (and through $S_1 = 112.5$ kg/m) and on the broken curve ($S_2 = 100$ kg/m) so that for $S_1 = 112.5$ kg/m and $S_2 = 100$ kg/m $\epsilon_2 = +0.13\%$.

In accordance with the above statements, the N.C's hold good only for a definite state, and change after prolonged or repeated loading.

In order to establish the N.C., the tensions and elongations must be measured in both directions simultaneously. With this object in view, loadings increasing or decreasing relatively to each other, are imposed on a single cross of fabric, or several loadings are imposed simultaneously on a multiple cross. The method is essentially as given by Von Haas, but requires some modifications owing to the conditions. All fabrics are tested in a vertical position.

While residual strain, time effect, and the effect of previous loadings show their effects in every successive reading, this can be avoided by the simultaneous test of a multiple cross. For the same reasons, the test of a single cross is specially adapted for testing the influence of variable and repeated loading.

Test Apparatus and Methods.

The following apparatus was used in measuring loadings and elongations.

1. A Schopper's tearing apparatus (Note: Loaned by the directorate of the technological collection of the High School, for this research) for tension and tearing tests in one direction, of strips 5 cm. (1.97 in.) wide (Fig. 4) and later an Amsler tearing apparatus from the Constructional Engineering Laboratory of the High School.

2. A frame to take a simple cross-shaped piece of fabric for individual tests (Fig. 5).
3. Several frames for the various multiple-cross experiments.
4. A double recording apparatus for registering the deformation of the fabric in two directions at right angles to each other.

This instrument was made by "Atmos" Ltd., to the designs of the author, and embodies a fixed point which pierces the fabric, while two other needles, which also pierce the fabric, transmit the movements arising from the elongations of the area through an arrangement of levers which multiplies the actual deformation by from 10 to 20 times and this is recorded on a revolving drum. The apparatus is specially applicable to experiments on time effect. In experiments of short duration, as well as in the simultaneous measurement of several elongations, definitely known distances are marked off on the fabric and these are measured before and during loading. The fabric is always suspended vertically and loaded by weights. In the later experiments in time effect with sand loading, the instrument was used to advantage.

In the single-cross, the square to be measured had 17 cm (6.69 in.) sides and the side flaps were slit, so that the tensions were taken up uniformly. The sides and the medial lines of the square were measured at each observation.

In determining the N.C. by single-cross experiments, the following procedure must be adopted.

1. Horizontal load constant, vertical load rising to maximum.
2. Horizontal load increased, vertical load decreasing to zero.

3. Horizontal load further increased, vertical load rising to maximum (in 5 or 6 steps in the case given).

The elongations obtained include errors on account of residual strain in the fabric. According to the method of Haas,* this error is eliminated by double application and we obtain simultaneously both sets of the N.C. curves (elongations and contractions) in both directions with relation to S_1. The elongations in the directions S_1 (filling) are shown by full lines and the extensions in the direction S_2 (warp) as dotted lines (Fig. 6). Then the same experimental point lies, in one case, above and, in the other case, below the true curve, in consequence of residual strain in the fabric, which is very apparent in this case.

The true curve is then drawn as an arithmetical mean between the two sets of points. In this way the final N.C. of a once-doped fabric W is obtained (Fig. 7) and is here shown as a function of S_1.**

The multiple-cross experiments are of special service in determining the N.C. rapidly. Four multiple crosses are used at the same time, each of which consists of eight single crosses and each is subjected to a different horizontal load: each load, however, remaining constant through the whole test.

Of the eight vertical strips, four are loaded vertically at the same time with increasing loads, the other four remaining unloaded. After 15 to 30 minutes, a reading is taken and the load is then put on the other strips, and their change of shape is determined after 15 minutes. By this means, the cross is only once

---

* Haas and Dietzius. Elongation of fabric and forms of envelopes, pp. 45 to 47.

** The experimental points are omitted in Fig. 7. See also Haas, Fig. 53.

exposed to a definite load and the influence of the residual effect (that is, the effect of what has happened with the material before the test) is eliminated as far as possible.

In this way, two crosses are arranged for each experimental point (on the N.C.), one of which is first stressed vertically and the other horizontally. Thus, without a double application, two pairs of points are obtained at once (for ϵ_1 and ϵ_2) of which the arithmetical mean is taken. In Fig. 8, the two pairs of points for S_2 = 100 kg/m (5.60 lb/in) and S_2 = 155 kg/m (8.68 lb/in) are represented and the true curve drawn between them. By this means, lack of uniformity of fabric is sufficiently averaged, so that the resulting N.C. actually represents the mean qualities of the fabric for momentary and varying loads, as in flight.

The arrangement of the multiple crosses, their suspension and the taking of readings, as well as the plotting of the experimental values are, in any case, tedious operations. For simplification, we recommend the following procedure, which is sufficient for most cases.

In practice, the N.C. are only employed within a small range. As already brought out elsewhere,* it is sufficient to represent the N.C. by two sets of parallel lines.

$$\epsilon_1 = \beta_1 S_1 - c_1 S_2$$

$$\epsilon_2 = \beta_2 S_2 - c_2 S_1$$

$$\text{For } S_2 = 0 \begin{cases} \epsilon_1 = \beta_1 S_1 \\ \epsilon_2 = - c_2 S_1 \end{cases}$$

---

* A. Pröll. The problem of the strength of wing fabrics. Zeitschrift für Flugtechnik und Motorluftschiffahrt, 1915.

$$\text{For } S_1 = 0 \begin{cases} \epsilon_1 = - c_1 \; S_2 \\ \epsilon_2 = \beta_2 \; S_2 \end{cases}$$

By this means the drawing of the N.C.'s is much simplified and reduced to the determination of the four quantities β_1, β_2, c_1, c_2, by two elongation experiments on two simple strips of fabric, whereby the elaborate tests on single and multiple crosses are eliminated. The strips are loaded once in the direction S_1 and once in direction S_2; while the other tension remains zero. The quantities ϵ_1 and ϵ_2 are measured directly as elongations or contractions; from which the four constants can be calculated (See tables V and VI). Since in airplane wings, frequent but small stressing of the fabric is to be expected, it is recommended that the strips should be repeatedly stretched slightly before measurement.

In a number of cases of loadings occurring in practice, the tensions S_1 and S_2 are almost equal. They can then be determined from the curves γ_1 and γ_2 (Fig. 3), for which $S_1 = S_2$ and then introduced into the N.C's.

$$\text{For } S_1 = S_2 \begin{cases} \epsilon_1 = S_1 \; (\beta_1 - c_1) & \text{curve } \gamma_1 \\ \epsilon_2 = S_2 \; (\beta_2 - c_2) & \text{curve } \gamma_2 \end{cases}$$

This corresponds to lines through the origin.

Actually the lines γ_1 and γ_2 are slightly curved and can be replaced by their tangent only in the neighborhood of the origin. Up to about 100 kg/m (5.6 lb/in.) however, the simplified representation by straight lines is applicable without error.

If, on the contrary, in the simple elongation experiments, the quadratic terms in the expressions have a serious influence, a more accurate calculation is to be recommended by means of

$$\epsilon_1 = \beta_1 S_1 - S_2 (c_1 + q_1 S_1)$$
$$\epsilon_2 = \beta_2 S_2 - S_1 (c_2 + q_2 S_2)$$

Here again, the N.C's are given by two sets of parallel lines but with different dispositions. The curves γ_1 and γ_2 for $S_1 = S_2 = S$ are now parabolas

$$\epsilon_1 = S (\beta_1 - c_1 - q_1 S)$$
$$\epsilon_2 = S (\beta_2 - c_2 - q_2 S)$$ which

conform well with facts.

The simple tensile experiments described again give the values β_1, c_1 and β_2, c_2 while q_1 and q_2, in any case, can only be found from experiments with simultaneous stressing in two directions. Since, however, the terms $q_1 S_1$ and $q_2 S_2$ are small in all cases, they can be considered as correction terms and q_1 and q_2 can be assumed from complete experiments with single and multiple crosses already made, or from known N.C's for fabric similarly doped. For example, for twice doped fabric

$$q_1 = \frac{0.28}{10^6} \qquad q_2 = -\frac{0.1}{10^6}$$

Example. From the simple elongation and tensile experiments, Tables V and VI, on fabric "B" twice doped the magnitudes of β_1, β_2, c_1, c_2, can be first drawn out as functions of the tensions S_1 and S_2, in which β_1 and c_2 appear as varying rapidly.* For small tensions, mean values can, however, be used and

---

* This variability depends on the arrangement of the cloths according as the threads are stretched or vibrated.

we get

$$\beta_1 = \frac{119}{10^6}, \quad \beta_2 = \frac{53}{10^6}, \quad c_1 = \frac{44}{10^6}, \quad c_2 = \frac{72}{10^6}$$

and for the N.C. equations

$$10^6 \epsilon_1 = 119\ S_1 - 44\ S_2$$

$$10^6 \epsilon_2 = 53\ S_2 - 72\ S_1 *$$

For fabric which has been repeatedly stressed, initially and twice doped, other elongations and contractions were found which showed much more uniform distribution, (Tables XI and XII). The mean values for these are

$$\beta_1 = \frac{85}{10^6} \quad \beta_2 = \frac{73}{10^6} \quad c_1 = \frac{20}{10^6} \quad c_2 = \frac{20}{10^6}$$

---

* If one takes the corresponding values of the approximately straight lines of N.C's (Fig. 3) determined from multiple-cross experiments then we have

$$\beta_1 = \frac{120}{10^6} \quad \beta_2 = \frac{60}{10^6} \quad c_1 = \frac{30}{10^6} \quad c_2 = \frac{51}{10^6}$$

The figures are taken as the basis of some examples in the later investigation.

Table XI.

Elongation tests.

Fabric B, doped twice and initially stressed.

Loading S_1 in direction 1 of filling		Contraction ϵ_2 in direction 2 of warp			Mean	Elongation ϵ_1 in direction 1 of filling	$\beta_1 10^6$	$c_2 10^6$
kg/m*	lb/in*	%	%	%	%	%		
60	3.36	0.12	0.23	--	0.12	0.47	78.5	20.0
120	6.72	0.12	0.34	--	0.16	1.00	83.5	13.3
180	10.08	0.36	0.57	0.11	0.35	1.57	87.5	19.4
220	12.32	0.36	0.79	0.45	0.53	1.9	86.5	24.1
260	14.56	0.72	1.0	0.69	0.8	2.3	88.5	30.8
300	16.80	0.72	1.1	0.91	0.91	2.7	90.0	30.3
340	19.04	--	--	--	--	2.9	85.5	--

* Unit of width.

Table XII.

Elongation tests.

Fabric B, doped twice and initially stressed.

Loading S_2 in direction 2 of warp		Contraction ϵ_1 in direction 1 of filling			Mean	Elongation ϵ_2 in direction 2 of warp	$\beta_2 10^6$	$c_1 10^6$
kg/m*	lb/in*	%	%	%	%	%		
60	3.36	0.11	0.116	0.24	0.15	0.43	72.0	25.0
120	6.72	0.11	0.116	0.36	0.19	0.9	75.0	15.8
180	10.08	0.23	0.23	0.47	0.31	1.38	76.5	17.2
220	12.32	0.34	0.23	0.83	0.47	1.57	71.5	21.2
260	14.56	0.34	0.23	0.95	0.5	1.85	71.0	19.2
300	16.80	0.57	0.35	1.07	0.66	2.11	70.3	22.0
340	19.04	0.46	0.58	1.07	0.7	2.33	68.5	20.6

* Unit of width.

In the elongation of a fabric in any given direction, stresses are only transmitted by the interior friction in the plain fabric or by the dope which forms a stiff film. It is thus apparent why the proposal to determine the simultaneous tension and elongation in two directions by loading along a diagonal is impracticable. With a small load, e.g. 160 - 240 kg/m (8.96 - 13.44 lb/in.) for once-doped fabric, the fabric loses its rigidity and contracts with a scaling of the dope.

Diagonal stressing seldom occurs, since the fabric is always so attached that the meshes do not become oblique. For complete elucidation, however, a few experiments of this kind were carried out on strips 5 cm (1.97 in.) wide and 32 cm (12.6 in.) long (See Table XIII). From the results, diagrams can be constructed as the counterparts of the stress ellipses of solid building materials, which show the extremely small resistance of the fabric to lateral tensions and at the same time the strengthening effect of the dope.

Haas has established formulas for the change of shape of a diagonally stressed plain fabric which can be broadened as desired. They also give the tensions which the film of Cellon dope alone supports. At 45°, this is the force per unit length which can be withstood without appreciable deformation. Diagonal mounting is to be recommended under certain conditions, on account of the smaller wrinkles formed.

The fabric in this case is always stressed in two directions and since its threads are firmly fastened at the edges, the meshes cannot become oblique. This was demonstrated by experiments in which a twice-doped fabric was stretched and made fast on a rectangular wooden frame 100 x 30 cm (39.37 x 11.81 in.), with the threads inclined about 45° to the sides, and then loaded with sand. The measurement, before and after loading, of various squares and rectangles drawn on the under side showed that the sides and diagonals had only lengthened proportionately, without affecting, however, the rectangular relation.

Table XIII.

Elongation tests in a diagonal direction.

Angle between direction of stress and filling α	Stresses S kg/m*	Stresses S lb/in*	Stresses S_{max}** kg/m*	Stresses S_{max}** lb/in*	Elongation ϵ_1 in direction of filling S %	Elongation ϵ_1 in direction of filling Smax %	Remarks
0°	400	22.40	1100	61.60	4.2	8.7	$S_{max} = K_z$ (filling)
9° 40'	310	17.36	428	23.97	3.4	6.2	
15°	228	12.77	325	18.20	1.3	5.7	
30°	194	10.86	292	16.35	1.25	2.8	
45°	144	8.06	730	40.88	1.25	3.6	
60°	165	9.24	516	28.89	1.0	---	
75°	285	15.96	412	23.07	~0.9	2.2	
80°	332	18.59	432	24.19	-1.5	---	
90°	1075	60.20	1075	60.20	-5.2	-5.2	$S=S_{max}=K_z$ (warp)

* Unit of width.

**S_{max} is the tension at which the fabric completely loses its rigidity. A smaller tension S was also investigated.

Behavior of different fabrics and their differences.

The experiments have shown, in almost all cases, that the doping eliminates the differences in the behavior of the fabrics, in proportion to the amount of dope. Nevertheless, the properties of the fabrics in the undoped state - weight, rigidity and elongation were also determined. Linen fabrics, "W" and "B", were tested. There is also available a half-linen fabric "H", which it is intended to test.

The following are some particulars of these fabrics:

Mark	Source	Weight undoped		Mean number of threads in direction of				Tearing strength of raw materials in direction of			
				Filling		Warp		Filling		Warp	
		g/m²	oz/yd²	per cm	per in.	per cm	per in.	kg/m	lb/in	kg/m	lb/in
W	Raw material*	29.7	3.83	22	55.9	21.5	54.6	1310	73.36	855	47.88
B	Hauser and Spiegel	114.8	3.39	23	58.4	20.0	50.8	940	52.64	1000	56.00
H		128.5	3.79	29	73.7	28.0	71.1	1100		550	30.80

The dope used was obtained from the Hannover Carriage Works (manufactured by Mombour, Wiesbaden).

Comparative elongation tests on the plain fabric B have already been given in Tables III and IV. From experiments made on fabric W, (Tables XIV and XV) it appears that, with the plain fabric W, the elongation along the warp is greater, while with fabric B, that along the filling is decidedly greater. This difference continued, even after doping twice with Cellon, and necessitated further experiments, with interchanging of the directions of warp and filling of fabric B. The rigidity of fabric W is

---

* Raw material from warehouse of the "Inspection der Fliegertruppen."

Table XIV.

Elongation test with Fabric W in direction 1 (of filling).

Test No.	Treatment	Threads per		Tension		Percent	$\beta_1 10^6$	
		cm.	in.	kg/m*	lb/in*	elongation		
1	Undoped	--	--	50.0	2.80	0.61	122	
		--	--	100.0	5.60	0.92	92	
				150.0	8.40	1.20	80	
2	Doped once	23	58.42	50.9	2.85	0.25	49.3	
				101.8	5.70	0.63	61.8	
				155.0	8.68	0.81	52.1	mean 57.5
				204.0	11.42	1.25	61.2	
				510.0	28.56	2.81	55.1	
3	Doped twice	24	60.96	83.4	4.67	0.62	74.4	
				160.6	8.99	0.85	52.7	
				250.0	14.00	1.27	50.8	52.5
				500.0	28.00	2.77	55.4	
				750.0	42.00	3.84	51.2	
				1082.0	60.59	4.70	43.3	
4	Doped twice, painted & varnished	23	58.42	83.0	4.65	0.38	45.8	
				166.1	9.30	0.69	41.5	
				249.1	13.95	1.15	46.2	55.3
				498.3	27.90	3.68	71.0	
				747.4	41.85	5.17	69.2	
				996.6	55.81	5.98	60.0	

* Unit of width.

Table XV.

Elongation tests with Fabric W in direction 2 (of warp).

Test No.	Treatment	Threads per cm.	Threads per in.	Tension kg/m*	Tension lb/in*	Percent elongation	$\beta_2 10^6$	
1	Undoped	--	--	50.0	2.80	3.3	660	
				100.0	5.60	5.16	516	
				150.0	8.40	6.0	400	
2	Doped once	23	58.42	50.9	2.85	0.25	49.3	
				101.8	5.70	0.63	61.9	mean
				155.7	8.72	0.81	52.1	58.2
				204.6	11.46	1.30	63.6	
				510.0	28.56	2.81	55.1	
				1869.0	104.66	3.68	197.0	
3	Doped twice	24	60.96	76.9	4.31	0.31	40.3	
				153.8	8.61	0.92	59.8	
				231.0	12.94	1.54	66.7	70.5
				539.0	30.18	4.46	82.8	
				769.0	43.06	5.59	72.7	
				1000.0	56.00	6.45	64.5	
4	Doped twice, painted & varnished	23	58.42	83.4	4.67	0.384	46.1	
				166.6	9.33	0.692	41.5	
				250.0	14.00	1.000	40.0	45.7
				500.0	28.00	2.480	49.7	
				750.0	42.00	3.840	51.2	
				1000.0	56.00	4.760	47.6	

* Unit of width.

Since it has been shown by the experiments that the strength of all the fabrics was sufficient, fabric B would naturally be preferred. The deformations are, however, decisive, being greater for fabric B than for W and remaining so even after repeated doping, though in a less degree. It still remains to determine how much the elongation coefficient can be decreased by repeated doping under the best conditions. In general, the fabric is to be preferred, however, which shows the smaller elongation in the undoped condition.

From the above experiments it may be assumed that the elongation of undoped fabric for low loading is diminished to about 1/2 or 1/4 by the usual repeated doping.

This is supported by the following table for fabric B.

Elongation % Under 150 kg/m (8.4 lb/in.)

	Undoped	Doped 2 times	Doped 3 times	Doped 4 times
Filling	7.0	1.8	1.55	1.48
Warp	1.08	0.88	0.65	0.82
		Breaking load elongation		
Filling	12.4	10.3 10.5	(9.9)	11.0
Warp	3.5	3.45	3.3	3.3
	Elongation with 150 kg/m (8.4 lb/in) as a percentage of load at breaking point.			
Filling	56.4	17.5	14.8	13.4
Warp	31.0	25.5	19.7	24.8

For fabric B undoped, the elongation along the filling was exceptionally large.

Results. Although the differences in the tenacity of the raw materials can be partially eliminated, this is without practical significance on account of the small working stresses. The differences in the changes of shape along the two principal directions and the amount of elongation are more important.

Even in this case, however, repeated dopings diminish the differences. In the first place, the plain fabrics should be tested to see that their tenacity is not less than 700 kg/m (39.20 lb/in) in any direction. The change of shape of the raw fabric applied in the ordinary manner (warp parallel to the ribs) should not exceed 2% along the warp for a tension of 150 kg/m (8.4 lb/in), or 1.5% along the filling for a tension of 150 kg/m (8.4 lb/in)*

It is concluded from the above that the total elongation due to the combined stretching and straightening of the threads under small loads, after a certain initial stretching of the fabric, should be as small as possible when the usual loads are applied. Since the elongation of the threads under 150 kg/m (8.4 lb/in) with a breaking strength of about 1000 kg/m (56 lb/in) amounts to only 10 to 15% of the maximum elongation and on the other hand, the straightening of the threads gives an initial increase (up to 30% of maximum elongation), a total elongation of 40 to 50% of the maximum elongation can be assumed under average conditions. By decreasing the stretching of the threads, the total elongation could be considerably diminished.

According to the method of manufacture, one or the other of the principal directions shows greater elongations (in fabric B the filling and in fabric W the warp). Since, in wings, the

---

* In so far as conclusions are warranted by experimental results thus far obtained.

greater elongations occur at right angles to the ribs (filling) it is desirable to allow for a smaller elongation across the ribs than parallel to them.

Behavior of the Wing Fabric under Various Secondary Influences.

The N.C. are well adapted for showing the differences in behavior of the fabric under different conditions. In the first place, the difference in behavior of plain and doped fabric is shown by comparative experiments (Tables I to XII and Fig. 9). Most striking are the much greater deformations of the plain fabric, which reach 4 or 5% for a tension of 100 kg/m (5.6 lb/in) and its apparently greater elasticity (smaller creeping) than those of the treated fabric. Especially the freshly doped, and previously unstressed fabric shows remarkable N.C. for small loads, in the single-cross experiments. On loading plain linen, the elongation continually increases in one direction simultaneously with contraction in the direction at right angles to it and both change with changing loads. With doped fabric, the process is at first reversed. This is, apparently, to be explained by the mutual adhesion of the globules of "Cellon" to each other and to the fabric. Only when these are detached by higher stresses (above 70 to 100 kg/m (3.9 to 5.6 lb/in)) will the behavior of the fabric agree with that of the raw material.

With initial loading in one direction (S_2) an elongation first occurs in this direction with a contraction perpendicular to it (See curve $S_1 = 0$, Fig. 6). For a small increase of the transverse load, (S_1 = 50 kg/m (2.8 lb/in)) and a simultaneous decrease of the load in direction S_2, this transverse load is not sufficient, due to the effect of the dope, to change the initial contraction ϵ_1 into an elongation (increased residual effect as compared with raw material). Hence, on double application of stress (Fig. 7) there appears the above remarkable difference, as compared with the curves in Fig. 9.

The testing of the fabric by the multiple-cross method does not permit of a recognition of this abnormal behavior. It shows, however, that by this method the residual effect in the fabric can be eliminated. The curve of the N.C.'s so found (Fig. 3) show a great similarity in the deformations along warp and filling. In the subsequent testing of the fabric on airplane wings, only the N.C's obtained by the multiple-cross method were used; while other subsidiary influences were investigated by the single-cross method.

In these tests, the effect of the doping is apparent in almost all the properties of the fabric, hence elongations were also determined with

(1) Fabric, doped once
(2) " " twice
(3) " " three times
(4) Same as in (2) but painted with an oil color and varnished.

The results are combined in Figs. 10 and 11 (along filling and warp).

In a further series of experiments with the same fabric and dope, using an Amsler tearing machine, diagrams were made of deformations, along filling and warp, of strips of fabric, undoped; doped three times; and doped three times, painted and varnished (Figs. 12 to 14); as well as with strips of fabric B doped three times, painted and varnished (Fig. 15). The strips were 5 cm (1.97 in.) wide. As was to be expected, the heavier dopings decreased the change of shape in all cases. With the addition of painting with oil color, the elongations for small loads increased again. The oil of the paint therefore appears to reduce the brittleness of the dope and to increase the extensibility of the fabric. Further experiments on this point are planned.

Lastly, in a series of experiments by the single-cross method, the N.C. of (1) Fabric doped once (Fig. 7)
and of (2) Fabric doped once and painted (Fig. 16)
were compared.

It was also shown that once-doped linen was restored by subsequent painting to an elastic fabric more nearly resembling undoped linen in behavior. The initial contraction observed in the doped fabric has disappeared in the unbroken curves (Fig. 16). Only the small initial rise of the dotted curve corresponds to the characteristic behavior of the doped fabric.

All these experiments give no final judgment on the influence of the doping scheme. So much only is seen, that for small tensions, such as arise in flying, the influence of doping preponderates heavily. With very large tensions, especially if the film of dope is torn, the doped fabric behaves like plain fabric. Then the fabric itself alone appears to be the carrier of the stress and the decisive factor.

Further experiments, particularly with different dopes, and with sheets of dope alone, are urgently needed.

Influence of Time.

With the very imperfect elasticity of the fabric, residual effects play an important role. They upset the regular course of the curves and also, the regularity of the physical relations, for, owing to the effect of various time effects in a given state of tension, many different changes of shape can arise under the same conditions of load. The most important time effects are:

(a) The time taken for deformations with steady load (time effect experiment);

(b) The residual effects of previous stressing with varying load (residual strain and hysteresis).

Time Effect Experiments.

Every change of shape taken on the recording apparatus shows the characteristic course of the lines in Figs. 17 and 18.

Fig. 17 shows the course of the elongations due to a vertical load V, which increases from 0 to 30 kg with constant horizontal load H = 5 kg (11.02 lb); Fig. 18, the course of the elongations for a vertical load V which decreases from 15 to 0 kg, with a constant horizontal load of H = 25 kg (55.11 lb).

In Fig. 17 the horizontal divisions correspond to 3.63 min. and in Fig. 18, to 7.6 min.

As will be seen, the elongations follow the load directly to a value ϵ_0, they then change very slowly to an approximately constant value ϵ_1 which is reached after about 15 to 30 min. It may be asked whether the elongations change for longer testing periods. For an elucidation of this question, a preliminary multiple-cross experiment on fabric doped three times and painted (Figs. 19 to 21) will serve, extending over several months, in which to each elongation in both directions there was a corresponding definite load, unaltered throughout the test. It may be concluded from the results that a steady condition, which only changes imperceptibly on further loading, is only reached after about six weeks.

If there are large differences in the side tensions, e.g. S_2 = 200 kg/m (11.2 lb/in), and S_1 = 0, the delayed effects of elongation and contraction are considerable. In the limiting case mentioned, the contractions show much greater differences, up to $7\frac{1}{2}$ times, as compared with the elongations after about 10 minutes. The differences decrease, the more the tensions approach each other in magnitude. The elongations increase with time up to 150% of the elongation immediately after loading. Fig. 2 shows the increase of the elongation ϵ_2 with the time, for two different stresses, S_1.

Two further time experiments of 25 and 10 days' duration were carried out on fabric doped three times (Figs. 22 to 25) with two different horizontal stresses S_2 = 100 and S_2 = 267 kg/m (5.6 and 14.95 lb/in). They confirm the behavior of the doped and painted fabric; but the differences - as compared with the elongations for short period loads - are not as large. It is noteworthy that the curves always pass through a point near the abscissa axis

$(\epsilon \sim 0)$. For the vertical elongations (ϵ_1), this point lies in a region of low stresses S_1; but for horizontal elongations (ϵ_2) it lies in the region of larger stresses S_1. It follows that only such conditions of the fabric, remain unaltered with the lapse of time in any definite direction, which show no change, or only a very small change of form in this direction, in consequence of previous stressing in both principal directions.

It is also shown by all the experiments, that the elastic deformations during flight, which are practically the only important ones, occur after about ½ hour. The fact that they considerably increase in the course of a few weeks plays no part, since such long-continued loadings are not experienced in practice.

Heavily loaded fabric which exhibits deformations tends to return to its original condition after removal of the load. This recovery is shown, for example, in Figs. 28 and 29 at the places where the loading under the vertical force V, was interrupted for a long time. This is specially important in experiments with wings. If the surface after heavy loading has become slack and shows wrinkles and then becomes taut again after 12 to 24 hours (depending on the amount of deformation and the humidity), its tension will not, however, return to its original magnitude, as can be shown by the dropped-ball test.

Residual Strain.

In single-cross experiments and also in simple-elongation tests, if the load is altered for a brief interval, different states of torsion occur after return to the previous loads and stresses, in consequence of time effects. This effect of the internal friction of the material may be called the "residual strain," according to Mr. Haas.

To study this effect, which is almost eliminated in the N.C. obtained by double stressing, hysteresis loops were investigated, in which the lateral tension (e.g. S_1) remained unchanged, while S_2 was altered first in the increasing and then in the decreasing direction (Fig. 26). (In this figure the full line is for 0 kg/m and <u>not</u> for 50 kg/m (2.8 lb/in.); the next curve to it is for 50 kg/m) The elongation curves do not coincide, and the area enclosed by them is a measure of the strain-energy spent in overcoming the internal friction. The loops are narrower, the greater the constant lateral loading.

It is important to know the following:

(1) How do these after effects change with time and with repeated loading and unloading.

(2) Whether the N.C's do not alter with time or repeated loading, in spite of the elimination of such effects.

To test the first question, the time tests already mentioned were extended, in which the material was subjected to several and variable loadings and unloadings. The hysteresis loops were drawn one after the other by means of the recording apparatus (Figs. 27 and 28). Fig. 27 shows the diagram of strip No. 2; horizontal load H = 5 kg (11 lb) and later, 30 kg (66 lb), S_1 = 30 kg/m (1.68 lb/in) and 180 kg/m (10.1 lb/in; the vertical load V, increases each time from 0 to 35 kg (77.2 lb), S_2 = 0 to 210 kg/m (463 lb) and again falls to 0 kg.

These diagrams show that the hysteresis almost completely vanishes for large horizontal stresses; while, for small ones, pronounced loops can be drawn.

In a second experiment, a varying load of 1 to 30 kg (66.1 lb), S_2 = 6 kg/m (34 lb/in) to 180 kg/m (10.1 lb/in) was repeatedly applied and removed for S_1 = 30 kg/m (1.68 lb/in). The lines drawn for the strip No. 3 for V = 1 kg (2.2 lb) continually increase with time; but approach a limit (Fig. 29). A kind of permanent set occurs and further hysteresis loss disappears.

This behavior, observed in many similar experiments, suggested a solution of the second question. The time tests have proved that even in the case of the multiple-cross process, a time effect in the N.C's undoubtedly occurs; but simultaneously showed that these slow changes of shape are not important in practice. The influence of repeated and varying initial loadings appears more important. Hence on the same fabric (once-doped linen) the N.C's which are given in Fig. 7, were again determined as shown in Fig. 30. From this it appeared that the curves for doped fabric after repeated and increasing loadings and unloadings approximate more closely those of the raw fabric.

How far the magnitude of the loading and unloading affects the matter was cleared up by further experiments. To this end, two N.C's of a test piece of fabric, taken from the undamaged wing of a wrecked airplane, were determined.

The first, Fig. 31, corresponds approximately to Fig. 7 for new fabric, with allowance for the difference due to the latter having been several times treated and painted. The second, Fig. 32, was more like Figs. 30 and 16. The fabric had experienced in any case repeated loading and unloading during a series of flights which could, however, scarcely have exceeded 50 to 60 kg/m (2.8 to 3.4 lb/in). For the compilation of the first N.C., on the other hand, tensions up to 300 kg/m (16.8 lb/in) were applied. Hence, it appears that small loading and unloading, as in ordinary flight, have only a small influence on the properties of the fabric; while high stresses (as in stunting) a considerable influence is exerted.

From these experiments we have the following, as regards the calculation of stresses.

(1) It is sufficient to know the N.C. of a new fabric, in order to determine the elongations to be expected. Hence the N.C. determined by the multiple-cross method would be taken as the basis for further investigations of most initially unstressed fabrics.

(2) One must, however, ascertain whether after occasional high overloading, the elongations and tensions are permissible, otherwise, a second, or even further N.C's should be applied. It also depends largely on whether the fabric is suitable for the upper or lower side or the front or rear edge of the wing.

The influence of humidity was studied on strips of once-doped fabric, which were stretched in one direction only, when quite dry and again when very moist (after lying for a long time in water and expected, that wet fabric gave considerably greater elongations for the same loads (Fig. 33). Further experiments are in preparation in connection with the testing of dopes.

Translated by
National Advisory Committee
for Aeronautics.

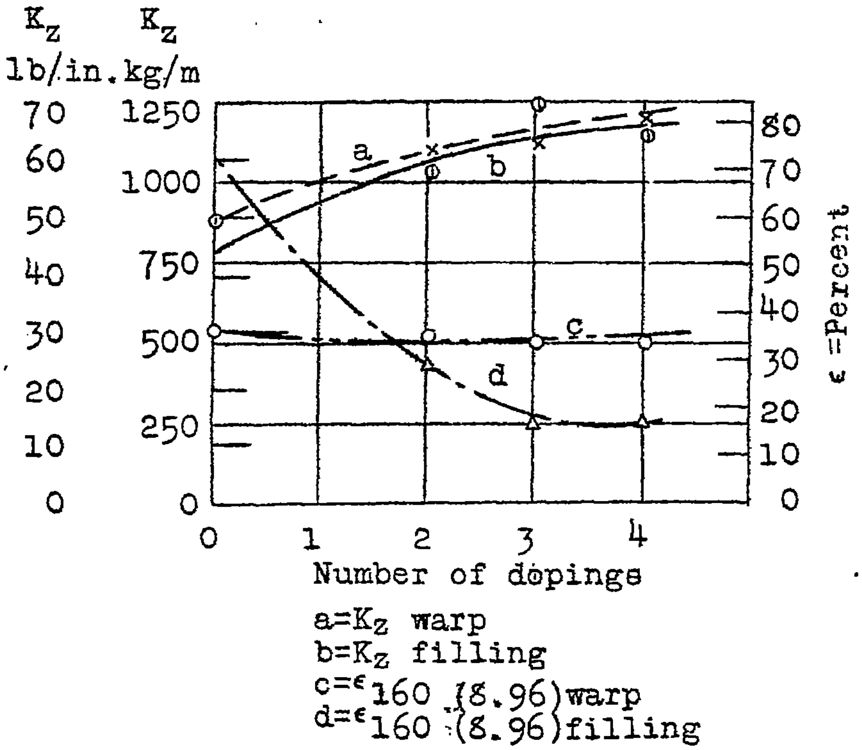
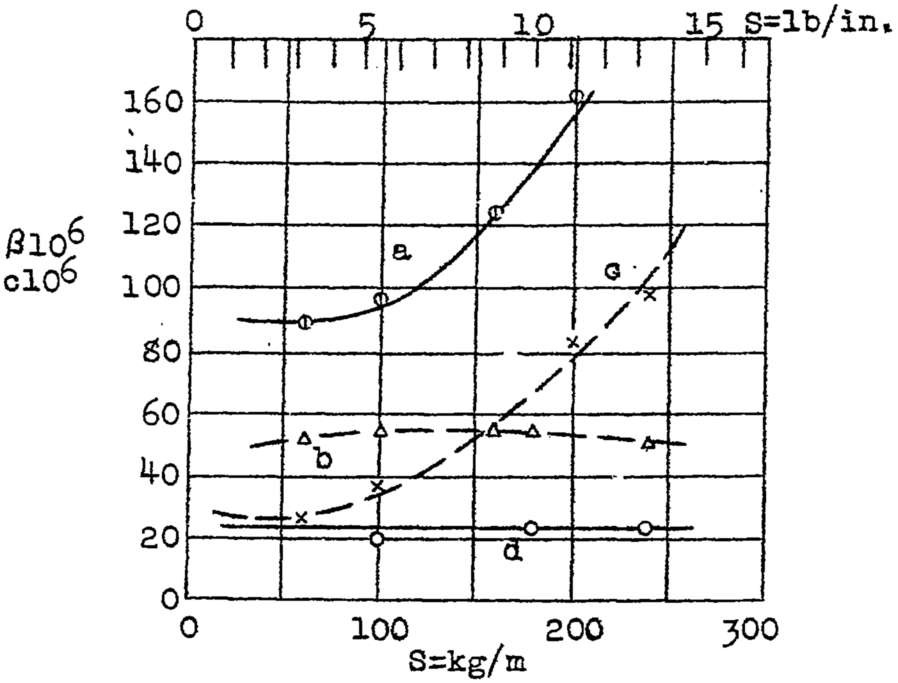
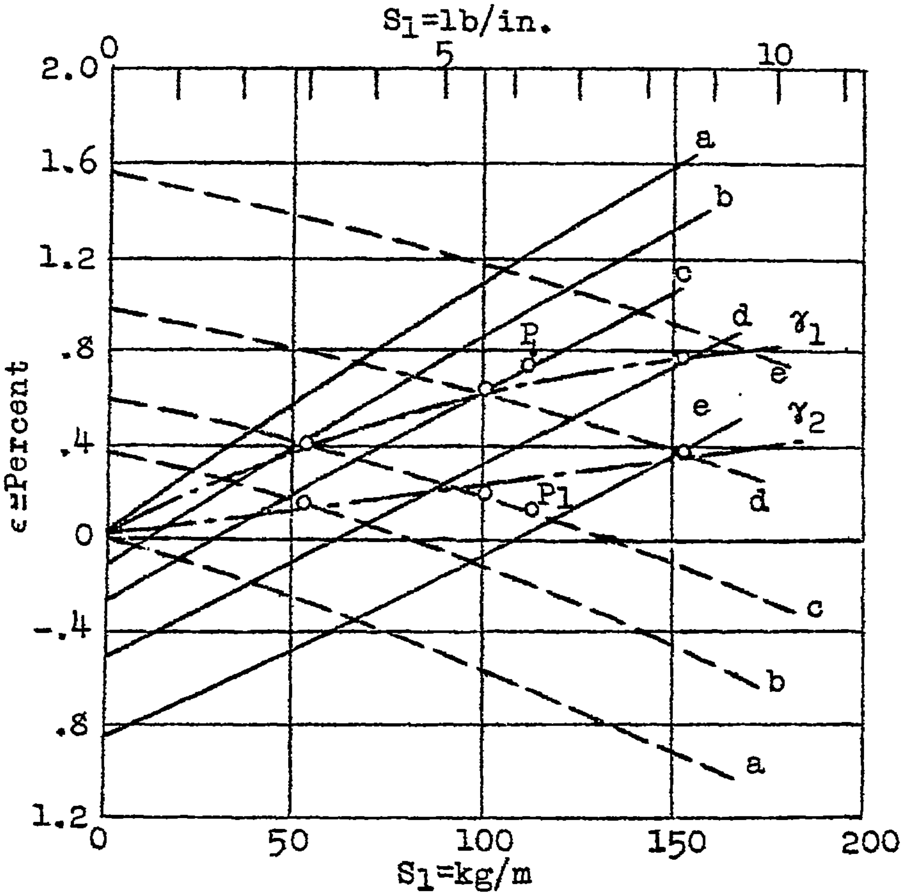


Fig. 1 Mean tearing strength and elongation.
Fabric B



$a=\beta_1\ 10^6$ filling
$b=\beta_2\ 10^6$ warp
$c=c_2\ 10^6$ warp
$d=c_1\ 10^6$ filling

Fig. 2



a=S_2=0 kg/m (0 lb/in.)
b=S_2=55 kg/m (3.08 lb/in.)
c=S_2=100 kg/m (5.6 lb/in.)
d=S_2=155 kg/m (8.68 lb/in.)
e=S_2=267 kg/m (14.95 lb/in.)

Fig. 3 Normal characteristics of fabric B
(Multiple-cross experiments)

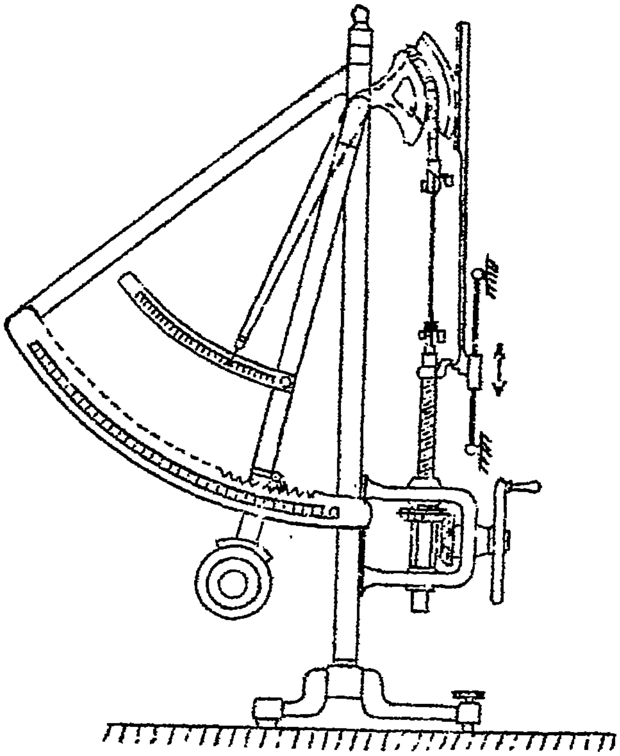


Fig.4 Fabric testing machine

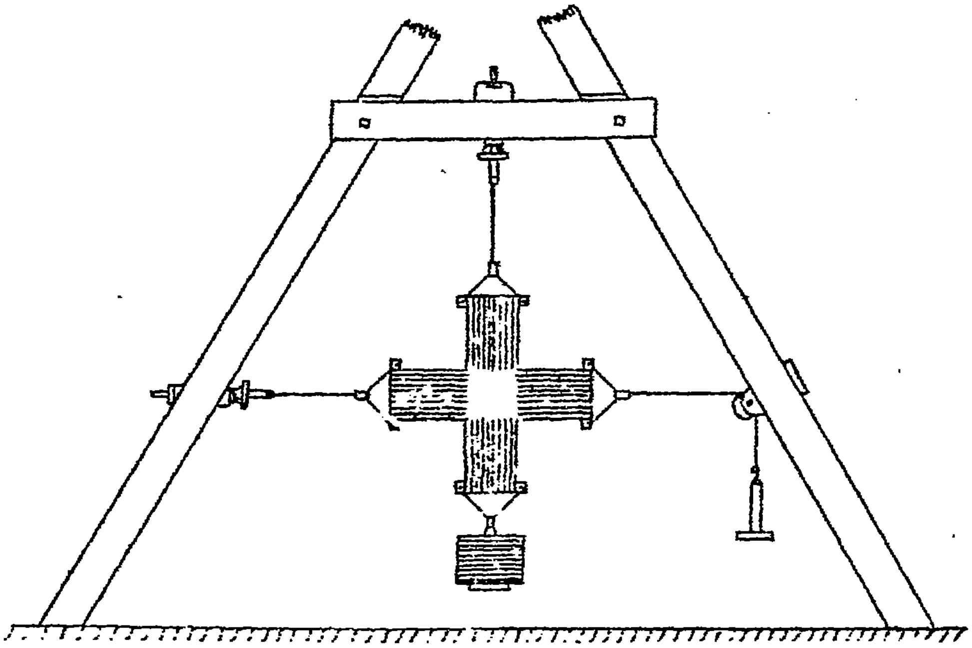
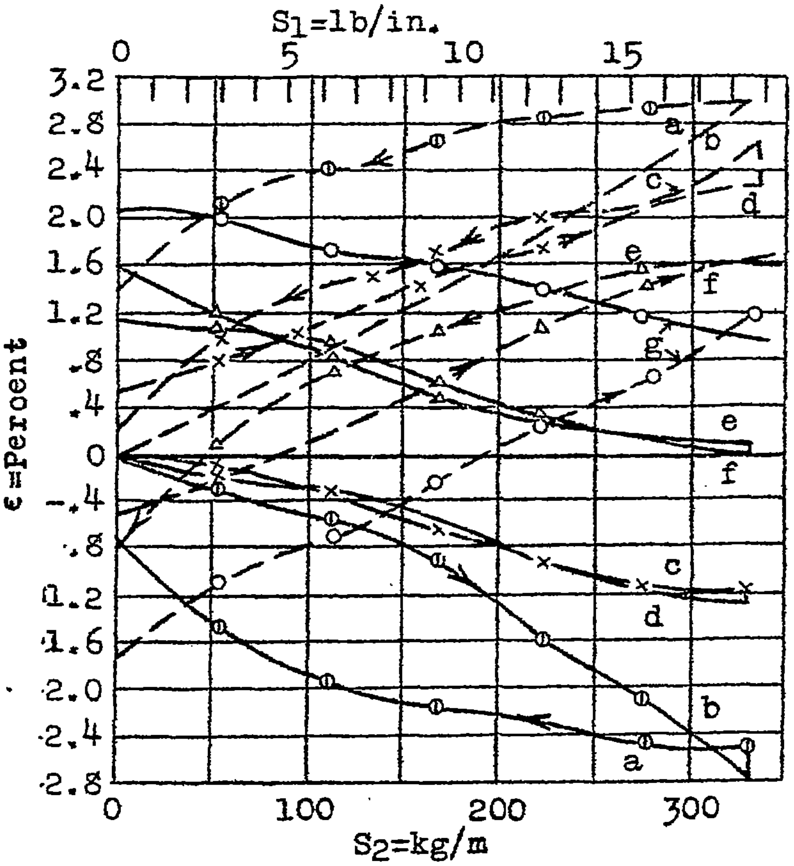
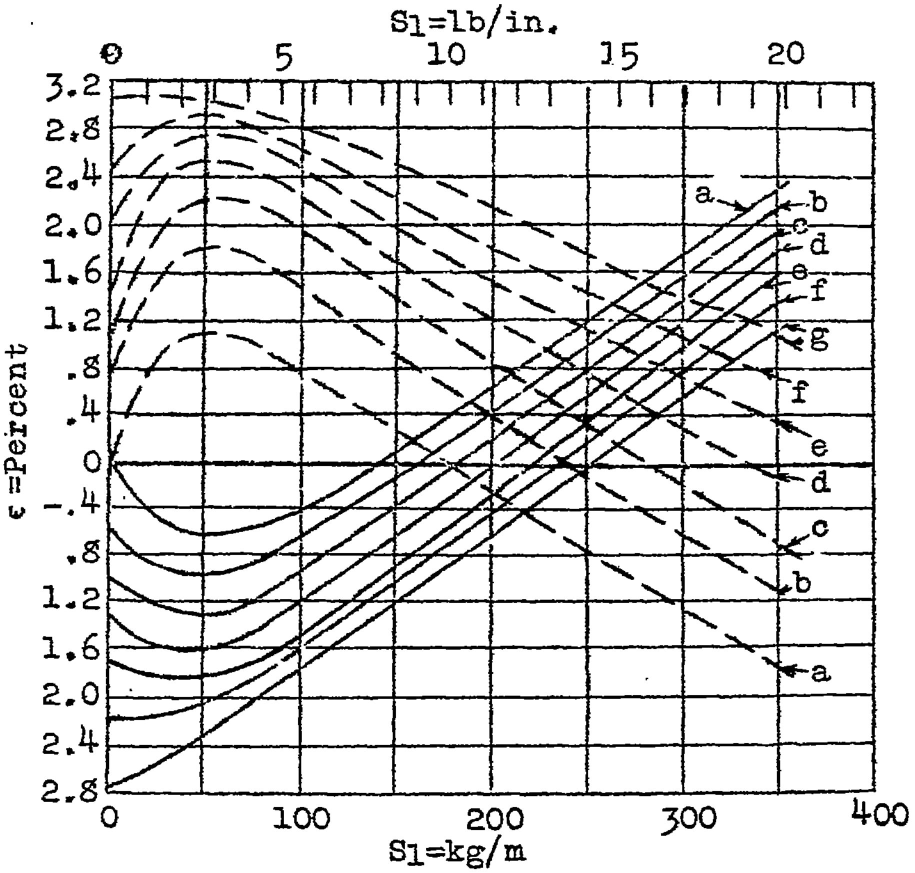


Fig.5 Frame for mounting the fabric for the single-cross experiments



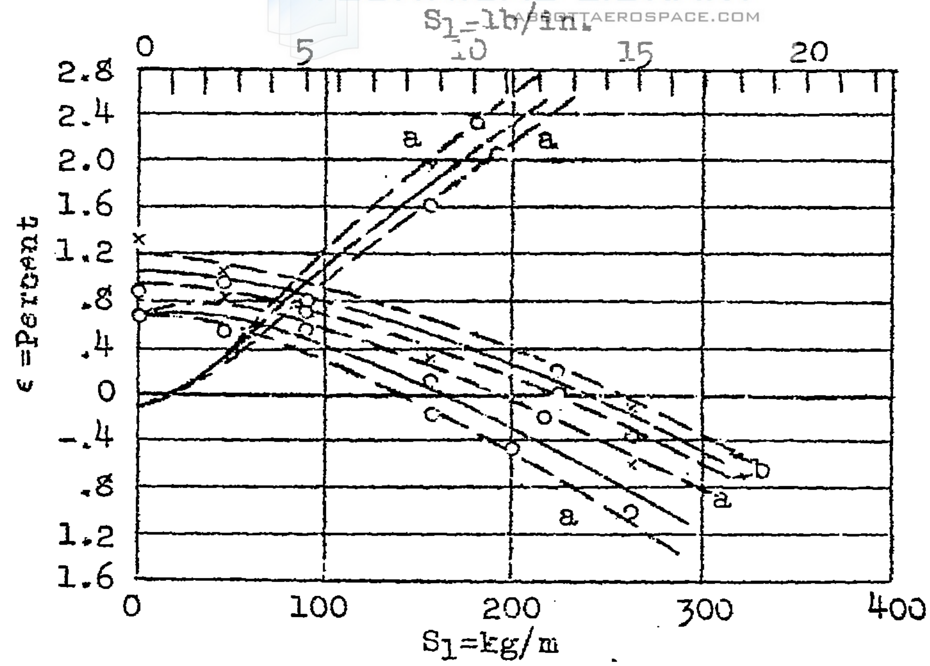
a=S_1=55.5 kg/m (3.11 lb/in.)
b=S_1=0 kg/m (0 lb/in.)
c=S_1=166.7 kg/m (9.33 lb/in.)
d=S_1=111.0 kg/m (6.22 lb/in.)
e=S_1=278.0 kg/m (15.57 lb/in.)
f=S_1=222.0 kg/m (12.43 lb/in.)
g=S_1=333.0 kg/m (18.65 lb/in.)

Fig.6 Normal characteristics of fabric W (Single-cross experiment, first loading)



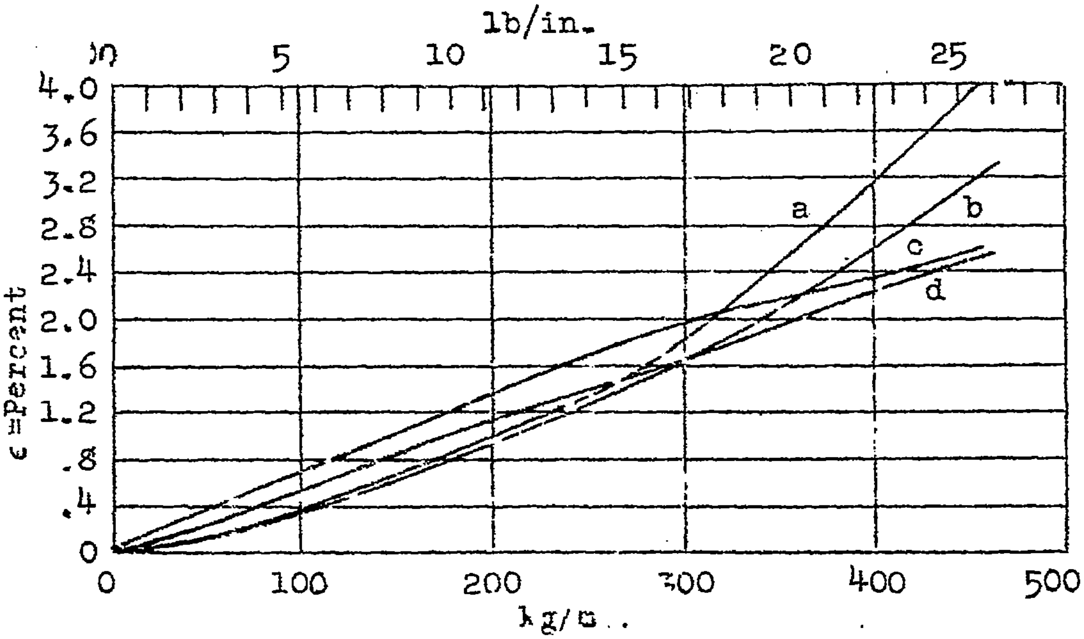
a=S_2=0 kg/m (0 lb/in.)
b=S_2=55.5 kg/m (3.11 lb/in.)
c=S_2=111.0 kg/m (6.22 lb/in.)
d=S_2=166.7 kg/m (9.33 lb/in.)
e=S_2=222.0 kg/m (12.43 lb/in.)
f=S_2=278.0 kg/m (15.57 lb/in.)
g=S_2=333.0 kg/m (18.65 lb/in.)

Fig. 7 Normal characteristics of fabric W
(Second loading)



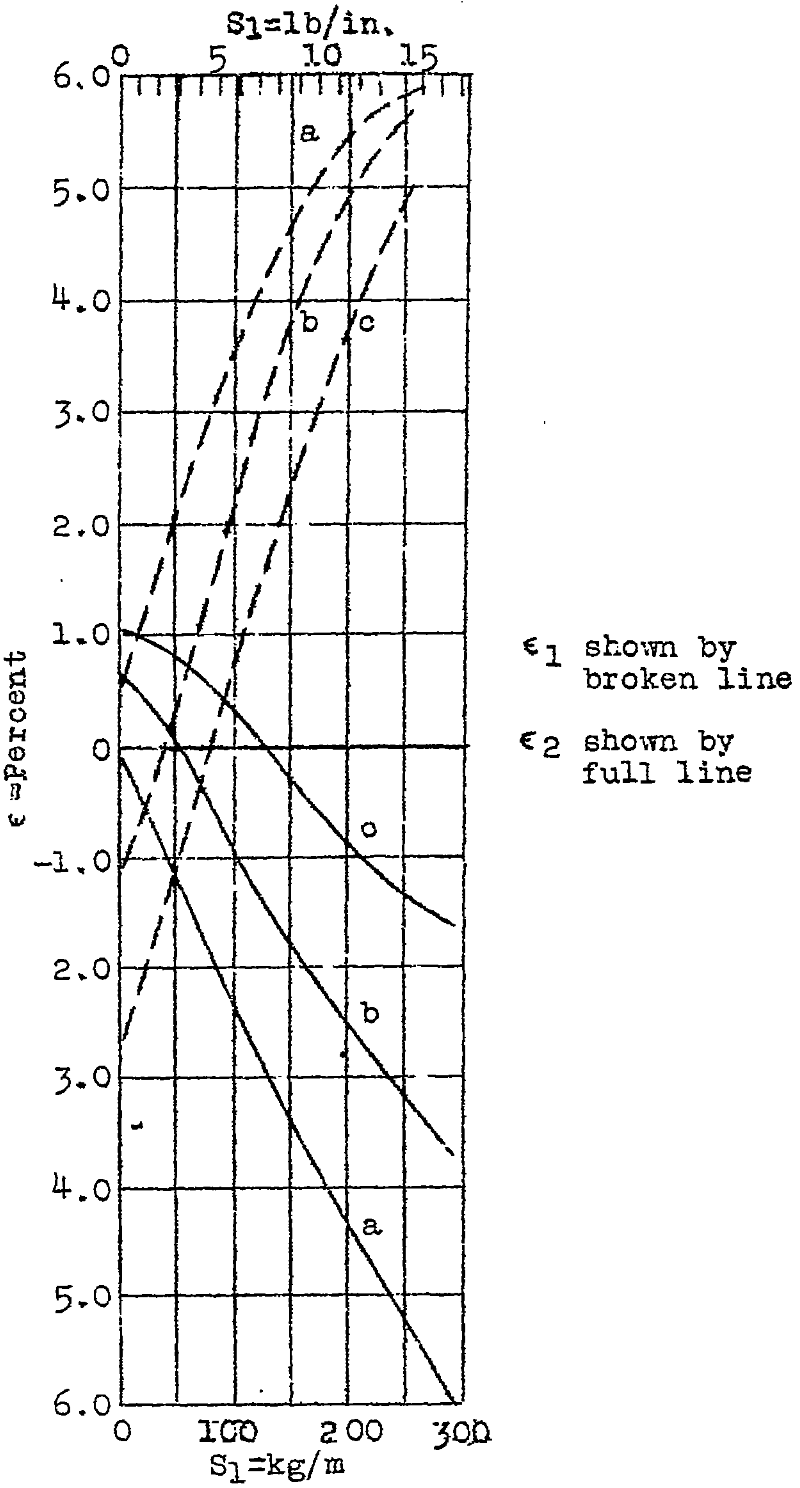
a=S_2=100 kg/m (5.60 lb/in.)
b=S_2=155 kg/m (8.68 lb/in.)

Fig. 8



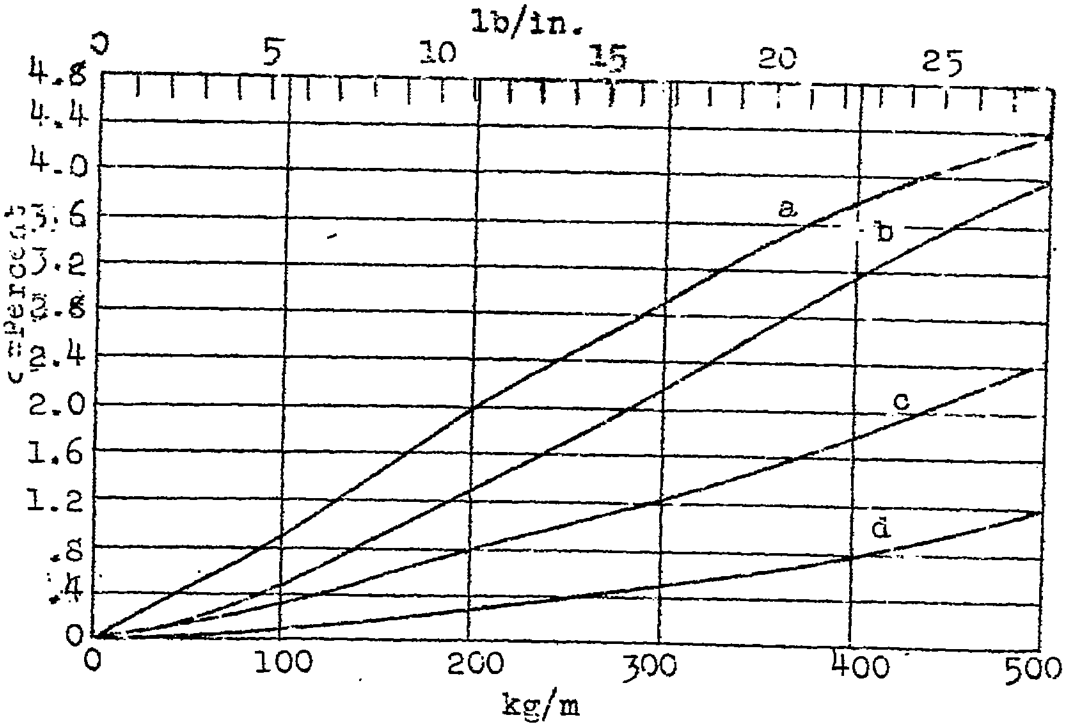
a=Doped 2 times and painted.
b=Doped 3 times
c=Doped 1 time
d=Doped 2 times

Fig. 10 Direction 1 filling



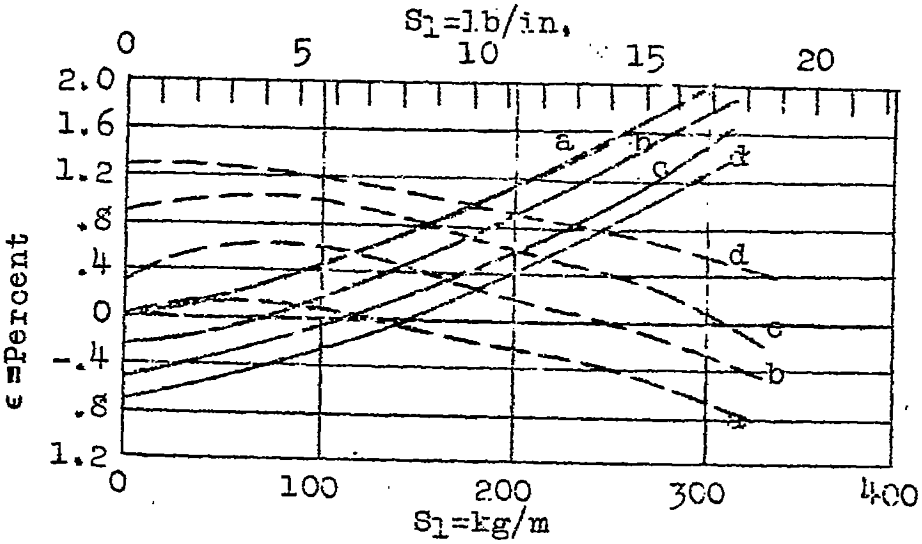
a=S_2=0 kg/m (0 lb/in.)
b=S_2=50 kg/m (2.80 lb/in.)
c=S_2=150 kg/m (8.40 lb/in.)

Fig. 9 Normal characteristics for undoped fabric



a=Doped 1 time
b=Doped 2 times
c=Doped 3 times
d=Doped 2 times and painted

Fig. 11 Direction 2, warp



a=S2=0 kg/m (0 lb/in.)
b=S2=117.5 kg/m (6.58 lb/in.)
c=S2=235.0 kg/m (13.16 lb/in.)
d=S2=353.0 kg/m (19.77 lb/in.)

Fig. 16

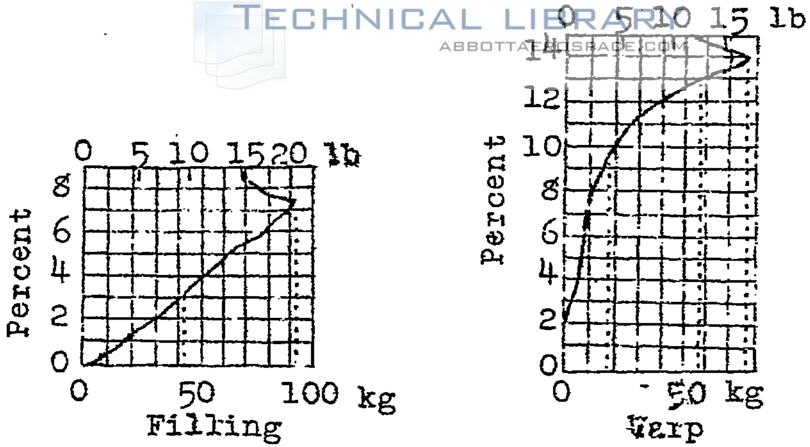


Fig. 12 Fabric W, undoped. Load on 0.1 m (3.9 in.) strip

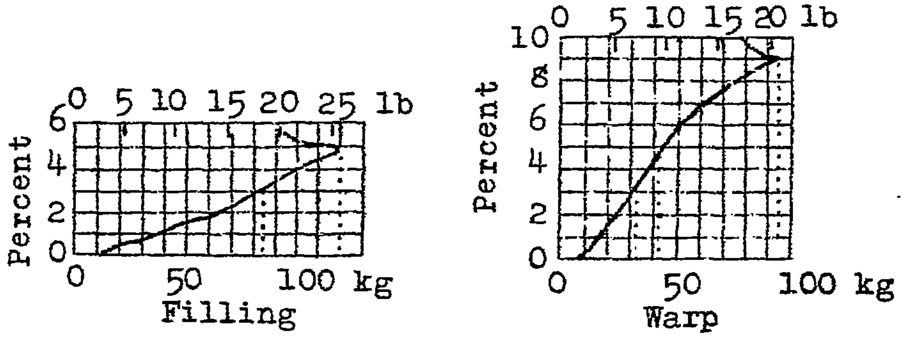


Fig. 13 Fabric W, doped 3 times. Load on 0.1 m (3.9 in.) strip

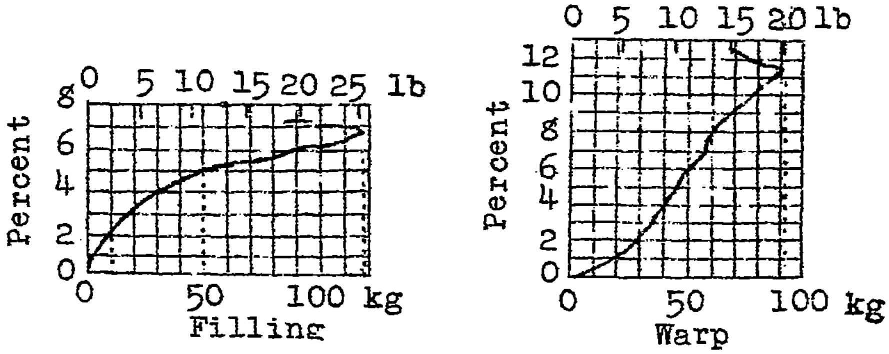


Fig. 14 Fabric W, doped 3 times, painted and varnished Load on 0.1 m (3.9 in.) strip

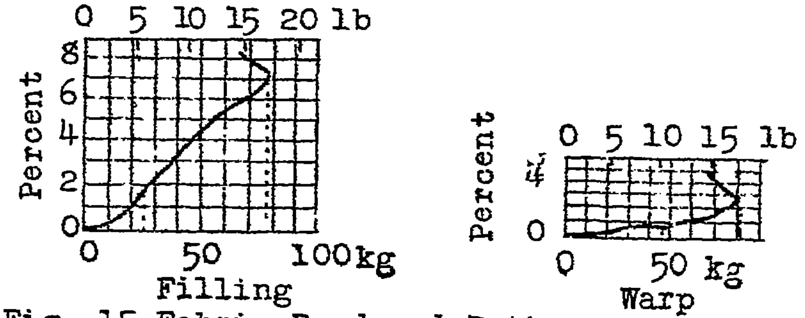
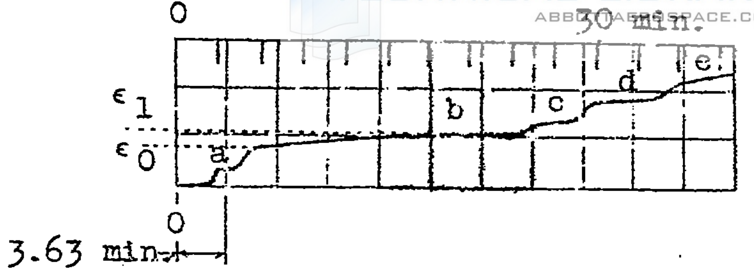


Fig. 15 Fabric B, doped 3 times, painted and varnished. Load on 0.1 m (3.9 in.) strip



a=V=10 kg (22.04 lb)
b=V=15 kg (33.06 lb)
c=V=20 kg (44.09 lb)
d=V=25 kg (55.11 lb)
e=V=30 kg (66.13 lb)
f=V=00 kg (0 lb)

Fig. 17 H=5 kg (11.02 lb)

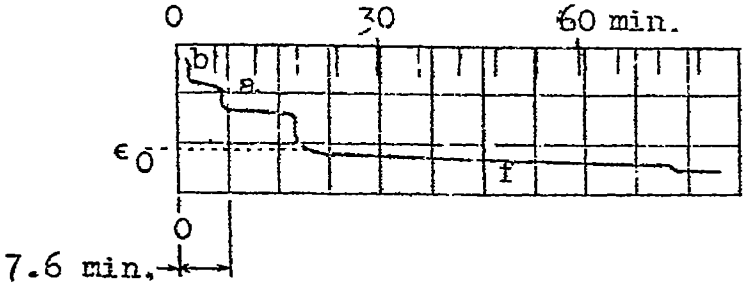
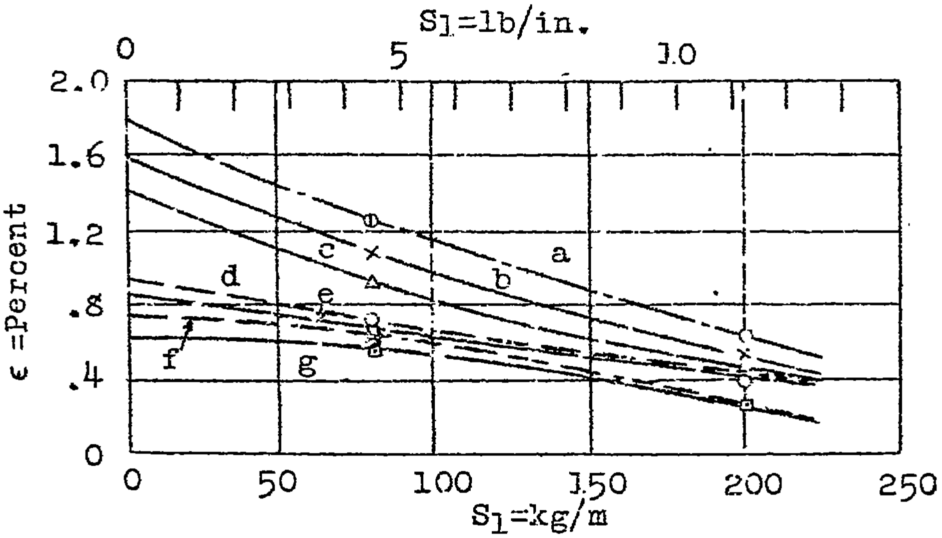
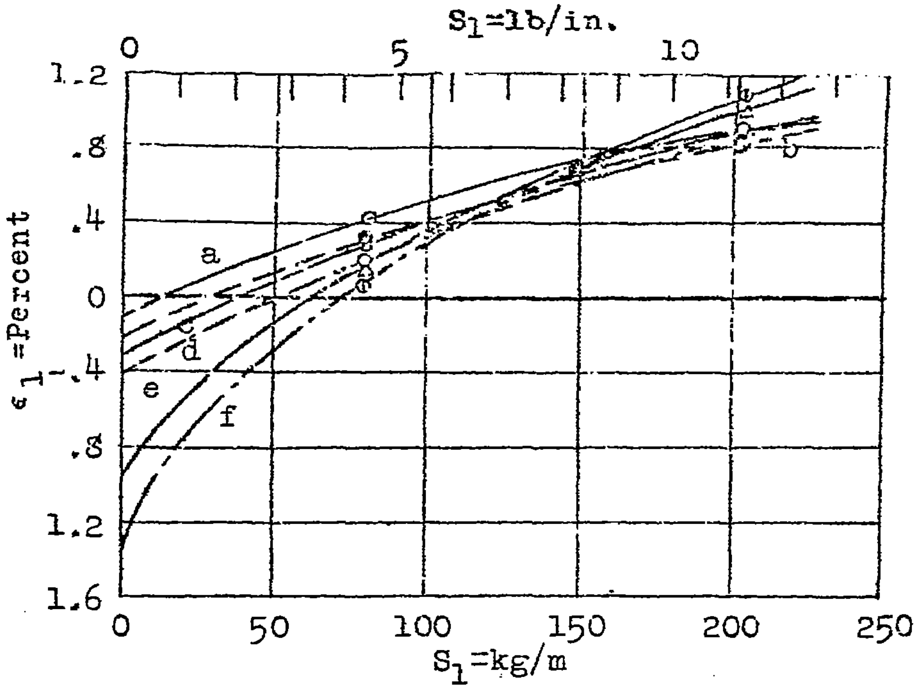


Fig. 18 H=25 kg (55.11 lb)



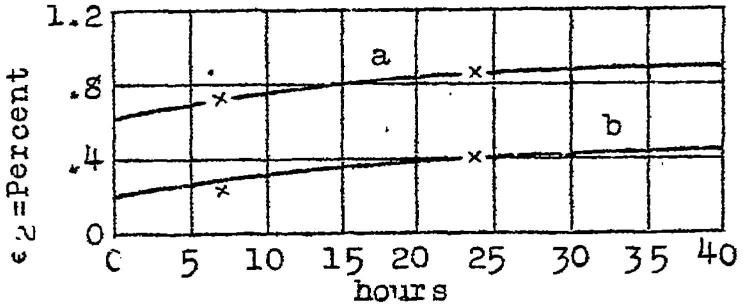
a=46 days
b=9.2 days
c=7.2 days
d=54 hours
e=23 hours
f= 6 hours
g=10 minutes

Fig. 19 S_2=200 kg/m (11.20 lb/in.)



a=.25 hours
b= 6 hours
c= 23 hours
d= 54 hours
e=7.2 days
f= 46 days

Fig. 20



a=S_1=0 S_2=200 ϵ_2
b=S_1=200 S_2=200 ϵ_2

Fig. 21

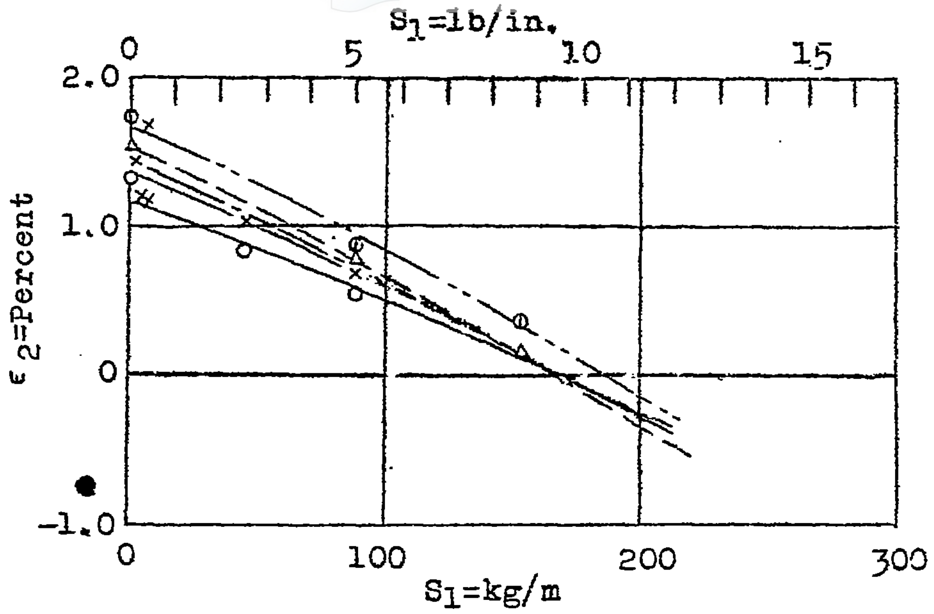


Fig. 22 S_2=100 kg/m (5.60 lb/in.)

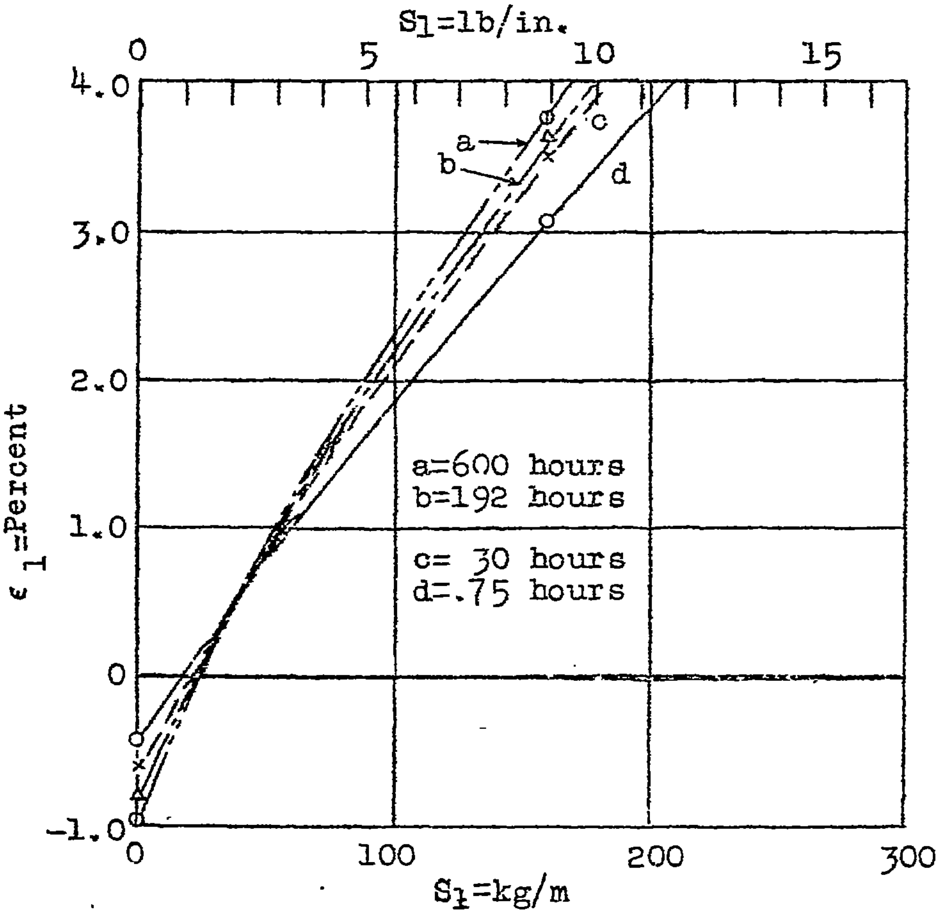
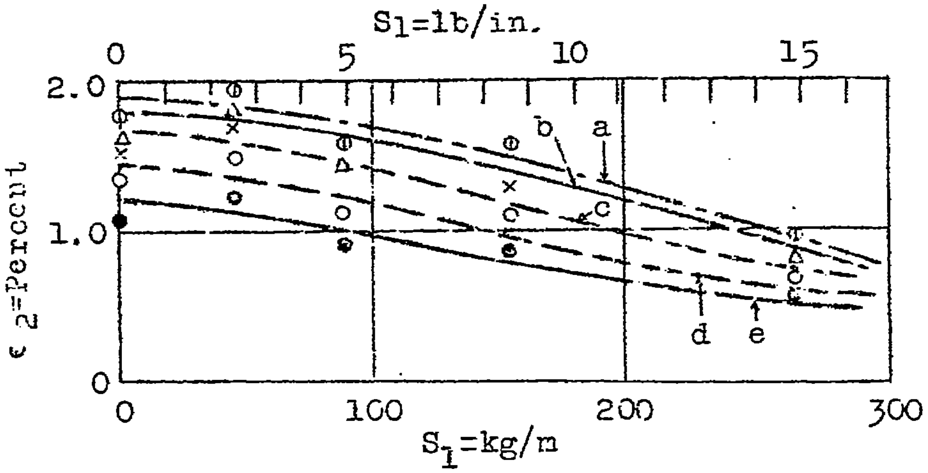


Fig. 23 S_2=100 kg/m (5.60 lb/in.)



a=242 hours
b= 79 hours
c= 55 hours
d= 25 hours
e=.25 hours

Fig. 24 S_2=267 kg/m (14.95 lb/in.)

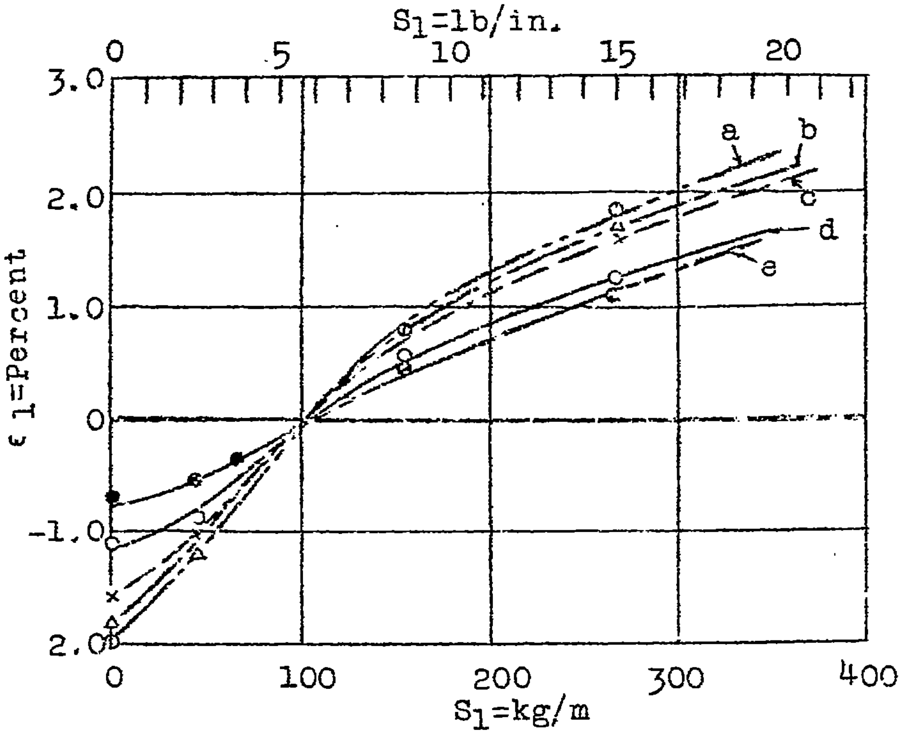
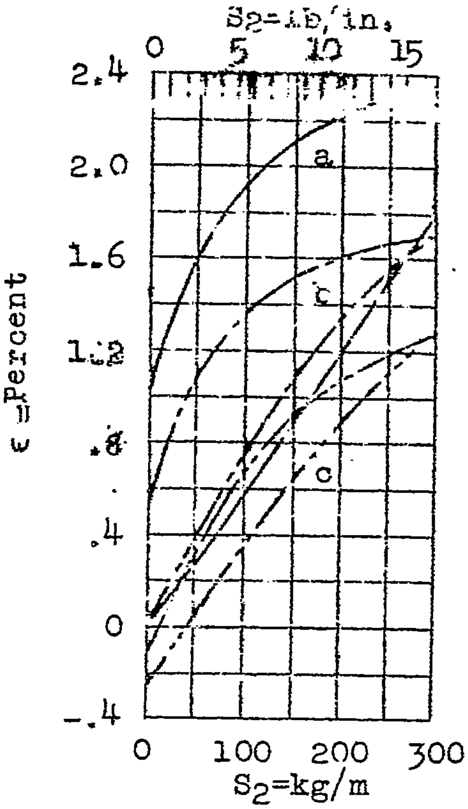
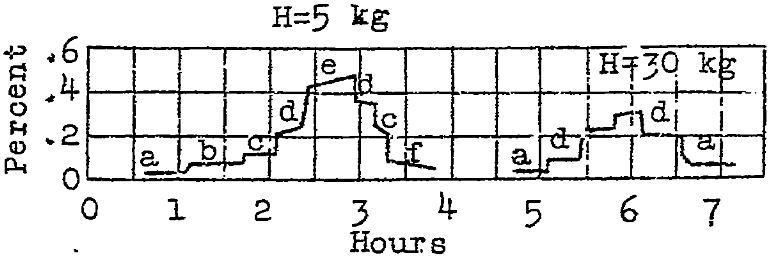


Fig. 25 S_2=267 kg/m (14.95 lb/in.)



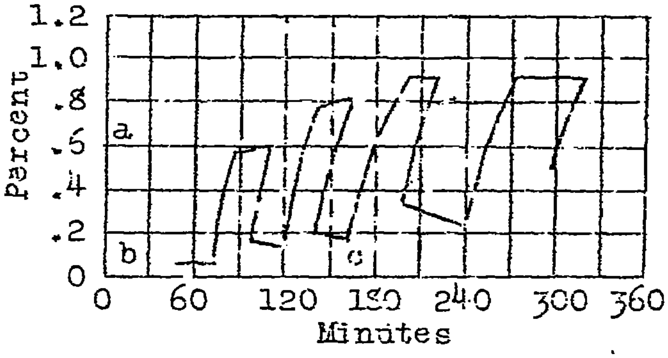
a=S_1=50 kg/m (2.80 lb/in.)
b=S_1=0 kg/m (0 lb/in.)
c=S_1=250 kg/m (14.00 lb/in.)

Fig. 26



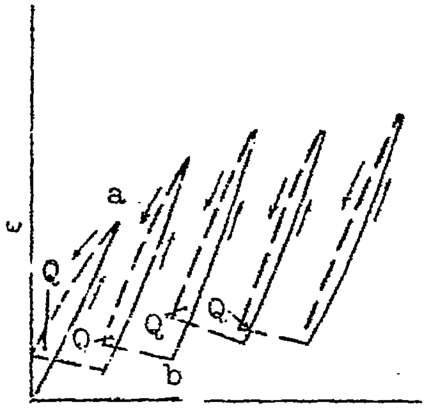
a=V=1 kg (2.20 lb)
b=V=5 kg (11.02 lb)
c=V=10 kg (22.04 lb)
d=V=20 kg (44.09 lb)
e=V=35 kg (77.16 lb)
f=V=0 kg (0 lb)

Fig. 27



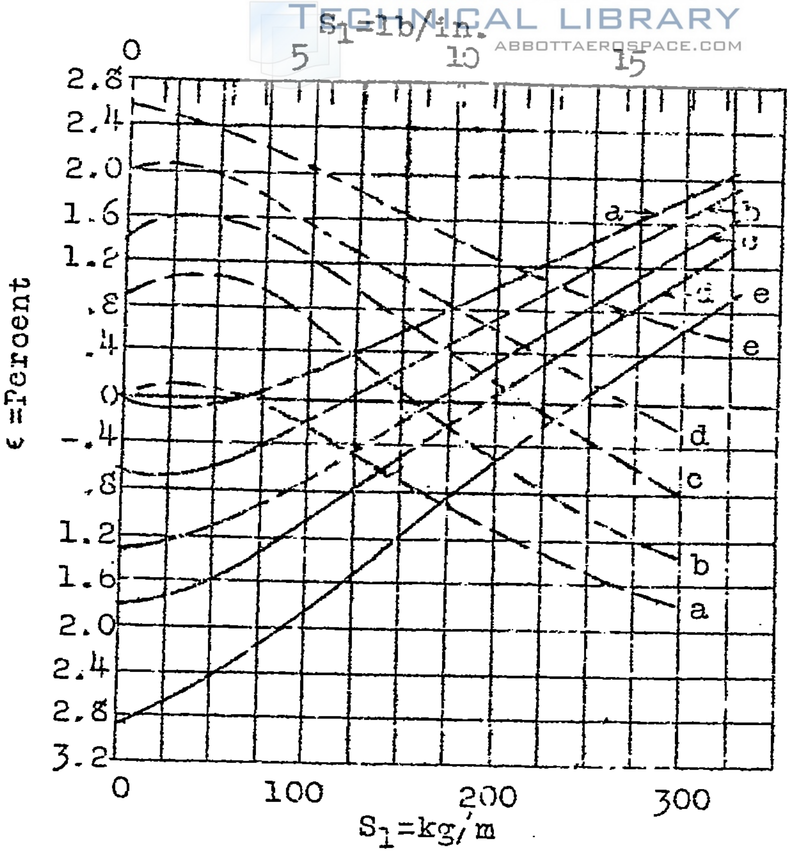
a=V=30 kg (66.14 lb)
b=V= 1 kg (2.20 lb)
c=H= 5 kg (11.02 lb)

Fig. 28



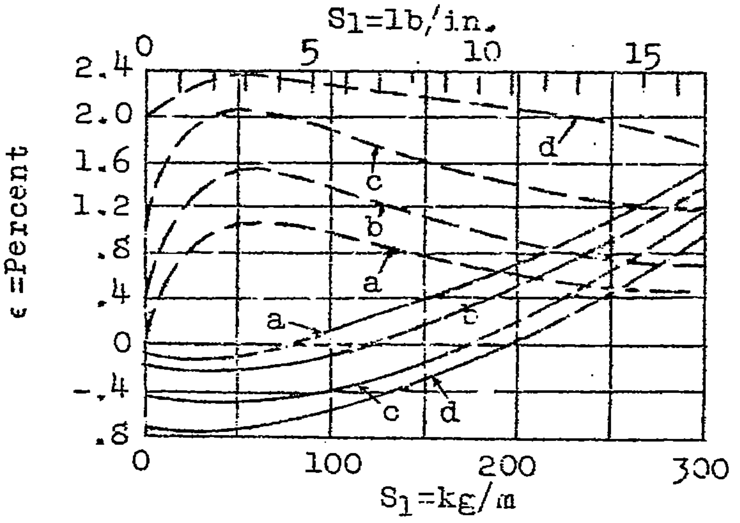
a=V=30 kg (66.14 lb)
b=H= 5 kg (11.02 lb)

Fig. 29 Successive hysteresis curves with half-hour recuperation intervals (Q is the end point for V=1 kg (2.20 lb)



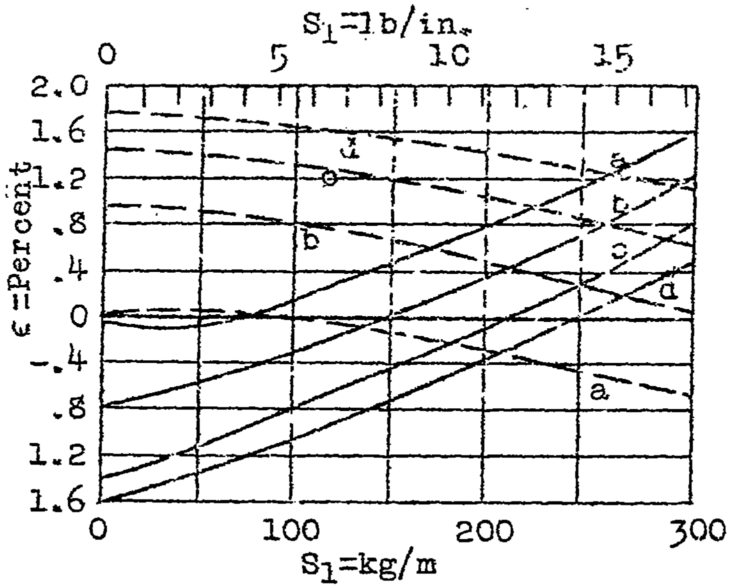
a=S_2=0 kg/m (0 lb/in.)
b=S_2=55.5 kg/m (3.11 lb/in.)
c=S_2=111.0 kg/m (6.22 lb/in.)
d=S_2=166.7 kg/m (9.33 lb/in.)
e=S_2=228.0 kg/m (12.77 lb/in.)

Fig.30



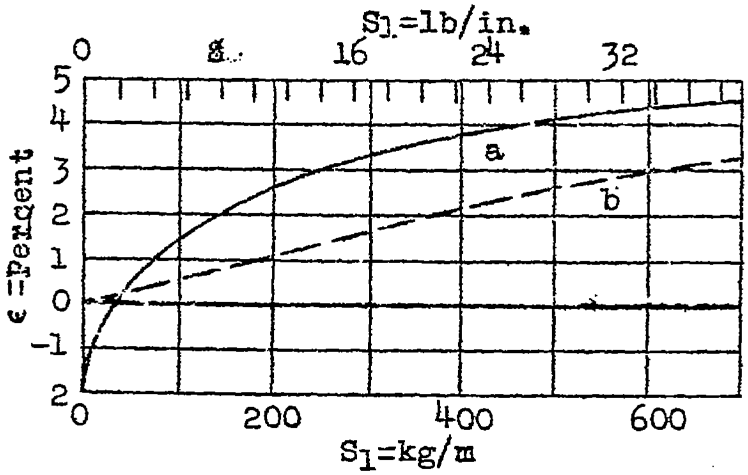
a=S_2=0 kg/m (0 lb/in.)
b=S_2=50 kg/m (2.80 lb/in.)
c=S_2=150 kg/m (8.40 lb/in.)
d=S_2=300 kg/m (16.80 lb/in.)

Fig.31



a=S_2=0 kg/m (0 lb/in.)
b=S_2=100 kg/m (5.60 lb/in.)
c=S_2=250 kg/m (14.00 lb/in.)
d=S_2=350 kg/m (19.60 lb/in.)

Fig. 32



a=damp b=dry

Fig. 33 Filling