Tensile Behaviour of Cotton Fibres

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IT has been stated[7,13,14,15], that the wet strength of a cotton fibre is greater than its dry strength. The tensile strength[14] of a viscose fibre in the wet state, on the other hand, is lower than that in the dry state. This being the case, there arises an anomaly as to why cellulose, as cotton, should behave differently from cellulose, as viscose. It is proposed in this article to judge the validity or otherwise, of the statement regarding the tensile strength of cellulose fibres, by considering the available data.

Cotton fibre[12], as defined by technologists, is that which "is a very fine, much elongated, single cell seed hair, which grows on the outside of a cotton seed." For a textile physicist, it is a bundle of cellulose chain molecules, held by lateral cohesive forces so as to present regularly oriented patterns at places where these forces are powerful, and disordered regions where the forces are relatively weak. When a load is applied to a cotton fibre at one end, while the other end being fixed rigidly, the fibre gains in length but at the same time, it suffers a lateral contraction. When the load is increased gradually, a stage will be reached when the fibre breaks and this breaking load per unit area of cross-section at break, is defined as the tensile strength of the fibre. Stress at any instant during loading is equal to the load (expressed as force, which is obtained by multiplying load by g, the acceleration due to gravity) per unit area of cross section, at that instant. Strain, in this case, is the ratio of the increase in length of the fibre to the initial length. The ratio of stress at break to the strain at break is called Young's Modulus or Modulus of Elasticity of the fibre, which represents the resistance of the fibre to extension, and is a fundamental physical property of the fibre. It is well-known that when an elastic material becomes plasticized, e.g. by the absorption of moisture in the case of a cotton fibre, its Young's Modulus decreases.

The three typical classes of high polymers[11], viz. rubbers, plastics and fibres are not intrinsically different in fundamental structure. Their apparently different behaviour seems rather to be a matter of degree concerning the magnitude of intermolecular forces and the capacity of the individual chains to fit into a crystal lattice. Strong intermolecular forces, combined with high tendency to crystallize, give typical fibres.

Cellulose is considered as an extraordinary assemblege of α-gluco-pyranose components, linked through 1:4-positions, and continued by reason of stereochemical arrangement of its primary valency bonds, as a straight chain of six atom ring units (Fig. 1)[16]. Like most of the high polymers[6], cellulose in the solid state seems to consist of two phases—one is geometrically highly organized, usually referred to as crystallized, ordered or miscellar state; the other in which a high degree of randomness prevails, is called amorphous or disordered state. Cellulose structure[3] is also considered "as a three-dimensional network of more or less parallel molecular chains" so arranged as to form crystalline or amorphous regions.

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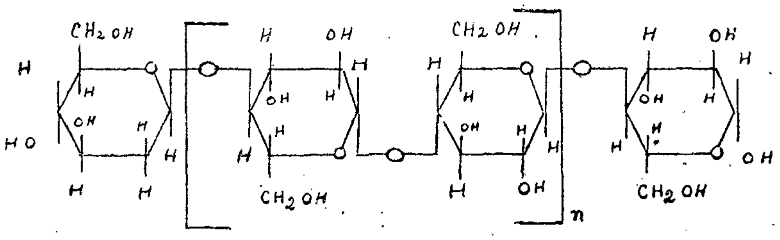

The crystalline and amorphous regions of cellulose should not be considered as separate and distinct regions. For, as Thomas Graham pointed out[1], "in nature there are no abrupt transition and distinction of class are never absolute". It is considered that one and the same molecular chain can go through a crystalline area, enter an amorphus portion, go through it, and enter another crystallite and so on.

Some of the factors, affecting tensile strength of cotton fibres, are discussed below. The most important among these is relative humidity. Before considering this, it is necessary to study cellulose-moisture relations. Filby and Maass[10] determined the absolute specific volume of cellulose by using helium gas and obtained a value of 0.64±0.001 c.c. The volume of the system cellulose-water vapour was found to be much smaller than that given by the components—cellulose and condensed water, as long as the adsorbed water was below 4%. With more than 8% adsorbed water, they had found out that the density of subsequently sorbed water was the same as that of the liquid water. A hypothesis was put forward in which it was stated that the water sorbed first is held by definite chemical combination with cellulose (hydration ?), considerable contraction being taking place. Subsequently sorbed water first causes an increase in cellulose surface with further consequent contraction in the volume of the two components and then filling up the so-called capillary spaces in which the water maintains its liquid properties.

Upto 1922, physical investigations on textile fibres had been chiefly confined to measurements of length, diameter and "breaking stress" and the measurements of true elasticity of fibres had, apparently, not been attempted. In that year, Barratt[2] devised a "fibre balance", which was designed for "the exact measurement" of breaking strength, extensibility and recovery from strain of individual textile fibres and the following results were obtained (Table I). Since the fibre is not a true solid throughout, so that a correct measurement of area, which varies along the length, is not possible and also the fibre is not perfectly elastic.

The investigations of Barratt were continued by Brown *et al.*,[4] who after modifying the "fibre balance", so as to maintain any desired humidity, studied the influence of humidity on tensile behaviur of cotton hairs. Sets of fifty load-extension curves were observed on Sakel and Texas cotton hairs, tested under dry, moderate and wet conditions. Other series of tests were also carried out on 2,000 hairs at various humidities. The influence of humidity on breaking load and on extension at break is shown in Fig. 2.

From this, it can be seen that the effect, on breaking load, of R.H. below 50% R.H. is considerable, while above 60% R.H., there is no appreciable change. The extension at break is affected in the same way.

Drawing load-extension curves for individual hairs, Brown *et al.*, found that curves obtained at one humidity vary in slope and in length, but have a fairly constant slope. An interesting feature apparent in the following curves (Fig. 3) is the convex upwards in the case of cotton. The form usually observed on imperfectly elastic material is concave, as in the case of viscose.

In studying elastic properties of textile fibres, Meredith[15] obtained stress-strain curves (Fig. 4) at 65% R.H. and 20°C, using cotton fibres of 1 c.m. test length. From these curves, he concludes that strong fibres have low extension at break. According to Meredith, the energy of elastic deformation may be stored in the fibre by one of the two mechanisms. Firstly, the atoms may be displaced from their potential troughs and after the removal of the tension, fall back again (as in glass), or secondly, primary valence chains may be straightened by tension and may return to their original shape as a consequence of thermal agitation (as in nylon). Cellulose corresponds to the first case.

In flax and Fortisan (Fig. 5), the degrees of crystallinity and molecular orientation are high, so that they show low extension at break and no slipping of the long molecules, which are securely anchored in the crystallites. Cotton shows a higher extension at break because the chain molecules spiral round the fibre axis (at an angle of about 30°) and the elongation of the spiral contributes to the extension. The average inclination[9] of the cellulose chains to the fibre axis is determined by Dulitskaya and Belenky for each of a wide range of cotton varieties by geometrical and photometric examination in the X-ray diffraction pattern. The values when plotted against the tensile breaking stress of the fibre (Kgm/sq.mm.) are found to be distributed about a straight line, low chain inclination being associated with high strength and *vice versa* (40°— 35kgm/sq.mm. ; 25°— 60 kgm./sq.mm.).

As shown in the figures (6) and (7), native cellulose fibres[15] (cotton) usually increase in strength (ability to take a load and not to withstand a stress) with increase in R.H., while artificial fibres—viscose, for example—decrease in strength. The decrease in strength of rayons is ascribed to the penetration of the water molecules, which weaken the lateral cohesion on which their strength depends. In other words, the lowering of tensile strength (usually 50-70%) of rayon in wet state is explained by assuming that the hydroxyl linkages between the adjacent cellulose chains in the amorphous region, held by various forces (Van der Waals and possibly, still weaker), depending upon their distances, are weakened by the lateral intrusion of water molecules or other low molecular (weight) compounds, such as methyl alcohol, ethyl alcohol, acetic acid, formic acid etc. The increase in strength of native cellulose fibres (cotton, ramie, flax), states Meredith, is due to the water in the amorphous regions, acting as a lubricant, releasing internal stresses in the long chain molecules, anchored to the crystalline regions and so increasing the strength by a more uniform internal distribution of stress.

The strength of a cotton fibre[13] depends on the length and orientation of molecular chains, on the strength of primary valency bonds along these chains, and on the secondary valency bonds across the chains. In Fig. 8, the relation between fluidity in cuprammonium solution and the strength of cotton fibres which have been acid tendered, is shown. Fluidity is an indirect measure of chain length and the curve indicates that strength decreases with decrease in chain length.

Fig. 9 shows the relation between molecular orientation and strength of cotton fibres.[13] In the figure, specific strength—defined as the ratio of the strength to the weight per unit length of cotton fibres—is plotted against double refraction, which is the difference between refractive indices when measured along and across the fibre axis.

Native cellulosic fibres[14] exhibit interesting relationships between elasticity and structure. Their modulus of elasticity is very high and was determined by Meyer and Lotmer by means of longitudinal acoustic waves. Drying, high tension, low temperature, and good orientation favour high values. Some of the values are given in the Table II. The fact, that the values for unoriented fibres are much lower, indicates that molecular process taking place during stretching differs from that occurring in oriented fibres. Unoriented fibres consist of a network of crystallites and chains in contact with each other and clinging together like threads in a macroscopic tissue. In this, texture determines the elastic properties.

Investigating the relation between the breaking load and the wall thickness of cotton hairs, Clegg[5] worked on a large variety of cotton hairs and obtained the following results (Table III). Here again, extension at break and cross-sectional area are not provided so that a rigorous mathematical treatment is not possible. From the figures it is clear that cotton, with approximately equal thickness, may have very different breaking loads and *vice versa*. No definite relation, concludes Clegg, between breaking load and wall thickness has been obtained due to the fact that it is the wall thickness at the actual point of rupture which is important, so that finer cottons with thinner walls need not necessarily possess low breaking "strains".

The tensile strength[14] of a native cellulose fibre is extraordinarily high. From the following values (Table IV) for the tensile strength of several other important materials, it is clear that it is only the finest steel possesses a much higher tensile strength than the best celluloses. A strikingly high value for the strength has been deduced from the primary valence chain structure of native fibres. In a fibre composed of primary valence chains of indefinite length, each extending over the whole length of the fibre, all the chains must be broken in the same region. From the projection of the unit cell, it follows that the cross-sectional area of a chain amounts to 32 sq. Å i.e. a fibre, 1 cm. in cross-section, will contain 3×10^{12} primary valence chains lying parallel to each other. We may suppose that the work necessary to rupture such a fibre is equal to the chemical work required to separate the organic primary valence linkage. This is of the order of 70 kgm. cal./mol. or 5×10^{-12} ergs for an individual primary valence chain, if we further assume this rupture at the oxygen bridge. Inter-atomic forces diminish very rapidly with distance and the potential energy of the two atoms displaced 2 Å (*Ca*) from their equilibrium, is only of the order of 1 kgm. cal. If we assume, as an approximation, that the separation of this amount occurs and that the force remains constant over this distance, the mean tensile strength can be calculated from the equation

$$\text{Work} = \text{force} \times \text{distance} \quad \ldots \ldots \quad (1),$$

the force necessary for the rupture of a primary valence chain (=work/distance),

$$\frac{15}{2 \times 10^{-8}} \approx 8 \times 10^{8} \text{ dynes/sq.mm.}$$

$$\approx 800 \text{ kgm/sq.mm.}$$

It is stated[14] that a more refined calculation by de Boer yields a value of 2000 kgm/sq.mm. The theoretical values for tensile strength considerably exceed the experimentally determined values and therefore we must assume that, in practice, the tension is not shared equally between the primary valence chains, as we have assumed above. The less the orientation, the less the number of chains and micellar threads simultaneously placed under tension and hence, less the tensile strength.

Since the theoretical tensile strength of a cotton fibre is considerably greater than the actual, it is clear that all the primary valence linkages do not break at the same place and it may be that the cellulose chain molecules slip against each other prior to complete breakdown. The tendency of slipping is reduced, if there are more number of sites in the chains providing lateral cohesion. In cellulose, these sites are hydroxy groups providing hydrogen-bonding forces.

When it is reported, in the literature, that the wet strength of cotton is greater than its dry strength, most of the investigators are unaware of the fact that they are not comparing cotton in the same state, i.e. when cotton takes up moisture, it is different from dry cotton, for moisture uptake alters the dimensions of the fibre and even the density of the fibre changes. Thus, for example, when a dry cotton fibre can take up a certain maximum load without rupture, the same load, when applied to a wet cotton fibre, whose diameter evidently increases due to moisture uptake, will be distributed over a larger area and therefore the wet fibre can take up a higher load than the dry fibre. If one wants to compare the wet and dry fibres with respect to their tensile strength, one has to consider the load per unit area at break in the two cases. This gives the actual tensile strength, which is the ability of the fibre to "withstand a stress" and not to "take a load".

Elastic measurements[8] are carried out by means of tension-testing machines. When interpreting results, the actual area of cross section during test is what is important. The error due to negligence of the decrease in the area of cross-section, resulting from stretching, is negligible in the case of metals where the extension is very small, but the error is not allowable in the case of organic fibres—cotton, for example. The actual tensile strength can be calculated provided breaking load (W), extension at break (Δl) and initial area of cross-section (A) are known and if we assume that during the test, the volume of the fibre does not change. If the test length is L, then the volume V is given by

$$V = A \times L \text{ ....} (2)$$

$$= A_1 \times L(1 + \Delta l) \text{ ....} (3)$$

$$\therefore A_1(\text{area at break}) = \frac{A}{(1 + \Delta l)} \text{ ...} (4)$$

and Actual Tensile Strength

$$= \frac{W(1 + \Delta l)}{A} \text{ ......} (5)$$

By applying this treatment, the actual tensile strength of cotton fibres is calculated below :

The following data[4] is provided by Brown *et al.*,:—(See Table V).

The hair weight of Sakel cotton at 70% R.H. is 149×10^{-8} gm./cm. Taking the external specific volume of the fibre at 0% R.H. as 0.65, the dry area of cross-section $= 89.3 \times 10^{-8}$ sq.cm. The increase in area is taken as 3% for 10% R.H. and 44% for wet (100% R.H.). Any value of F/E is converted to Young's Modulus (q) by the formula:

$$q = \frac{F}{E} \times \frac{g}{s} \times 100 \text{ dynes/sq. cm. ...} (6)$$

$$= \frac{F}{E} \times \frac{1}{s} \times \frac{0{\cdot}9814}{1} \times 10^6 \text{ dynes/sq.cm.}$$

If A_0, A_1 and A_2 are the actual areas of cross-section at relative humidities o, h_1 and h_2 respectively, we may take as an approximation, the following equations to hold good:

$$A_1 = A_0\,(1+\alpha h_1)\ldots\ldots\ldots\ldots(7)$$

and $$A_2 = A_0\,(1+\alpha h_2)\ldots\ldots\ldots\ldots(8)$$

α, being the "*humidity cœfficient*". Solving equations (7) and (8),

$$\frac{1+0\cdot03}{1+0\cdot44} = \frac{1+\alpha\times10}{1+\alpha\times100}$$

$$\therefore\ \alpha = 0\cdot004629$$

Using this value of α, the increase in area at different humidities is calculated and are given in Table VI (column 2).

To calculate the area of cross-section of the dry fibre, hair weight (gm/cm) and specific volume should be known (specific volume is 0.65 at 0% R.H.). From the Table II (First Series) it is seen that the hair weight is 149×10^{-8} gm./cm. If A is the dry area of cross-section,

Mass = length × area × density ... (9)

$$i.e.\ 149\times10^{-8} = 1\times\frac{A_0}{0\cdot65}\times1\cdot44$$

$$A_0 = 67\cdot24\times10^{-8}\ \text{sq. cm.}$$

Assuming that there is no change in volume on stretching, the equation (4) gives the actual area of cross-section at break:

$$A_1 = \frac{67\cdot24\times10^{-8}\times1\cdot44}{1+0\cdot09}$$

$$= 88\cdot86\times10^{-8}\ \text{sq. cm.}$$

Actual tensile strength:

$$= \frac{5\cdot3}{88\cdot86\times10^{-8}}\ \text{gm/sq.cm.}$$

$$= 59\cdot65\ \text{kgm/sq. mm.}$$

Following on similar lines, the columns 6, 7, 8 and 9 of the Table VI are constructed. The last column gives Young's Modulus at various humidities. From the column 9, it is clear, that the wet strength (at 100% R.H.) is greater than the dry strength, if we compare the tensile strength of cotton fibres in wet and dry states. It is also clear that the strength goes on increasing with R.H. from 0% R.H., reaches a maximum at a certain R.H. and then decreases. But the Young's Modulus, as is seen, decreases continuously as R.H. increases from 0% to 100%. If we measure strength with respect to Young's Modulus, the wet strength of cotton fibres is definitely lower than the dry strength.

For a correct interpretation of data on tensile strength measurements, the hair weight, the breaking load, extension at break, initial area of cross-section at all humidities, at which the measurements are made, should be known. Without this complete picture, no definite conclusions may be arrived at.

TABLE I[2]

Fibres	Breaking strength (gm)	Extension (%)
Bog-cotton ...	4.7	2.4
Viscose	10.8	14.5

TABLE II[14]

Material	Modulus of Elasticity (kgm/sq. mm.)
Native Flax	8,000 to 11,000
Native Hemp	6,000 to 8,000
Native Ramie	5,000 to 7,000
Viscose (damp)	135
Viscose (dry)	1,170
Viscose (oriented)	3,400

Table III[5]

Cotton	Breaking load (gm)	Wall thickness (μ)
Durango (Annual) ...	4.5	4.4
Durango (Ratooned) ...	3.8	3.8
Queensland	4.8	4.8
Texas	6.2	5.0
Bengal	7.1	7.7
Peruvian	8.3	6.1
Sakel	5.5	3.7
Sea Island	4.9	3.2
Zaria	5.7	4.3
Punjab-American ...	4.9	4.1
Punjab-American ...	6.8	4.5

Table IV[14]

Material	*Tensile strength (kgm/sq.mm.)*
Cast Iron	10 to 20
Hardened steel spring ...	60 to 300
Copper wire	45 to 50
Lead	2 to 2.5
Silk	35 to 60
Cotton	20 to 80
Irish Flax	> 100

Table V[4]

Effect of Humidity on the Breaking Load and Extension of Single Cotton Hairs at 19°C (Sakel cotton)

Relative Humidity	Breaking Load (gm) F	Extension at Break (%) E	Hair wt. (gm/cm.) × 10^{-8}
	First Series, 200 tests		
100	5.30	9.00	149
77	5.55	8.81	,,
44	5.06	7.58	,,
15	3.63	5.76	,,
	Second Series, 200 tests		
100	5.60	9.63	133
66	5.12	8.76	,,
15	3.30	5.26	,,
	Third Series, 200 tests		
100	5.38	9.54	143
66	5.30	9.10	,,
15	3.53	5.65	,,

Table VI

R.H. (%)	Increase in area of cross-section (%)	Breaking Load (gm) F	Extension at break (%) E	Hair weight (gm/sq. cm.) × 10^{-8}	Initial area of cross-section (sq. cm.) × 10^{-8}	Area of cross-section at break (sq.cm.) × 10^{-8}	Apparent Tensile Strength (kgm./sq. mm.)	Actual Tensile Strength (kgm/sq.mm.)	Young's Modulus (gm/cm. sec.^{2}) × 10^{11}
100	44.0	5.13	9.00	149	96.84	88.86	54.72	59.65	6.506
77	35.4	5.55	8.81	,,	91.06	86.21	60.95	64.37	7.171
44	18.5	5.06	7.58	,,	79.70	75.83	63.49	66.73	8.640
15	5.3	3.63	5.76	,,	70.81	68.36	51.26	53.10	9.260
100	44.0	5.60	9.63	133	86.45	78.87	64.77	71.00	7.239
66	28.5	5.12	8.76	,,	77.13	70.90	66.37	72.23	8.009
15	5.3	3.30	5.26	,,	63.21	60.03	52.20	54.96	10.260
100	44.0	5.38	9.54	143	92.94	84.85	57.90	63.40	6.524
66	28.5	5.30	9.10	,,	82.91	76.01	63.91	69.73	7.510
15	5.3	3.53	5.65	,,	67.94	64.29	52.07	54.91	9.542

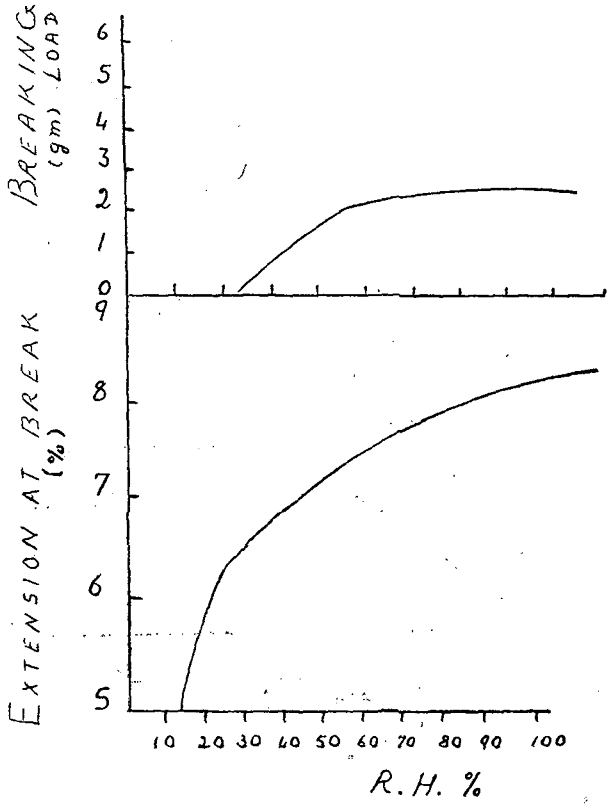
BREAKING (gm) LOAD
6
5
4
3
2
1
0
EXTENSION AT BREAK (%)
9
8
7
6
5
10 20 30 40 50 60 70 80 90 100
R.H. %

Fig. 2.

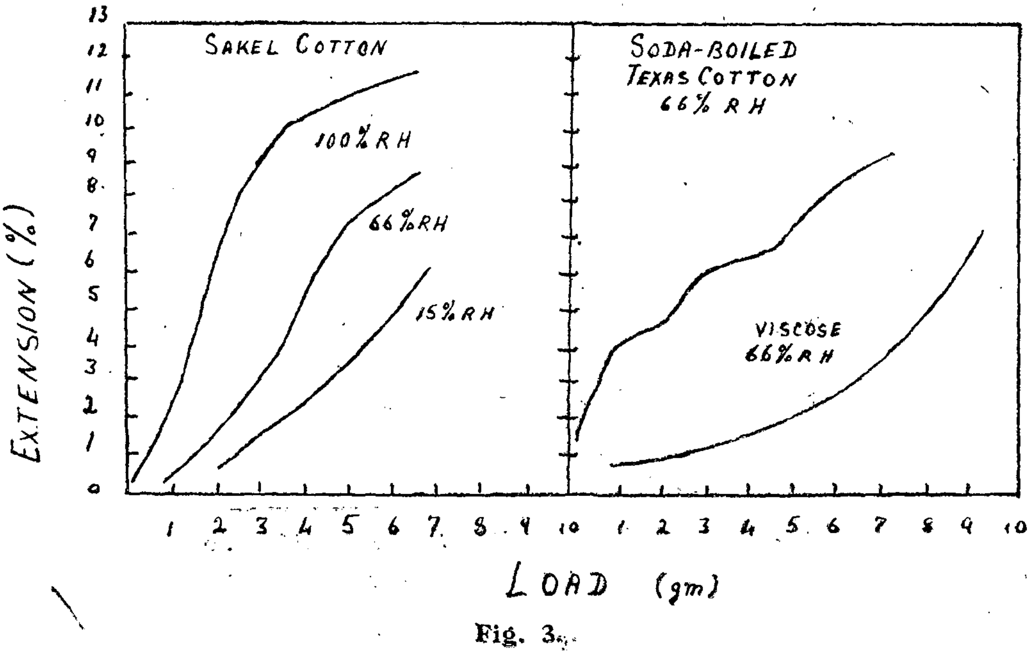
EXTENSION (%)
13
12
11
10
9
8
7
6
5
4
3
2
1
0
SAKEL COTTON
100% RH
66% RH
15% RH
SODA-BOILED TEXAS COTTON 66% RH
VISCOSE 66% RH
1 2 3 4 5 6 7 8 9 10
1 2 3 4 5 6 7 8 9 10
LOAD (gm)

Fig. 3.

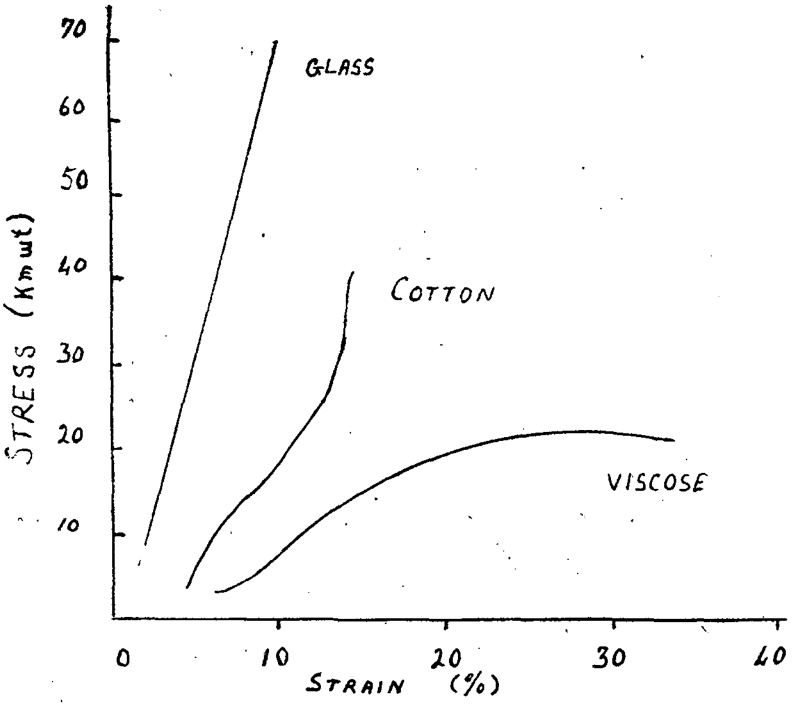
70
60
50
40
30
20
10
STRESS (Kmwt)
0
10
20
30
40
STRAIN (%)
GLASS
COTTON
VISCOSE

Fig. 4.

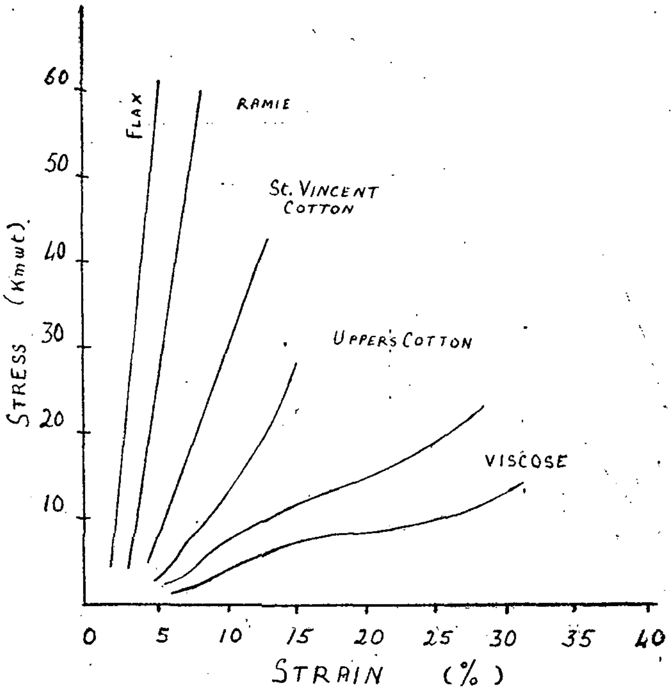
60
50
40
30
20
10
STRESS (Kmwt)
0
5
10
15
20
25
30
35
40
STRAIN (%)
FLAX
RAMIE
St. VINCENT COTTON
UPPER'S COTTON
VISCOSE

Fig. 5.

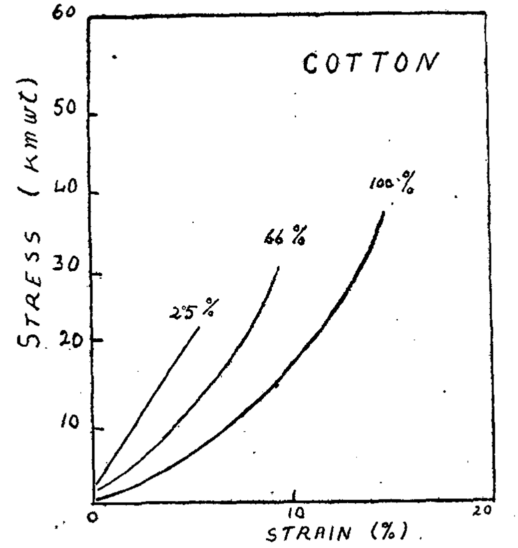

Fig. 6.

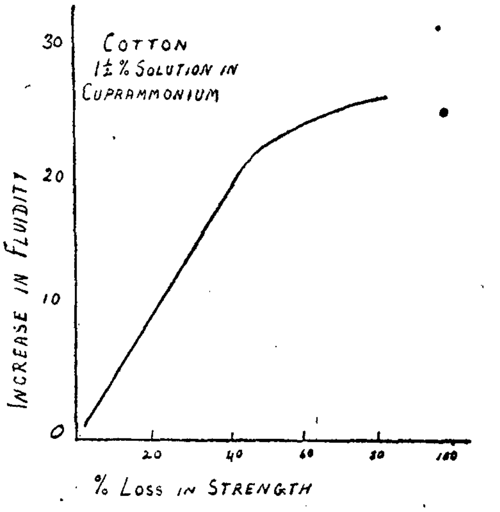

Fig. 8.

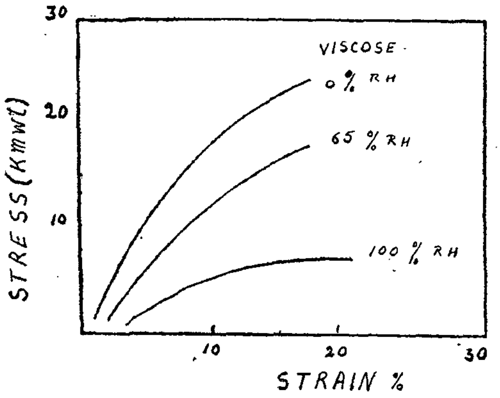

Fig. 7.

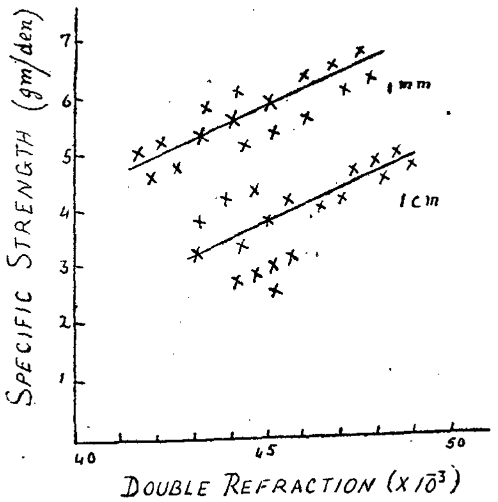

Fig. 9.

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