THE FRICTIONAL BEHAVIOUR OF ANIMAL FIBRES

AND

ITS RELATION TO SOME TECHNICAL PROCESSES.

T H E S I S

presented to

THE VICTORIA UNIVERSITY OF MANCHESTER

for the Degree of

DOCTOR OF PHILOSOPHY

by

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January 1948.

ACKNOWLEDGEMENTS.

Tha author wishes to express his gratitude to Mr.J.M.Preston, B.Sc.,F.R.I.C.,F.T.I., Lecturer in the Department of Textile Chemistry, for his most valuable guidance and assistance; to Mr.F. Scholefield, M.Sc.,F.R.I.C.,F.T.I., Head of the Department of Textile Chemistry, for his continued interest and encouragement.

The author also sincerely thanks Dr.W.S.Shaw, D.Sc., Ph.D., F.R.I.C., Director of Porritts and Spencer Limited, for his friendly and generous support. The facilities granted by the above Company are also gratefully acknowledged.

The present work was carried out during the tenure of the MacLaren Research Scholarship and the Wool Research Scholarship founded by the International Wool Secretariat to whom the author is greatly indebted.

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INTRODUCTION.

The interest which attaches to the friction of animal fibres arises from the fact that they possess two coefficients of friction according to the direction of rubbing, the frictional resistance being greater on rubbing from tip to root than from root to tip.

This frictional asymmetry, which is also referred to as the differential frictional effect and which is not observed with any other class of fibres, is associated with the unique surface structure of animal hair, the surface consisting of a sleeve of imbricated cuticular scales all pointing in the same (tipwards) direction.

However, the mechanism by which this structure gives rise to frictional asymmetry was obscure when the present work was undertaken, for it had been shown by Martin that the plain ratchet mechanism is untenable on many grounds; similarily, Martin's alternative theory, ascribing the differential frictional effect to the peculiarities of the molecular structure on the scale surface, had been disproved by the work of Speakman and his collaborators and Mercer and his co-workers.

Apart from its great theoretical interest the problem of the mechanism of the frictional asymmetry is also of considerable technical significance, for the differential frictional effect is the primary cause of the felting power of animal fibres, which property forms the basis of several important processes.

The present work has been concerned with the fundamental problem of the frictional asymmetry of animal fibres. It has been thought that the matter may be elucidated in terms of the fluid film theory of lubrication, and this has led to the putting forward of a hypothesis interpretating the friction of animal fibres on this basis. The experimental work, both on friction and on felting, has proved the correctness of this approach, and it has thus been possible to postulate a theory which appears to interpret satisfactorily the frictional asymmetry of animal fibres.

The thesis begins in Chapters 1 and 2 with reviews of the published work on the felting process and the friction of animal fibres, respectively, These are followed in Chapter 3 by a discussion of lubrication theory and its applicability to the frictional properties of animal fibres. The experimental part, which follows in Chapters 4 - 7, consists of the description of the new apparatus for measuring fibre friction in Chapter 4, the presentation of the frictional results in Chapter 5, the examination of the felting process in the light of the observations on friction in Chapter 6 (where a new method of assessing the felting power is described), and the experimental results on the felting behaviour of wool fibres in Chapter 7. The first part of the discussion (which is given in Chapter 8) is concerned with the friction of animal fibres, whilst the second part deals with the felting process in relation to the frictional properties.

CHAPTER 1.

REVIEW OF THE FELTING PROCESS.

THE FELTING OF WOOL.

General Definition.

Felting is a phenomenon, peculiar to animal fibres, which is brought about by subjecting the mass of fibres to the action of suitable mechanical forces in the presence of aqueous solutions. When this is done the fibre mass becomes entangled and consolidated. The reason for this is the facility for uni-directional motion of individual fibres, which, in conjunction with the external mechanical forces, causes the fibres to migrate. The facility for uni-directional motion is due to the characteristic surface properties of animal fibres. These possess different coefficients of friction according to whether they are rubbed from tip to root or from root to tip, the difference being often referred to as the 'Differential'-or the 'Directional Frictional Effect'.

Importance.

The felting property is operative in several important techni-cal processes involving animal fibres, and wool fibres in particular, namely the manufacture of felts, the milling or fulling of wool cloths, and it is principally responsible for the undesirable shrinkage of woollen materials in washing.

Thus whilst on the one hand, as in the first two instances, the felting property is harnessed so that it gives rise to an important and characteristic class of fibrous materials (felts) and to a large variety of equally important and distinctive finishes on wool cloths (through milling or fulling), on the other hand the felting shrinkage which occurs in the washing of woollen goods is probably the most serious single drawback in the utilization of wool.

Historical. Encyclopaedia Britannica (1) reports that processes based on the felting property of animal fibres were already known in anitiquity (two well preserved 'fulleries' can still be seen in Pompeii, where men stood 'walking' the cloth), and it is obvious therefore that in common with so many other manufacturing techniques the felting processes achieved the present forms through centuries of empiricism.

The mechanical methods were introduced gradually during the second half of the 18th and the first half of the 19th century, and it was probably under this impact and in the new spirit of scientific inquiry that for the first time the phenomenon of felting of animal fibres began to be the subject of investigations.

Early Literature. The early literature is, however, scattered and unsystematic. Although most authors were concerned mainly with points of manufacturing techniques, some of them also discussed the nature of the felting process, albeit in a very speculative manner and without any clear experimental basis.

Whilst the connection between felting and the frictional properties was suggested as long ago as 1790 by Monge in his 'Observations sur la mecanisme du feutrage'(2), this view appears to have been completely disregarded for almost a century. In the intervening period a multitude of publications appeared, which attributed felting to various other causes.

Thus, for example, in 1837 Jotemps, Faby and Girod (3) and in 1885 Bowman (4) put the main emphasis on the tendency of wool to curl, whilst in 1888 Witt(5) suggested that felting is due to the actual interlocking of scales of contiguous fibres. This latter view, although quite unacceptable to anyone who examined felted wool microscopically when no scale interlocking can be detected, has nevertheless persisted for very long time and it is not uncommon to find it expressed even today in less specialized publications.

Gelatinisation of the fibre surface resulting in the adhesion of contiguous fibres was held to be the primary cause of felting by Zacharias (6), Justin Muller (7), Rinoldi (8) and Ganswindt (9).

Also a theory of direct chemical combination was advanced, namely in 1923 by Becke (10) who suggested that the alkaline felting agents cause a breakdown of the peptide linkages by hydrolysis with the result that a new bond could be formed between two molecules, each belonging to a different fibre. This peculiar theory has recently been revived by a Japanese worker, Ishida (57).

The fundamental observation of Monge (2) was that on rubbing from tip to root the friction of wool or hair is greater than on rubbing in the opposite direction, i.e.from root to tip. He thought that the cause of this phenomenon was that the fibre surface was covered with imbricated scales, by analogy with ear of barley. Monge further demonstrated that when rubbed between two fingers a wool fibre or a hair will creep in the direction of its root, i.e. in the direction of lower friction, and suggesting that similar migration takes place in felting he considered this to be the cause of the felting phenomenon.

This point of view, although in a modified form, was then taken up by a number of authors at the end of the last and at the beginning of the present century, e.g. Ditzel (11), Löbner (12), Fiske (13), Reiser (14), and Shorter (15) who all agreed that felting arises in consequence of the uni-directional freedom of motion of the fibres.

Modern Theories.

Arnold:-Differential Friction & Plasticity.

The first systematic study of the problem appears to have been carried out in 1929 by Arnold in Germany (16), who in the light of his findings on the felting behaviour of loose wool fibres and their swelling and plastic properties postulated the so-called 'earthenworm theory'. According to this view, in felting fibres creep forward in the direction of their root ends owing to their peculiar frictional properties, but since most of them are entangled they do not possess complete freedom of motion, and the creep occurs therefore by local extension followed by contraction, in the manner of the movement of an earthenworm.

Speakman et al.: Differential Friction & Elasticity.

In 1931 the problem of felting was taken up at Leeds by Speakman and his collaborators (17,18) who must be credited with the first thorough and far-reaching examination of the phenomenon.

Having measured the difference between friction in the two directions of rubbing for a large number of different types of wool and having failed to establish a strict direct relationship between the differential frictional effect and the felting power of these wools, they concluded that other factors, apart from the frictional properties, must be taken into account in determining the felting power of wool. From this there followed a long series of important experiments which dealt in turn with the influence in felting of gross structural properties of wool, swelling, pH, temperature and elastic properties. (All these points will be discussed separately later).

As a result of this work Speakman et al. put forward a theory according to which

> "shrinkage of wool fabrics in a milling machine is due to the peculiar mode of migration of the component fibres. Because of their surface scale structure the fibres tend to migrate in the direction of their root ends under the repeated application of pressure but free migration is impossible in a fabric owing to the restraints imposed by twist in the yarns and their interlockings with one another. Migration is achieved by local extension and contraction of the fibres, and milling shrinkage is promoted by conditions which favour these processes".

This view, which is not dissimilar from Arnold's, places particular stress on the elastic properties of the fibres, for, according to Speakman and his collaborators, the existence of critical temperature and pH in milling can be accounted for on the basis of the ease of deformation and power of recovery of wool fibres.

New emphasis on friction.

Whilst fibre elasticity undoubtedly plays an important role in felting, it was shown by Bohm (20) that there is a correspondence between the effect of pH on the rate of felting and its influence on the magnitude of the differential frictional effect. This observation was confirmed by Mercer (23) and in part by Whewell, Rigelhaupt and Selim (56), which demonstrated that chnages in the frictional properties may also account for the differences in the rate of felting, it being assumed that, with other factors constant, the rate of felting is proportional to the difference between the two coefficients of friction (which is the driving force causing migration).

Moreover, Mercer also found (22), in the case of yarn felting, certain significant discrepancies between the observed shrinkages and those to be expected from the theory that fibres stretch and contract during migration, although it must be borne in mind that Speakman's theory refers more particularly to the felting of fibres in woven fabrics and not in looser states of aggregation such as yarns.

In view of these observations it became clear again that the frictional properties play the principal and most fundamental role in felting, and they have formed therefore the centre of most of the recent work on these pro-blems, the interest in which has been increased by the publications of Martin's (21) unorthodox views on the cause of the differential friction in keratin fibres.

Before discussing the literature on the friction of animal fibres it is necessary, in order to present a complete picture of the phenomenon, to consider some of the other aspects and factors which influence felting, viz.

1. Structural Properties of Wool Fibres.

(a) Length.

Speakman, Stott and Chang (18) found that in the case of Merino wool felting power increased with decreasing fibre length, whereas with Wensleydale wool decreasing fibre length led to the opposite effect, i.e. to an increase in felting power. This difference in behaviour of the two varieties of wool was attributed by Speakman and Sun (24) to the greater crimp and 'scaliness' (which was not measured) of Merino fibres. They believed that the relationship between fibre length and milling properties is a complex function of both yarn and fibre characteristics.

The observations reported by Boxser (25) and Nitschke (26) are cofflicting, for the former maintained that the felting power is greater with shorter fibres, whilst according to Nitschke the longer the fibres the greater their felting power.

(b) Fineness.

There appears to be a general agreement among the various authors that felting increases with fibre fineness.

(c) Crimp.

The importance of crimp was often stressed by the early writers, and recently this tendency of wool to curl was discussed in detail by Milton Harris (27) who considered, on qualitative grounds, that it contributed materially to the felting power of wool.

(d) Twist.

This was investigated recently by Freney, Deane and Anderson (55) who thought that the potential torsional forces which are always present in the fibre and which are released on wetting will play a part in felting.

(e) Differential Friction.

This will be dealt with in detail in the next Chapter but some of the data published which are relevant here will be mentioned now.

(i) Differential Friction and Wool Quality.

In the absence of complicating factors, the milling power of wool appears to be directly related to its differential frictional effect as measured in the appropriate milling media. This was found by Bohm (20), and Speakman and Stott's results (17) showed a similar broad parallelism.

(ii) Differential Friction and pH.

There is no doubt that at least one reason for the influence of pH on the rate of felting lies in the effect of pH on the differential frictional effect. Bohm (20) and Mercer (23) found a close correlation between the changes in the magnitude of the differential frictional effect and the rate of felting over the pH range, although Whewell, Rigelhaup and Selim (56) failed to confirm this parallelism on the alkaline side of the pH range. One the other hand, Martin and Mittelmann (46) found that the differential frictional effect appeared to be independent of pH.

(2) Swelling.

The swelling of wool in relation to felting was investigated by Speakman, Stott and Chang (18) and Götte and Kling (28) who are in agreement that swelling itself does not determine the felting properties of wool.

(3) Temperature.

For the milling of cloth Speakman, Menkart and Liu (19) found the optimum temparature for soap and ~~boarx~~ borax to be 35-37°C. There was no evidence for a critical temperature in sulphuric acid, the milling in which increased up to 70°C. and which is in agreement with Schofield's finding (29) for the felting of loose wool. On the other hand, in contrast with Speakman's observations, Mercer (22), working on yarn, found that felting increases up to $60^{o}C$. not only in acids but also in alkaline and neutral media.

(4) pH.

Three systematic investigations of the effect of pH in felting are reported in the literature. Speakman, Stott and Chang (18) findings for the milling of woollen flannel are in essential agreement with those of Mercer (22) for the felting of yarn, as im both instances the most intense felting took place in strongly acid solutions, the felting power then dropped in solutions of pH 5-7 (approx.) and it rose again on the alkaline side. In Götte and Kling's experiments (28) on loose wool, there was a continous drop in the felting power from pH 1 to pH 12.6, but unlike the other two sets of experiments, theirs were carried out at approximately $100^{o}C$.

(5) Effect of Presence of Non-Animal Fibres.

A comprehensive examination of this aspect of felting was carried out by Whewell and his collaborators (30,31,32) who investigated the milling behaviour of cloths composed of wool with the admixture of various non-animal fibres. They found that, compared with the felting of a 100% wool fabric, cloths containing an admixture of viscose or acetate rayon showed lower milling shrinkage, whilst the presence of casein or Ardil (peanut protein)fibres enhanced the milling power of the cloths.

The last phenomenon was explained by

Speakman (33) in terms of the plasticity of the non-wool component, and he suggested that the greater ease with which it can be deformed causes the casein fibre to act as a matrix in which the wool fibres can move more readily.

Similarily, according to Whewell et al. the superior milling power of wool-Rayolanda fabrics, compared with wool-Fibro cloths, was due to the greater ease of deformation of Rayolanda.

However, cellulose acetate rayon presented a more difficult case, since in spite of the well-known plasticity of cellulose acetate the wool-acetate fabrics shrink less than similar all-wool materials. No explanation to account for this divergence has as yet been forthcoming.

(6) Fibre Movement if Felting.

The fibre migration which occurs in felting was well demosntrated by some photographs of Cunliffe (34), which showed the boundary line between a white and a black portion of a woollen fabric to be perfectly distinct prior to milling and very blurred after milling, a consequence of the migration of both white and black fibres.

Also Reumuth (35) produced a series of cinemaphotographs of yarns and cloths at various stages of milling showing clearly the gradual changes in the organisation of the fibre mass.

The actual manner in which consolidation of the wool mass occurs in felting was first discussed in detail by Shorter (15, 36) who considered the operative fibres to be tightly entangled at the tip ends and loosely held at the root ends. On application of the external force the two areas of entanglement were pressed together, and the operative fibres, which would then be in a slack state, were thus enabled to creep in the direction of the root ends through the regions of looser entanglements. When the compressive forces were removed the entanglements were then brought together more closely than they were originally owing to the creep of the operative fibres.

On the other hand, according to Martin (21,37) compression causes looping of some of the fibres, whilst the operative fibres migrate through these loops with a result that the loops are locked or knotted and a region of increased entanglement is thus created on the removal of the compressive force.

(7) Arrangment of Fibres in the Material.

In view of the fundamental importance of unidirectional fibre travel it is clear that the orientation of the fibres in the material has a decisive influence on the rate of felting. This was proved by Martin (21) who found that a material composed of fibres whose scales were pointing all in the same direction felted considerably less than a similar material in which all fibres were quite at random.

Martin also studied the effect on fibre travel of the removal of the differential frictional effect (by means of an enzyme treatment) from either the root or the tip portion of the fibres. As was to be expected from the considerations of the part played by the root ends in migration, the root-treated material felted enormously less than the untreated or the tip-treated cloths.

Somewhat similar experiments were carried out by Menkart and Speakman (38) who found that the softening of the tip halves of the fibres by means of a meta-bisulphite treatment or the hardening of the root halves by cross-linking reactions (mercuric acetate) led to a considerable increase in shrinkage.

(8) Prevention of Felting.

The great practical advantages of wool fibres modified so as to reduce their felting powers led to a great amount of work on this aspect of the felting phenomenon, which has certainly received more attention than the fundamental theory.

The majority of these 'anti-shrink' methods achieve their object through the attack on the cuticular scale substance with the aim of reducing or completely eliminating the differential frictional effect.

Apart from the mechanical method of Speakman and Whewell (58), in which the scale edges are broken by means of abrasives, all other processes are of chemical nature and employ a great variety of reagents, the earliest to be used was sodium or calcium hypochlorite.

The newer patents and articles specify sulphuryl chloride (59), chlorine gas (60), alcoholic solutions of sodium or potassium hydroxide (61), proteolytic enzymes such as trypsin or papain (62), etc. Some of the most recent examples include mercapto-alcohols (64), ethereal solutions of styrene or acrylonitrile in the presence of iodine (63), acid potassium or sodium permanganate followed by a reducing or oxidising agent (65).

There is little information available on the precise mechanism of these reactions but their effect on the configuration of the scales was recently demonstrated by Mercer and Rees (51) by means of electron-microscope. They showed that sulphuryl chloride treatment (59) resulted in the rounding off of scale edges, which led to a reduction of the differential frictional effect.

The other class of methods designed to reduce felting consists of altering those mechanical properties of the fibres which assist in their migration, namely elasticity, rigidity, etc. These methods include cross-linking reactions introduced by Speakman and his collaborators, e.g. anhydro-carboxy-glycine (66), benzoquinone (67) and mercuric acetate (67, 68) and various methods of depositing high polymeric substances inside the fibres, e.g. melamine resins (69).

A recent process of Anderson (70) involving hydrogen peroxide in the presence of copper does not seem to come under either of these two categories, for it is claimed that it does not affect the frictional properties, whilst the ease of extension is increased without any decrease in recovery from deformation. Anderson's experimental findings should be checked and extended before any theoretical deductions are made.

(9) Promotion of Felting.

Freney and Harris (71) reported that by treating for three hours wool fabrics with benzoyl chloride dissolved in ether followed by an immersion in ammonium hydroxide the felting power of the fabrics was increased by 18% compared with the untreated standard, but they offered no explanation for this observation.

SUMMARY.

The primary cause of felting is the facility of animal fibres for uni-directional motion, which property arises in consequence of the differential frictional effect of the fibres. When a fibre mass is subjected to the action of suitable mechanical forces in the presence of aqueous solutions, fibre movement occurs and the mass becomes entangled and consolidated, i.e. it becomes felted.

Whilst the fundamental importance in felting of the differential frictional effect is now no longer disputed, there appear to be many points of disagreement among the many workers in this field regarding the part played in felting by other factors such as the pH of the felting medium, temperature and the relative importance of some of the structural properties of the fibres.

The reason why no comprehensive and generally acceptable theory of felting has yet been advanced is no doubt due to the multiplicity of factors affecting the process. and the difficulty in disentangling them.

It would seem that the rate of felting is the resultant of the interplay of many variables, some arising from the structural properties of the fibres themselves and others being associated with the external factors.

CHAPTER 2.

REVIEW OF THE FRICTIONAL PROPERTIES OF ANIMAL FIBRES.

REVIEW OF THE FRICTIONAL PROPERTIES OF ANIMAL FIBRES.

Structure of Wool Cuticle.

The cuticle of keratin fibres consists of a sleeve of flattened, imbricated cells enveloping the cortex, as illustrated in Fig.1 which is a reproduction of a low-magnification electron-micrograph of a wool fibre (39).

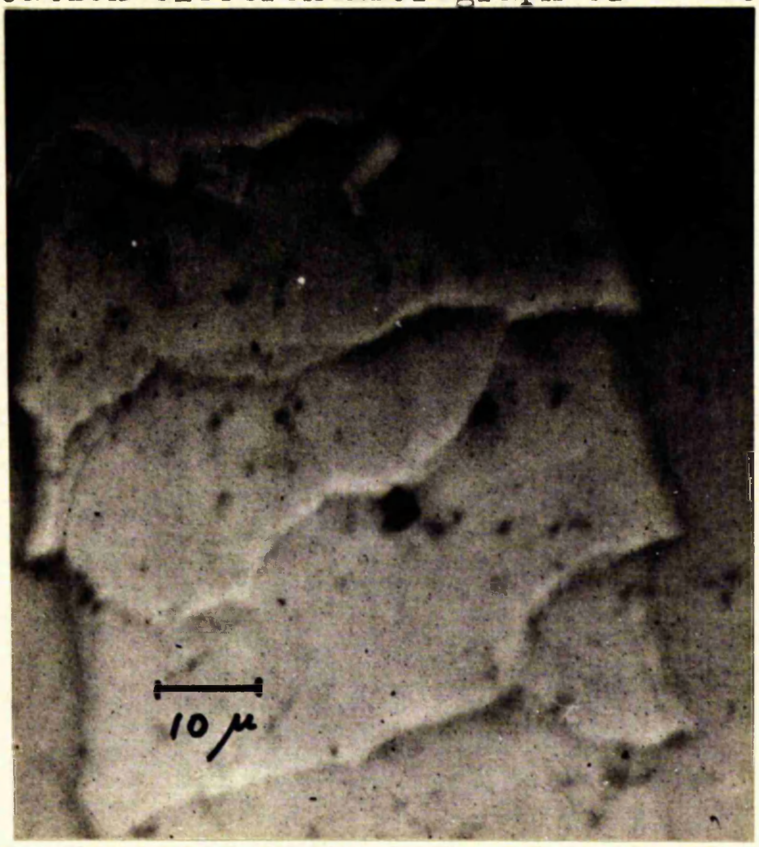


FIG.1. ELECTRON-MICROGRAPH OF WOOL FIBRE. 12,000 X.

The cuticle cells are flat, roughly oval-shaped bodies about 30 μ in diameter and of thickness ranging from 0.5 to 1.5 μ (77). The number of scales per unit area and their shape vary considerably with the type of wool. For example, according to Hoffmann (40), Leicestershire wool has 1,510 scales per 1,000,000 μ^2 surface, whilst the Hampshire variety has as many as 3,623.

The degree of overlapping or the angle of scale projections relative to the fibre axis in various wools does not appear to have been studied, but it undoubtedly varies considerably judging by the microscopic appearance of different fibres.

The inner structure of wool cuticle was investigated by Roberts (74) using ultra-microscope and cine-photography, by Geiger (75) who examined the scale substance chemically and by Zahn (76) and Mercer and Rees (51) who used electron-microscope. The latter workers found that the scale consists of two components, the first forming the superficial layer and being devoid of organised structure; underneath it they discerned the second component which was resistant to trypsin attack and which forms a honey-combed structure with characteristic pores, ridges and valleys arranged roughly linearly and parallel.

Functions of Cuticle.

The cuticle of animal fibres fulfils several important functions: owing to its physical toughness and chemical inertness it protects the more vulnerable cortex; it is a limiting factor in the processes of absorption; it confers on the fibre the property of asymmetrical friction.

The biological aspect of this last characteristic was discussed by Martin (21) who thought that the peculiar frictional properties of the hair perform important toilet functions in the life of the animals by assisting in ~~the~~ maintaining the skin clean; he suggested that when the skin is twitched or rubbed against a post any small foreign bodies near the skin will tend to move to the surface of the coat, because this is the direction of low friction of the hair.

Asymmetric Friction and Fibre Travel.

The connection between the differential frictional effect and fibre migration and felting was first indicated by Monge (2) in 1790 but not until the recent times has this property been studied in a systematic and quantitative manner, largely because of the new emphasis placed on frictional properties of wool by Martin(21), Bohm (20) and Mercer (22).

Methods of Measurement of Wool Friction.

Most of the workers in this field approached the problem almost exclusively from the point of view of static friction, and the design of their measuring techniques was developed accordingly. In most methods friction is determined on single fibres, in others a sheet composed of a large number of oriented fibres is used. The complexity of the apparatus varies from the elaborate instrument of Mercer, for example, to the simple arrangment of Lipson.

1. Speakman and Stott.

The first method was introduced by these workers (17) and was later also used by Bosman and van Wyk (47) and Whewell, Rigelhaupt and Selim (56), and it consisted of mounting fifty fibres with their scales all pointing in the same direction, between two bars, placing this 'violin bow' on the surface of a woollen cloth stretched on a frame, tilting the frame and measuring the angle of slip for the motion in the root (θ_1) and in the tip direction (θ_2). The measure of 'scaliness' was expressed as

$$\text{coefficient of scaliness} = \frac{\tan\theta_2 - \tan\theta_1}{\tan\theta_1},$$

Although this method of expressing the frictional difference may clearly lead to a fictitiously high value when the minimum firction is very low.

2. Speakman, Chamberlain and Menkart.

Although very sensitive, the 'violin bow' method proved too tedious and was eventually supplemented by the so-called 'lepidometer' designed by the above workers (41). In this instrument friction is determined by measuring the tension required to restrain a fibre from movement when it is mechanically rubbed along its length by two opposed reciprocating plane surfaces composed of felt, rubber or polythene.

Freney pointed out (48) that in the case of very rough fibres in which the difference in friction is small the lepidometer might characterise them as possessing a lower differential frictional effect than they actually have, since the tension developed will be of greater importance when the frictional coefficients are low than when they are high.

3. Bohm.

In Bohm's method (20) several hundred oriented wool fibres were mounted on a slide and placed on a plate glass surface immersed in appropriate liquids. A light container was attached to the slide by means of a thread passing over a pin, and water was added to the container from a burette until the slide just moved. The force required to produce motion was determined for the with-scale and the against-scale direction, the coefficient of friction was calculated by dividing this force by the weight of the slide, and the frictional difference was expressed as the absolute difference between the two coefficients.

4. Mercer.

An adapted form of Bowden and Leben's 'stick-slip' apparatus (42), originally used in investigations on boundary lubrication of metals, was employed by Mercer (23) and Mercer and Makinson (43) for measuring the friction of single fibres against a very slowly moving cylindrical piece of polished horn, or in some cases, against another fibre.

The principle of this instrument depends on the fact that, according to Bowden and his collaborators, (ibid.), the ~~velociti~~ relative motion between rubbing surfaces at low average velocities is not usually uniform but it consists of a series of alternate 'sticks' and 'slips'. The traces of the 'sticks' and 'slips' are reproduced photographically as deflections of a spring, and the maximum value of the force of static friction is calculated from the height of the peak of each 'stick'. The directional frictional effect was expressed in the form $\frac{\mu_2 - \mu_1}{\mu_2 + \mu_1}$ or $(\mu_2 - \mu_1)$ where μ_2 is the maximum coefficient of friction and μ_1 is the minimum coefficient.

(5) Gralen and Olofsson.

The recently described instrument of these Swedish workers (44) has many similarities to Mercer's apparatus. It measures both the static and the dynamic (but at very low speeds) coefficient of friction between two single fibres which may be arranged at various angles to each other. Friction is determined by means of a torsion head, the changes in the torsional angles being recorded photographically. The movement of the fibre is caused by a hydraulic arrangment to avoid vibration.

(6) Lipson.

In Lipson's Capstan method (45) small hooks are attached to the ends of a single fibre which is placed round a cylindrical rod of polished horn, whilst the appropriate solution is arranged to flood the fibre-horn junction. The weight required to cause the fibre to commence sliding is determined by placing small weights on the hook; the movement is very slow, usually about 0.5 cm. per sec. and almost imperceptible to the naked eye. The coefficient of friction is determined from the formuale: $\ln (T/T_1) = \mu\theta$ and the directional coefficient expressed as $\dfrac{\mu_2 - \mu_1}{\mu_2 + \mu_1}$

(7) Martin and Mittelmann.

The principle of this method (46) is similar to that of Lipson's as described above. A single fibre is placed round a cylindrical 'rubber' (glass or metal) and the slipping is caused by changing the position of a carriage to which one end of the fibre is attached. The force involved is determined by means of a spring and a balance beam to which the other end of the fibre is fixed and which is displaced as the result of the motion. The coefficients of friction are calculated in a similar way to Lipson's.

(8) Miscellaneous Methods.

There are described in the literature

several early methods of measurement of fibre friction, e.g. Barker and Marsh (79), Skinkle and Morrison (80), Adderley (81), Morrow (82), Schmeidhäuser and Stoll (83) and Henning (84), most of which, however, were rather primitive and not very accurate.

NATURE OF WOOL FRICTION.

Martin's Rejection of Ratchet Theory.

The problem of the cause of frictional asymmetry of animal fibres has received a great deal of attention since Martin (21) first indicated his reasons for the incompatibility of the view attributing the differential frictional effect simply to the ratchet action of the scales.

Reasons.

His critical examination of the problem led him to reject this view because of (1) the lack of correlation between the microscopical appearance and the frictional properties and (2) the frictional behaviour of wool fibres against hard polished surfaces.

The first point he illustrated by showing that porcupine quills whose surface appeared smooth under the microscope nevertheless exhibited a differential frictional effect; similarily, the microscopic appearance of fibres whose differential frictional effect has been reduced or altogether eliminated by means of an 'anti-shrink' treatment was unchanged when compared with the appearance of untreated fibre.

Considering the second point, the behaviour of wool fibres against a hard surface, ~~after~~ he found that they showed a very marked differential friction when rubbed against hard smooth surfaces such as polished glass, and since it is inconceivable that scale edges could grip such surfaces, Martin concluded that in this instance the plain ratchet theory is quite untenable.

Martin's 'Molecular Pile' Theory.

As an alternative explanation of these phenomena Martin put forward the so-called 'Molecular Pile' hypothesis, according to which the differential frictional effect is due not to the imbrications of the scales but to a particular kind of molecular structure in the scale, i.e. to an asymmetry of the molecular fields at the scale surface.

By analogy with Tomlinson's theory (49), on rubbing the atoms on the scale surface were assumed to be first displaced from the equilibrium positions and then, at a critical point, rapidly brought back to the original position, so dissipating in vibrations the energy acquired during the displacement. By assuming additionally that the potential energy of the atom at critical displacement was greater in one direction than in the other Martin thought that the existence of differential friction could be explained.

Lipson & Howard's Support.

Some support for these novel views was given by Lipson and Howard's finding (50) that in the case of friction between wool fibres and a smooth horn a decrease in the differential frictional effect can be observed by 'anti-shrink' treating not only the fibres but also the horn cylinder, leaving the fibres unchanged. In other words it appeared that without at all interfering with the scale structure of the fibres the differential frictional effect can be reduced by altering the surface properties of the other rubbing surface.

Criticisms of Molecular Pile Theory.

However, the 'molecular pile' hypothesis has come under heavy fire from many sources and with the exception of the behaviour of wool against hard surfaces, all other points of evidence in its favour appear to have been demolished.

Correlation between Microscopic Appearance & Frictional Properties.

Thus with regard to the lack of correlation between microscopic appearance and frictional properties it seems that the changes in scale configuration due to 'anti-shrink' treatments are beyond the resolving power of the ordinary microscope, for Mercer and Rees found recently (51) by means of electron-microscope that in fact, as the result of sulphuryl chloride treatment, the contour of the fibres is considerably altered, the small gap between the overlapping edge of the scale and the main body of the fibre being sealed. Similarily, the differential frictional effect of porcupine quills observed by Martin was also presumably due to a roughness of the surface which was not resolved by the ordinary microscope.

As to Lipson and Howard's finding, Mercer and Makinson suggested (43) that as the horn is more susceptible to sulphuryl chloride attack, it is the horn surface rather than the scale edges that is broke or deformed, and so the extra force required for the against-scale motion (compared to the with-scale motion) should be less, which prediction is in fact confirmed by the low value of Lipson and Howard's frictional coefficients. Moreover, Mercer and Makinson reported having actually observed, by microscopic section technique, a degraded layer on the horn surface.

<u>Lack of Organisation on Scale Surface.</u> Further evidence against Martin's theory was provided by Mercer and Rees' electron-microscopic observations (51) that the outer layer of cuticle cell appears to be completely devoid of organised structure, whereas Martin's hypothesis would require the presence of an oriented layer of polypeptide chains on the scale surface.

Yet another point was brought out by Mercer and Makinson (54) who suggested that since, as they found, the frictional difference is significantly increased by the presence of lubricants, this also points against Martin's theory, for the supposed asymmetrical field on the scale surface could have hardly penetrated a contaminating layer hundreds of molecules thick.

Friction of Silver-Coated Fibres.

Probably the most decisive evidence against the 'molecular pile' theory was provided by Thomson and Speakman's experiments (52). Wool fibres were coated with various thicknesses of silver or gold by exposing them in a high vacuum to the vapour from molten metal, and the differential friction of the coated fibres was then measured by both the 'violin Bow' method (17) and by the 'lepidometer' (41).

Although reduced, the differential frictional effect of the fibres coated with a layer of silver approximately 0.03 μ thick was very well defined, and the fibres were also found to creep when rubbed between wet glass plates, which seemed to prove beyond doubt that the scale configuration and not the nature of the molecular structure on the surface of the scale is responsible for the differential frictional property of animal fibres.

Rejection of Martin's Theory.

Although Martin's 'molecular pile' hypothesis thus becomes untenable, it is equally impossible to accept the simple ratchet theory in view of the numerous observations on the behaviour of wool fibres against hard smooth surfaces, since it is clear that the plain ratchet mechanism cannot conceivably operate under such conditions.

Lack of Evidence for Simple Ratchet Mechanism.

Now this point is of really crucial importance, for the fibre against fibre friction, such as occurs in the various technical processes referred to previously, comes in fact under the same category, i.e. it is similar to friction of wool against such hard surfaces as glass. The two rubbing surfaces being equally hard there can be no question of the scale edges of different fibres biting into each other, whilst the interlocking of scalex edges was proved to be non-existent long ago.

Moreover, the anology between fibre-fibre friction and fibre-glass friction is further supported by the fact that, as Martin found (21), the behaviour of wool against rough surfaces such as ground glass is essentially the same as against smooth surfaces, e.g. polished glass.

It would seem, therefore, that there is no need to assume a different mechanism to operate in these cases.

Rudall-Speakman Interpretation of Friction against Hard Surfaces.

An explanation to account for the existence of differential friction of wool against hard surfaces was put forward by Speakman and his collaborators (53) on the basis of Rudall's model of wool fibre, which is constructed as shown in Fig.2 :

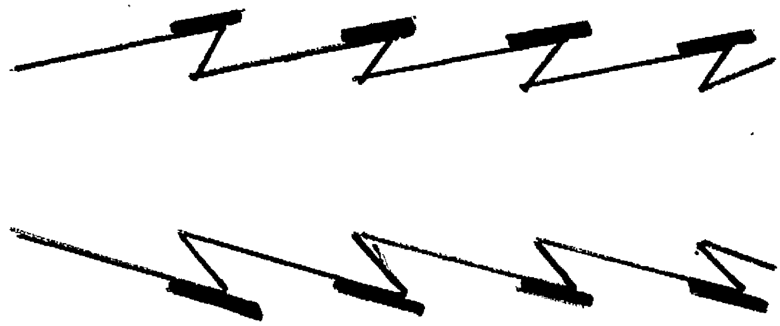


Fig.2. Diagram of Rudall's Model of Wool Fibre.

The model consists of a piece of wood with ratchet teeth cut on both sides, each tooth being provided with a separate leaf of rubber glued to the tooth. This model exhibits a frictional behaviour similar to wool fibre, for when it is dragged along a glass plate in the direction of the 'root' end the friction is lower than in the direction of the 'tip', and when rubbed between two glass plates the model also moves in the manner similar to the movement of a wet wool fibre.

The reason for the existence of two different coefficients was suggested by Menkart and Speakman(53) to be the different configuration adopted by the edges of the rubber 'scales' according to the direction of rubbing. Although they do not elaborate the point, they probably mean that ~~since~~, as in the model, the area of contact is larger in the tip direction than in the root direction of motion. However, it is difficult to see how this should account for the existence of different coefficients of friction, since under the conditions of their experiment, i.e. under conditions of dry or boundary friction, according to Amontons' Law friction is independent of the area of contact between the rubbing surfaces.

Evidence against Rudall-Speakman Hypothesis.

Evidence against Rudall-Speakman Hypothesis.

The experimental evidence of Rudall was, moreover, disputed by Martin (21) who suggested that when the 'root' end moves first, the area of the rubber in contact with the glass being small becomes dirty quickly and a low coefficient results. On the other hand, when the 'tip' end in dragged first the whole of the loose end of the rubber'scale comes in contact with the glass and so the rubber stays cleaner and the coefficient of friction is higher in this direction. Martin claims that, accordingly, when both the rubber and the glass were carefully washed the model did not show any differential frictional effect.

However, even if Rudall's experimental findings be accepted, there is as yet no direct evidence that the scale edges of the wool fibres behave like the rubber leaves of the model.

Furthermore, and this point is still more important, in the absence of any quantitative data on the friction of the model it is exceedingly difficult to see how, from the quantitative point of view, the Rudall-Speakman interpretation can account for the observed relatively enormous differences in friction in the two directions.

Mercer and Makinson's Incomplete Theory.

The only other (and as yet incomplete) attempt to interpret the frictional behaviour of animal fibres was made recently by Mercer and Makinson (43) who suggested that asymmetric friction arises from the configuration of the scales and that because of the angle of slope of the scales the against-scale motion can only result from breakage or deformation of some of the scale edges. From this they deduced that if the with-scale coefficient (μ_1) is varied by lubrication or change of pH, the against-scale coefficient (μ_2) should vary in the same sense as μ_1, and ($\mu_2 - \mu_1$) and $\frac{\mu_2 - \mu_1}{\mu_2 + \mu_1}$ in the opposite sense. This prediction they confirmed by experiment.

Mercer and Makinson's full theory has not yet been published, and in the absence of further information it is rather difficult to picture the mechanism which they have in mind. Moreover, the basis of frictional measurements depending on 'stick-slip' determinations (which technique was employed by these authors) has recently been critisized by Bristow (78) who questioned the significance of the 'stick-slips' claiming that their occurrence was due to the dynamics of the apparatus rather than to the character of the surfaces.

Summary.

The inadequacy of the simple ratchet theory to give a complete interpretation of the frictional asymmetry of animal fibres was first pointed out by Martin (21, 46) who thus stimulated the inquiry into the fundamental cause of the phenomenon of felting.

Martin postulated an alternative explanation, the so-called 'molecular pile theory', according to which the differential frictional property of animal fibres is due to an asymmetry of molecular field on scale surface, but this hypothesis must now be considered disproved by the results of Thomson and Speakman (42) and Mercer and his collaborators (51, 54, 43). The former workers showed that despite covering the scale surface with a fairly thick layer of silver differential friction persisted, from which they concluded that the differential frictional effect cannot be possibly due to the peculiarities of the molecular fields on scale surface. The same conclusion was reached by Mercer and his co-workers largely on the basis of electron-microscope findings.

The only other available theory attempting to explain the frictional properties of animal fibres is that of Rudall, Speakman and Menkart (53) who suggested that the different configuration adopted by scale edges according to the direction of rubbing is responsible for the existence of two different frictional coefficients. However, various objections to this hypothesis have been

raised, firstly as regards the accuracy of the actual experimental findings using Rudall's model and secondly as to the ade inadequacy of this theory to account quantitatively for the frictional difference.

It must, therefore, be concluded that no satisfactory theory of frictional asymmetry of animal fibres has been published as yet.

CHAPTER 3.

LUBRICATION THEORY AND ITS APPLICABILITY TO THE FRICTION OF ANIMAL FIBRES.

LUBRICATION THEORY.

Introduction.

It is noteworthy that so far none of the workers angaged on the problem of friction of animal fibres has considered the possibility of applying to it the film theory of lubrication.

It is hoped to show later that the fluid film theory of lubrication is capable of clarifying the nature of the frictional asymmetry of animal fibres and of many features of the phenomenon of felting.

As an introduction ~~the~~ a review of current views on friction and lubrication will be given.

Types of Friction.

Three broad types of friction are commonly recognised: (1) solid to solid, (2) boundary and (3) fluid film friction.

(1) Solid to solid friction occurs when two solids slide on each other without any contaminant between their adjacent surfaces. In practice such perfectly clean surfaces are very difficult to obtain, but they can be produced by an outgassing technique in a vacuum when, as Bowden and Hughes showed (95), perfect solid to solid friction obtains, with the coefficient of friction being as high as 6. Under such conditions

friction is a problem of the chemical forces of attraction between the surfaces. (In air, when the surfaces are not perfectly clean, the coefficient of friction for unlubricated metals is about 0.5 - 1.0)

(2) When the surfaces are wholly or partially separated by a thin film of lubricant friction is influenced by the chemical character of the lubricant as well as by the nature of the surfaces, and such state is referred to as 'boundary lubrication'. Under such conditions the coefficient of friction, in the case of metals, is of the order of 0.05 - 0.15.

(3) Under conditions of fluid film lubrication the moving surfaces are separated by a fluid film of lubricant of such thickness that the characteristic properties of boundary layers are completely suppressed and the behaviour of the lubricating film is governed entirely by the principles of hydrodynamics.
The coefficient of friction is of the order 0.01 - 0.02, which means that fluid film lubrication is by far the more efficient.

SOLID AND BOUNDARY FRICTION.

The classical laws of friction which resulted from the experiments of Amontons (1699) and Coulomb (1781) postulated that (1) friction is independent of the area of contact between the surfaces, (2) friction is proportional to the load between ~~su~~ the surfaces, (3) friction is independent of the speed of rubbing, but the last point is now recognised as untrue, for at high speeds friction usually decreases.

The cause of the first two laws of friction has been explained only in recent years by the remarkable work of Bowden and his collaborators who are mainly responsible for the great advance in the understanding of the mechanism of friction between solid surfaces.

Thus an investigation by Bowden and Tabor (96) of the area of contact between rubbing metal surfaces by electrical conductivity measurements showed that the real area of intimate contact is exceedingly small, since the metals touch only at the summits of the surface asperities. For example, in the case of flat steel surfaces the real area of contact may be less than 1/10,000th of the apparent area. Clearly, therefore, since the area of real contact is nearly independent of the apparent area, friction should also be independent of the apparent area, which the first law of friction in fact postulates.

Furthermore, Bowden and Tabor also found that because of the high local pressure and temperature at these points of contact the surfaces are deformed plastically and so the real area of contact is directly proportional to the load which is applied to the surfaces. Hence the tangential frictional force required to break these junctions between the surfaces should be proportional to the applied load, which is the substance of the second law of Amontons.

The occurence of high temperatures at metallic junctions ('hot spots') was first discovered by Bowden and Ridler (97) and Bowden and Hughes (95), and their observations were later corroborated by Thomson and Logan (98), Matthew (99)& Beeck et al.(91). The temperature of these 'hot spots' was found to depend on the load, the speed and the heat conductivity of the solids. With readily fusible metals the temperature corresponded to the melting point of the metal, with less fusible metals local temperature reached about 1000°C. (e.g. constantant). Moreover, even when the surfaces are flooded with water or a lubricant the 'hot spots' persist, although higher frictional forces are required. 'Hot spots' were also observed in the case of non-metallic surfaces such as glass or quartz.

The phenomena of plastic deformation, with which these high temperatures are associated, are of importance in problems of polishing of metals, seizure of bearings, etc, They also play a part in the initiation of explosions (e.g. of nitroglycerine), as has recently been shown by Bow-den, Stone and Tudor (100).

Since the friction of solids is accompanied by enormous molecular tearing, welding and deformation at the rubbing surfaces, some surface damage always occurs even with lightly loaded and well-lubricated surfaces. Bowden, Moore and Tabor (101) found that at low speeds the nature of the damage depends on the combination of metals used. Thus when a hard metal slides over a soft one, ploughing and tearing of the latter takes place; when a soft metal moves over a stationary hard metal, the soft metal is found to be welded to the hard one; and lastly, when metals of similar hardness are used greatest damage occurs and so high friction results. Moreover, it was found that even under lubrication conditions some metallic interchange takes place, which was confirmed by Sackmann, Burwell and Irvine (102).

In view of these observations it became clear that friction is not merely a surface effect, since bulk properties of the solids, such as their relative hardness and melting point, influence the frictional resistance.

According to Bowden et al., therefore, frictional force in the case of unlubricated metals is made up of two components, (i) the force of shearing (S) of local junctions, and (ii) the work of ploughing (P) of surface irregularities by the harder metal. Hence frictional force $F = S + P$. When the ploughing term P is negligible, $F = S$, and if A is the real area of contact and s the shear strength of the softer metal, then $S = As$ and $F = As$.

Thus to obtain low friction both A and s should be as small as possible. When a hard metal slides (1) over a soft one s is small but A is large, (2) over another hard metal A is small but s is large - in both cases friction is therefore high. If, however, in the latter case a very thin film of a soft metal is deposited on the stationary hard surface, the shear strength s will be that of the deposited soft metal, i.e. it will be low, whilst A will remain small, for the area of contact is not appreciably affected by the plastic deformation of hard metals.

That the latter phenomenon does in fact take place was found by Bowden, Moore and Tabor (101) who showed that when a film of lead or indium, a few hundred atomic layers thick, is deposited as indicated, the coefficient of friction is reduced from approximately 0.6 to approximately 0.04.

Now the lubrication of surfaces is an analogous proce-ss to the depositions of such films, for the lubricating film, being of low shear strength, performs similar functions.

The first systematic study of such boundary lubricating films was carried out by Hardy (103) on films composed of homologous series of paraffins, fatty acids and alcohols. For static friction the coefficient of friction was found to decrease linearly with the chain length, but Beare and Bowden (104) found later that this relation does not hold in the case of kinetic friction.

The work of Langmuir (105), Bowden and Leben (106), Hughes and Whittingham (107), Frewing (108) and Isemura (109) showed conclusively that in the case of metallic surfaces lubricated by fatty acids the lubricating power of the boundary layer is due primarily to the first adsorbed fatty acid layer.

Recent experiments of Bowden, Gregory and Tabor (110) further indicated that the lubricating properties of the acids also depend on the nature of the underlying metal surfaces, and it was shown that the most efficient lubrication obtains with those metals which are most readily attacked by the fatty acid. Lubrication, therefore, is not due just to the acid itself but to the metallic soap resulting from the reaction between the metal and the fatty acid, and this soap will act as a lubricant until the temperature reaches its softening point. The study of these metallic soaps showed that they possess remarkably high tenacity; for example, one soap monolayer was found to provide effective lubrication under conditions when efficient lubrication by a metallic film (as described above) would require a much thicker film, e.g. 10^{-6} cm.

The mechanism of boundary lubrication proposed by these workers follows on their views on the friction of unlubricated metal surfaces as discussed previously.

Thus, as before, the frictional resistance is considered to be due to two causes: firstly to the metallic junctions between the surfaces which always occur, even under best boundary lubrication, their formation being dependent on the nature of the boundary film, the speed of sliding and the temperature developed; secondly, to the resistance to sliding offered by the film itself.

Hence the friction force F can be written as

$$F = A\left[\alpha s_m + (1 - \alpha) s\right]$$

where A is the area that supports the applied load, α is the fraction of A over which metallic junctions have occurred s_m is the shear strength of metallic junctions and s is the shear strength of the lubricating film.

Bowden et al. concluded therefore that

> "the main purpose of the lubricating film is to reduce the amount of metallic contact between the surfaces by interposing a layer that is not easily penetrated and that possesses relatively low shear strength. In order to prevent appreciable contact, the lubricating layer must, in addition to being firmly attached to the surface, possess a strong lateral adhesion between the hydrocarbon chains. If the film softens or melts, that is, if the lateral adhesion between the chains falls to a low value, metallic seizure occurs with a corresponding increase in friction and wear. The fact that solid films of saturated hydrocarbons are more effective in lubricating unreactive metals than fatty acids above their melting points shows that the strength of the lateral adhesion between the large hydrocarbon molecules is at least as important as the strength of attachment to the surface."

A transitional stage between boundary film and fluid film lubrication was shown by Beeck, Givens and Smith (91) to take place when the lubricant is a compound which is most highly oriented with its carbon chains most nearly perpendicular to the surfaces and when the speed of sliding is increased. Under such conditions a sudden reduction in resistance to friction occurs, and this was ascribed to the wedging of oil under the surface. As this condition resembles the fluid or hydrodynamical lubrication, Beeck et al. termed this phenomenon 'quasi-hydrodynamic' lubrication.

This now leads to the discussion of the last type of lubrication, namely the fluid film lubrication.

FLUID FILM LUBRICATION.

Under conditi-ons of fluid film lubrication the rubbing surfaces are separated by completely by a film of lubricant of such a thickness that the friction between the surfaces depends entirely on the behaviour of this film, which behaviour is governed by the principles of hydrodynamics.

The basis of the present knowledge and understanding of fluid film lubrication was laid by Osborne Reynolds (89) who in 1886 gave a theoretical interpretation to these phenomena, the first observations of which were made three years earlier by Beauchamp Tower (89). The importance of Reynolds work was not realised at once but in 1897 the principles which he had enunciated were applied by Kingsbury (113) to the design of thrust bearings. In 1905 pivoted thrust bearings were developed by Michell (114) also as the result of investigations based on Reynold's work. Since them a vast amount of work has been carried out, both of experimental and theoretical nature, on frictional phenomena in various types of bearings. The mention of only a few of the outstanding contributors should include Sommerfeld (115), Harrison (116), Boswall (85), Hersey (86), Stanton (117), etc.

The main point of the pioneering work of

Beauchamp Tower was the discovery of the existence of pressure in the lubricating film which separated the surfaces of rotating journal bearing and of the fact that the component of the total oil pressure in the direction of the load was numerically equal to the load.

The formation of this thick pressure film depends on several factors, viz. speed, load, geometrical characteristics and size of the rubbing surfaces and the viscosity and the inertia of the fluid.

Thus when two surfaces are suitably inclined and move relative to each other at a sufficient speed and under a suitable load they will tend to separate because of the wedge formed between them by the lubricant.

The mechanism of formation of this wedge-shaped fluid film is illustrated by Fig.2a (reproduced from Clower's book, 88).

AB is a plane surface, of unlimited length and breadth, moving in the direction of the arrow, i.e. to the left, below the inclined surface CD which is of limited dimensions. Owing to its viscous drag the lubricating oil is carried into the wedge-shaped space between these surfaces. The volume of oil that is brought in is proportional to the inlet area BDE, but the volume discharged at the exit end AC is proportional to the area ACF and is

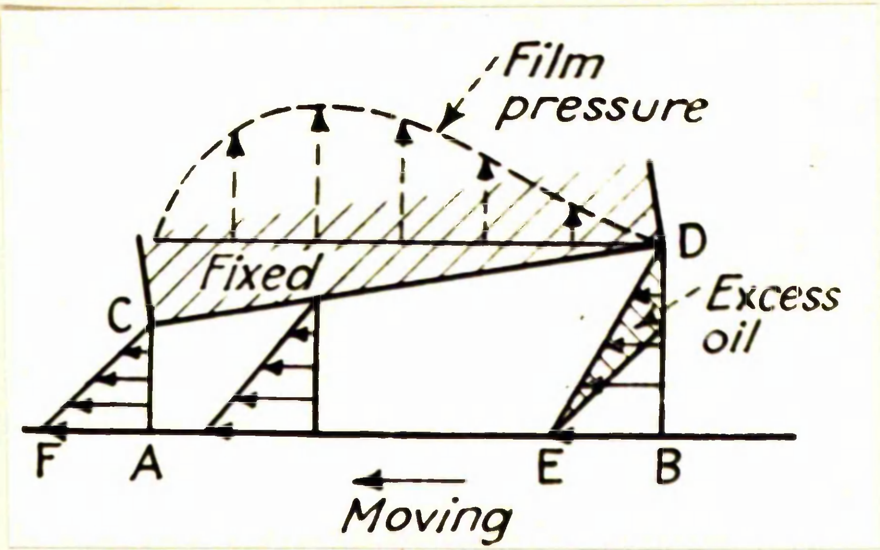


FIG. 2a. MECHANISM OF FLUID FILM FORMATION.

therefore smaller than the volume carried in, for the area ACF is smaller than the area BDE.

The excess volume which is thus carried into the space, is, therefore, squeezed out between the surfaces in the direction at right angles to the motion of AB. Because of its viscosity, the oil resists this squeezing action. In consequence a pressure is built up within the oil film, and this pressure causes the surfaces to move apart when fluid film lubrication is set up.

The film pressure causes the oil to leak away from the space between the surfaces. Since the inlet end is larger than the exit end, the oil escapes much more freely at the end BD and the sides near it than at the exit end AC. As a result, the maximum film pressure is nearer the apex of the wedge than the inlet, which is indicated by the pressure curve in Fig.2a.

Continued separation of the surfaces, i.e. efficient lubrication, is achieved when conditions of speed and load (for a given lubricant and surfaces) are such that the oil is carried into the wedge-shaped space faster than it is carried out. This ensures that the pressure is maintained and so the surfaces will continue to be kept apart.

This mechanism of fluid film formation is exemplified by the Michell Thrust Bearing. In this type of bearing a plane bearing surface acts on an opposing surface which is composed of a system of sector-shaped pads. These pads are arranged in the form of a ring and are inclined at an angle to the direction of the motion, the angle being such as to promote the maintainance of the fluid film.

In other types of bearings fluid film is formed in a manner similar to that described above. In the case of journal bearings, for example, the oil wedge results from the difference between the diameters of the journal and the shaft. Thus when the shaft is stationary it rests on the bearing and there is very little oil between the two surfaces. However, as the shaft begins to rotate and as it gathers speed oil is drawn around underneath it and forms a wedge-shaped pressure film which will lift the shaft away from the bearing surface.

In the case of two parallel surfaces, such as are used in certain types of thrust bearings, the wedges (which are much smaller than those occuring in inclined pad and journal bearings) arise in consequence of the imperfections in the surfaces, as has recently been pointed out by Karelitz (112).

The manner in which fluid film formation is affected by the geometrical characteristics of the bearing design is illustrated in Fig.3 (also from Clower's treatise, 88).

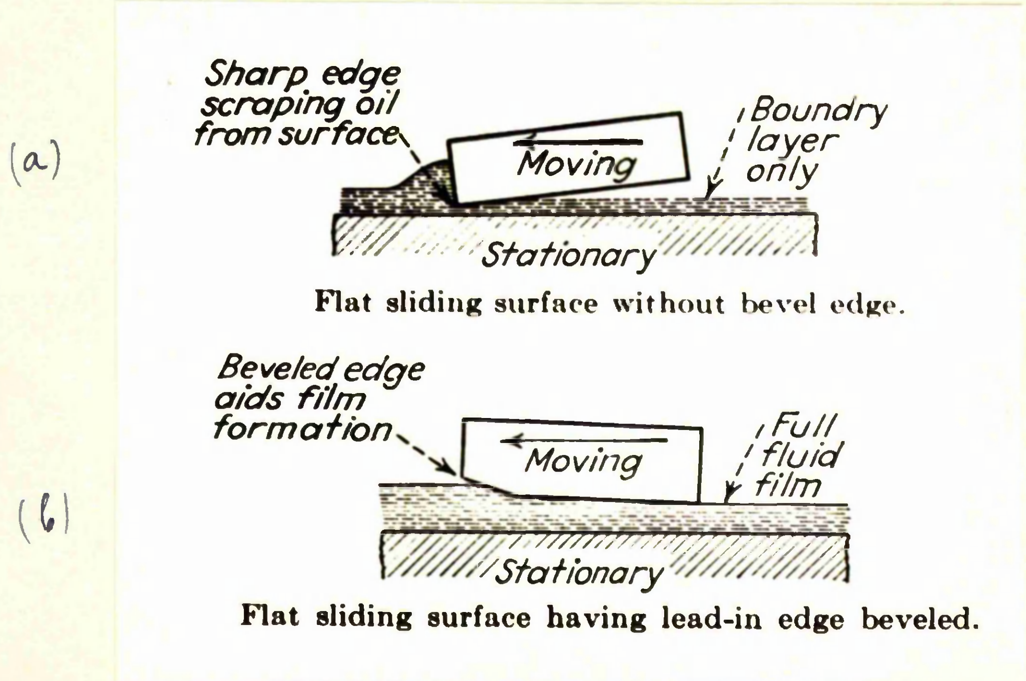


FIG. 3. INFLUENCE OF BEARING DESIGN ON FLUID FILM FORMATION.

The figure represents a short block sliding on a flat surface, as, for example, a piston ring and cylinder wall. In (a) the block tends to tilt and the sharp leading edge will tend to remove the oil from the surface thus reducing the film thickness, possibly down to boundary conditions. In (b), on the other hand, the leading edge is bevelled, which, as shown, tends to aid the formation of the fluid film.

THE ZN/P RELATION.

The dimensionless expression, absolute viscosity (Z) x speed (N) divided by pressure (P), or ZN/P, has been found by both theory and practice to be of special significance in lubrication problems. Thus it has been found that for a given bearing one experimental point resulting from a given viscosity, angular speed and load per unit of projected area will give the coefficient of friction for any other set of conditions for which ZN/P has the same value.

If the frictional conditions in a given

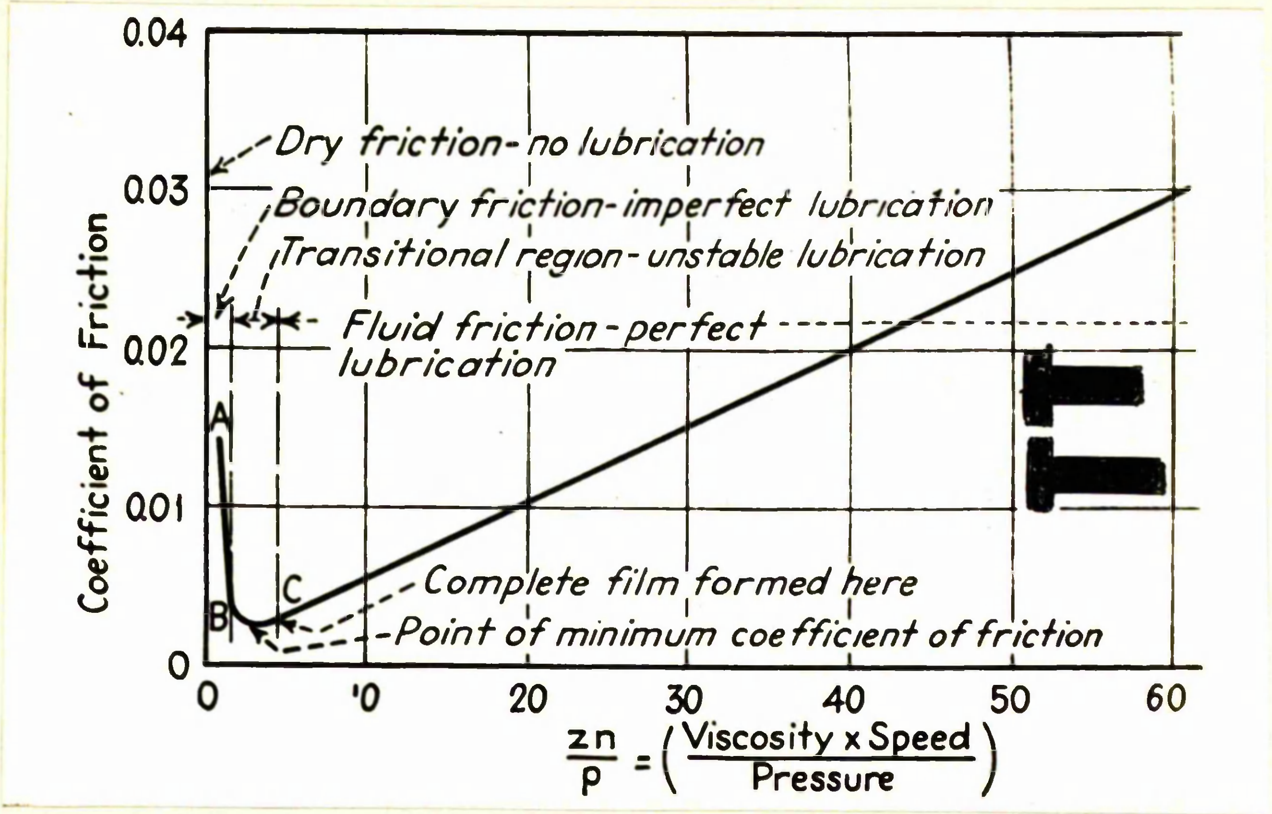


FIG. 4. THE FRICTION VERSUS ZN/P RELATION.

lubricated bearing are studied under various loads and speeds, and if the observed values of the coefficient of friction are then plotted against the corresponding values of ZN/P, a characteristic curve similar to that shown in Fig. 4 results. This curve, which is an actual experimental curve for a journal bearing reproduced from Clower's monograph(88), reveals the various types of frictional conditions which occur in a bearing.

Thus when a stationary bearing is set in motion (the ZN/P value being therefore very small) the first resistance to movement is due to static friction of the solid to so lid type, for, as indicate before, there will be very little, if any, oil between the stationary surfaces; the coefficient of friction will therefore be high.

As the speed of rotation increases, oil will be carried into the space between the surfaces which will therefore tend to separate. At the beginning, for small values of ZN/P (from A to B, on Fig.4) when the speed is still relatively slow, the oil film is very thin and the bearing operates in the region of boundary friction.

As the velocity increases further, however, a transition stage between boundary and fluid film lubrication is reached, indicated by BC, which represents the lowest friction attainable.

Beyond this critical value of ZN/P, when the speed increases still further, full fluid film lubrication is achieved, but the coefficient of friction will begin to rise again with increasimg velocity owing to the viscous drag of the lubricant. The part of the curve from C to D is essentially a straight line.

The position of the minimum on the friction versus ZN/P curve is of particular interest, for it indicates the critical value of ZN/P required for the establishment of conditions of fluid film lubrication for the given bearing.

The interdependence of Z, N and P has been ind/icated above, and it is clear therefore that this value of ZN/P represents a critical viscosity which is required, at a given speed and under a given pressure, to form a fluid film. Similarily, this value of ZN/P may be said to represent a critical speed or a critical pressure, with the other two factors remaining constant, for fluid film formation.

When friction versus ZN/P curves for various bearings are compared it is found that the general shape of all curves is always similar to that shown in Fig.4. They vary, however, in detail, namely regarding the position of the minimum £ value of the coefficient of friction and the shape of the various parts of the curve. This is so because the coefficient of friction is also dependent, apart from Z, N and P, on the geometrical characteristics of the bearing, e.g. clearance, length-diameter ratio, etc.

THE LUBRICATION THEORY APPLIED TO FRICTION OF ANIMAL FIBRES

When in a mass and under pressure, as in the felting process, animal fibres are bent round each other owing to their flexibility. The appearance of two such fibres can be represented as in Fig.5 which is a section in the plane of one of the fibres.

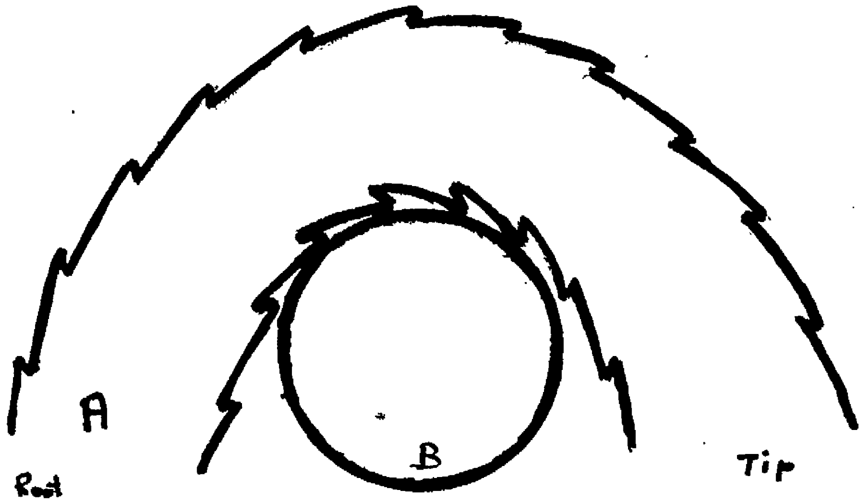


FIG. 5. FRICTION BETWEEN TWO ANIMAL FIBRES.

There is a close resemblence between this figure and a badly worn journal bearing, and so, just as in the case of journal bearing, when fibres A moves round fibre B the fluid will be dragged into either of the two wedge-shaped spaces on either side of the area of contact, depending on the direction of motion of the fibre.

Under suitable conditions of speed, load and viscosity the two fibre bearing surfaces should separate and low friction, characteristic of fluid film lubrication, would result and it would be identical in both directions of motion of fibre A if the fibre bearing surfaces were smooth.

In the case of animal fibres, however, the surface consists of a layer of imbricated cuticular scales whose edges all point in the same (tip) direction, as shown in Figs. 1 and 5, and the ease with which the film will be formed between the fibre surfaces will depend on whether fibre A moves in the direction of its tip (i.e. to the right on Fig.5) or in the rootwards direction (i.e. to the left). The reason for this is that the scales act in a manner similar to the action of the facets in Michell bearing, as described previously, and therefore when fibre A moves to the left the angle of inclination of these scale facets is such as to promote the formation of the fluid film, whereas in the case of motion to the right (i.e. tipwards) the angle of the scales directly opposes film formation.

It follows, therefore, that the frictional resistance to motion in the tipwards direction, when fluid film formation is opposed, may be expected to be greater than the resistance in the rootwards direction when scales aid lubrication.(cf.Fig.3).

Furthermore, as has been shown earlier, the conditions under which the fluid film is formed can be well defined by the minimum on the coefficient of friction vs. ZN/P diagram (cf.Fig.4), which gives a critical value of ZN/P required for the setting up of a fluid film. in a given bearing. Clearly, therefore, the differences in the ease with which the fluid film is formed between the fibre surfaces according to the direction of rubbing will be reflected in the corresponding values of ZN/P. In other words, in the case of rootwards movement, when the slope of the scales favours film formation, the fluid film should form at lower values of ZN/P (i.e. at a lower viscosity and speed or under a higher pressure) than in the case of tipwards movement when the angle of scales opposes the setting up of the film.

Consequently, on the μ vs. ZN/P diagram for the fibre bearing surfaces the minimum for the rootwards movement (rubbing with the scales) should lie to the left of the minimum for the tipwards motion (rubbing against the scales).

Yet another forecast can be made on the basis of the lubrication theory as applied to the friction of animal fibres, namely regarding the Differential frictional effect.

The differential frictional effect should be low in air, since owing to the low viscosity of this fluid the hydrodynamical effect will be negligible at the speeds likely to be attained. Under these conditions the friction will be of the boundary type and therefore similar for both directions of rubbing. When, however, the viscosity of the fluid increases the differential frictional effect should rise, e.g. in water, as the conditions of fluid film lubrication begin to set up. Moreover, beyond a certain critical viscosity the differential frictional effect should gradually diminish as the fluid film thickness increases to such an extent as to mask the influence of the scale facets.

However, the analogy which is being suggested here has certain limits due to the important dimensional and geometrical diferences between ordinary bearings and the 'fibre bearings'.

Thus in the example, shown in Fig.2a, of the mechanism of the formation of a fluid film in an inclined plane bearing the surfaces, in order to simplify the illustration were considered to be plane and infinite. Such surfaces, with other factors being equal, provide ideal conditions for the setting up of the fluid film.

The fibre bearing surfaces considered in Fig.5, however, clearly depart from this ideal in two important respects. Firstly as regards their finite dimensions which, as indicated in Chapter 2, are exceedingly small by comparison, say, with the facets of the Michell bearing; and secondly as regards the curvature of the surfaces transverse to the direction of motion, which arises from the approximately cylindrical shape of the fibres.

These two departures from the characteristics of the ideal state can be expected to increase greatly the leakage of the lubricating fluid from between the rubbing fibre surfaces. This would result in a lowering of the fluid film pressure and therefore in a reduction of the efficiency of separation of the surfaces, which would be reflected in an increase in the value of the coefficients of friction.

Hence in the case of fibre friction the magnitude of the coefficients under conditions of fluid film lubrication can be expected to be considerably higher than in the case of ordinary bearings.

The experimental work described in the present thesis was designed and carried out to test the accuracy of the above hypothesis which, if true, would offer a simple explanation of the frictional behaviour of animal fibres.

The experiments fall naturally into two parts. The first deals with the frictional measurements on animal fibres and is concerned particularly with the study of factors affecting fluid film lubrication. In the second part experiments are reported in which the felting properties of wool were examined in relation to the new hypothesis and especially in relation to the observations on frictional behaviour described in the first part.

CHAPTER 4.

APPARATUS FOR FRICTION MEASUREMENTS OF FIBRES.

APPARATUS.

Necessity for new design.

A review of the existing methods of measurement of fibre friction, discribed previously, led to the conclusion that they had been designed primarily for investigations of static friction. None of the available techniques was suitable for the purpose of examining the frictional behaviour of animal fibres under conditions of fluid film lubrication, i.e. under dynamic conditions. A new apparatus had, therefore, to be designed.

Desiderata.

The study of problems concerned with fluid film lubrication involves the investigation of three principal factors, namely speed, viscosity and pressure. The new instrument had, therefore, to provide the means for measuring friction of fibres under the following conditions:

(i) Over a wide range of speed, bearing in mind that considerably higher velocities are required for setting up conditions of fluid film lubrication than the speeds that have so far been used by other workers. For example, in Mercer and Makinson's (43) experiments the speed ranged from 0.01 to 0.1 cm/sec., whilst it has been shown recently by Forrester (111) in experiments on metallic friction that under certain conditions the transition from boundary to fluid lubrication

occurred at considerably higher velicities, e.g. 2.26 cm./sec
(ii) In fluids of various viscosities, the amount of fluid present being sufficient to enable fluid film to be formed. This point wa entirely neglected by other workers in whose experiments the adequate flooding of the surfaces was never given proper attention.
(iii) Under various pressures between the surfaces, although the exact magnitude of the load required was not known in advance.

Choice of Rubbing Surface.

As regards the nature of the rubbing surfaces, whilst it was appreciated that it would be preferable to study the frictional behaviour of fibre against fibre so as to simulate the conditions occurring in the felting process, it was decided at the outset that in order to simplify the design of the apparatus one of the fibre surfaces would be replaced by a hard substance such as glass or horn.
It was felt that this course was justified because, as has been indicated previously, in fluid film lubrication the shape and not the character of the surface is of importance.

Composition of Fibre Surface.

As for the composition of the fibre surface which was to be rubbed against, say, glass, the previous experience of the present writer (20) indicated that the use of a fibre surface consisting of a large number of individual oriented fibres has definite advantages over the use of single fibres. Thus, for example, the necessity for a statistical treatment of results is eliminated, as the differences between friction of various pads are negligible, whereas in the case of single fibres the coefficiants of variation are usually very high. The experimemtal technique is also facilitated, for the forces involved in the friction of a sheet of fibres are clearly greater than in the case of an individual fibre. and so the degree of precision in measurements need not be so exacting.

Use of Human Hair.

The fibres used throughout this work were human hair which on account of their relative coarseness, rigidity and lack of crimp are far easier to manipulate (especially in mounting the pad) than wool fibres. Human hair have often been used by many workers in lieu of wool for these reasons (and for their greater chemical uniformity in cases where chemical processes were studied), and the similarity of frictional behaviour between these two varieties of animal fibres has been demonstrated frequently. To remove any doubt on this point some experiments were carried out, to be reported later, using wool fibres in place of human hair, and they fully justified the use of human hair in the present work.

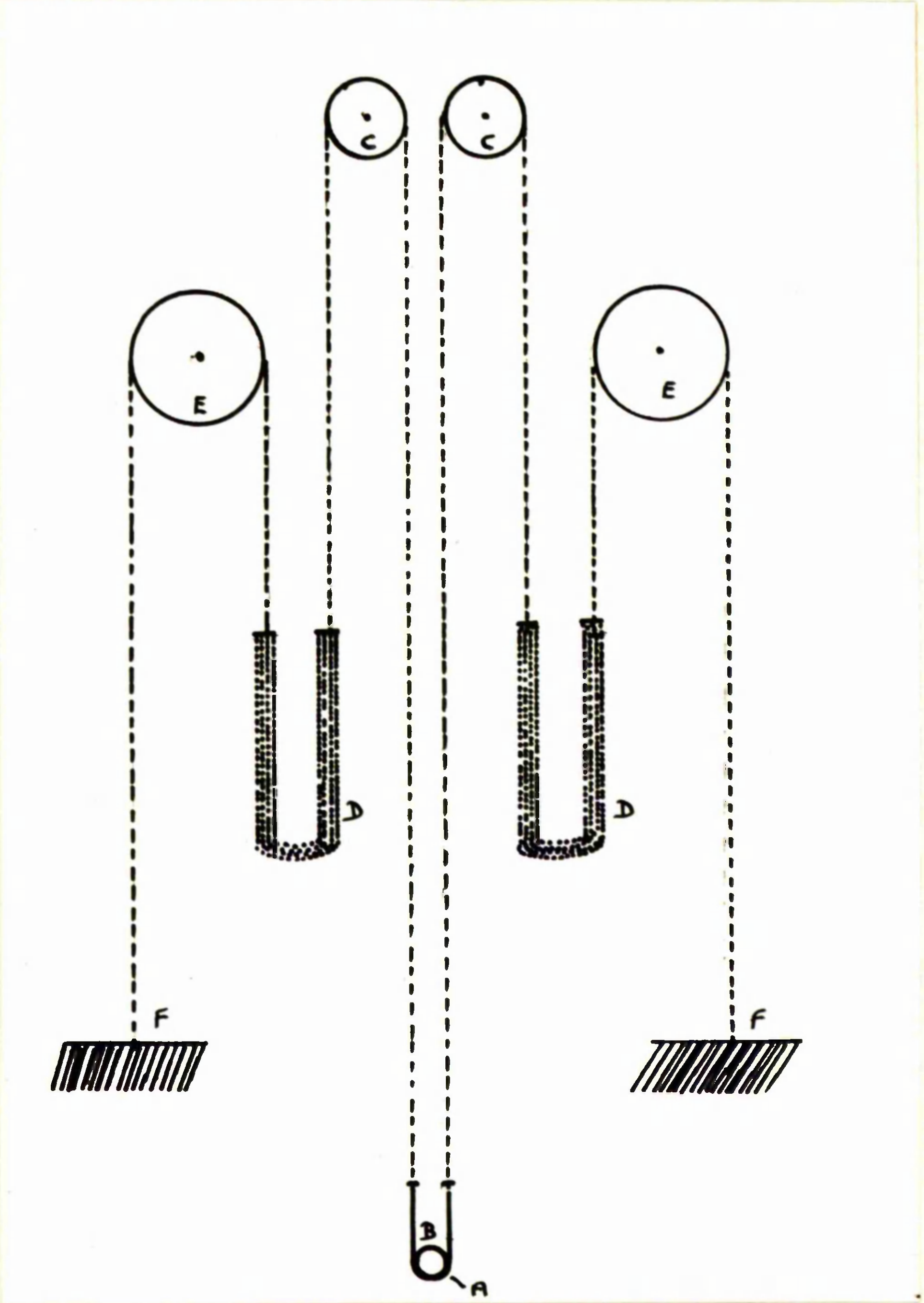
First Models.

The development of the ~~final design of the~~

final design of the apparatus took considerable time as it proceeded through several unsucessful intermediate stages. Before the present apparatus was finally evolved several other designs had been constructed but found unsatisfactory.

Chainomatic.

The first prototype is shown diagramatically in Fig. 6



The hard rubbing surface is in the form

of a cylinder mounted on to a shaft of an electric motor so that it can rotate at various speeds im both directions. The fibre pad A is placed round the cylinder B as shown, with the ends upwards, whilst the area of contact between the fibres and the cylinder is flooded with the appropriate liquid delivered from a separating funnel (not shown on the diagram). Frictional forces were measured by means of a chainomatic device, designed for another purpose by Demeuleemester and Nicoloff (92), consisting of two systems of chains, one for each direction of rubbing. Each set of chains is composed of a light chain suspended over a frictionless pulley C, one of the chain being attached to one end of the fibre specimen, whilst the other end of the chain is connected to a set of four parallel chains D which are in turn supported by another pulley as shown, E.

Assuming that the cylinder was to rotate in the clockwise direction, a suitable pressure was placed on the fibres by increasing the pull of the chainomatic system on the left-hand side ~~and~~ of the specimen. On setting the cylinder in motion the fibre pad was dragged in the clockwise direction owing to friction. The frictional forces were determined by restoring the fibres to their original equilibrium position by increasing the pull of the right hand side chain system, i.e. by increasing the operative weight of the four-chains component.
For measuring friction in the opposite direction of rubbing the rotation of the cylinder was reversed and the measure-

ment repeated using the other set of chains. The coefficient of friction was calculated from the formulae $\ln (T/T_1) = \mu\theta$.

The chainomatic systems were constructed in the form of a scaffolding, about 7 ft. tall, erected on top of a thermostatically controlled electric oven in which were arranged the rubbing surfaces. The controls for altering the positions of the chains (F) being fixed outside the box.

This apparatus failed to give satisfactory results. The reasons for the failure were firstly that the pressure applied to the fibres varied along the circumference of the cylinder, and secondly, the chainomatic measuring system was insufficiently sensitive.

Springs.

Before this apparatus was finally discarded another attempt was made to improve it by using sensitive calibrated springs (similar to those used in the Cambridge Fibre Extensometer) instead of chains for loading and measuring the frictional resistance. Again, however, the degree of accuracy, apart from the difficulty regarding even application of pressure, was quite inadequate.

Torsion heads.

In the last of the series of unsuccessful endavours, illustrated diagramatically in Fig.7, the capstan system of arranging the fibres and the cylinder was retained but the loading and the measurements of frictional forces were done by means of two especially constructed torsion heads.

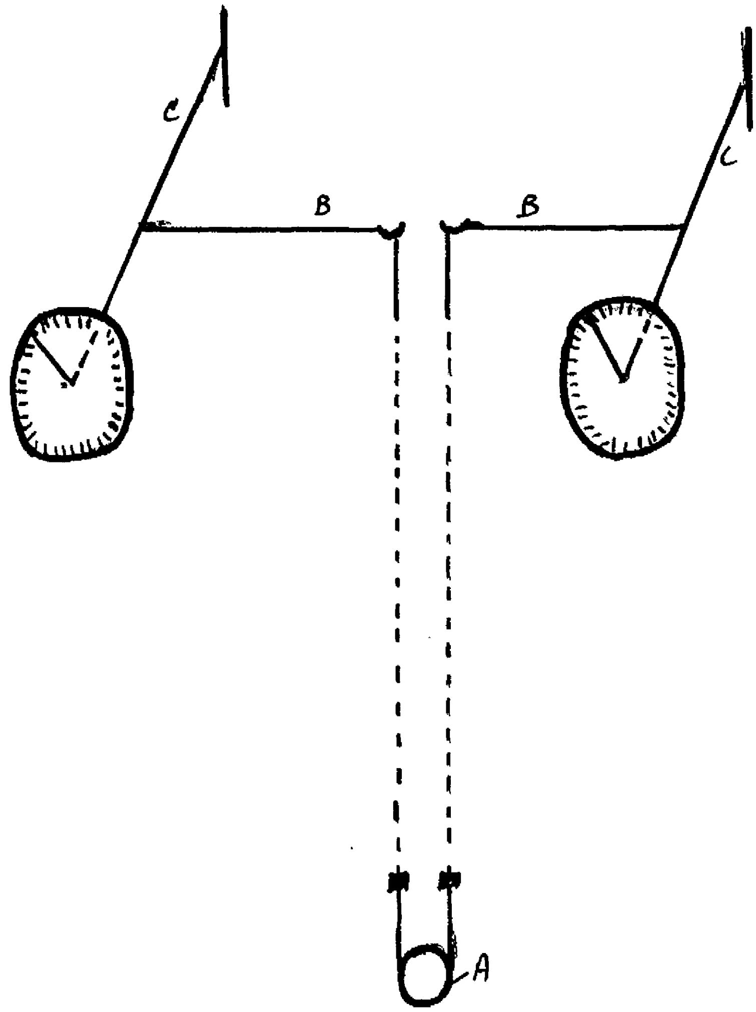


Fig. 7 Torsion Heads Model.

Each end of the fibre specimen A was connected by means of a fine chain to a rod B which was fixed very firmly to the centre of the torsion wire C. As in the original prototype, the load was placed by increasing the pull on one of the end of the fibres, this time by turning the torsion wire. On setting the cylinder in motion the pad was dragged, as before, and by turning the other torsion head until the original equilibrium position was reached the force equivalent to the frictional force was thus determined.

Reason for Failure of First Models.

Unfortunately, this method was only a slight improvement on its predecessors, and it can be concluded that all the methods based on the capstan principle, which have been described, notwithstanding the nature of the friction-measuring mechanism, suffer from the same serious disadvantage, viz. it is exceedingly difficult, if not impossible, to ensure an even contact between the fibres and the cylinder surface. This leads to great difficulties in estimating accurately the magnitude of the load placed on the fibres, which in turn renders the calculated values of the frictional coefficients of doubtful value.

In view of this it was decided to abandon altogether the capstan type of method.

The Final Design.

In the present apparatus the critical difficulty encountered previously, i.e. the method of presenting the fibre surface to the cylinder surface so as to ensure accurate measurement of pressure on the fibres, was finally solved.

The new device consisted of first mounting the fibres on a metal frame in the form of a straight, taut violin bow which was then brought into contact tangentially with the cylinder surface, whilst the pressure was applied by a novel method involving the use of a float.

The mechanism for measuring the frictional forces consisted of an adapted torsion head.

The present form of the apparatus is shown in Figs. 8 and 9. The first photograph gives a general view of the instrument, whilst the second is a close-up of the surfaces in contact and other features.

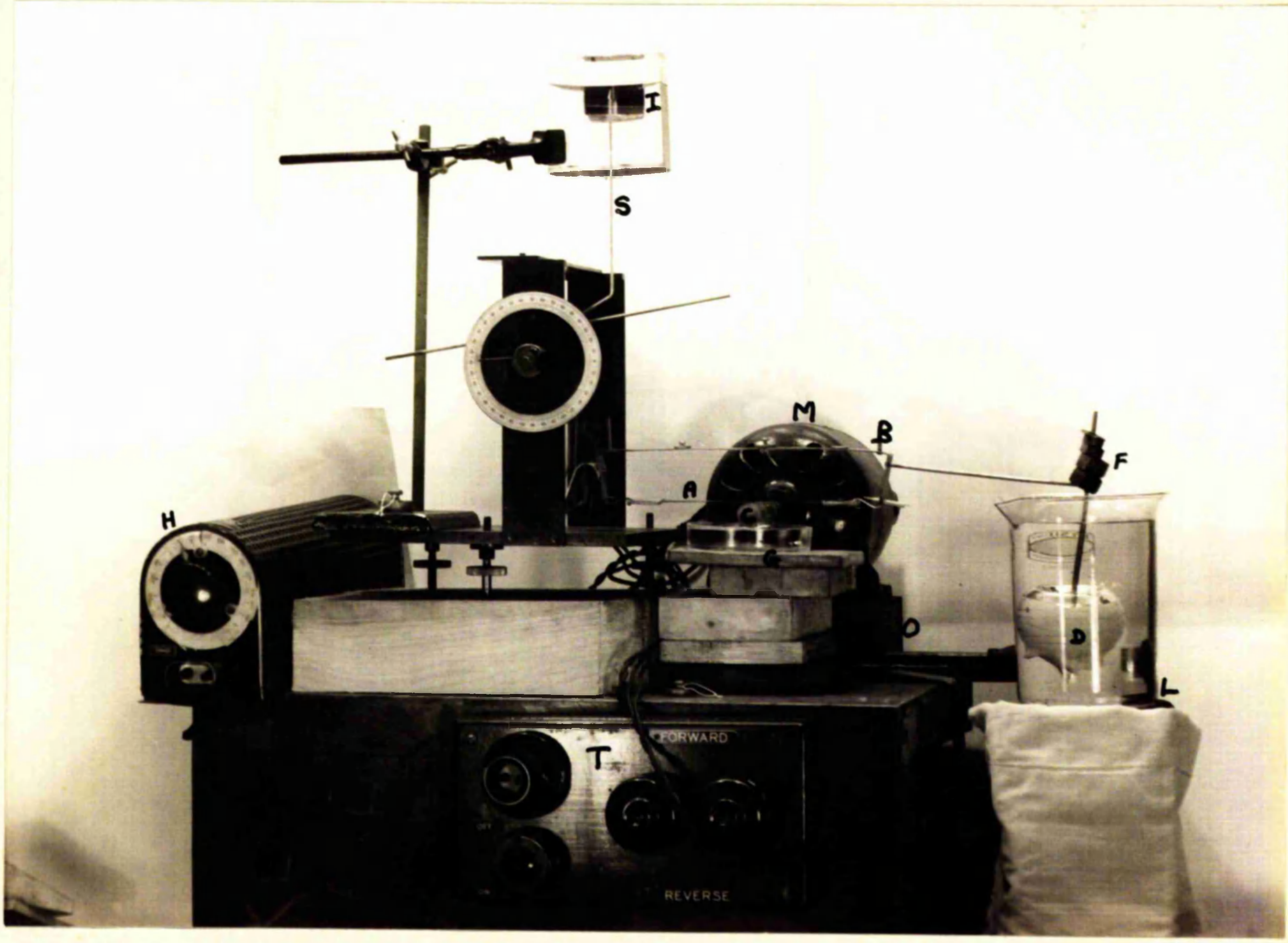


Fig. 8 General View of the Apparatus.

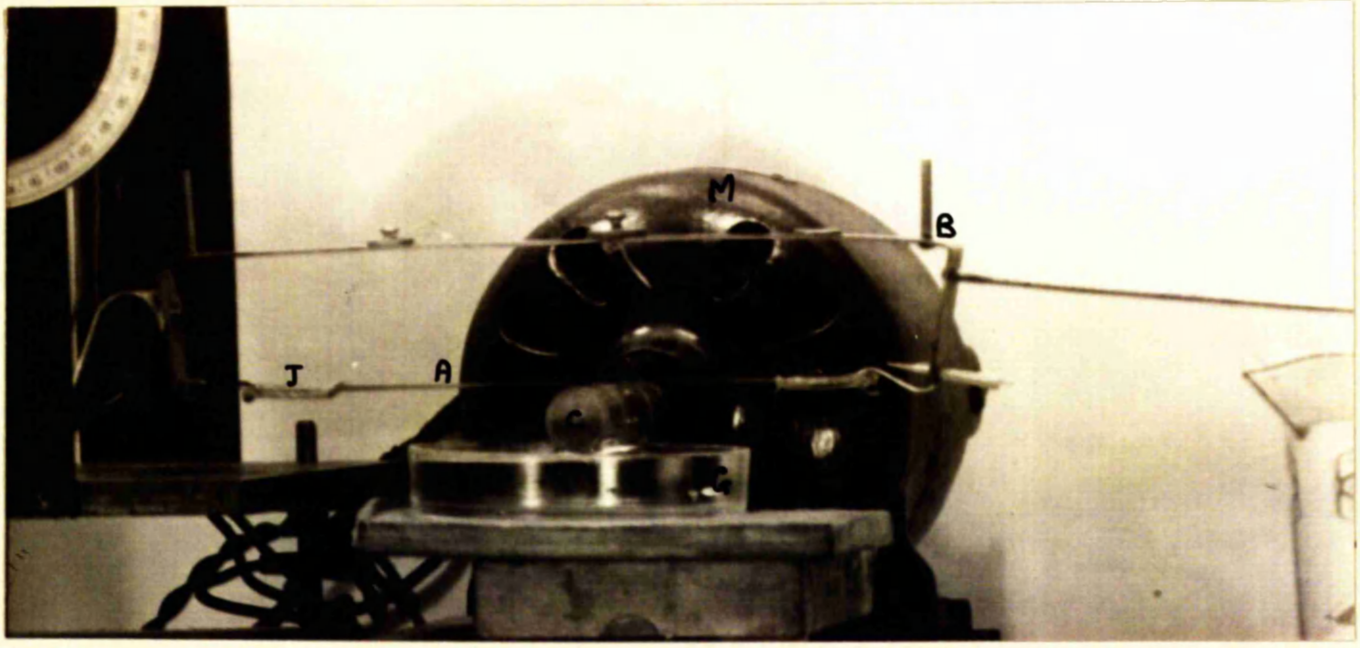


Fig. 9 Close-up of Surfaces etc.

(a) The Rubbing Surfaces.

Friction is measured between approximately 100 human hair, mounted in the form of a violin bow, and a cylinder made of glass or ivory.

(i) The Cylinder, which is about 6 cm. long and 1.5 cm. in diameter, is turned inside in the shape of a Morse taper which fits on the shaft of an electric motor. All cylinders used were provided with the same taper so that they could be used interchangeably on the same motor shaft. Both the glass and the ivory cylinders were made especially for the purpose of these experiments and their surfaces had been polished with particular care. Before use the cylinders were cleaned by prolonged Soxhlet extraction with pertroleum ether, followed by alcohol and by washing in distilled water.

(ii) The Fibres. After a thorough purification by means of Soxhlet extraction, first with petroleum ether (40-60°C.) then with alcohol, each extraction taking about 12 hours, followed by washing in distilled water, a suitable portion of the hair is separated from the lock. One end of the hair is then attached to a small (about 1 x 2 cm.) plate J of 1/16thin thick cellulose acetate sheeting, the plate being kept in a templet.

Before the ends are fixed permanently with acetate dope (the acetate evaporating off and leaving the fibres firmly gripped between the plate and the new layer of acetate) they are arranged to lie parallel to each other in one plane thus forming a pad about one centimetre wide. With one set of ends fixed in this way the hair are then combed with a clean piece of felt which arranges them parallel to one another with a minimum of interlacing. The remaining loose ends are then attached with cellulose acetate to another small cellulose acetate plate. After all the loose, crimped and interlacing fibres have been removed individually the hair specimen is then attached, by means of hooks, to the frame B.

This frame is made of brass and is constructed in such a way that it holds the fibres, now in the form of a taut, straight bow.

(b) Application of Pressure.

The frame holding the fibres in this way is then placed over the cylinder in the manner of a cantilever, being firmly supported at one end by means of an knife-edge resting on a wire attachment connected to the torsion wire. The other end of the frame, which is fitted with a thin vertical rod, rests on the glass float D in the beaker L filled with water.

The buoyancy of the float is such that unless extra weight is placed on it the frame will be lifted away from the cylinder. However, by placing suitable loads F on the frame the resultant buoyancy of the float can be just neutralised and an equilibrium condition can be reached, which allows the fibres to touch the cylinder without significant pressure. Final determinations of this load can be made by adjusting the position of a 0.5 g. weight on the upper surface of the frame. In this way this position of effectively zero pressure can be established with considerable precision.

The load or pressure under which the measurements are to be taken is then applied very simply by placing the appropriate weight on the upper part of the frame just above the line of contact between the two rubbing surfaces. (A weight of 5 g. is shown in this position on Fig.9).

With suitable means for measuring friction, the load may be varied over a wide range, the range used in these experiments being from 2 to 30 g. per 100 fibres, or 0.01 to 0.3 g. per fibre. Higher loads may also be used but the fibres will then tend to curve round the cylinder giving rise to the capstan effect when a different formulae ($\ln(T/T_1 = \mu\theta$) has to be applied; a coarser torsion wire would also be then required. For loads lighter than 2 g. readings can also be taken using a finer torsion wire.

(c) Speed of Rubbing.

As indicated before, the instrument had to provide the means of rubbing the surfaces at relatively higher speeds, and it was thought therefore that this could be arranged by maintaining the fibre surface stationary whilst rotating the cylinder by fitting it on the shaft of an electric motor whose speed could be varied over a wide range by means of a rheostat.

The motor M is a 1/8 H.P. D.C. Shunt motor in series with a 450 ohms rheostat H, and is capable of running in both directions of rotation, the reversing mechanism being provided on the switchboard T.

The speeds were calibrated by means of a Tachometer and were marked in the form of a circular dial against the appropriate positions of the rheostat pointer. The range of speed available with this arrangment was from about 10 to about 110 cm./sec.

The motor is firmly screwed to the wooden base O which in turn is strongly clamped to the main base W. The motor can be moved in the direction parallel to the frame, as the base O can slide on a rail, the position of the base being adjusted by means of a screw. In this way the cylinder can be presented to various portions of the fibre surface along the length of the specimen.

(d) Supply of Liquid.

This was arranged simply by placing a small Petrie dish G, full of the appropriate liquid, underneath the cylinder which is submerged in the liquid to the depth of 2-3 mm. On running the motor the liquid is carried round the rotating cylinder so that there is always an ample quantity of it at the junction of the two rubbing surfaces.

(e) Friction-Recording Mechanism.

The mechanism for measuring the frictional forces developed at the rubbing surfaces consists of the torsion head E, the fibre holding frame being coupled with it as described.

It was found by trial that the most suitable diameter of the torsion wire (which is made of steel) for the present purposes is 0.020 in., since it gives the widest range of readings for the loads used. The wire can be turned by means of the knob R and the readings, indicated by a fine pointer P, can be taken off the circular scale which consists of two parts, each extending over 180 degrees and consisting of an equal number of divisions.

Another pointer S which is very light, being made of aluminium, is sealed to the centre of the torsion wire as shown, and the small mirror I, with a single fine vertical line index mark on it, is placed against the fine end of pointer S.

Before the experiment is began, the original position of the frame is fixed by adjusting the torsion wire so that the pointer P is at zero on the circular scale, whilst the position of the mirror I is also adjusted until the pointer S coincides with it exactly.

When the cylinder is set in motion, say in the clock-wise direction, the whole frame B is dragged to the right owing to friction between the two rubbing surfaces with the result that the torsion wire is twisted and the pointer S therefore displaced from its zero position against the mirror mark. Now by slowly turning the knob R the torsion wire is turned in the opposite direction to the direction of twist imposed by the movement of the frame until the original state of the wire is restored, i.e. when the pointer S returns to the level of the index line on the mirror. The amount of turn (in degrees) required to do this is regostered by the pointer P and is, of course, equivalent to the twist caused by the movement of the frame, i.e. by the frictional forces. The value for the latter in grams is then obtained from the calibration curve of the wire (fig.10). For measurement of friction in the opposite direction of rubbing, i.e. when the cylinder moves anti-clockwise, the same procedure is repeated, except that in this case the frame will of course be displaced to the left and so the torsion wire has to be turned in the opposite direction.

CHAPTER 5.

EXPERIMENTAL RESULTS ON FRICTION OF ANIMAL FIBRES.

PRELIMINARY EXPERIMENTS.

These experiments were carried out in order to survey the ~~appa~~ behaviour of the apparatus and the method described in the preceding Chapter.

1. CALIBRATION OF TORSION WIRE.

As indicated in the description of the instrument in Chapter ~~X~~ 4, the 0.020 in. dia. steel torsion wire was found to be most suitable in the present experiments. The wire was calibrated by arranging the bracket in such a way that the metal rod attachment (which provides the connection between the frame and the torsion head and which is clamped and soldered to the centre of the torsion wire) was in a horizontal position. Various ways weights were then hung at the end of the rods, and each time the torsion wire was turned by the weights the pointer S was displaced from the zero position. The twist imposed on the wire by the weights was counterbalanced by turning the torsion head until the pointer S returned to its original zero position. The angle of twist was noted from the position of pointer P, and the results for five different weights are given in Table 1 and plotted in Fig.10.

All subsequent readings (in degrees) were converted into grams by reference to Fig.10. To obtain the frictional coefficient the value for the frictional force (in grams) was then divided by the load (in grams). The coefficient of friction on rubbing from tip to root (i.e. against scales) is designated throughout as μ_T , whilst the coefficient on rubbing from root to tip (i.e. with scales) is indicated as u_R.

LOAD g.	ROTATION OF TORSION HEAD Degrees.
1	4.5
2	9.0
5	22.5
7	31.0
10	45.0

TABLE 1. CALIBRATION OF TORSION WIRE.

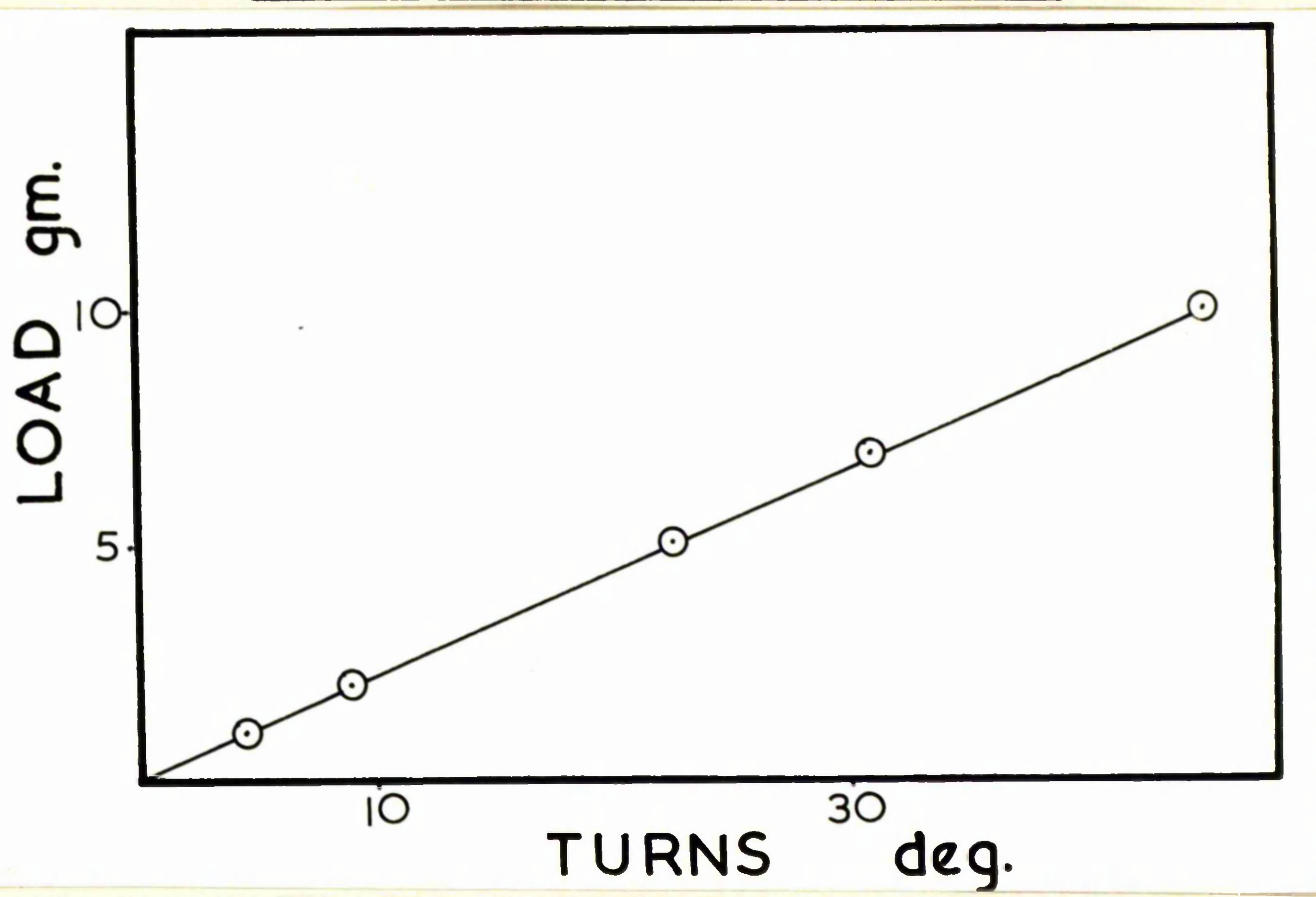


FIG. 10. CALIBRATION OF TORSION WIRE.

2. ESTABLISHMENT OF EXPERIMENTAL PROCEDURE.

(a) Immersion of Fibres Before Measurement.

It was found that irregular results were obtained unless the fibre specimen had been immersed in the appropriate liquid, in which friction was to be measured, for several minutes prior to the taking of the reading. In general the fibres were allowed to remain in the liquid for about 10 minutes before measurement.

(b) Wear on The Fibre Surface.

When the fibres are rubbed against the cylinder in liquids of relatively low viscosity, e.g. in water, the readings tend to become somewhat erratic if the same portion of the fibre surface is used too often. It was found by experience that one part of the fibre bow can be used safely for some 20-30 determinations before the readings become unreliable.

(c) Friction of Various Portions of Fibre Bow.

In view of the above observation it was important to establish whether there are any differences in friction between various parts of the fibre surface. The experiments were carried out in water and measurements were taken at intervals of about one centimetre along the whole length of the bow, but all readings were found to be similar within the experimental error. It is therefore permissible to use any part of the bow and to compare freely the results for various portions of the fibre surface.

(d) Friction of Various Fibre Bows.

It was found that for human hair taken from the same lock there were no differences in the values of frictional coefficients between two bows, provided the number of fibres in the ~~locks~~ bows were roughly similar.

(e) Accuracy of Readings.

The general procedure was to take at least three or four readings for every determination, the readings being taken with an accuracy of half a degree. Generally the readings agreed within half a degree. In viscous media the reproducibility was practically perfect. In subsequent tables the values of frictional coefficients are always stated as mean values.

Half a degree scatter represents a sensitivity of about 2.5% in the case of the against scale coefficient and of about twice as much in the case of the with-scale coefficient. This degree of reproducibility is quite sufficient in the present work.

(3) FRICTION OF HUMAN HAIR COMPARED WITH WOOL.

Human hair was used in most experiments, and in order to justify its use in this work in place of wool fibres, as discussed in Chapter 4, some comparative measurements were carried out using both these types of animal fibres under similar conditions. The wool fibres were 42-44s English Crossbred, and they were mounted also in the form of a bow very similar to the pad of human hair.

As it will be evident from Table 2 both types of fibres exhibit a very pronounced differential frictional effect, the values of the coefficients being, in this instance, of similar order.

FIBRE	LOAD: 5 g. SPEED: 42 cm/sec.			LOAD: 10 g. SPEED: 42 cm/sec.		
	μ_T	μ_R	$\mu_T - \mu_R$	μ_T	μ_R	$\mu_T - \mu_R$
Human Hair	.68	.18	.50	.64	.18	.46
Wool Fibres	.73	.32	.41	.73	.30	.43

TABLE 2. COMPARATIVE VALUES OF FRICTIONAL COEFFICIENTS OF HUMAN HAIR & WOOL.

1. EXAMINATION OF THE EFFECT ON FRICTION OF VISCOSITY, SPEED AND LOAD.

In order to test out the hypothesis outlined in Chapter 3 experiments were designed to investigate the applicability of the fluid film theory of lubrication to the friction of animal fibres. An exhaustive examination was carried out of the frictional behaviour of animal fibres whilst varying in turn the various factors which it was considered could affect their frictional properties.

As indicated earlier, the principal interest in the present hypothesis lies in the suggestion that the cause of the differential friction of animal fibres may be explained on the basis of the fluid film lubrication theory.

Friction under conditions of fluid film lubrication is determined, for given bearing surfaces, by three main factors, viz. the viscosity of the fluid, the relative speed of rubbing of the surfaces and the pressure applied to the rubbing surfaces. It was, therefore, appropriate to investigate first the effect of those factors on the friction of animal fibres.

Most of the experiments consisted of measuring the friction between human hair and polished glass. The hair was mounted in the form of a taut violin bow and was rubbed by the rotatimg glass cylinder as described before.

The speed of rubbing was varied by adjusting the velocity of rotation of the cylinder, whilst the pressure between the surfaces was controlled by placing appropriate weights above the line of contact of the two surfaces.

Viscosity was studied by using mainly aqueous solutions of sucrose of various concentrations, from pure water to 65% sucrose (by weight), which gave a range of viscosity from 1.0 to 160 centipoises at 20°C. The viscosity of each solution used in the frictional measurements was first determined by means of an Ostwald Viscometer (BSS 188) and checked against the viscosity data of Bates et al. in their 'Polarimetry, Saccharimetry and the Sugars' (93).

The viscometer was standardised by means of 60% sucrose (by weight) whose density (ρ) was 1.2837 and viscosity η = 43.55 The viscometer reading for this solution was found to be 128.6 seconds at 25°C. The viscometer constant K was then calculated from the formulae $\eta = K \rho t$, which expression was then used for calculating the viscosity of the solutions. (K = 0.2638).

All measurements reported in this section were carried out at room temperature (20-21°C.) using fibre pads composed of about one hundred hair and using the same glass cylinder.

(a) Variations of Friction with Viscosity and Load at 42 cm./sec.

In the first part of these experiments the speed was kept constant (at 42 cm./sec.) and measurements taken in seven sucrose solutions of different viscosities under five different loads in each solution. The viscosities were 1.0, 5.4 , 9.4 , 16.0 , 30.4 , 52.0 and 160 centipoises, whilst the loads used were 2, 5, 10, 15 or 20 g.

The results are set out in Table 3 which gives the values of both the against-scale coefficient (μ_T) and the with-scale coefficient (μ_R). The value of the ZN/P relation (where Z = viscosity in centipoises, N = speed in cm./sec. and P = load in grams) is also stated against each frictional coefficient.

These results are plotted in Figs.11, 12 and 13, and it must be borne in mind that whilst the scale for the frictional coefficients is linear, the viscosity and the ZN/P scale is in all cases logarithmic. (This, in fact, applies to all diagrams in the present series).

Thus Fig.11 shows the variation of the against-scale coefficient with viscosity under each load, Fig. 12 shows the same relation for the with-scale coefficient, whilst in Fig.13 are plotted both coefficients against ZN/P, the ZN/P relation embodying all the conditions of viscosity and load (at 42 cm./sec.) used in this set of experiments.

VISCOSITY in centipoises	FRICTION														
	2 g.			5 g.			10 g.			15 g.			20 g.		
	μ_T	μ_R	ZN/P	μ_T	μ_R	ZN/P	μ_T	μ_R	ZN/P	μ_T	μ_R	ZN/P	μ_T	μ_R	ZN/P
1.0	.63	.17	21.0	.64	.18	8.4	.64	.18	4.2	.63	.20	2.8	.62	.19	2.1
5.4	.55	.28	113	.54	.25	45.2	.54	.24	22.6	.50	.19	15.0	.47	.15	11.3
9.4	.57	.42	197	.48	.29	79.0	.45	.25	39.5	.45	.20	26.2	.45	.18	19.7
16.0	.62	.45	335	.42	.30	135	.40	.27	67.5	.36	.22	45.0	.36	.20	33.7
30.4	.76	.57	640	.48	.42	256	.42	.33	128	.36	.29	85.5	.34	.28	64.0
52.0	1.07	1.02	1090	.68	.63	437	.52	.44	218	.41	.38	145	.33	.33	109
106.0	1.37	1.25	2220	1.20	1.10	890	.89	.86	445	.75	.72	297	.61	.60	222

TABLE 3. VARIATIONS OF FRICTION WITH VISCOSITY AND LOAD AT 42 CM./SEC.

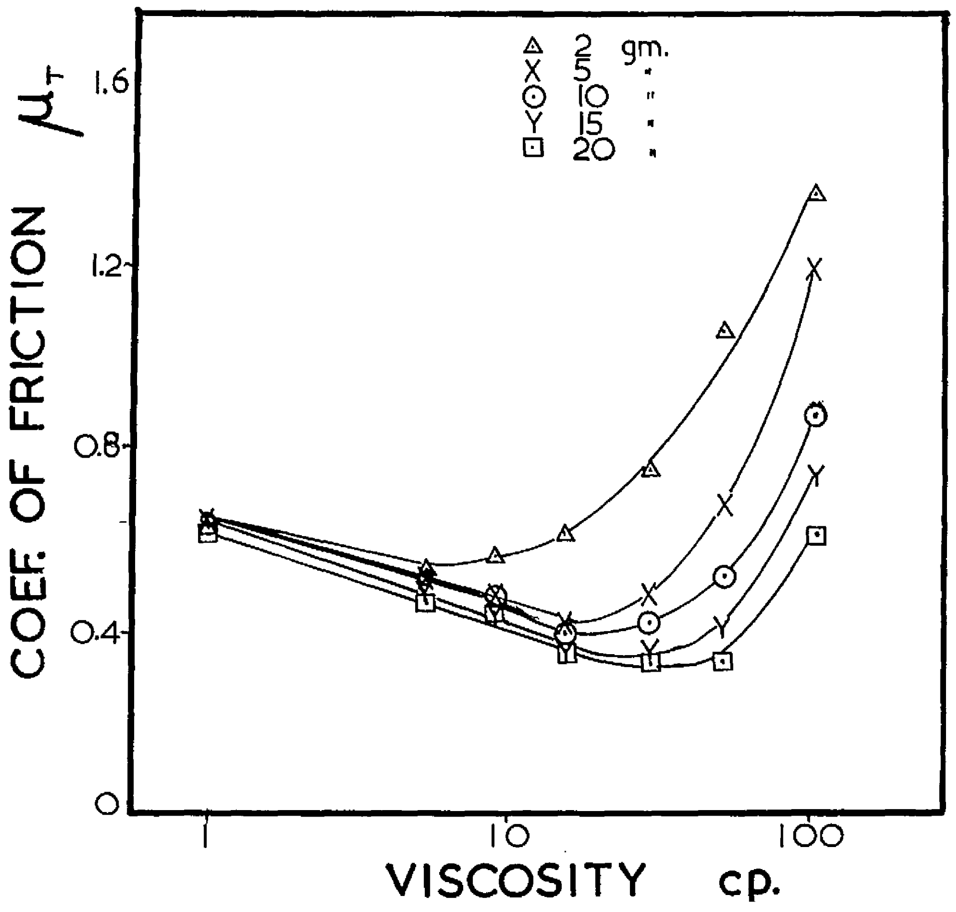


FIG. 11. VARIATIONS OF AGAINST-SCALE COEFFICIENT WITH VISCOSITY AND LOAD AT 42 CM./SEC.

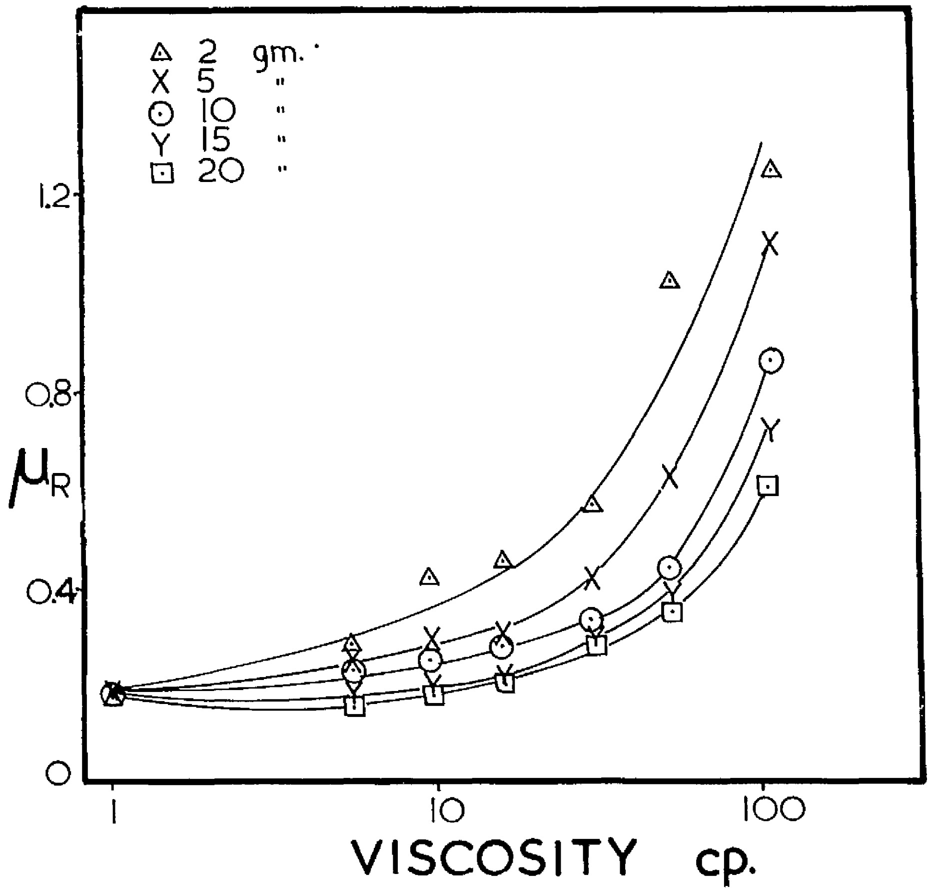


FIG. 12. VARIATIONS OF WITH-SCALE COEFFICIENT WITH VISCOSITY AND LOAD AT 42 CM./SEC.

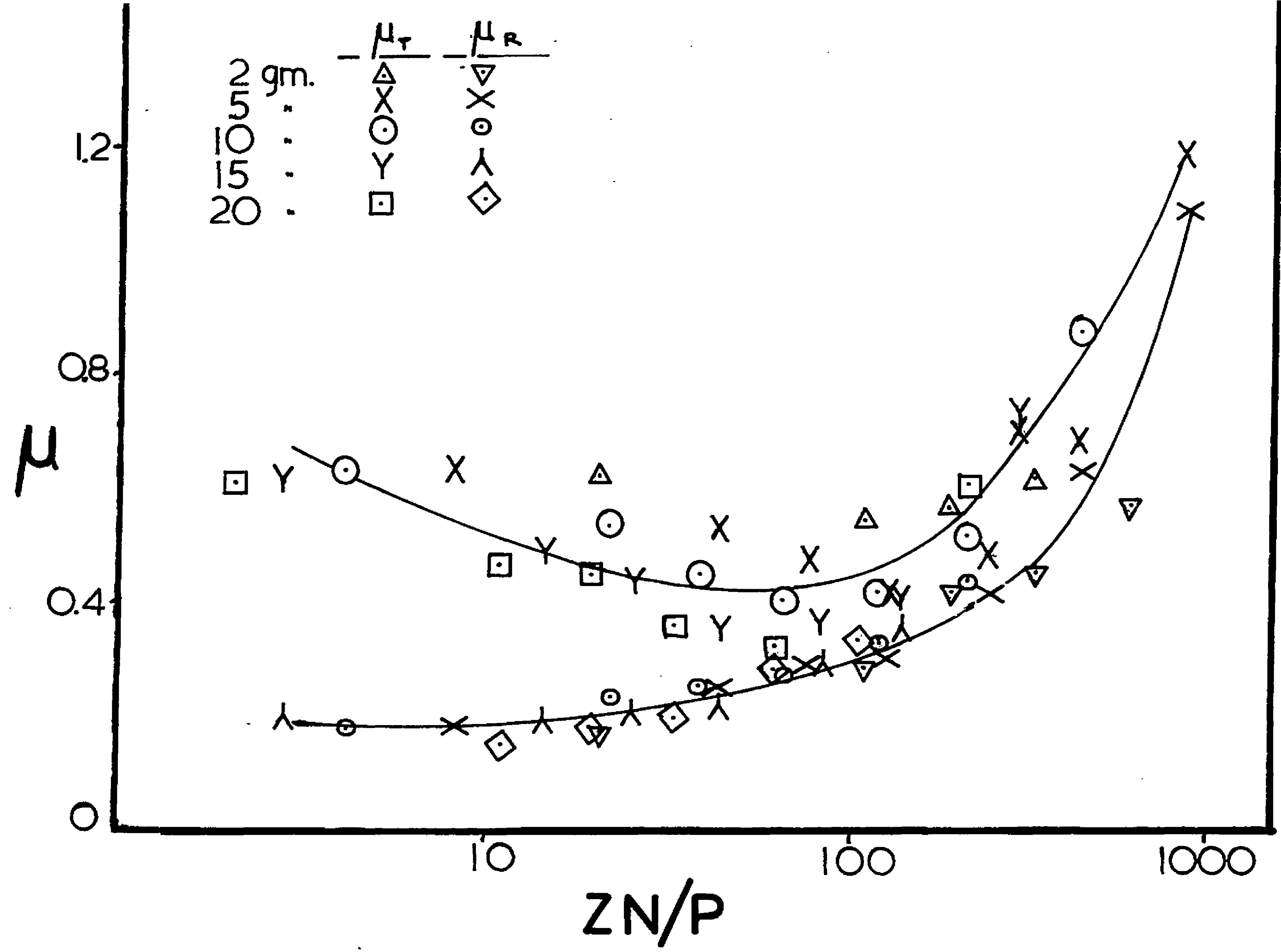


FIG . 13. VARIATIONS OF AGAINST-SCALE AND WITH-SCALE COEFFICIENTS WITH ZN/P (EXPTS.1a).

(b) Variations of Friction with Viscosity and Speed Under 2 g. Load.

In this series the load was kept constant (2 g.) and both viscosity and speed varied. Again seven sifferent sucrose solutions were used (1.0, 5.4, ~~6.4~~, 9.4 16.0, 30.0, 45.4 and 158 cp.) and in each of them measurements were carried out at four different speeds (11.5, 25.0, 42.0 and 65 cm./sec.).

The values of μ_T and μ_R and also the ZN/P value for each coefficient are given in Table 4 and are illustrated in Figs. 14 and 15, the former giving the values for the against-scale coefficient and the latter for the with-scale coefficient against viscosity, each curve representing a different speed.

VISCOSITY in centipoise.	FRICTION											
	11.5 cm/sec.			25.0 cm./sec.			42.0 cm./sec.			65.0 cm./sec.		
	μ_T	μ_R	ZN/P	μ_T	μ_R	ZN/P	μ_T	μ_R	ZN/P	μ_T	μ_R	ZN/P
1.0	.70	.50	5.7	.68	.46	12.5	.63	.17	21.0	.54	.13	32.5
5.4	.65	.44	31.0	.66	.40	67.5	.55	.28	113	.42	.32	175
9.4	.68	.43	54	.66	.40	117	.57	.38	197	.48	.40	305
16.0	.68	.40	92	.66	.42	200	.62	.44	335	.60	.46	520
30.0	.64	.37	172	.70	.44	372	.74	.53	630	.80	.59	980
45.4	.63	.40	260	.74	.57	565	1.08	.96	740	1.25	1.08	1470
158.0	1.20	.97	910	1.82	1.82	1970	3.30	3.30	3300	4.10	4.10	5150

TABLE 4. VARIATIONS OF FRICTION WITH VISCOSITY AND SPEED (under 2 g. load).

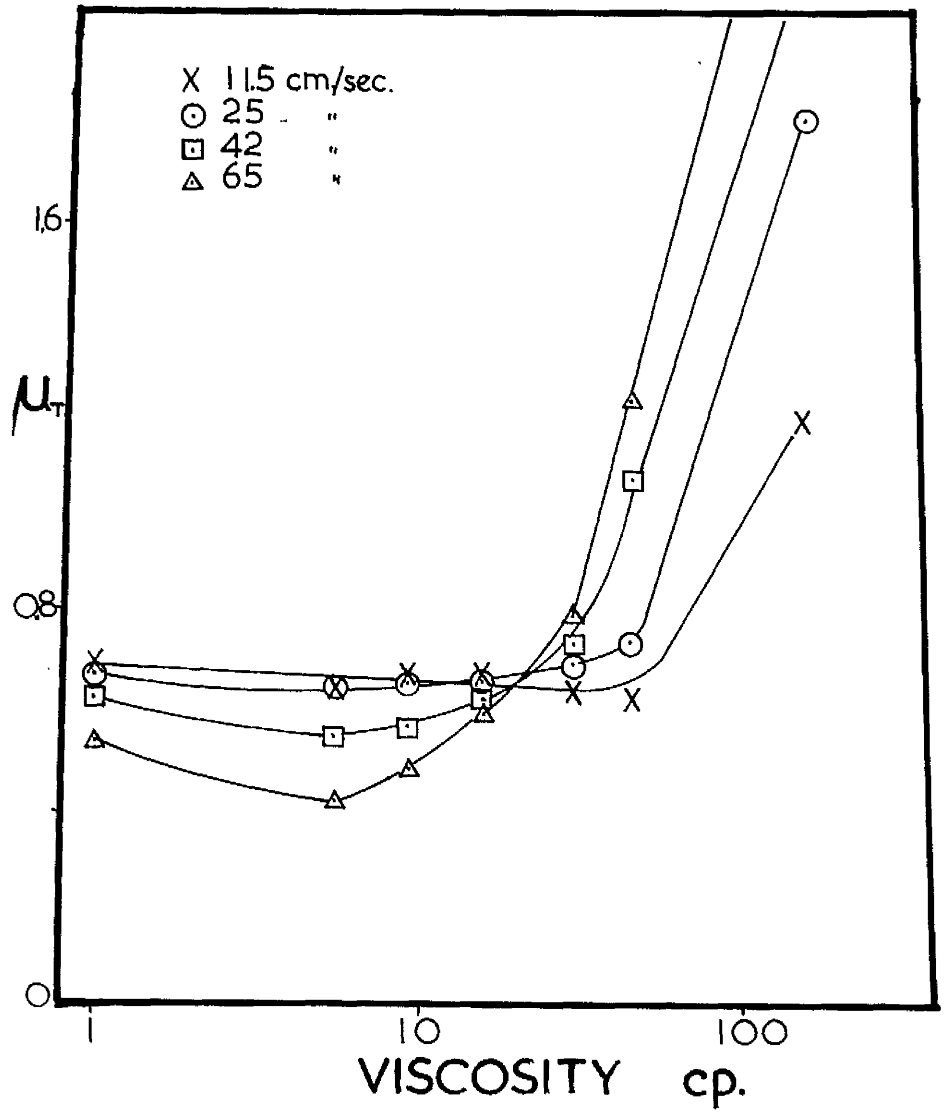


Fig. 14. VARIATIONS OF AGAINST-SCALE COEFFICIENT WITH VISCOSITY AND SPEED UNDER 2 g. LOAD.

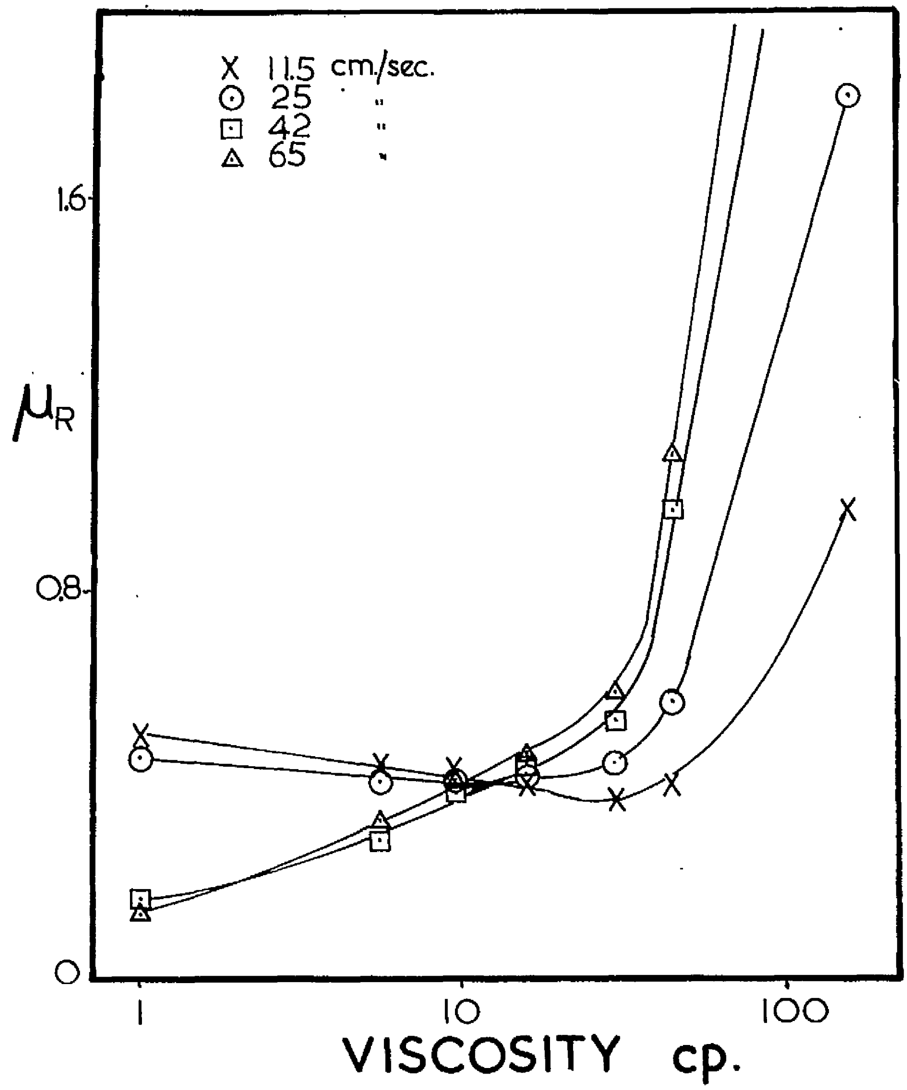


FIG. 15. VARIATIONS OF WITH-SCALE COEFFICIENT WITH VISCOSITY AND SPEED UNDER 2 g. LOAD.

VISCOSITY in centipoises	FRICTION											
	11.5 cm./sec.			25.0 cm./sec.			42.0 cm./sec			65.0 cm./sec.		
	μ_T	μ_R	ZN/P	μ_T	μ_R	ZN/P	μ_T	μ_R	ZN/P	μ_T	μ_R	ZN/P
1.0	.73	.40	2.3	.73	.35	5.0	.68	.18	8.4	.66	.18	13.0
5.4	.61	.34	12.4	.59	.29	26.0	.57	.25	45.2	.45	.23	70.4
9.4	.57	.36	21.6	.52	.35	47.0	.48	.29	79.0	.43	.32	122
16.0	.57	.32	36.8	.50	.29	80.0	.45	.29	135	.42	.36	195
30.0	.52	.34	69.0	.45	.38	150	.48	.42	252	.50	.48	390
45.4	.45	.41	105	.50	.48	226	.68	.63	380	.77	.75	590
134.0	.73	.64	310	1.16	1.04	670	1.54	1.50	1120	1.77	1.74	1740

TABLE 5. VARIATIONS OF FRICTION WITH VISCOSITY AND SPEED (under 5 g. load).

(c) Variations of Friction with Viscosity and Speed Under 5 g. Load.

The procedure was exactly as under (b) except that the load used was 5 g. The results are stated in the same manner in Table 5 and are plotted in Figs.16 and 17.

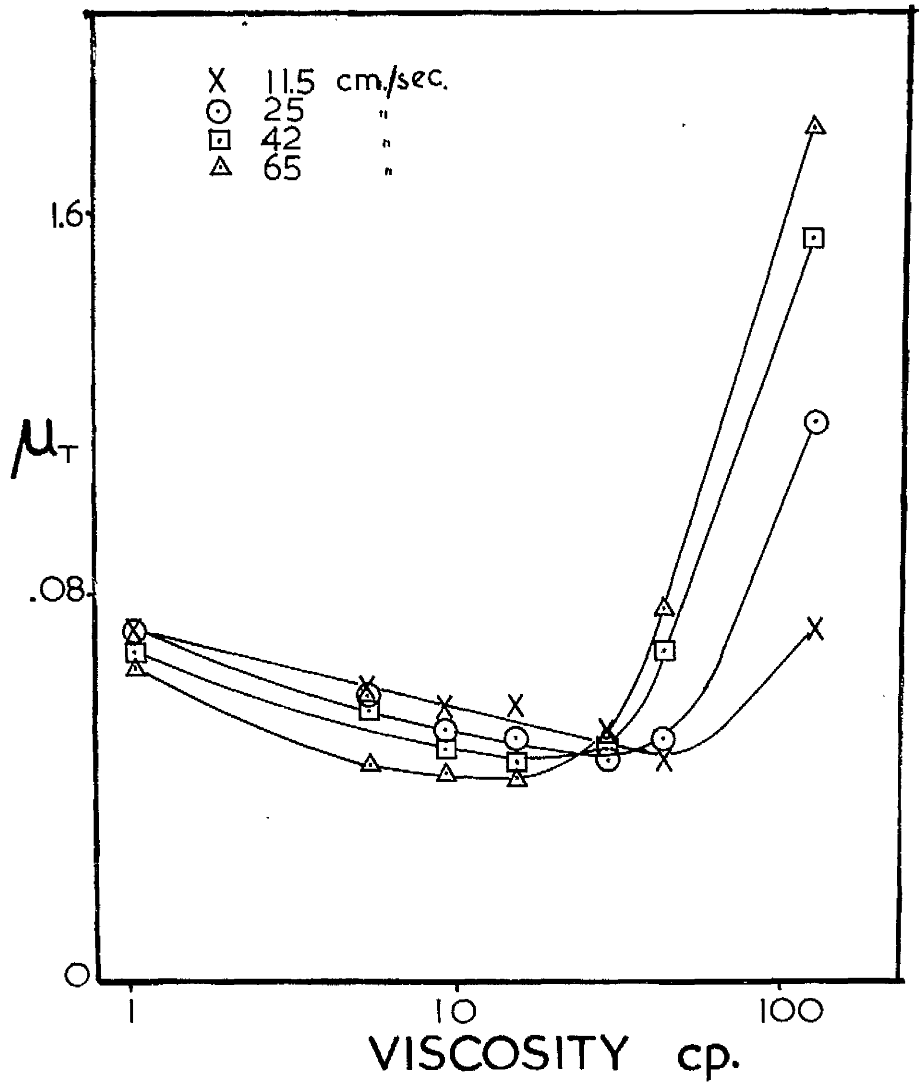


FIG. 16. VARIATIONS OF AGAINST-SCALE COEFFICIENT WITH VISCOSITY AND SPEED UNDER 5 g. LOAD.

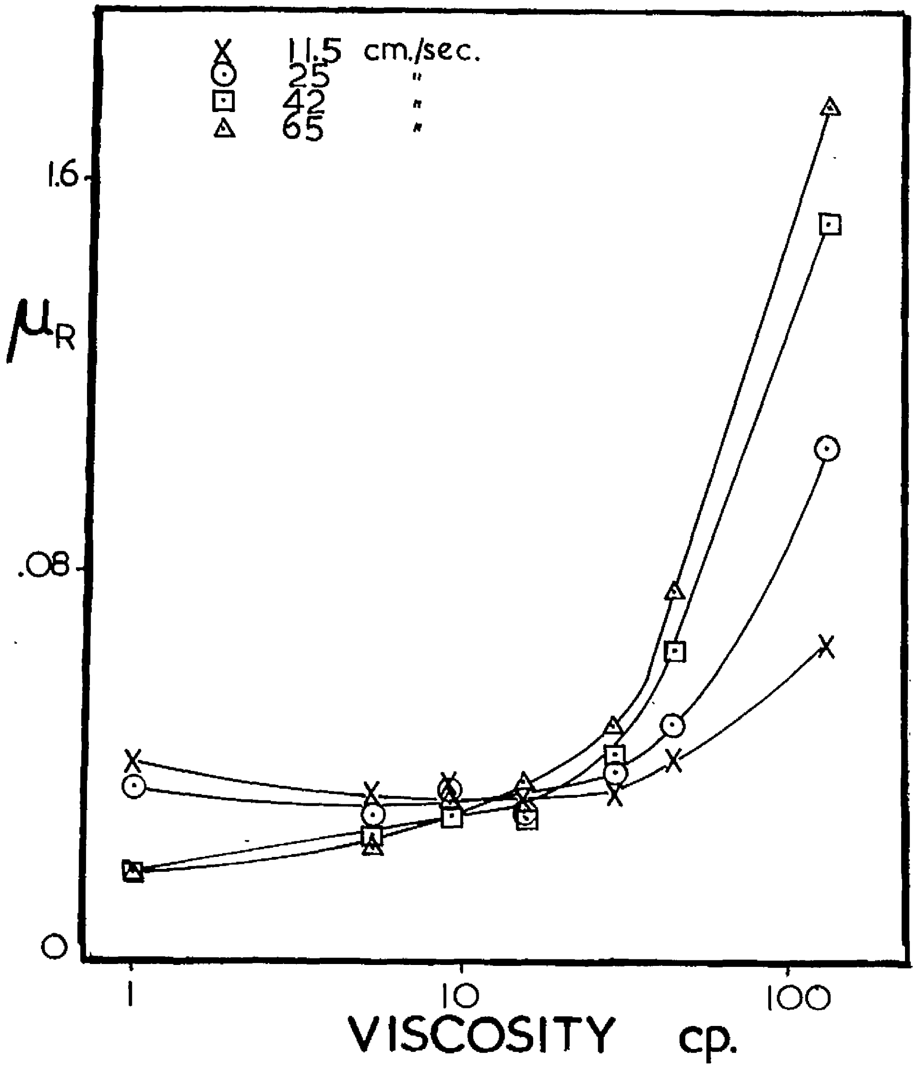


FIG. 17. VARIATIONS OF WITH-SCALE COEFFICIENT WITH VISCOSITY AND SPEED UNDER 5 g. LOAD.

VISCOSITY in centipoises.	FRICTION											
	11.5 cm./sec.			25.0 cm./sec			42.0 cm./sec.			65.0 cm./sec.		
	μ_r	μ_s	ZN/P	μ_r	μ_s	ZN/P	μ_r	μ_s	ZN/P	μ_r	μ_s	ZN/P
1.0	.73	.40	1.1	.73	.35	2.5	.68	.18	4.2	.62	.18	6.5
5.4	.59	.40	6.2	.58	.35	13.5	.51	.27	22.6	.43	.25	35.2
9.4	.57	.37	10.8	.48	.34	23.5	.41	.28	39.5	.36	.27	61.0
16.0	.57	.35	18.4	.53	.33	40.0	.41	.29	67.5	.38	.32	97.5
30.0	.50	.34	34.5	.40	.34	75.0	.40	.33	126.0	.41	.37	195
45.4	.42	.29	52.3	.47	.33	113	.50	.47	190	.58	.57	295
150.0	.54	.49	173	.77	.70	375	1.14	1.09	630	1.40	1.36	975

~~Figx~~ TABLE 6. VARIATIONS OF FRICTION WITH VISCOSITY AND SPEED (under 10 g. load).

(d) Variations of Friction with Viscosity and Speed Under 10 g. Load.

This series is analogous to the preceding two sets of experiments (b and c) except that the load was increased to 10 g. The data obtained are given in Table 6 and Figs.18 and 19.

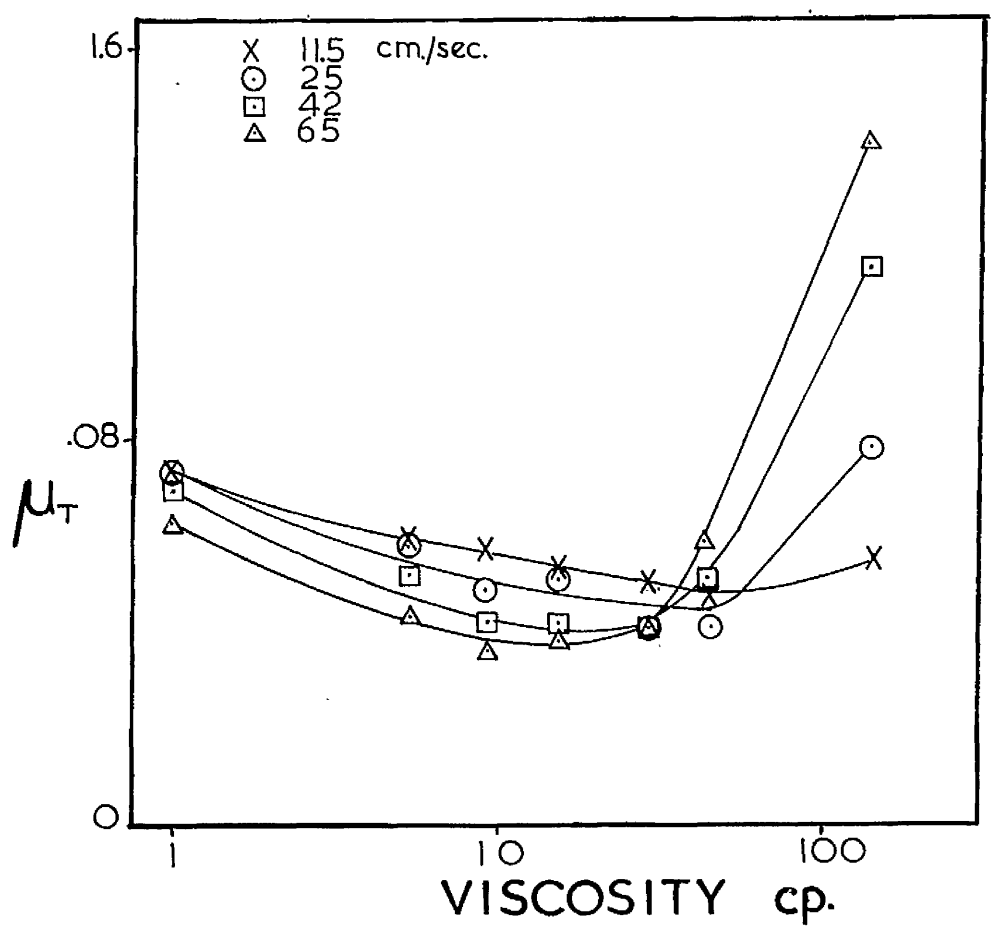


FIG. 18. VARIATIONS OF AGAINST-SCALE COEFFICIENT WITH VISCOSITY AND SPEED UNDER 10 g. LOAD.

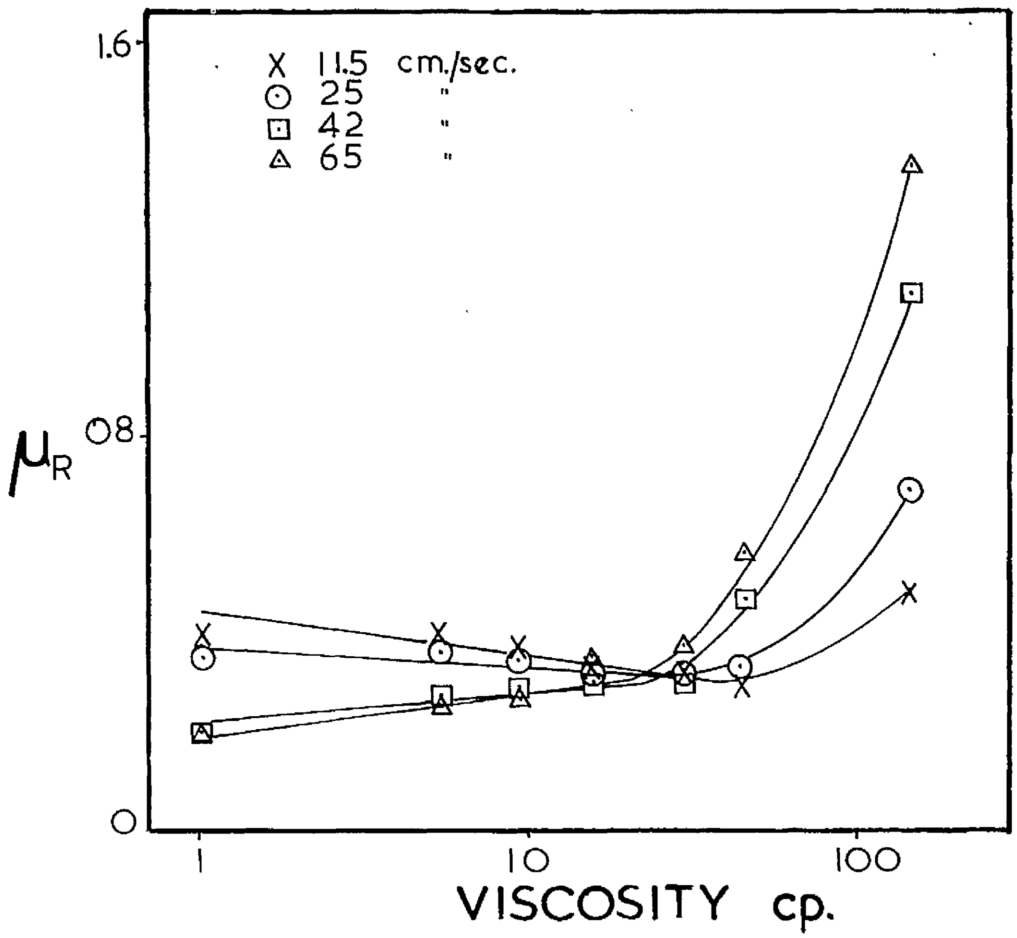


FIG. 19. VARIATIONS OF WITH-SCALE COEFFICIENT WITH VISCOSITY AND SPEED UNDER 10 g. LOAD.

(e) Variations of Friction with ZN/P.

The type of relation between the frictional coefficient and the expression ZN/P, which incorporates all three factors (viscosity Z, speed N and load P), has already been indicated in Fig. 13 for the first series of experiments (a) in which the speed was kept constant.

Now in Figs. 20 and 21 friction is plotted against the ZN/P values which have been derived from the series (c) and (d). (In order not to confuse the graph the experimental points from series (b) are not included, but they also fit the curves.)

The against-scale coefficient of friction against ZN/P is shown in Fig.20 and the with-scale coefficient is plotted in Fig.21.

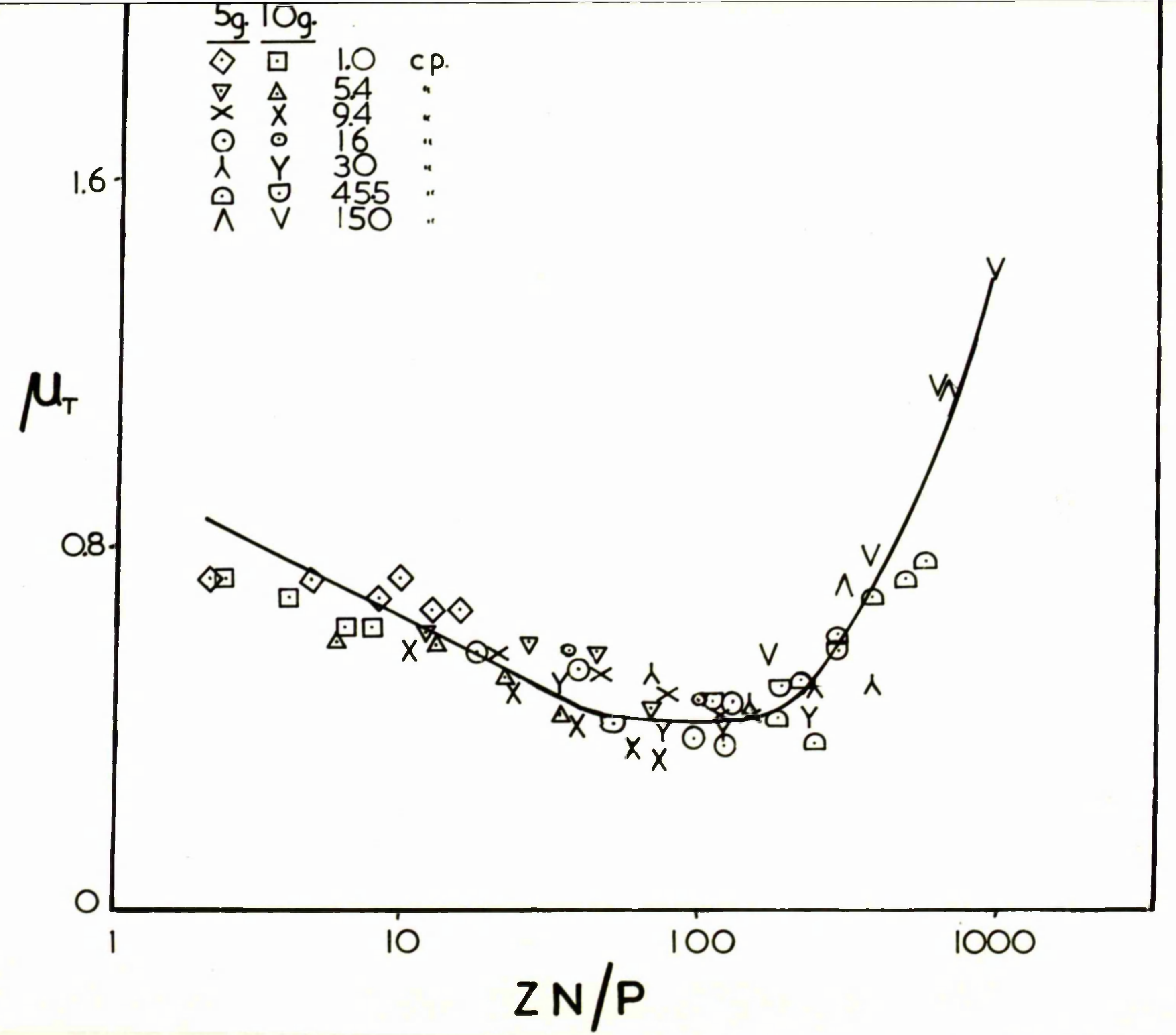


FIG. 20. VARIATIONS OF AGAINST-SCALE COEFFICIENT WITH ZN/P (from Expts.1 b-d).

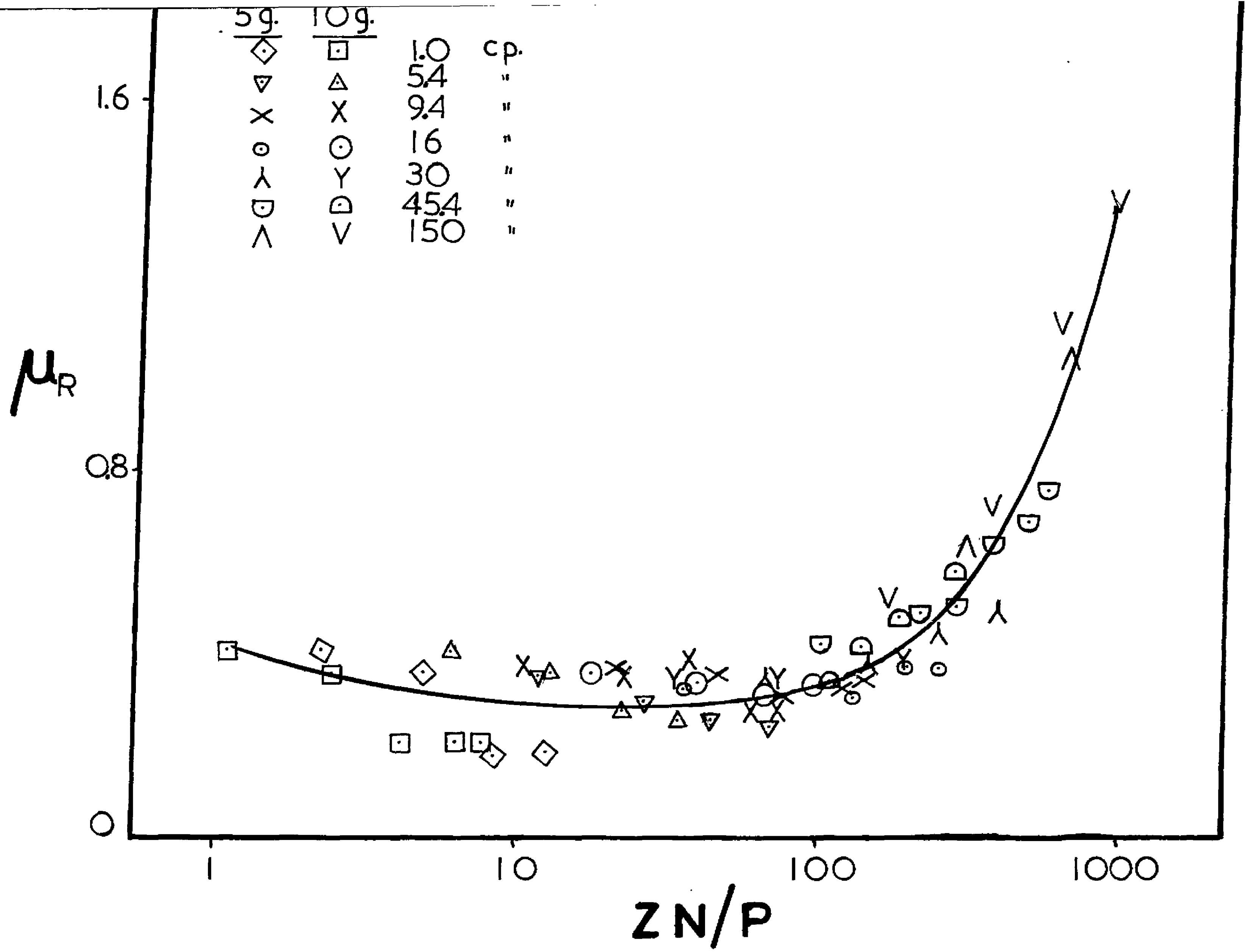


FIG. 21. VARIATIONS OF WITH-SCALE COEFFICIENT WITH ZN/P (from experiments 1 b - d).

The results presented in the above five sections are of the greatest interest, for they show a striking simil/arity in frictional behaviour between of animal fibres and bearings thus strongly suggesting the analogy as predicted by the present hypothesis.

As indicated in Chapter 3 the various types of friction obtaining in bearings can be depicted diagramatically as shown in Fig.4 where the frictional coefficient is plotted against the ZN/P relation. A similar method of representing frictional conditions as determined in the present experiments has been adapted in Figs. 13, 20 and 21, and it will be observed that there is a remarkably close resemblance between the latter curves and that from Fig. 4 for a bearing.

The same dependence of the coefficient of friction of animal fibres on these three factors when they are considered individually can be noted from the remaining diagrams. Thus in the against-scale coefficients the minima on the curves are always displaced to the right as the load increases or to the left when the speed increases. In the case of the with-scale coefficient these minima are not always so pronounced, for the rise of the curves to the left of the minima does not occur in all cases but only when the ZN/P relation is sufficiently low, e.g. under heavy load and at low speed and viscosity.

Moreover, by comparison of the curves for the against-scale and the with-scale coefficients it will be observed that the minima of the latter curves are always to the left of the against-scale curves.

All these findings are in full agreement with the lubrication theory and confirm the predictions of the present hypothesis. They will be discussed fully later.

2. FRICTION IN SOME VISCOUS SOLUTIONS OTHER THAN SUCROSE.

In order to ascertain whether the viscosity effect as shown in the preceding experiments is independent of the chemical nature of the lubricating fluid, some measurements were carried out using aqueous solutions of Gum Tragasol and of Methyl Cellulose (Celacol M450), both substances, like sucrose, being inert towards keratin and both giving neutral solutions.

The values of frictional coefficients obtained in these solutions are given in Table 7 in comparison with the data for friction in sucrose solutions of similar viscosities. All measurements were made at 42 cm./sec. and under 5 and 10 g.

As will be seen from the Table below there appears to be no significant difference between any of those solutions.

TABLE 7. COMPARATIVE VALUES OF FRICTION IN GUM TRAGASOL, METHYL CELLULOSE AND SUCROSE.

MEDIUM	VISCOSITY cp.	5 g. LOAD		10 g. LOAD	
		μ_T	μ_R	μ_T	μ_R
Gum Tragasol	30.0	.50	.43	.43	.35
Sucrose	30.4	.48	.42	.42	.33
Methyl Cellulose	54.0	.64	.60	.50	.42
Sucrose	52.0	.68	.63	.52	.44

3. FRICTION OF HUMAN HAIR AGAINST AN IVORY SURFACE.

The influence of the nature of the surface against which the fibres are rubbed was examined by comparing the frictional behaviour of human hair against polxished glassx, as used in the preceding experiments, with the behaviour against another hard surface of different chemical composition, namely ivory. The ivory was also in the form of a cylinder which had been made and polished especially for the purpose of these experiments.

The glass and the ivory surfaces were compared by means of the 'Talysurf', an instrument made by Messrs. Taylor, Taylor, Hobson Ltd., which measures surface roughness by the Stylus method where the ~~oscillations~~ ondulations of a diamond-pointed pick-up are magnified by electrical methods.

Unfortunately, as no suitable pick-up was available, it was found impossible to determine surface roughness in the circumferential direction, i.e. in the direction in which the cylinders are rubbed against the fibre bow. The surfaces had, therefore, to be tested in the direction parallel to their axes, and the traces obtained are reproduced in Fig.22.

The deviation of the curves from the straight horizontal direction represents the waviness of

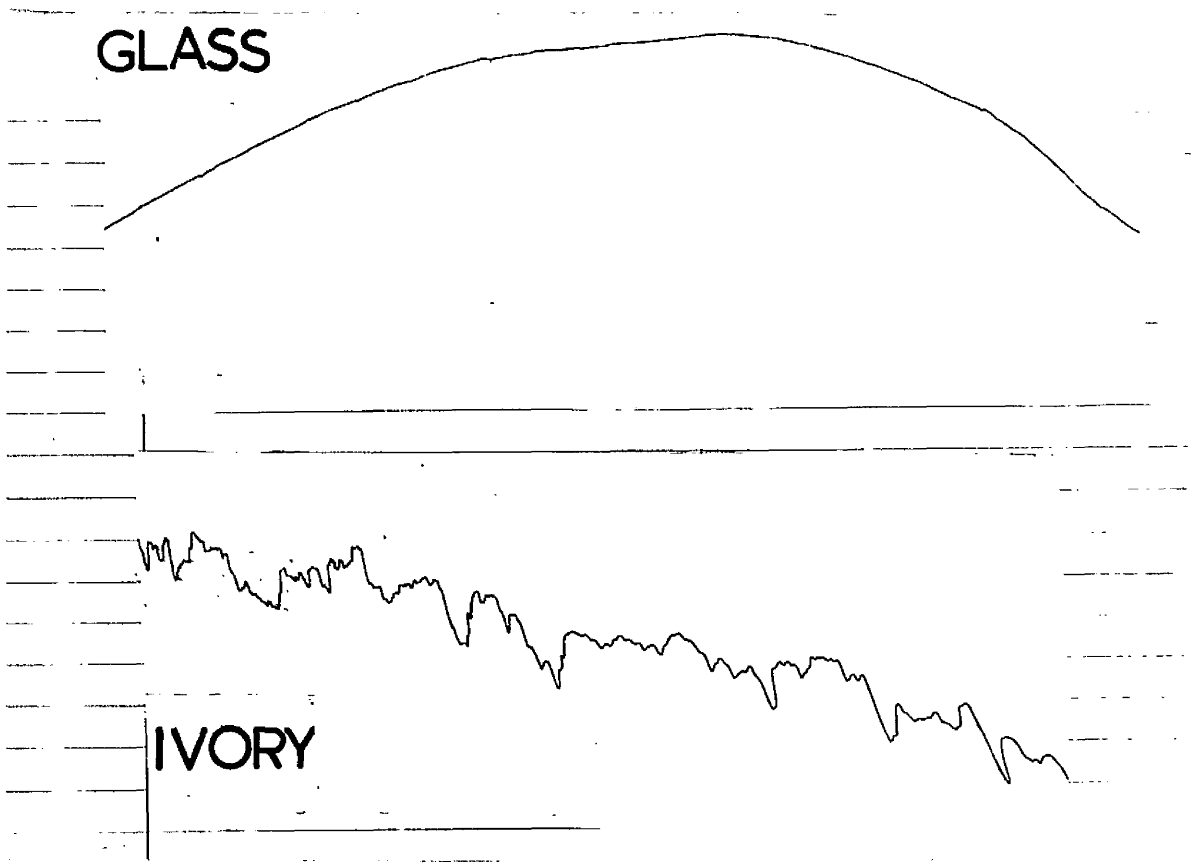


FIG. 22. STYLUS TRACES SHOWING THE NATURE OF THE GLASS AND IVORY SURFACES.

the cylinder surface, whilst the actual texture of the surface, which is of greater importance in this connection, is portrayed by the smoothness or otherwise of the curves in the vertical direction, the magnification in this direction being 40,000.

As the traces reveal, whilst the glass surface is perfectly smooth the ivory surface is not, the size of the irregularities, judging from the size of the peaks and valleys of the curve, being of the order of 0.25 μ. The order of size of the scale edges on fibre surface is about 0.5 μ.

The serious limitation of these findings is due to the fact that they do not reveal, for reasons explained above, the nature of the surface in the circumferemtial direction, which is of primary interest here. There is a strong probability that the surface is in fact smoother in the circumferemtial direction, ~~th~~ for it had undoubtedly received a greater amount of polishing than the direction parallel to the ~~fibre~~ cylinder axis.

Hence it may be presumed that the irregularities of the surface as actually presented to the fibres are considerably smaller than 0.25 μ, that is, they are likely to be of ~~a much~~ an appreciably lower order than the size of the scales. Under such conditions no interlocking of the scales with the asperities of the cylinder surface would be likely to occur.

In Table 8 are stated some comparative results for glass and ivory using aqueous solutions of sucrose of various viscosities, the measurements having been carried out under 5 g. load, at the speed of 42 cm./sec. and at room temperature.

MEDIUM	VISCOSITY cp.	FRICTION			
		against IVORY		against GLASS	
		μ_T	μ_R	μ_T	μ_R
Dist. Water	1.0	0.65	0.20	0.68	0.18
Sucrose	16.0	0.44	0.32	0.42	0.30
"	20.4	0.48	0.43	0.48	0.42
"	106.0	1.22	1.10	1.22	1.12

TABLE 8. COMPARISON BETWEEN FRICTION AGAINST GLASS AND AGAINST IVORY.

As will be observed from the above Table the friction against ivory appears to be very similar to that against glass, and the influence of viscosity is the same im both cases.

4. EFFECT OF TEMPERATURE ON FRICTION.

In view of the strict dependence of friction on the viscosity of the fluid, as established in the preceding experiments, it appeared that the effect of temperature on friction may be associated with changes in viscosity.

The matter was investigated in two series of experiments. In the first, (a), frictional measurements were carried out under the same conditions of speed and load in six different sucrose solutions, in each over a temperature range from about 20 to 60°C., the total viscosity range thus obtained being from 0.45 to 135 cp.

In the second series (b) the influence of temperature on friction was determined in water and un-thickened aqueous solutions of sulphuric acid and soap. In all cases glass was the rubbing surface.

(a) Measurements of Friction at Various Temperatures in Sucrose Solutions of Different Viscosities.

The temperature was varied by commencing the measurements with the solution at a high temperature, usually about 55-60°C., and the readings were then taken at intervals as the liquid was cooling off. At elevated temperatures the temperature was maintained by small additions of very hot liquid to the dish; this was found to be unnecessary below about 45°C. as the readings in both directions of rubbing could be taken sufficiently rapidly before a drop in temperature has occurred.

In this manner each of the six liquids was used in turn under the same conditions of speed and load (speed of 42 cm./sec. and load of 5 g.), and the six viscosity ranges, most of them overlapping, were as follows:

Solution	A	0.45 - 1.0	cp.
"	B	2.6 - 5.4	"
"	C	3.7 - 9.4	"
"	D	5.4 - 18.0	"
"	E	9.3 - 33.0	"
"	F	13.5 - 135.0	"

The temperature-viscosity relation of each solution (except for water whose values were taken from Bates' Tables,93) was determined by means of the Ostwald Viscometer (BSS 188), the viscosity measurements being taken in a water bath at various temperatures. The data are given in Table 9 and in Fig.23. In the frictional measurements the viscosity at the temperature in use was read off the appropriate curve in Fig.23.

The frictional results are stated in Table 10 for the solutions A, B and C and in Table 11 for the remaining three media, D, E and F.

In Fig.24 both the against-scale and the with-scale coefficient of froction are plotted against viscosity, the points for each solution being indicated by a different symbol.

It is evident from this diagram that viscosity and not temperature is the governing factor, for friction appears to be the same provided the viscosity of different solutions is the same, even if the temperature of the solutions is quite different. This leads to considerable overlapping of results for various solutions as shown on the diagram.

SOLUTION B.		SOLUTION C.		SOLUTION D.		SOLUTION E.		SOLUTION F.	
Temp. °C.	Visc. cp.	Temp. °C.	Visc. cp.	Temp. °C.	Visc. cp.	Temp. °C.	Visc. cp.	Temp. °C.	Visc. cp.
21.0	5.0	19.5	9.3	18.0	16.3	18.0	30.4	17.5	454.0
34.0	3.6	30.5	6.2	32.0	8.5	28.5	17.8	21.5	230.0
41.5	3.3	43.0	4.2	42.0	6.5	36.0	12.6	30.0	93.5
56.0	2.7	58.0	3.8	56.0	5.2	50.0	9.2	40.0	46.0
								60.0	23.0

TABLE 9. THE VISCOSITY - TEMEERATURE RELATION OF SUCROSE SOLUTIONS B - F.

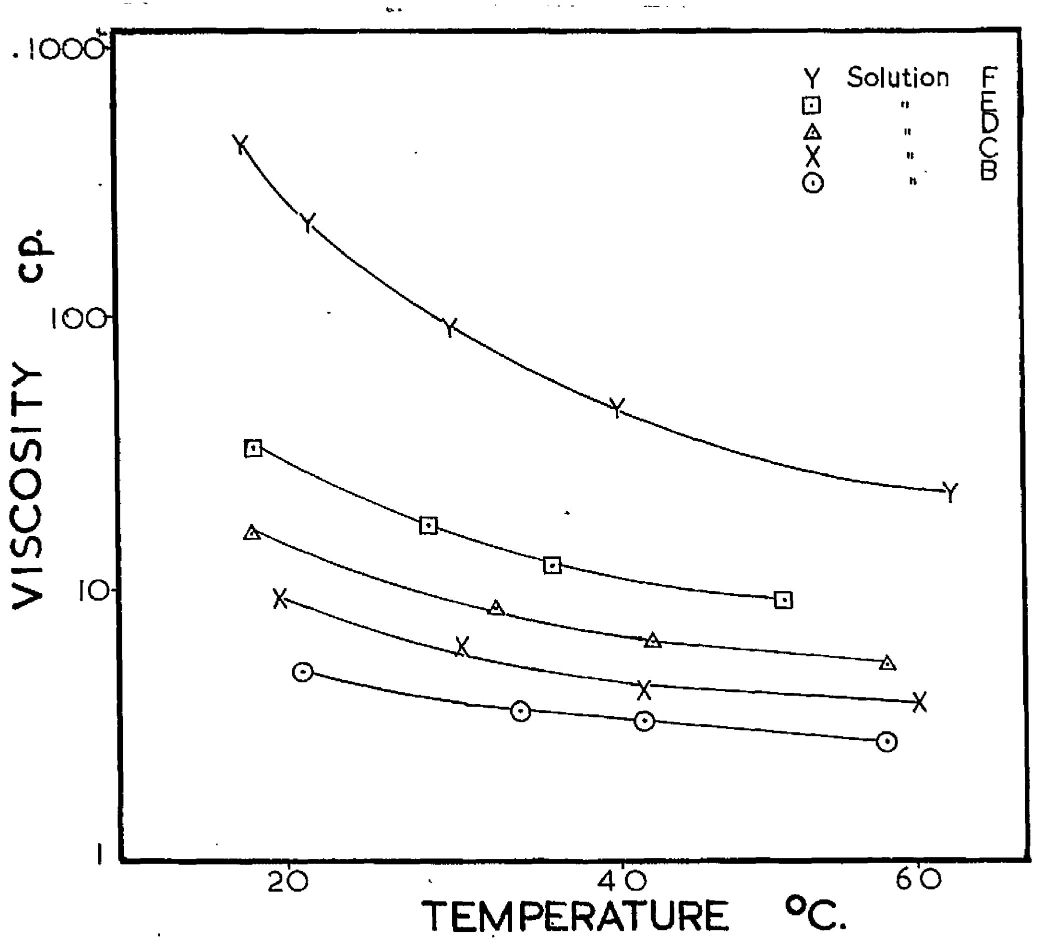


FIG. 23. THE VISCOSITY-TEMPERATURE RELATION OF SUCROSE SOLUTIONS B to F.

SOL. A. Viscosity .45 - 1.0cp.				SOL.B. Viscosity 2.6 - 5.4cp.				SOL.C. Viscosity 3.7 - 9.4cp			
Temp. °C.	Visc. cp.	μ_T	μ_R	Temp. °C.	Visc.cp.	μ_T	μ_R	Temp. °C.	Visc.cp.	μ_T	μ_R
				17	5.4	.57	.25	19	9.4	.48	.29
				25	4.4	.57	-	36	5.2	.51	.26
20	1.00	.68	.18	27	4.2	-	.27	38	4.9	-	.26
26	0.88	.73	.23	31	3.8	.59	.28	45	4.2	.58	-
36	0.70	.77	.30	38	3.4	-	.32	46	4.1	-	.23
39	0.66	-	.30	42	3.3	.66	.32	53	3.7	.66	-
43	0.61	.87	.30	43	3.3	-	.32	56	3.7	-	.23
48	0.57	.89	-	47	3.0	-	.33				
50	0.55	-	.31	52	2.8	-	.34				
58	0.48	.93	-	53	2.8	.68	-				
60	0.45	-	.32	57	2.6	-	.34				

TABLE 10. EFFECT OF TEMPERATURE ON FRICTION IN SOLUTIONS OF VARIOUS VISCOSITIES.

(Solutions A - B - C).

SOL.D. Viscosity 5.4 - 18.0cp.				SOL.E. Viscosity 9.3 - 33.0cp				SOL.F. Viscosity 13.5-135cp			
Temp. ^{o}C.	Visc.cp.	μ_T	μ_R	Temp. ^{o}C.	Visc.cp.	μ_T	μ_R	Temp. ^{o}C.	Visc.cp.	μ_T	μ_R
17	18.0	.41	.36	18	33.0	.49	.41	26	135.0	1.60	-
24	11.3	.40	.31	25	20.5	.45	.33	28	120.0	1.50	1.50
28	9.7	.41	-	30	16.5	.45	.31	30	94.0	1.30	1.27
36	7.4	-	.28	35	12.7	-	.27	31	86.0	1.23	1.18
38	7.1	.46	-	36	12.6	.50	-	34	70.0	1.00	-
44	6.2	.50	.28	41	11.0	-	.23	35	66.0	-	.93
51	5.4	.54	-	43	10.7	.50	-	37	56.0	.93	-
				49	9.5	-	.20	38	54.0	-	.84
				50	9.3	.50	-	41	41.5	-	.68
								43	38.0	.75	-
								47	30.5	-	.56
								49	29.0	.61	-
								50	28.0	-	.52
								51	24.0	-	.44
								53	23.0	.61	-

TABLE 11. EFFECT OF TEMPERATURE ON FRICTION IN SOLUTIONS OF VARIOUS VISCOSITIES.
(Solutions D - E - F).

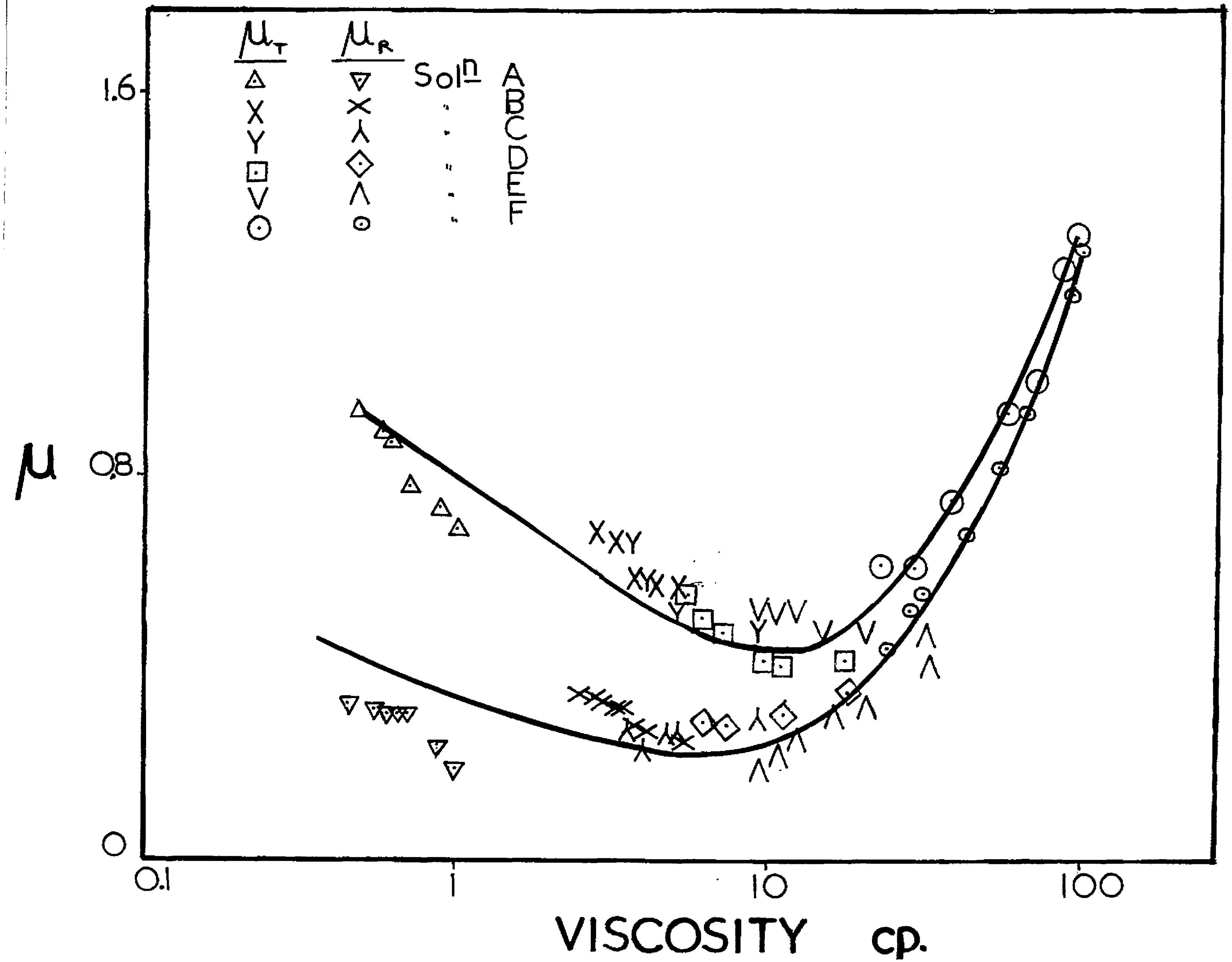


FIG. 24. EFFECT OF TEMPERATURE ON FRICTION IN SUCROSE SOLUTIONS OF VARIOUS VISCOSITIES.

(b) Effect of Temperature in Water and Unthickened Solutions of Sulphuric Acid and Soap.

These experiments were aimed at elucidating the influence of temperature on friction in those media which are commonly employed in the felting process.

Solutions of sulphuric acid (1%) and of soap (0.2%) were used in the same manner as the six media in the preceding series of experiments. A different bow was used in each solution and the results obtained at various temperatures are presented in Table 12 together with the data for water, the latter having been obtained previously in the (a) series.

The values for both coefficients in all the three liquids are plotted against temperature in Fig.25

In all cases the against-scale coefficient of friction rises appreciably with increasing temperature, the rise being particularly noticeable in sulphuric acid. As regards the with-scale coefficients they also increase with temperature in acid and in water but only very slightly in soap solution.

The effect of temperature on friction in these media is also related to the influence of temperature on viscosity, as will be shown later. For the purpose of subsequent discussion the fluidity vs. temperature curve for water (93) has also been included in Fig.25.

DIST. WATER			0.2% SOAP			1.0% SULPHURIC ACID		
Temp. °C.	μ_T	μ_R	Temp. °C.	μ_T	μ_R	Temp. °C.	μ_T	μ_R
20	.68	.18	19	.84	.12	20	1.03	.20
26	.73	.23	27	.86	.14	27	1.12	.22
36	.77	.30	32	.86	.14	35	1.20	.28
39	-	.30	40	.90	-	40	1.34	-
43	.87	.30	42	-	.15	42	-	.30
48	.89	-	46	.92	-	45	1.43	-
50	-	.31	50	-	.17	48	-	.33
58	.93	-	55	.94	-	50	1.48	-
60	-	.32	58	-	.17	55	-	.35

TABLE 12. EFFECT OF TEMPERATURE ON FRICTION IN DIST. WATER, 0.2% SOAP AND 1.0% SULPHURIC ACID.

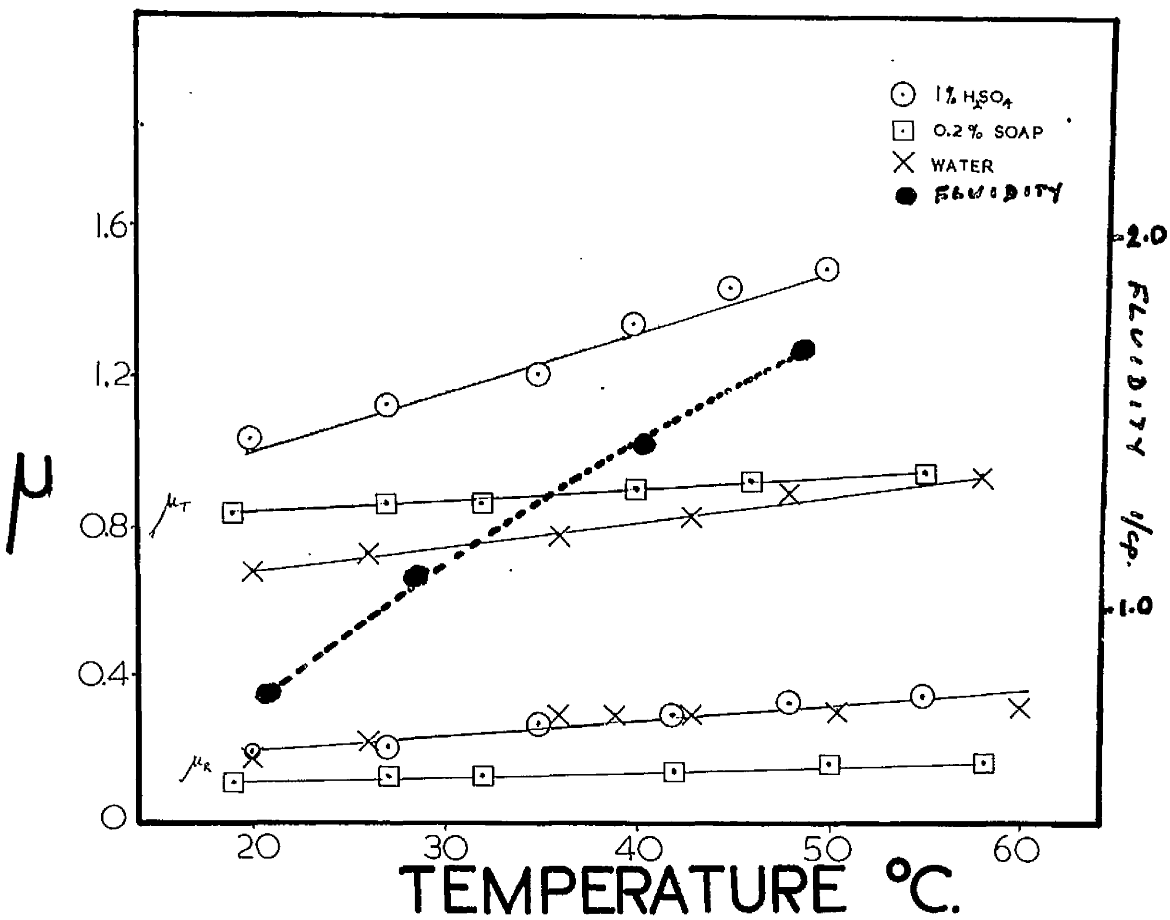


FIG. 25. EFFECT OF TEMPERATURE ON FRICTION IN WATER, SULPHURIC ACID AND SOAP.

5. FRICTION IN AIR.

As indicated in Chapter 3, the frictional behaviour of animal fibres in air as the lubricating fluid should be of particular interest. It was expected that owing to the low viscosity of this medium (0.02 cp.) the hydrodynamic effect should be negligible at the speeds used in the present experiments, and the friction, being of the boundary type, should therefore be similar for both directions of rubbing.

The results shown in Table 12a prove that this is actually the case, for even at the highest speed attainable (107 cm./sec.) both coefficients remain high indicating boundary conditions.

SPEED cm./sec.	FRICTION	
	μ_T	μ_R
25	0.53	0.40
65	0.52	0.40
107	0.52	0.40

TABLE 12a. FRICTION IN AIR UNDER 5 g. LOAD.

6. THE pH EFFECT IN FRICTION.

The influence of pH on friction has been examined by carrying out measurements in a series of unbuffered solutions at room temperature (20°C.), and using the same speed (42 cm./sec.) and load (5 g.) throughout.

The solutions used were sulphuric acid (N and 0.01 N), boric acid (0.1 N), distilled water, sodium bicarbonate (0.1 N) and sodium carbonate (0.1 N), In each case a fresh portion of the fibre surface was rubbed against glass.

The results are set out in Table 13 and are presented graphically in Fig. 26.

The coefficients of friction appear to be highest in strongly acid solutions, they then decrease to a minimum round neutrality but increase again on the alkaline side.

MEDIUM	pH	μ_T	μ_R
N H_2SO_4	0.3	1.15	0.25
.01 N "	2.1	1.05	0.20
.1 N H_3BO_3	5.2	0.80	0.18
Water	6.8	0.68	0.18
.1 N $NaHCO_3$	8.4	0.82	0.20
.1 N Na_2CO_3	11.6	0.95	0.32

~~TABLE~~ TABLE 13. THE pH EFFECT IN FRICTION.

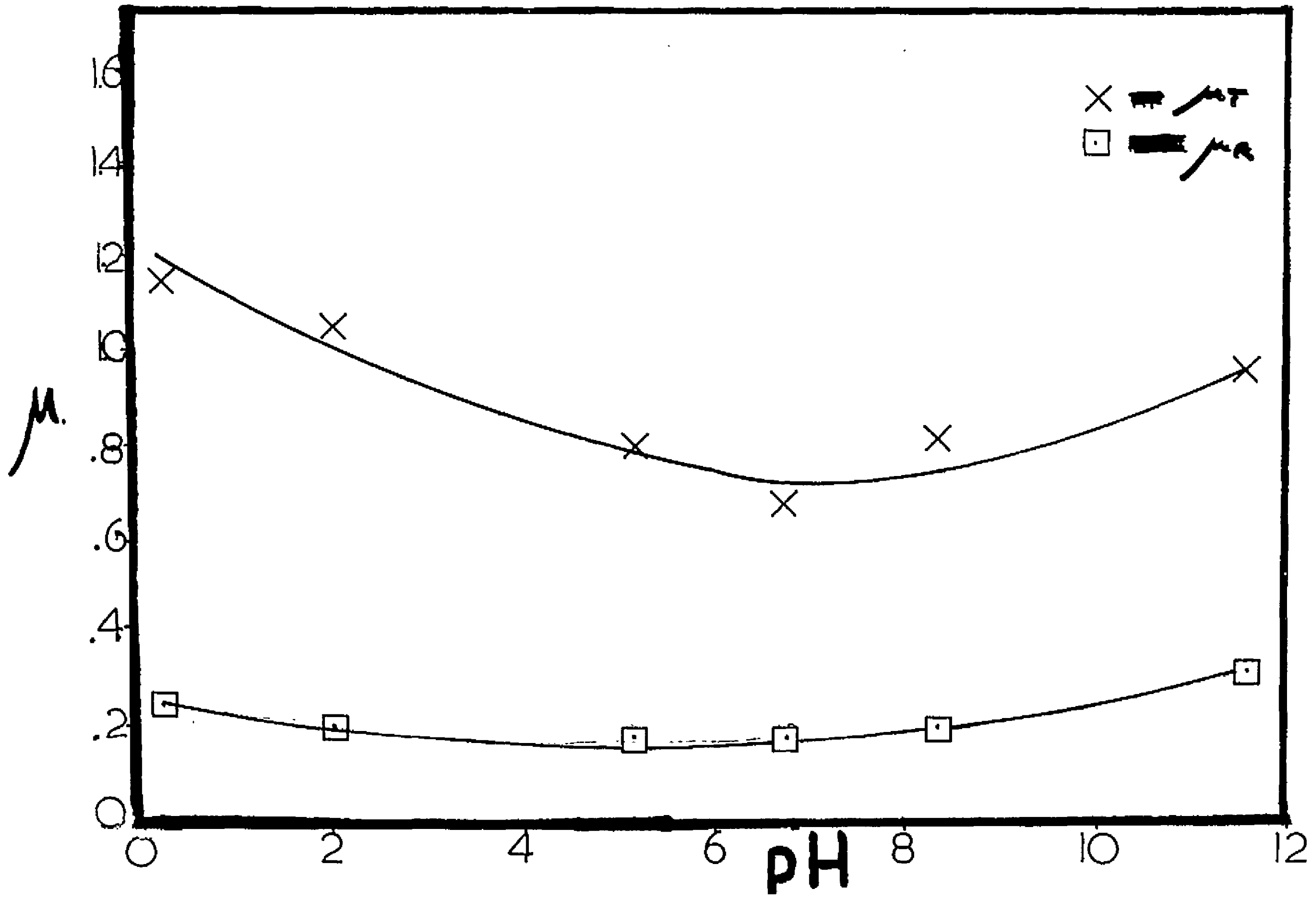


FIG. 26. THE pH EFFECT IN FRICTION.

7. FRICTION OF FIBRES MODIFIED BY TREATMENT WHICH REDUCES FELTING POWER.

A typical example of treatments which modify the felting power of wool fibres by their influence on the frictional behaviour is the reaction involving the use of sulphuryl chloride in an inert solvent, and the effect of this treatment on the friction of human hair against glass was examined by the present method.

The usual bow of human hair was treated by the method described by Lipson and Howard (50), which consisted of immersing the fibres for one hour in 2.5% solution of sulphuryl chloride in carbon tetrachloride, followed by a thorough washing in water.

Before subjecting the hair to this treatment their frictional coefficients were determined in distilled water (under 5 g. load and at 42 cm./sec.) in the usual manner and for five different portions along the length of the bow.

The treated fibres were then examined under similar conditions using the same five portions of the bow, and the results for the sulphuryl chloride-treated fibres are compared in Table 14 with the original frictional coefficients.

POSITION	FRICTION BEFORE TREATMENT			FRICTION AFTER TREATMENT		
	μ_T	μ_R	$\mu_T-\mu_R$	μ_T	μ_R	$\mu_T-\mu_R$
A	.68	.18	.50	.56	.27	.29
B	.69	.18	.51	.53	.22	.31
C	.68	.18	.50	.56	.23	.33
D	.67	.19	.48	.48	.22	.36
E	.68	.18	.50	.54	.26	.28

TABLE 14. FRICTION OF HAIR BEFORE AND AFTER TREATMENT WITH SULPHURYL CHLORIDE.

For each portion of the fibre bow the against-scale coefficient is decreased and the with-scale coefficient increased as the result of the sulphuryl chloride treatment, the differential frictional effect being therefore considerably lowered. (The differences between readings obtained after treatment suggest a lack of uniformity of the treatment).

CHAPTER 6.

APPARATUS FOR MEASURING THE FELTING POWER OF WOOL.

INTRODUCTION.

In this and the next Chapter the second part of the experimental work is described, which is concerned with an examination of the felting properties of wool fibres in the light of the new observations on their frictional behaviour as reported on the preceding pages.

The dependence of felting power on the frictional coefficients of the fibres has been discussed in some detail in Chapters 1 and 2. Since it is quite clear that there is a very close parallelism between the differential frictional effect and the felting power, it follows that the felting power should be affected by the same factors which influence the frictional behaviour of the fibres. By studying felting behaviour in relation to these factors (i.e. pressure, speed and viscosity, the last being selected in the present work) it should be possible to obtain corroborative evidence of the film theory of lubrication as applied to the friction of animal fibres. In addition the experimental evidence should provide a test of the interdependence of felting power and friction.

APPARATUS.

General Considerations.

The assessment of the felting power of wool fibres is a matter of some complexity, for although the felting property is essentially the consequence of fibre migration, the actual rate of felting (i.e. the rate of fibre entanglement or the rate of consolidation of the fibre mass) is governed by a multiplicity of external factors, as has been shown in Chapter 1.

The main points to be considered in connection with the methods of measuring felting are (1) the organisation of the original fibre mass and (2) the mechanical methods of causing felting.

(1) Organisation of Original Fibre Mass.

There are three main forms of aggregation of fibres encountered in practice: (i) loose fibre mass where the fibres have a fortuitous arrangment, (ii) yarn in which the fibres are parallelised and are kept in a relatively tight form by the twist, and (iii) fabrics in which the fibres are usually packed very tightly, being restricted in their freedom to move by both the twist in the yarn and the interlacings of the yarns with each other.

All these forms of aggregation have been used in estimating the felting power of wool, and the criteria of felting have, accordingly, been very diverse, in each case a physical property of the fibre mass being measured which changes as felting progresses.

Thus in the case of loose wool the indices used were air permeability and thickness (or volume), with yarns the felting rate was expressed in terms of changes in length, whilst in the case of fabrics the almost universal method of quantitative estimation of felting is in terms of area shrinkage.

The last method, involving the use of cloth is undoubtedly the most popular, for the practical problems of felting are most commonly associated with the shrinkage of wool in fabric form. However, apart from the use of this method in industry, it has also been employed, almost exclusively, by Speakman and his collaborators. On the other hand, the loose mass method is of particular interest to those concerned with the manufacture of felts, as it follows the principles of felt making. It was used in the work of Arnold (16), Götte and Kling (28) and Schofield (29). The yarn shrinkage method was introduced by Greely and LeCompte (94) and was also employed by Mercer (22).

(2) Mechanical Methods of Causing Felting.

In order to produce felting the fibre mass must be subjected to some form of agitation to provide the external stimuli for fibre migration. These forces are generally of intermittent compressive type. In the case of methods involving the use of loose fibres the mass is simply compressed between two oscillating metal plates,

In the more common shrinkage determinations on fabrics the mechanical forces are more diverse, and at least two general mechanisms can be discerned in the testing machines which are in use. The first of these is exemplified in the fulling stocks where pressure is applied to the folded fabric by direct blow from a falling hammer. In the second, the essential compressions are produced indirectly by the continous folding or flexing of the fabric. The latter is probably the chief felting mechanism in washers of the oscillating central paddle type, such as many domestic washing machines, where the flexing is produced by the violent eddies set up in the liquor and by the paddles. The milling machine and other washing machines such as the rotary laundry washers or the wash-wheel seem to combine both mechanisms.

The method of causing agitation in Creely and LeCompte yarn felting experiments consisted of shaking the yarn in the bottle partially filled with the appropriate liquid.

PRINCIPLE OF PRESENT METHOD.

The above review of the existing methods led to the conclusion that, as regards the state of organisation of the fibre mass, the most correct method in any fundamental work on the problem is to use fibres in the loose state. Under such conditions the felting behaviour of wool can be studded in its simplest form without any complications due to yarn and fabric structure.

The method used was to shake a small quantity (2 gms.) of loose wool in a bottle containing the felting liquid. After a period of time (depending on the frequency and throw of the shaker) the fibre mass becomes felted and it assumes an ellipsoidal or spherical shape, and it decreases in volume as the felting progresses. The degree of felting of these balls could conveniently and precisely be expressed in terms of their volumes or densities. The volumes were determined in a volumenometer designed for this purpose.

In the final form of the felting testing apparatus instead of shaking the wool in a bottle by means of a shaking machine the fibres were agitated in a modified washing machine of the oscillating central paddle type.

PROTOTYPE SHAKING MACHINES.

After obtaining preliminary evidence that the above ideas hold promise of being capable of translation into a valuable practical experimental method it was necessary to construct a suitable shaking machine. It was found that in order to achieve ade efficiently adequate felting when 2 g. of wool are placed in a 250 ccs. jar with about 100 ccs.

of liquid the shaker should oscillate at about 250 strokes per minute, the length of stroke being at least about 10 cm.

The first shaking machine built was adapted from an old crank-driven model but it was soon abandoned when it was found to be incapable of running at sufficiently high speed.

The next model was built on quite a novel principle which depends on causing oscillations by means of an electro-magnetic device operating on the principle of the electric bell.

The shaker so designed is shown in Fig.27

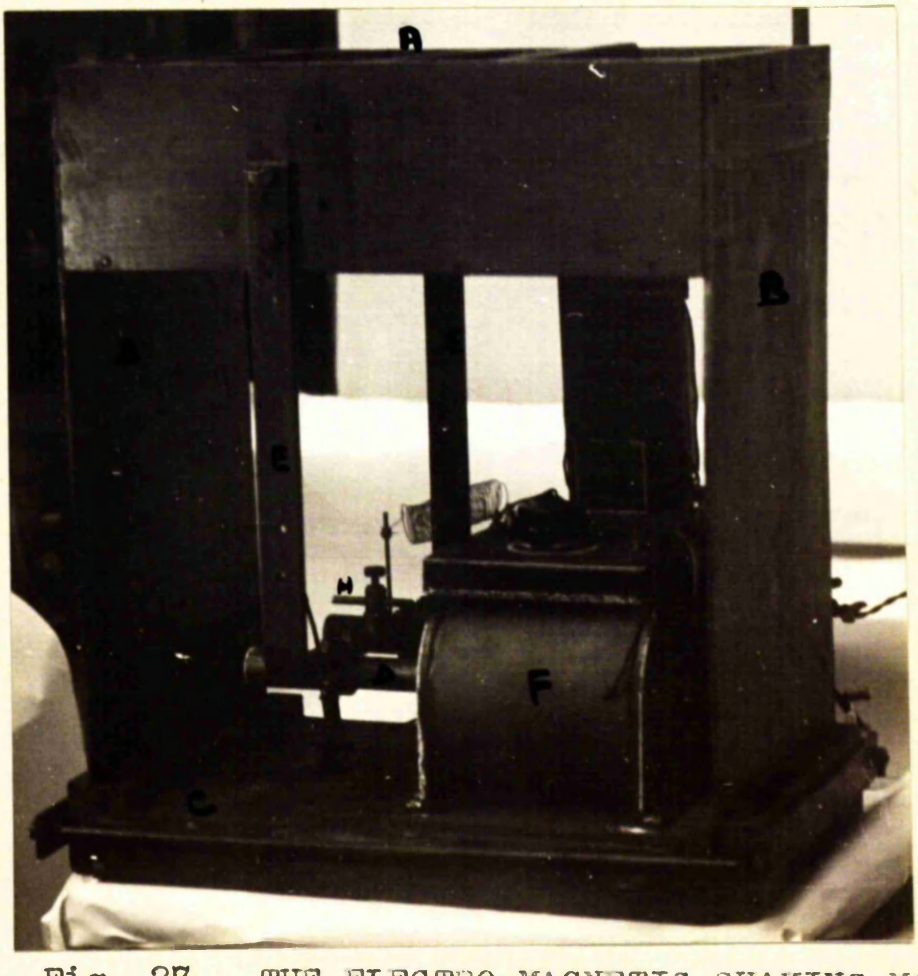


Fig. 27. THE ELECTRO-MAGNETIC SHAKING MACHINE.

The cradle A (approx. 20x12x6 ins.), which can hold about a dozen 250 ccs. jars, is held between two parallel pieces of flexible plywood B (12 ins. wide and 30 ins. high), the bottom edges of which are firmly gripped between the heavy base C and an iron frame. The base is securely clamped to a bench.

A pair of parallel heavy iron rods D, 1 in. in diameter and 12 ins. long, form the armature. They are firmly fastened to the bracket E which in turn is firmly attached to the cradle A as shown on the photograph. The armature is arranged in such a position that the two rods can freely enter a pair of heavy coils F. The coils, the second of which is behind the one shown on the picture, are 6 ins. in diameter each and are mounted on a heavy cast brass base.

When electric current is passed from the 220 v. D.C. mains through the coils (by way of a relay system) the armature D is drawn into the coils thus swinging the cradle A to the right. As this occurs, the circuit is interrupted by means of a simple contact breaker H.

When the contact is broken the coils release the rods which, owing to the flexibility of the plywood B, swing back to the left together with the cradle A. But by doing so contact is made again, the coils are again energised and the whole cycle repeated.

In this manner it was possible to cause shaking at the rate of up to 250 strokes per minute, the length of each stroke being about 10 cms.

This machine was quite satisfactory except that the plywood was not sufficiently strong to resist the stresses caused by long periods of shaking and it was decided therefore to replace it by steel spring leaves. However, in the meantime an entirely new shaking method was developed and as it eventually proved superior, it was adopted exclusively in the present work. Nevertheless the electro-magnetic shaker is undoubtedly a useful piece of laboratory equipment and can be used effectively in many connections.

THE NEW APPARATUS.

(a) Method of Shaking.

The new apparatus for felting tests consists of an adaptation of an electric washing machine of the oscillating central paddle type and is shown in Fig. 28

The design of the conventional washer of this type is well-known. The machine used in the present work was of the 'Servis' make. It consists of a metal box A, 3x2x2 ft., in the centre of which there is fixed a three-pronged paddle B. The paddle is oscillated by means of a $\frac{1}{4}$ H.P. motor placed underneath the box, and it turns through 180 degrees in each direction of rotation, the number of oscillations per minute being 50.

FIG. 28. THE NEW APPARATUS FOR FELTING TESTS.

In the present form a stainless steel cylindrically shaped contained C, 12 ins. in diameter and 7 ins. high, is fixed firmly on to the paddle so that it oscillates with it. The container is divided into three identical sector-shaped compartments, the dividing wall being provided with small perforations so as to ensure the same level of liquid in all compartments. A closely fitting stainless steel lid is placed over the container when in operation in order to avoid any loss of liquid which would otherwise splash out.

Felting is achieved simply by placing a prepared sample of loose wool in each compartment and adding an appropriate volume of the felting liquor. When the machine is set in motion the wool is violently thrown from one end of the compartment to the other, and the agitation which it receives is very fierce indeed, being due both to the impact of the wool on the walls and the eddying of the liquid. Consequently the time of felting (and so the length of each experiment) is relatively short compared with the shaker or most other testing machines.

The temperature control in the present apparatus is quite simple, for it consists of surrounding the container by water at any desired temperature which is maintained by means of a 750 watts immersion heater coupled with a thermostatic control. (The bimetallic strip apparatus D, the switch-board with the mercury relay, etc. E, and the thermometer T are all shown on Fig. 28). It was found that up to 60°C. the temperature can be kept constant within half a degree.

The appearance of the balls of felted wool which are produced by this method is shown in Fig. 29. This is a photograph of four typical balls which have been felted to different degrees, viz. (in the order of decreasing volume): 41.1, 32.0, 25.5 and 20.5 ccs., which volumes correspond to the following densities (the weight of wool being 2 g. in each case), viz. 0.047 , 0.062 , 0.078 and 0.098 .

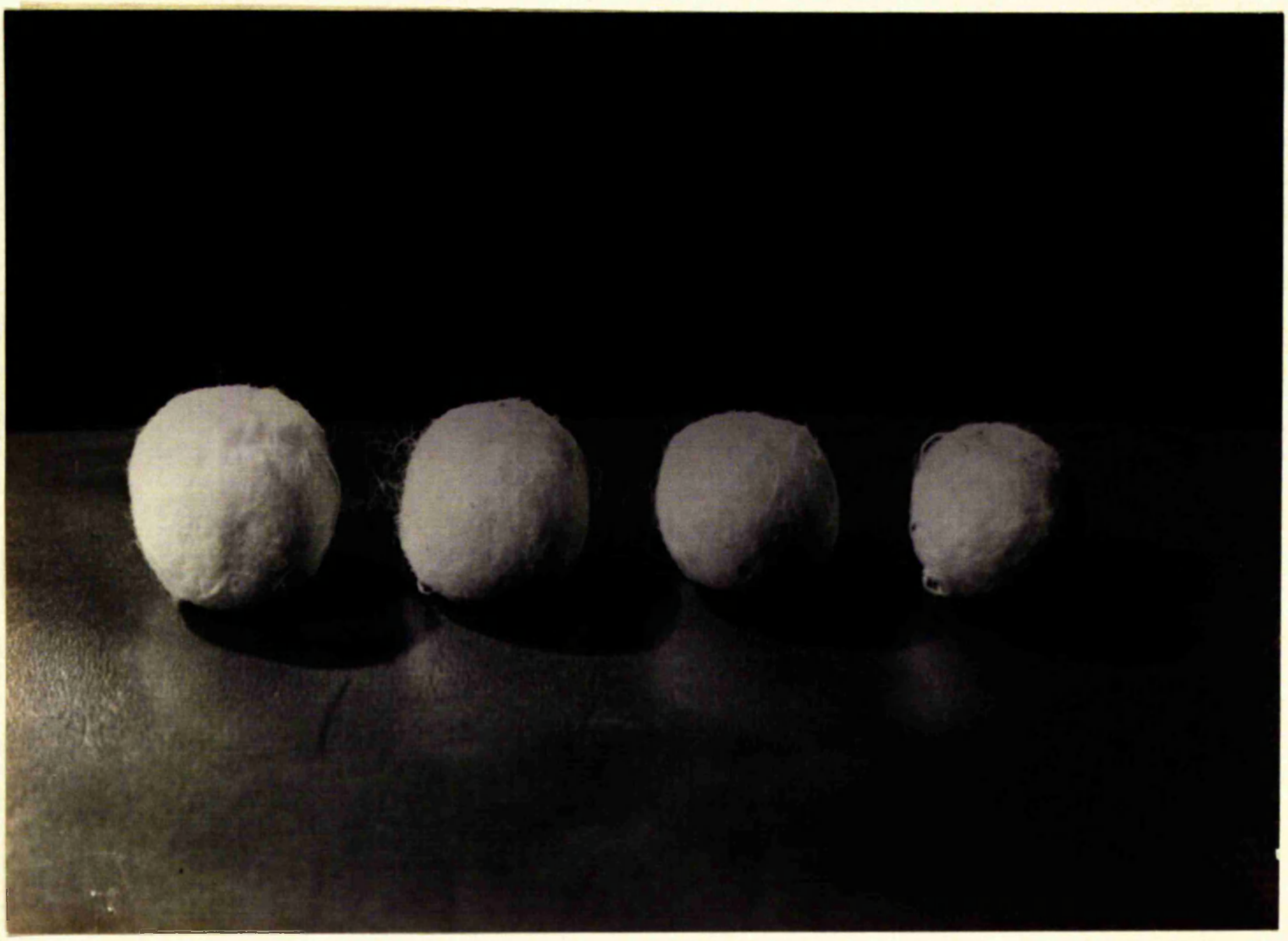


FIG. 29 BALLS OF FELTED WOOL.

(b) The Volumenometer.

The problem of accurately measuring the volume of these balls was solved by designing a new form of volumenometer operating on the liquid displacement principle, which is shown in Fig. 30 and which was found to be admirably suited for this purpose.

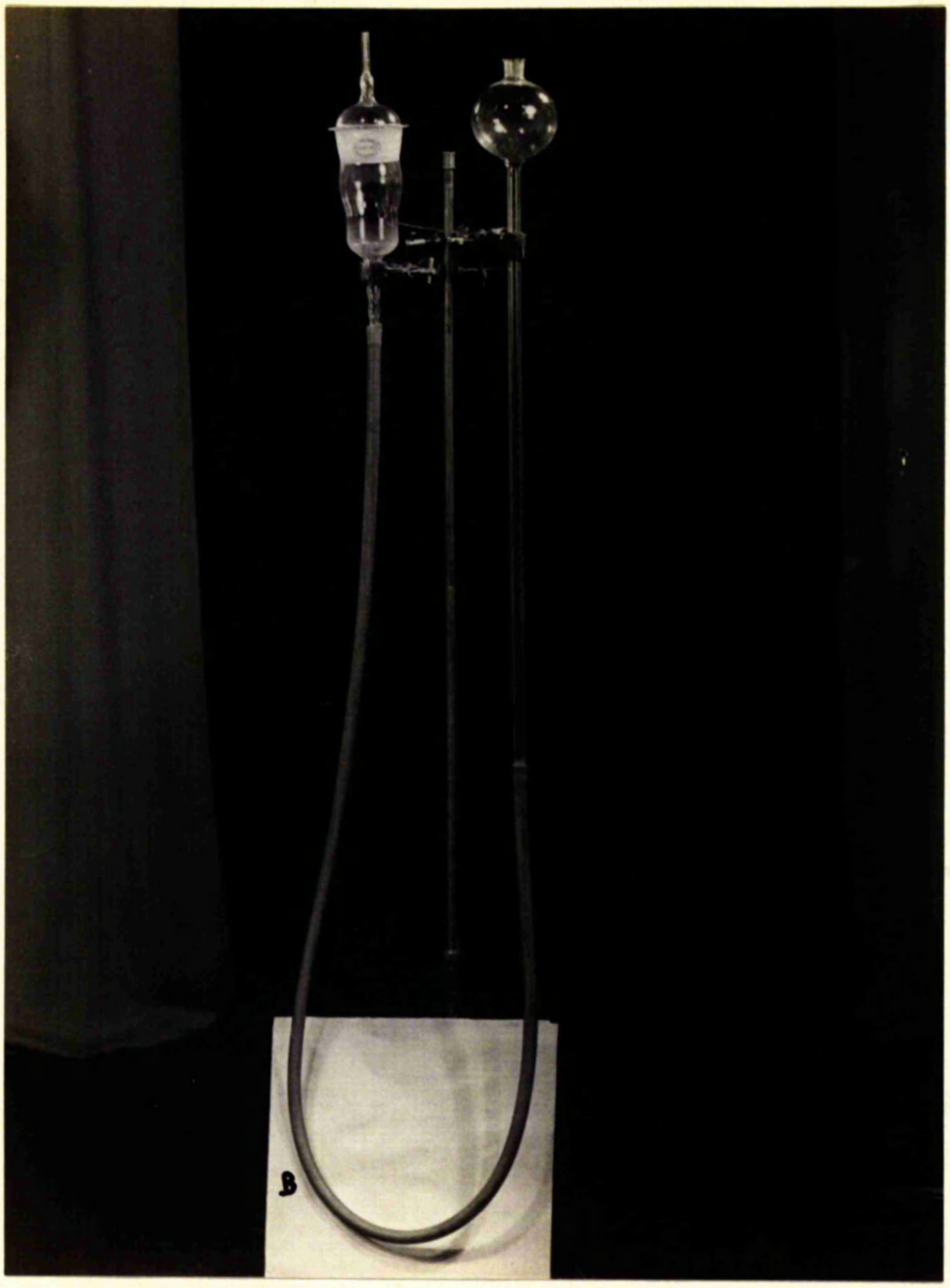


FIG. 30 THE VOLUMENOMETER.

The instrument consists of a glass head A, 2½ in. in diameter and 6 ins. high, which is connected at the bottom by means of rubber pressure tubing B, about 3½ ft. long, to the graduated burette tube C which is sealed on to the glass bulb D of approx. 250 ccs.capacity, the whole being firmly fixed on a retort stand.

The head A is closed with a hollow stopper E by means of a ground glass joint. The stopper E narrows gradually towards the top where it ends with a fine capillary, about 1½ in. long, on which a fine line is marked to indicate the level of the meniscus.

In operation the volumenometer is first filled with ~~th~~ a suitable amount of water; the right-hand portion is then raised gradually until the level of the water ~~just~~ on the left just reaches the line on the capillary when the level of the water in the burette tube is read off. The latter is then lowered until the level of the water on the left-hand side drops below the ground glass joint. The stopper is now taken off and the ball (which is saturated with the felting liquor) is carefully transferred to the head A. The stopper E is then replaced and the volume measurement repeated. Owing to the displacement of the water due to the presence of the ball the level of the water in the burette will now be higher. The volume of the ball is given by the difference between the original burette reading and the reading obtained with the ball inside the instrument.

(c) PROCEDURE.

It was found by experience that in order to obtain maximum accuracy it is necessary to prepare carefully the original wool samples prior to felting so as to ensure that in all cases the conditions of fibre organisation are initially the same.

The wool used throughout these experiments was of the Crossbred Cape variety, especially carded in its natural state without the customary addition of oil. The use of such wool was considered preferable to scoured wool, as the latter usually contains some residual alkali.

The test samples consisted each of 2 gms. of wool cut off from the uniform carded 'sliver' obtained from the mill. Each sample was then condensed into a rather tighter form by placing it in a jig consisting of four rigid glass rods and tying five metres of fine cotton thread round it. The use of the rods ensured that each sample was condensed to the same extent, i.e. approximately to the volume between the rods. The density of the wool samples so prepared was found to be 0.040 gm./cc., which value is taken as the measure of original density before felting.

The wool was then purified by Soxhlet extraction first in petroleum ether (40-60°C. B.P.) followed by ethyl alcohol, each extraction taking about 6 hours. The fibres were then allowed to condition in room atmosphere for at least 24 hours before use.

Each felting experiment consisted of placing three such wool samples in the container (one sample in each compartment) of the shaking machine together with

750 ccs. of the appropriate liquid, which amount was found adequate for an efficient felting rate.

After felting for a definite period the volume of the balls was measured by means of the volumenometer. The index of felting ~~is~~ used throughout is density (gms./ccs.) obtained from the measured ~~voul~~ volume and weight (constant); the density increases with increasing felting power.

(d) ACCURACY OF MEASUREMENT.

The reproducibility of the method is illustrated by the data given in Table 15 where the results of two parallel series of experiments are set out, both having been carried out in 0.1 N sodium carbonate under similar conditions.

It will be seen that the scatter between individual volume readings is 0.6 cc. at the most, and this represents 2-3% error in density values.

TIME mins.	1st SERIES			2nd SERIES		
	Volume cc.	Mean Vol. cc.	Mean Density g/cc.	Vol. cc.	Mean Vol. cc.	Mean Density g./cc.
10	42.4 42.9 42.3	42.5	0.0472	42.5 42.3 42.1	42.3	0.0474
20	33.5 32.9 33.5	33.3	0.0601	33.0 33.3 32.7	33.0	0.0607
30	25.6 25.8 25.4	25.6	0.0782	25.6 25.3 25.9	25.6	0.0782
45	20.5 20.4 20.0	20.3	0.0985	20.4 20.4 20.4	20.4	0.0980

TABLE 15. THE ACCURACY OF THE METHOD.

(a) INFLUENCE OF TIME ON RATE OF FELTING.

In order to standardise the conditions of experiment as regards the time of agitation it was necessary to obtain some information regarding the time-rate of felting relationship.

This was done by carrying out two series of experiments in which the degree of felting was measured after various time intervals. In the first set 0.1N sodium carbonate (pH 11.6) and in the second sodium-acetate - hydrochloric acid buffer (pH 0.6) was used, both at room temperature (20-21°C.)

The results are stated in Table 16 and plotted in Fig.31, from which it will be seen that whilst in the acid solution maximum felting appears to have been reached in 30 mins., in the alkaline medium felting increased up to 75 mins. and possibly more.

pH 0.6		pH 11.6	
Time mins.	Density g./cc.	Time min.	Density g./cc.
5	0.047	10	0.046
7	0.058	20	0.062
9	0.064	30	0.078
10	0.078	45	0.097
15	0.085	75	0.120
20	0.100		
30	0.128		
45	0.127		

TABLE 16. INFLUENCE OF TIME ON RATE OF FELTING.

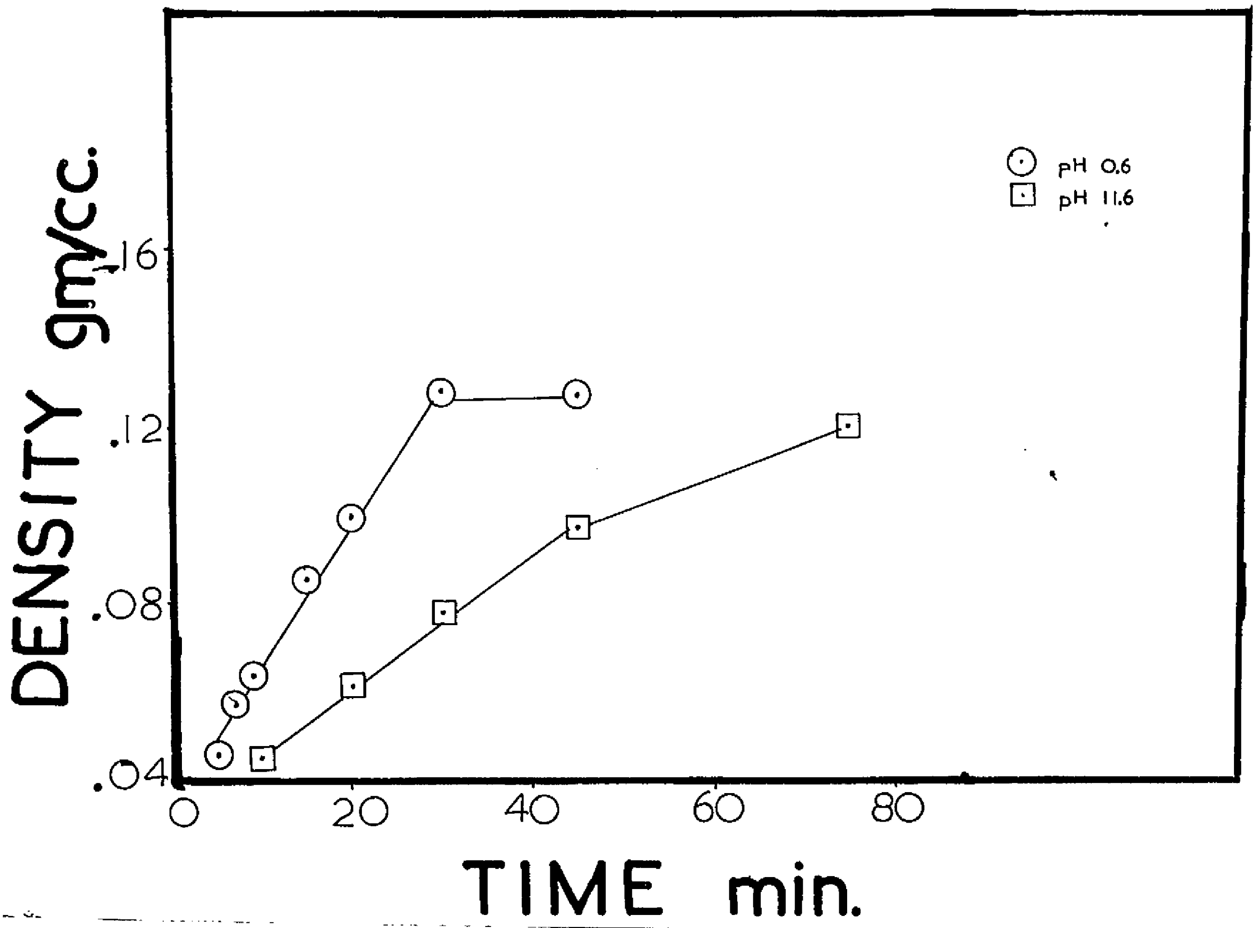


FIG. 31. RATE OF FELTING AT pH 0.6 and pH 11.6

CHAPTER 7.

EXPERIMENTAL RESULTS ON FELTING OF WOOL.

1. EFFECT OF VISCOSITY IN FELTING.

This is the most important series of experiments in the present work on felting, for its aim is to determine whether viscosity, which has such a pronounced effect on the frictional behaviour of animal fibres as has been shown in Chapter 5, affects their felting power similarily.

As indicated before in Chapter 1, felting power is proportional to the differential frictional effect, with other factors kept constant. As the differential frictional effect decreases as the viscosity of the liquid rises, it was expected that the felting power should decrease similarily and disappear altogether if the differential frictional effect became zero.

The influence of viscosity in felting was examined in an exhaustive manner by measuring the felting power of wool over a wide viscosity range and at five different pH values. At each pH value felting determinations were carried out at five or six different viscosities lying in the range from 1 to 45 cp. approx. As sucrose (which had been used in the frictional measurements) was not available in sufficient quantity, the thickening agent used in the present experiments was methyl cellulose ('Celacol M450' manufactured by British Celanese Ltd), the concentration of which ranged from nil to 1.5%. Viscosity determinations of these solutions were carried out by means of an Ostwald Viscometer (BSS 188) as before.

The pH values used were pH 0.6, 3.2, 5.9, 9.0, and 11.5 , and apart from that at pH 5.9 , all the solutions were buffered.

All data are set out in Table 17; they were all obtained at room temperature (20-21°C.) after 45 mins. agitation.

~~Ian~~ In order to avoid confusion these results are plotted on two separate graphs, Figs.32 and 33, which clearly show the density versus viscosity curves for each pH value.

It is thus clear from these diagrams that, as was expected, viscosity of the liquid exerts a most remarkable effect on felting power. It will be shown later that the decrease in felting power with increasing viscosity is most closely related to the effect of viscosity on the differential frictional effect.

Walpole BUFFER pH 0.6		WALPOLE BUFFER pH 3.2		WATER pH 5.9		BORAX pH 9.0		RINGER BUFFER pH 11.5	
Visc.cp.	Density gm./cc.	Visc.cp.	Density gm./cc.	Visc.cp.	Density gm./cc.	Visc.cp.	Density gm./cc.	Visc.cp.	Density gm./cc.
1.0	.127	1.0	.097	1.0	.090	1.0	.086	1.0	.093
8.7	.075	7.1	.071	5.1	.071	4.6	.074	4.6	.083
18.5	.065	15.3	.055	11.0	.059	13.5	.054	9.7	.064
37.0	.060	34.3	.052	23.0	.052	37.0	.052	24.0	.056
47.5	.057	44.0	.051	42.0	.049			29.0	.055
79.0	.040							43.5	.056

TABLE 17. EFFECT OF VISCOSITY ON FELTING AT VARIOUS pH VALUES.

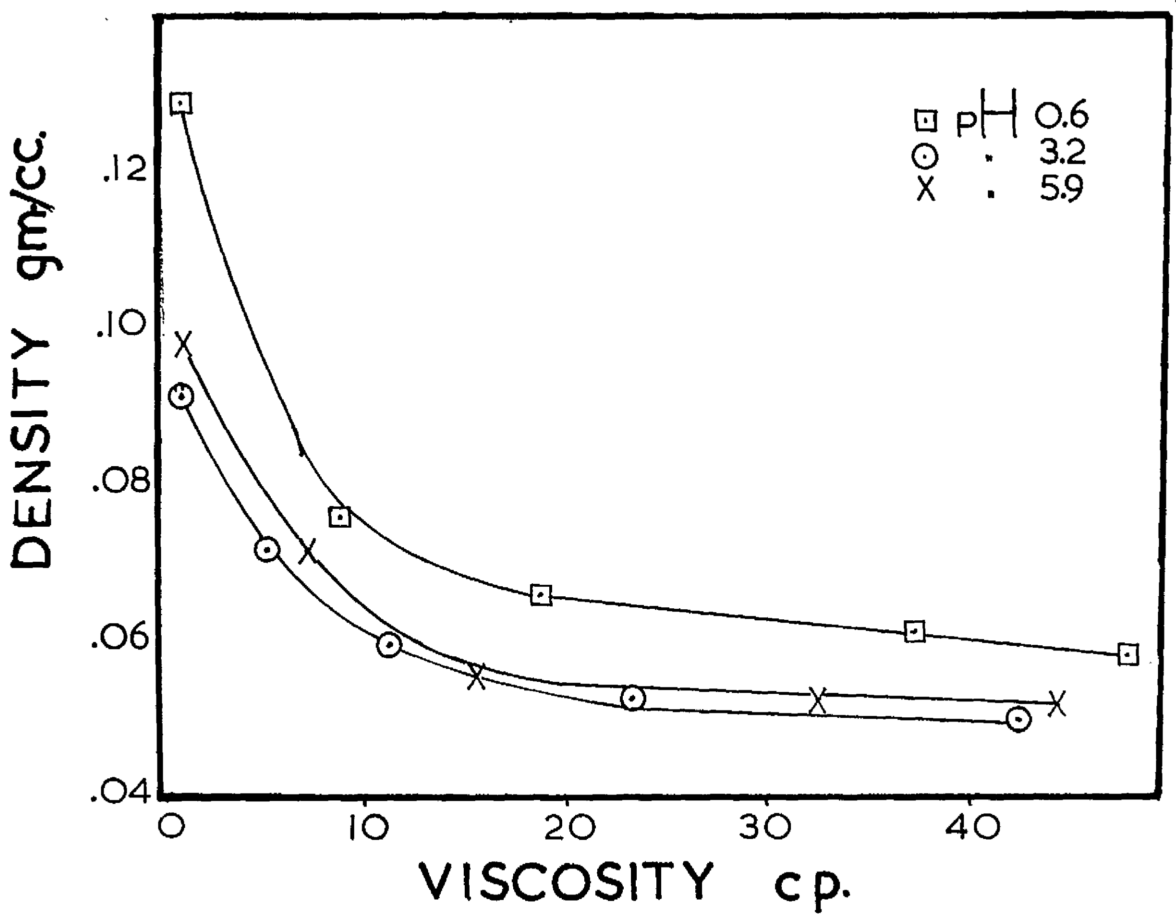


FIG. 32. EFFECT OF VISCOSITY ON FELTING AT pH 0.6, 3.2 and 5.9

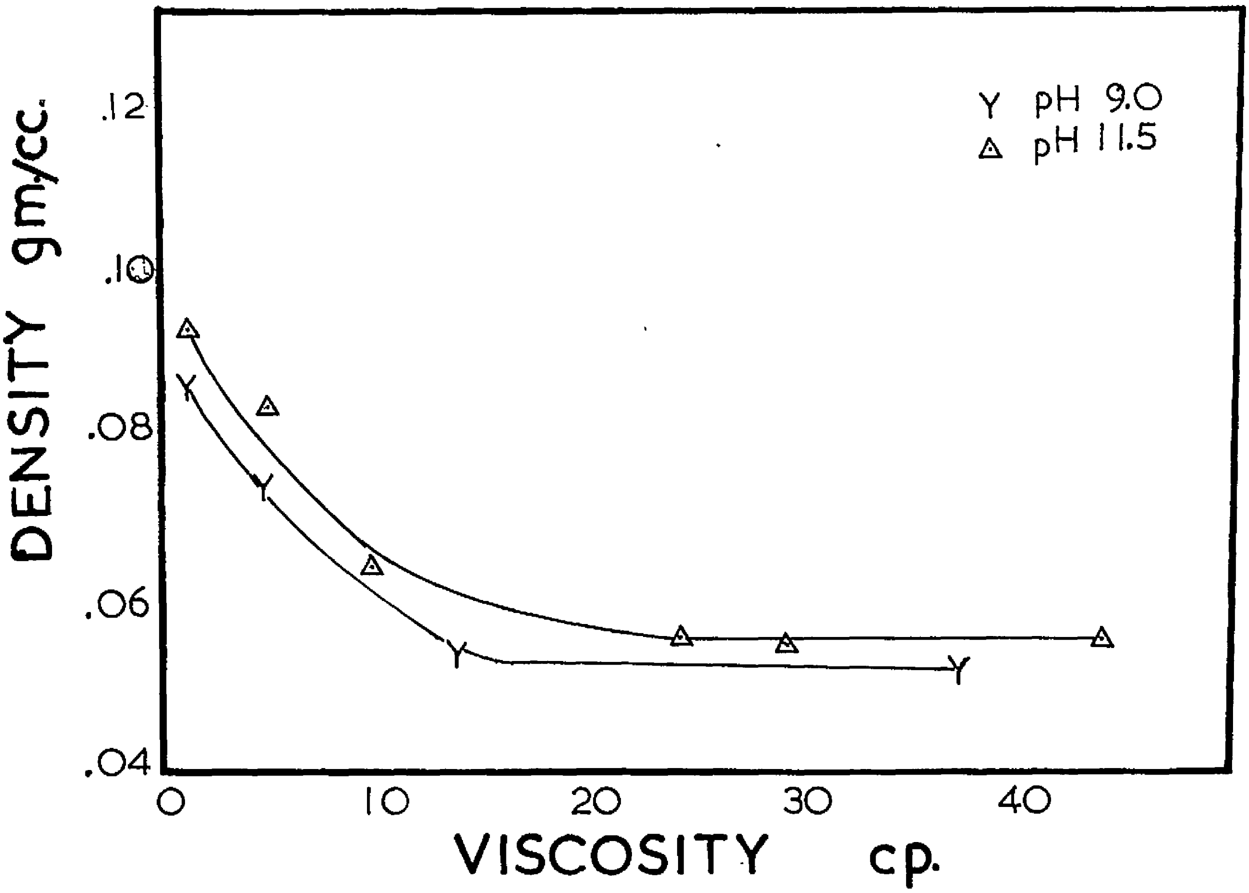


FIG. 33. EFFECT OF VISCOSITY ON FELTING AT pH 9.0 and 11.6 .

2. EFFECT OF pH IN FELTING.

The importance of pH in felting has been pointed out previously (Chapter 1), and this aspect of felting was studied using the new method of measurement.

(a) Unbuffered Solutions.

In this series five unbuffered solutions were used, the same media being employed as in the frictional measurements reported earlier (Chapter 5), viz. sulphuric acid, boric acid, water, sodium bicarbonate and sodium carbonate. The results, for 30 and 45 minutes felting, are set out in Table 18 and will be compared later with the data on friction under similar conditions.

MEDIUM	ORIG.pH	DENSITY (g./cc.) after	
		30 min.	45 min.
N H_2SO_4	0.3	0.118	0.136
.01N "	2.1	0.081	0.106
.1N H_3BO_3	5.2	0.078	0.097
Dist.Water	6.8	-	0.090
.1N $NaHCO_3$	8.4	0.074	0.096
.1N Na_2CO_3	11.6	0.078	0.097

TABLE 18. EFFECT OF pH IN FELTING (UNBUFFERED SOLUTIONS)

(b) Buffered Solutions.

This is an extension of the experiments reported in the preceding section,(1), the same buffered media being used, but the measurement were extended to include 10, 20 and 30 mins. agitation. The results are stated in Table 19 and plotted in Fig.34, and they also include measurements in Clark and Lubs' Buffer (potassium hydrogen phthalate and sodium hydroxide) at three pH values.

MEDIUM	pH	DENSITY (g./cc.)		
		10 min.	20 min.	30 min.
Walpole Buffer	0.6	0.078	0.100	0.128
ditto	3.2	0.056	0.071	0.088
ditto	4.3	0.052	0.070	0.086
Clark & Lubs Buffer	6.4	0.050	0.071	0.076
ditto	7.9	0.045	0.066	0.075
Borax	9.0	0.050	0.068	0.079
Ringer Buffer	11.3	0.049	0.074	0.085

TABLE 19. EFFECT OF pH IN FELTING.(BUFFERED SOLUTIONS).

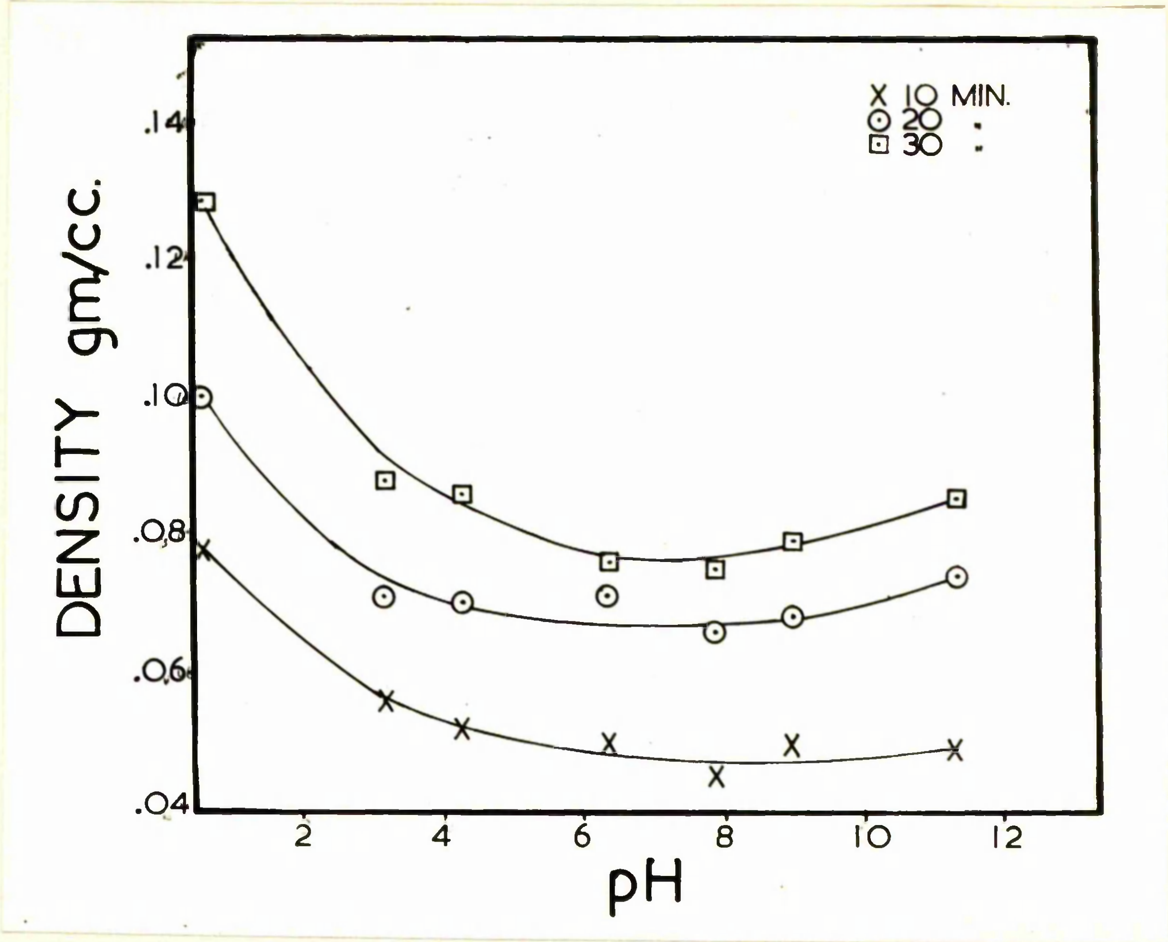


FIG. 34. EFFECT OF pH IN FELTING AFTER 10, 20 & 30 MINS. (BUFFERED SOLUTIONS).

3. EFFECT OF TEMPERATURE IN FELTING.

These experiments were intended to provide data which would enable a correlation between frictional behaviour and felting power. In the first series of experiments the effect of temperature in unthickened solutions of sulphuric acid, soap and borax was studied, and this was followed by an investigation of the felting behaviour in viscous solutions at various temperatures.

(a) Unthickened Solutions.

The solutions used were .1N Borax, 0.25% soap and .1N H_2SO_4, measurements being taken between 20 and 60°C. at intervals of 10°.(with 45 mins. agitation). As the results shown in Table 20 and Fig.35 indicate felting increases in all those media up to 60°C.

It will be shown later that this dependence of felting power on temperature is parallel to the effect of temperature on the differential frictional effect.

TEMPERATURE °C.	DENSITY (g./cc.) in		
	.1N Borax	.25% soap	.1N H_2SO_4
20	.086	.106	.117
30	.108	.118	.135
40	.119	.130	.140
50	.131	.134	.158
60	.138	.149	.165

TABLE 20. EFFECT OF TEMPERATURE IN FELTING (UNTHICKENED SOL

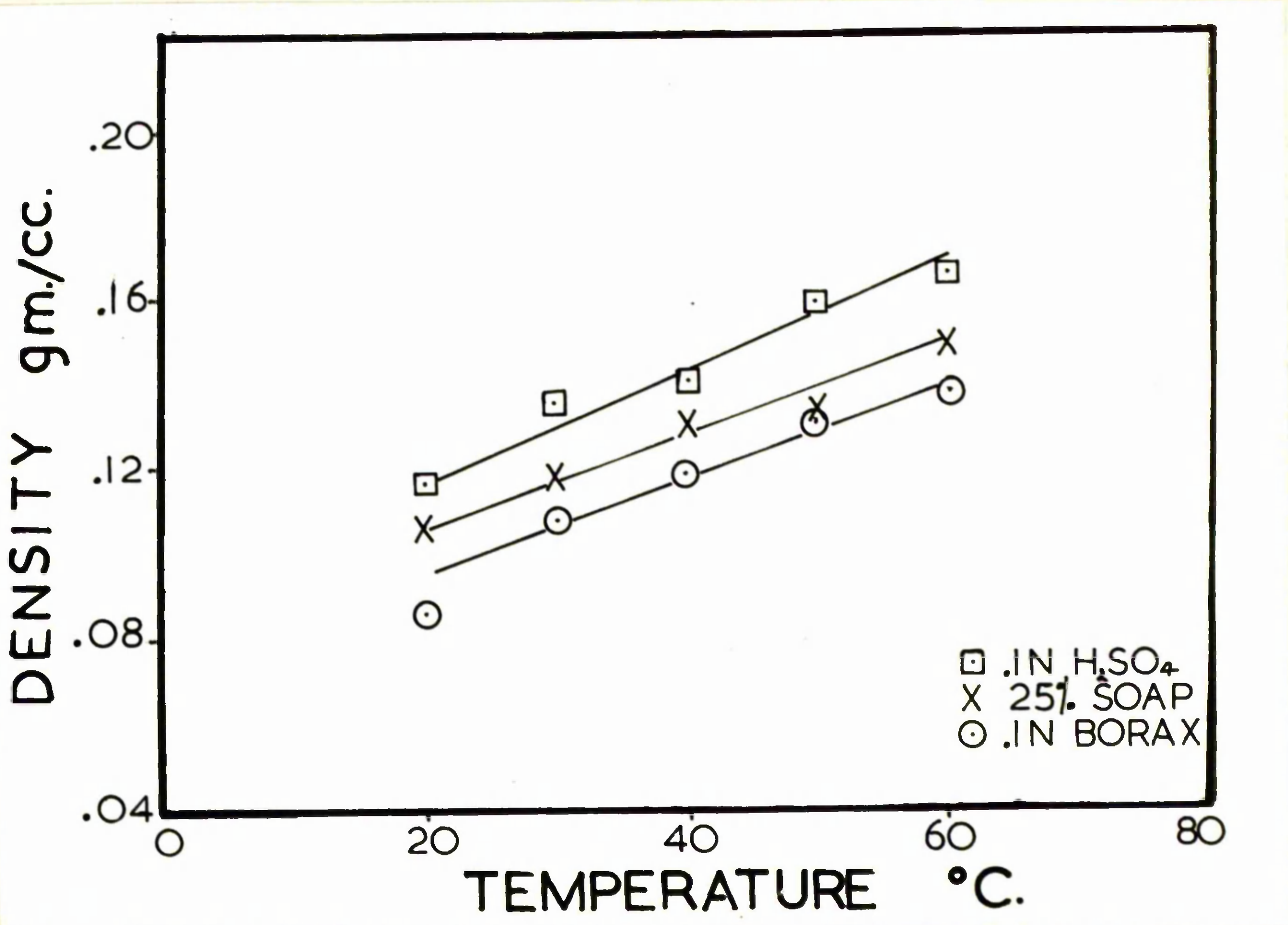


FIG. 35. EFFECT OF TEMPERATURE IN FELTING IN UNTHICKENED SOLUTIONS.

(b) Solutions of Increased Viscosity.

In this series of experiments five solutions of increased viscosity were selected so as to represent several suitable viscosity ranges, and felting determinations were carried out in each solution at various temperatures.

In these experiments the thickening agent used was Gum Tragasol, and the viscosity of each of the solutions was determined at various temperatures (in a water bath) by means of an Ostwald Viscometer in the usual manner. These preliminary data are given in Table 21 and Fig. 36.

Felting experiments were then carried out in each of these solutions over a temperature range between approximately 20 and 60°C. (generally at four points), the viscosity corresponding to the actual temperature used being obtained from Fig.36.

The results are set out in Table 22 and plotted in Fig.37. It will be observed that for any given viscosity the felting power depends on temperature. At any given viscosity the higher the temperature the greater the felting power. It is possible by means of the above data to derive a relationship for felting vs. viscosity at various temperatures and for feltings vs. temperature for various viscosities. These correlations will be indicated later.

SOLUTION A.		SOLUTION B.		SOLUTION C.		SOLUTION D.		SOLUTION E.	
Temp. °C.	Visc. cp.	Temp. °C.	Visc. cp.	Temp. °C.	Visc. cp.	Temp. °C.	Visc. cp.	Temp. °C.	Visc. cp.
15	24.3	10	34.6	17	46.5	26	43.6	25	69.2
20	19.8	24	20.0	30	26.5	37	30.1	30	60.0
30	14.5	32	15.5	36	23.0	44	25.6	38	45.7
35	13.2	45	10.3	54	17.0	49	22.7	50	37.7
40	11.6	57	7.8			60	16.6		
45	10.3								
50	9.0								

TABLE 21. THE VISCOSITY-TEMPERATURE RELATION OF TRAGASOL SOLUTIONS (A-E)

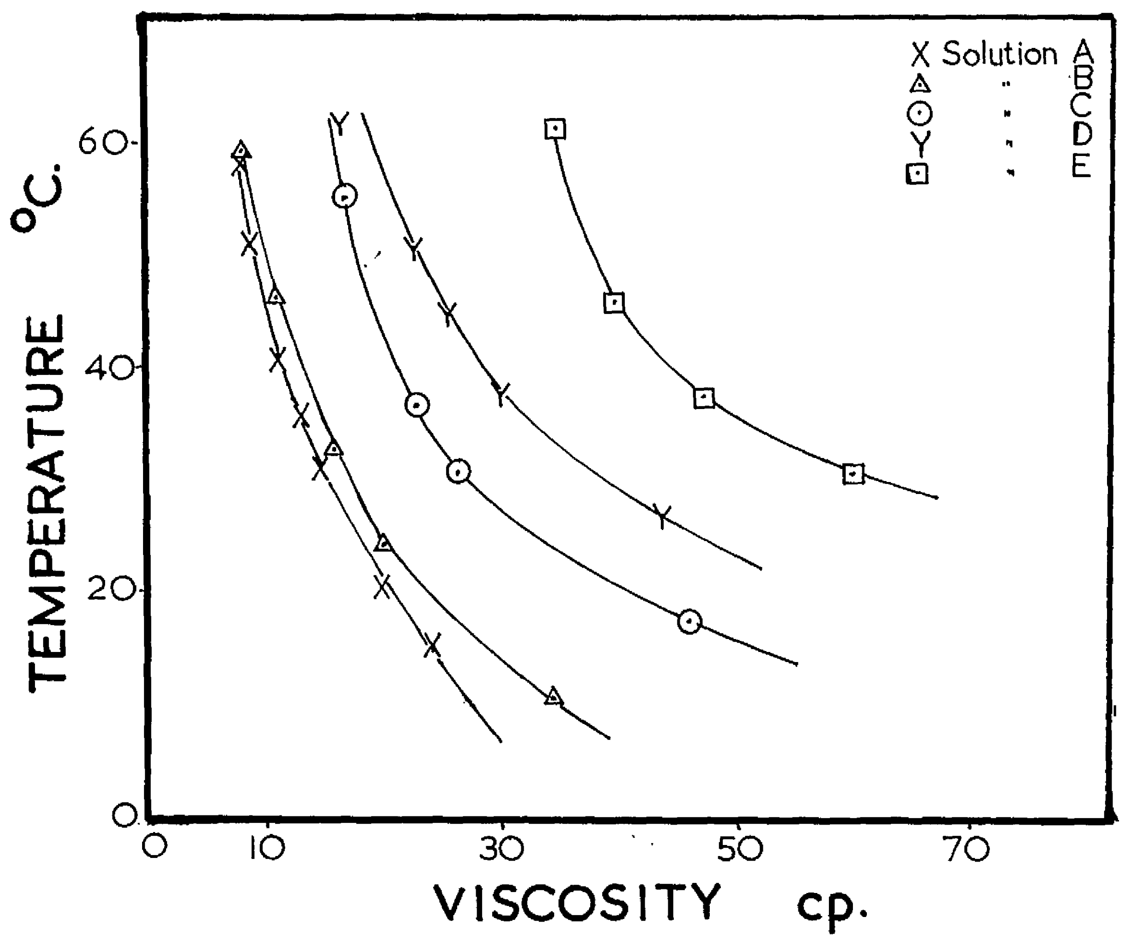


FIG. 36. TEMPERATURE-VISCOSITY RELATION OF GUM TRAGASOL SOLUTIONS A - E.

SOLUTION	TEMP. °C.	VISC. cp.	DENSITY gm./cc.
A	23 33 46 59	18.5 13.5 10.0 8.0	0.052 0.079 0.093 0.100
B	16 32 46 57	25.0 16.0 11.0 8.5	0.050 0.077 0.093 0.100
C	25 32 43 54	32.0 25.0 20.0 17.0	0.050 0.066 0.085 0.095
D	25 30 37 50	48.0 40.0 30.0 22.5	0.047 0.063 0.083 0.098
E	30 37 45	60.0 47.5 40.0	0.045 0.063 0.070

TABLE 22. EFFECT OF TEMPERATURE ON FELTING IN TRAGASOL SOLUTIONS OF VARIOUS VISCOSITIES.

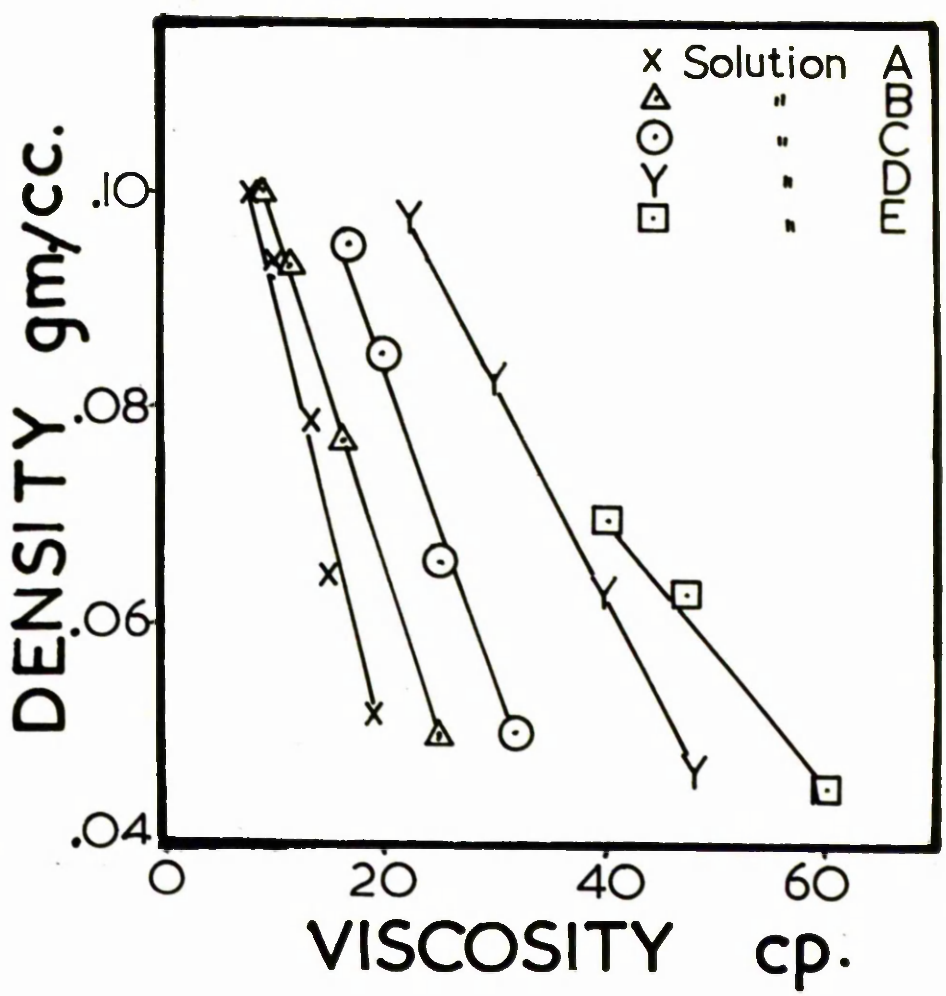


FIG. 37. EFFECT OF TEMPERATURE ON FELTING IN SOLUTIONS OF INCREASED VISCOSITY. (A-E).

4. FELTING TESTS ON WOVEN CLOTH.

The observations on the influence of viscosity on felting power described previously (section 1) have some very interesting practical implications.

It has been shown earlier (ibid.) that in the case of a mass of loose wool and using the present method of felting, the felting power of the fibres is practically completely inhibited when the viscosity of the felting medium is increased to about 25 - 30 centipoises.

This led to the belief that the felting of woollen goods in general may be controlled by adjusting the viscosity of the liquid. Thus, for example, it was thought that in washing the felting shrinkage of woollen cloths could be reduced, if not entirely prevented, by suitably increasing the viscosity of the detergent solution.

A considerable amount of work was done along these lines but most of it is really beyond the scope of this thesis as it dealt with practical and technical aspects of the problem.

It should be indicated, however, that this novel method of controlling felting proved highly successful when applied to the practical problem of washing and laundering.

The matter was investigated by studying shrinkage of various woollen cloths (knitted and woven) during washing in a domestic washing machine of the central oscillating paddle type. A typical set of results is given in Table 23, illustrated in Fig.38. In this set of experiments the percentage area shrinkage (which was used as the index of felting power) of a woollen flannel was determined in aqueous solutions of sodium alginate ('Manucol V' manufactured by Messrs. Allbright & Wilson Ltd.) of various viscosities at room temperature.

It will be observed that the felting power of the material was reduced from 23.1% area shrinkage in ordinary (unthickened) water to 3.0% in a solution of viscosity of 59.6 cp.

The practical importance of this observation is enhanced by the fact that, as some preliminary experiments have shown, the addition of suitable thickening agents does not appear to affect materially the detergent power of the solution.

VISCOSITY cp.	FELTING SHRINKAGE % area
1.0	23.1
5.8	12.1
17.4	5.9
33.0	5.0
59.6	3.0

TABLE 23. EFFECT OF VISCOSITY ON THE FELTING SHRINKAGE OF A WOVEN CLOTH.

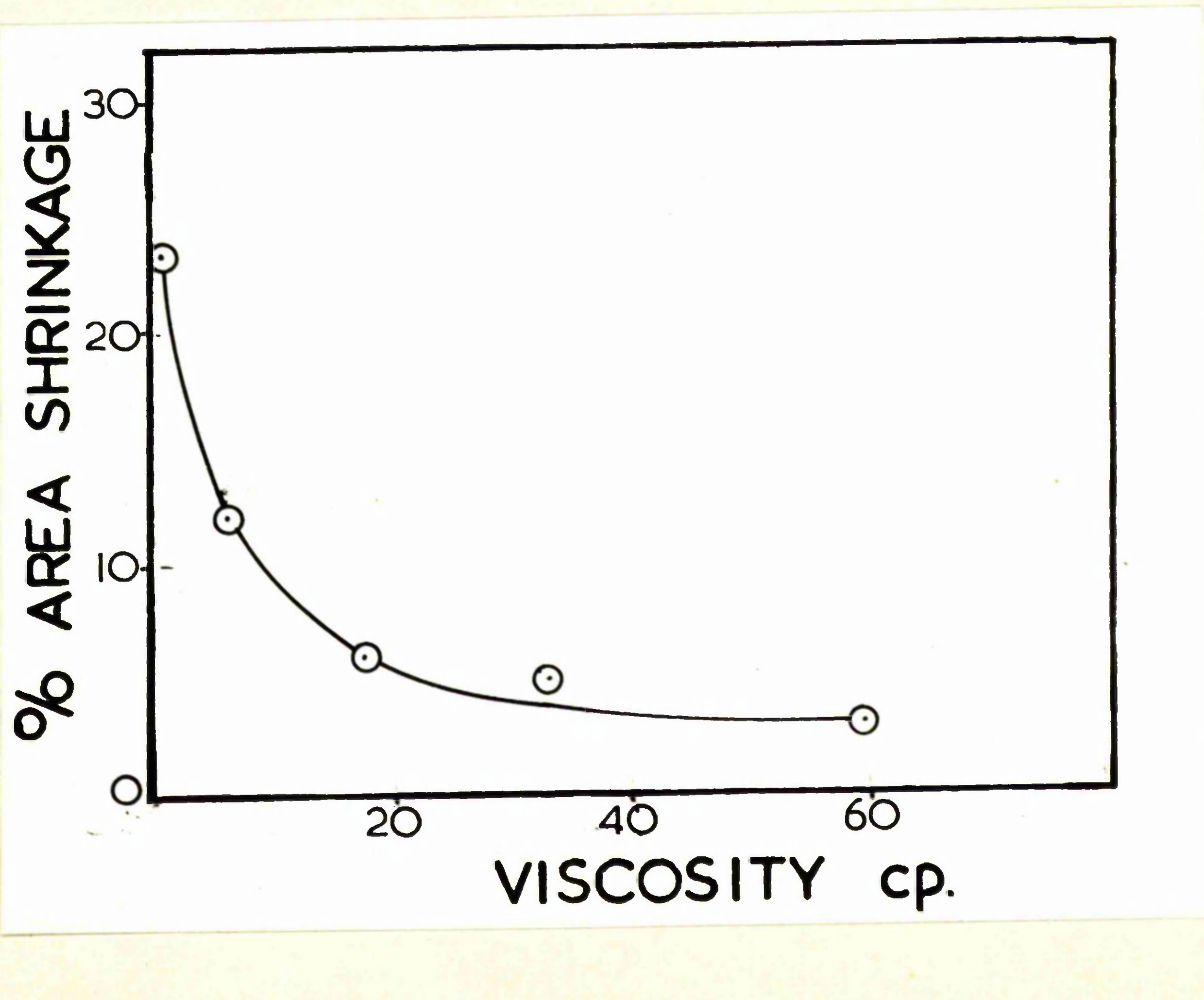


FIG. 38. EFFECT OF VISCOSITY ON THE FELTING SHRINKAGE OF A WOVEN CLOTH.

CHAPTER 8.

DISCUSSION.

DISCUSSION.

I. FRICTION OF ANIMAL FIBRES.

1. The Nature of Frictional Asymmetry.

The hypothesis outlined in Chapter 3 sought to account for the frictional asymmetry of animal fibres on the basis of the fluid film theory of lubrication. It was suggested, by analogy with the mechanism of fluid film formation in bearings, that the differential frictional effect arises in consequence of the characteristic configuration of the scales on the fibre surface, and the magnitude of the with-scale and of the against-scale coefficients of friction is governed by the relative ease of fluid film formation according to the direction of rubbing. It was thus shown that on rubbing from tip to root the slope of the scales opposes this process and so a relatively high coefficient of friction results. On the other hand, on rubbing from root to tip the fluid film formation is facilitated by the angle of inclination of the scales, which leads to a lower frictional coefficient.

It appeared, therefore, that if this hypothesis is true, the frictional behaviour of animal fibres should comply with the well-known general frictional phenomena occuring in bearings etc. In this event the general character of the friction of animal fibres should be expected to follow a certain definite pattern laid by the lubrication theory. On this basis several important predictions as to the frictional behaviour of animal fibres were made, viz.

(1) As was shown in Chapter 3 the frictional phenomena occurring in bearings can be clearly defined by means of the coefficient of friction versus ZN/P diagrams, where ZN/P = viscosity x speed divided by pressure. These curves all have a similar characteristic shape: at low values of ZN/P (i.e. at low speed and viscosity and under heavy pressure) the coefficient of friction is relatively high because of the prevalence of conditions of solid or boundary friction. As the value of ZN/P rises the coefficient of friction decreases, since conditions of fluid film lubrication begin to set up, and it reaches a minimum when full fluid film lubrication has been established. Beyond this critical value of ZN/P friction rises again owing to the viscous drag of the lubricant.

It was considered therefore that the animal fibre friction should reveal the same characteristic relation with ZN/P.

(2) The minima on these μ vs. ZN/P curves are of special significance, for they define the critical value of ZN/P required for the formation of a full fluid film in a given bearing. Since, as indicated earlier, in the case of animal fibres the fluid film is set up with greater ease

on rubbing from root to tip than on rubbing from tip to root, the minimum for the with-scale coefficient μ_R should correspond to a lower value of ZN/P than the minimum for the against-scale coefficient μ_T, i.e. the minimum on the μ_R curve should lie to the left of the minimum on the μ_T curve.

(3) As regards the friction of animal fibres in air, it was thought that in view of the low viscosity of this medium fluid film conditions could not be established (i.e. a sufficiently high value of ZN/P could not be reached) at the speeds likely to be attained. It was expected therefore that in air the friction will be of the boundary type ~~of~~ for both directions of rubbing.

(4) This forecast dealt with the magnitude of the differential frictional effect in relation to the viscosity of the fluid. It was suggested that the differential frictional effect should increase to a maximum as the viscosity of the fluid increases from that of air to some greater value, say that of water, and then to decrease again with increasing viscosity. The reason for this is, as indicated above, that in air the values of the two coeffcients can be expected to be similar, i.e. the differential frictional effect will be small. When, however, the viscosity increases conditions of fluid film lubrication will be set up on rubbing in the with-scale direction and so μ_R will diminish, which

will result in a rise in the differential frictional effect. On increasing the viscosity still further, μ_R will begin to rise again owing to the viscous drag but fluid film conditions may begin to obtain for the against-scale friction, i.e. μ_R will be high and μ_T low and the differential frictional effect will therefore be small again. Further increases in viscosity will only lead to a similar rise in the values of both coefficients (i.e.(μ_T - μ_R) will stay very low) owing to viscous drag.

(5) Considerations of the dimensional and geometrical differences between ordinary bearing surfaces and the fibre bearing surfaces led to the belief that owing to the greater tendency for fluid leakage in the latter case the coefficients of friction under conditions of fluid film lubrication would be considerably higher for the fibre surfaces than for ordinary bearings.

Of the above points, the study of the ZN/P relation, i.e. of the influence of viscosity, speed and pressure on friction, obviously promised to yield most information and it was therefore carried out in an exhaustive manner.

In the experiments which have been described each of these three factors was varied in turn. In most diagrams the results have been plotted as coefficient of friction μ against viscosity. The effect of load on the coefficients can be seen from Fig. 11 (μ_T) and Fig.12 (μ_R). The variations of the against scale coefficient (μ_T) with viscosity at different speeds have been plotted in Figs.14, 16 and 18 under 2, 5 and 10 g. load respectively. The same relations for the with-scale coefficient (μ_R) are shown in Figs. 15, 17 and 19 respectively.

Most of these experimental data on frictional behaviour have been combined by plotting the frictional coefficients against the corresponding ZN/P value for each reading. This gives rise to Figs. 13, 20 and 21, the latter two curves including a wider range and a greater variety of conditions of viscosity, speed and pressure than Fig.13.

It will be observed at once that the μ vs. ZN/P curves, both for the against-scale and for the with-scale coeffcients, are strikingly similar to the general μ vs. ZN/P curve for bearings, as discussed in Chapter 3 (cf. Fig.4 for a journal bearing). The resemblance becomes even closer when one bears in mind that in the present diagrams the ZN/P data have been plotted on a logarithmic scale throughout, whilst in Fig. 4 the ZN/P scale is linear.

When the plot of μ vs. ZN/P for the against-scale coefficient is considered (Fig.20), it will be noted that at low values of ZN/P the coefficient is high (about 0.7 - 0.8), which clearly suggests conditions of boundary friction. However, as the value of ZN/P increases the coefficient of friction diminishes until it reaches a minimum of $\mu_T = 0.4$ when ZN/P is of the order of 70-80, which value therefore represents conditions of viscosity, speed and pressure under which fluid film is formed. Beyond this critical value of ZN/P friction increases again with increasing ZN/P and it reaches very high values (e.g. $\mu_T = 1.4$ at ZN/P = 1000 approx.) simply owing to the viscous drag of the fluid.

Now considering the μ vs. ZN/P relation for the with-scale coefficient u_R in Fig.21 it will observed that the curve has the same characteristic shape as that for the against-scale coefficient, although the rise on the left of the minimum is not so pronounced. Thus at the lowest values of ZN/P which were used the highest value of the with-scale coefficient observed has been $\mu_R = 0.4$. This then falls to about $\mu_R = 0.28$ which represents the minimum on the curve, the corresponding value of ZN/P being 20-30. (Actually many experimental points give lower value of μ_R viz. 0.18 - 0.2). Beyond this critical range the curve begins to rise again and at high values of ZN/P it reaches similar values of $\mu_R > 1$ to those for μ_T.

Thus in the case of the with-scale coefficient it would appear, in contrast with the friction on rubbing against the scales, that even at very low values of ZN/P conditions approaching fluid film lubrication prevail, since under these conditions the value of the coefficient is only slightly higher than the value corresponding to the most efficient fluid film separation, i.e. to the minimum of the curve.

It will thus be clear that these experimental results offer a striking confirmation of the basis of the present hypothesis, since they leave little doubt as to the strict adherence of the frictional behaviour of animal fibres to the general frictional phenomena in bearings as indicated by the μ vs. ZN/P relation.

Furthermore, all the other forecasts regarding the frictional behaviour of fibre surfaces have been substantiated by experiment.

Thus the second forecast (2) regarding the relative position of the minima on the μ vs. ZN/P curves has also been fully confirmed, for, as has been mentioned above, the minimum on the against-scale curve occurs when ZN/P equals about 70-80, whilst the corresponding values of ZN/P on the with-scale diagram is only 20-30, i.e. as predicted, the minimum for the with-scale friction lies to the left of that for the against-scale friction.

As to the third forecast, regarding the frictional behaviour of animal fibres in air (3), it has been found (Table 12a) that the values of μ_T and of of μ_R do in fact lie close to each other (e.g. $\mu_T = 0.52$ and $\mu_R = 0.40$) as anticipated.

The next prediction (4) dealt with the magnitude of the differential frictional effect as affected by the viscosity of the fluid. It was then suggested that the differential frictional effect should pass over a maximum as the viscosity is increased from that of air, through that of, say, water to that of more viscous solutions. The correctness of this anticipation has in fact been proved, and it will be clear from Table 24 and Fig.39 where $(\mu_T - \mu_R)$ is plotted against ZN/P, the values of μ_T and μ_R and the corresponding values of ZN/P having been taken from Figs. 20, 21 and from Table 12a (for friction in air). Fig. 39 shows clearly that the value of the differential frictional effect rises from 0.12 (in air) to a peak of 0.49 (in water) and then falls gradually to 0.09 as the viscosity of the fluid increases (i.e. ZN/P increasing to about 100).

According to the last point (5) which was anticipated on the basis of the hypothesis put forward in Chapter 3, the magnitude of the frictional coefficient under conditions of fluid film lubrication was expected to be considerably higher in the case of fibre bearing surfaces than for ordinary bearings.

This has in fact been found in the present experiments, for the lowest value observed is of the order of 0.2, whilst in the case of bearings the coefficient is of the order of 0.01-0.02 under conditions of full fluid film lubrication. The reason suggested for this discrepancy

ZN/P	μ_T	μ_R	$\mu_T - \mu_R$
0.2	0.52	0.40	0.12
3	0.84	0.35	0.49
4	0.78	0.33	0.45
5	0.74	0.32	0.42
7	0.68	0.31	0.37
9	0.64	0.30	0.34
10	0.62	0.30	0.32
15	0.57	0.29	0.28
20	0.53	0.28	0.25
25	0.50	0.28	0.22
30	0.48	0.28	0.20
35	0.46	0.29	0.17
40	0.45	0.29	0.16
50	0.44	0.29	0.15
60	0.42	0.30	0.12
80	0.41	0.31	0.10
100	0.41	0.32	0.09
120	0.42	0.34	0.08
140	0.44	0.35	0.09
160	0.46	0.37	0.09
180	0.48	0.39	0.09

TABLE 24. VARIATION OF THE DIFFERENTIAL FRICTIONAL EFFECT WITH ZN/P

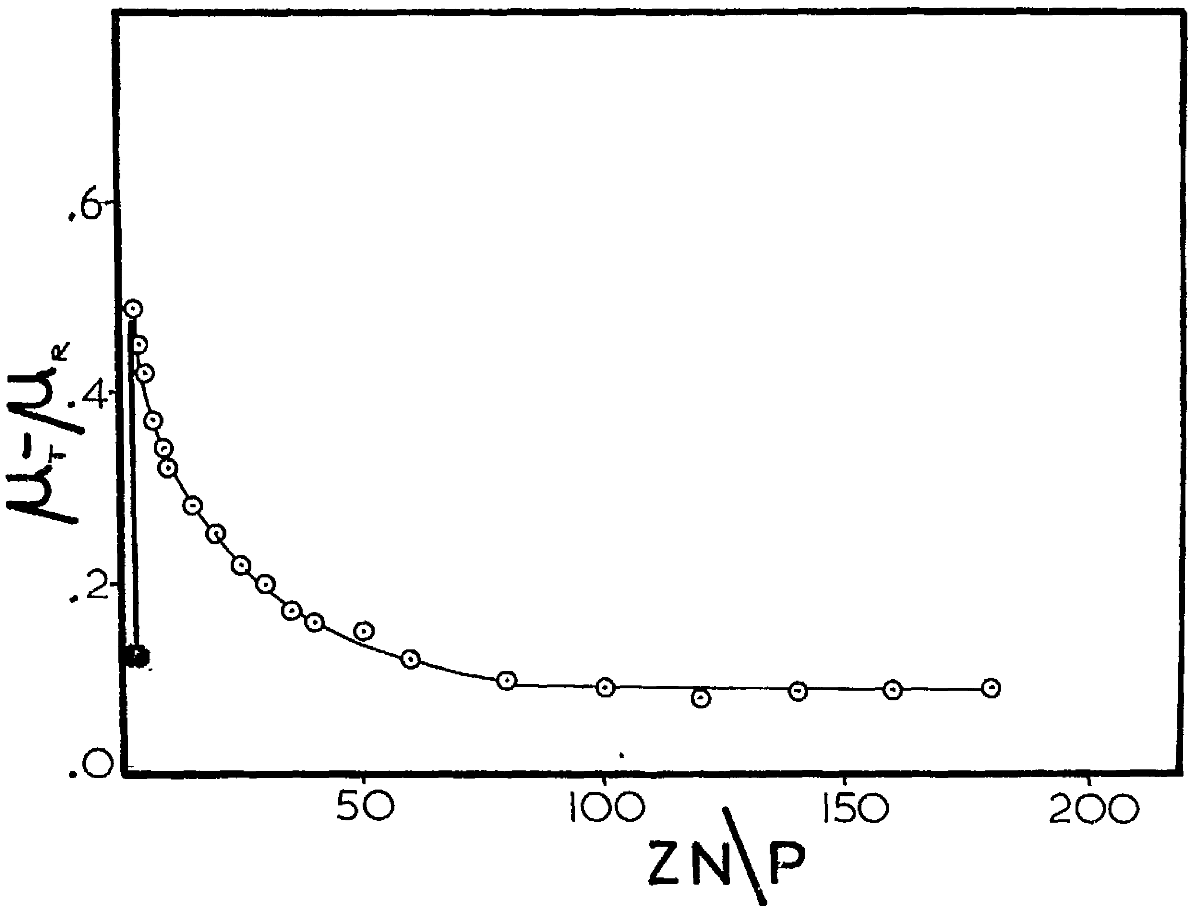


FIG. 39. VARIATION OF THE DIFFERENTIAL FRICTIONAL EFFECT WITH ZN/P.

was that owing to the small size of the scale surfaces and the fact that the fibre bearing surfaces are curved about two axes, the tendency of the fluid to leak away is greatly increased in comparison with ordinary bearings, which results in imperfect separation of the surfaces.

However, there may be another reason for this relatively high magnitude of these coefficients. It is thus possible that since not all the fibres in the bow are of equal tension (the practical difficulties in mounting them under equal tension being very great), they do not all separate from the glass cylinder at the same value of ZN/P. For example, to produce conditions of separation by a fluid film of taut fibres would require a higher ZN/P value than that required for fibres which are under less tension. and this may result in the system never attaining the very low coefficients of friction obtaining in a better constructed bearing.

The comparison of the values of the coefficients observed in the present experiments with those determined by other authors can be done only in a limited way, for, as indicated in Chapter 2, all other workers in this field were concerned with static friction or dynamic friction at very low velocities of rubbing. This means that their results can be compared only with the present data which correspond to low values of ZN/P.

Under such conditions the frictional coefficients observed in the present experiments are of the order of 0.70 (μ_T) and 0.40 (μ_R), whilst typical values given by Makinson (72) in the case of wool rubbing against horn in a buffer solution at pH 7 are 0.70 and 0.30 respectively; under similar conditions but at pH 4 Mercer (23) found the coefficients to be 0.66 and 0.32 respectively, which shows a good agreement. Comparison with Speakman's results is unfortunately impossible, since he and his collaborators did not publish the values of individual coefficients separately but only as a function of both.

Finally, additional evidence in favour of the present theory is provided by the experimental observation (Table 8) that the frictional behaviour of animal fibres against an ivory surface is very similar to that against glass in spite of the different chemical nature of the surfaces. This finding is in agreement with the theory, for as indicated in Chapter 3, under conditions of fluid film lubrication the chemical nature of the rubbing surfaces is immaterial.

2. Effect of Temperature.

The influence of temperature in friction was examined in two sets of experiments, both of which are of great interest.

In the first series friction was measured in six solutions of sucrose of different viscosities, readings being taken in each solution over a range of temperature from about 20 to 60°C.

As has already been indicated (FIG.24) it was found that the decisive factor that governs the magnitude of the coefficients, under given conditions of speed and load, is not the temperature but the viscosity of the fluid. Thus it was found that the frictional coefficient is the same in any of the solutions used provided their viscosities are similar, although the temperature may be quite different. This led, of course, to a considerable overlapping of the experimental points on the friction vs. viscosity (with constant speed and load) diagram for these six solutions, as will be clear from Fig.24.

That the manner in which temperature affects friction under the conditions of the present experiments is through its influence on the viscosity of the fluid is in full accord with the present theory. This will be obvious from the shape of both the against-scale and the with-scale coefficient curves in Fig.24, which curves bear a remarkable resemblance to those established earlier, in independent series of experiments, for the friction vs. ZN/P relation (Fig.20 and Fig.21).

This fact offers, of course, further important evidence in support of the present views of the nature of friction of animal fibres.

In the second series of experiments frictional measurements were carried out at various temperatures (between approximately 20 and 60°C.) in water and unthickened solutions of soap and sulphuric acid. Again, a broad agreement with the theory has been found.

Thus in the case of the against-scale motion in fluids of such low viscosity conditions of friction prevail which correspond to values of ZN/P smaller than that for the minimum of the curve; consequently the coefficient of friction can be expected to increase with increasing temperature, i.e. decreasing viscosity.

This has in fact been observed, for, as shown in Fig.25, the against-scale coefficient rises with increasing temperature. In the case of sulphuric acid this rise appears to be almost directly proportional to the decrease in viscosity of the medium, for the coefficient curve is almost parallel to the fluidity curve. In water and soap the coefficients also rise appreciably with increasing temperature but the correspondence with the viscosity changes is not quite as close.

The values of the against-scale coefficients at elevated temperatures, e.g. at 50°C. μ_T in acid is 1.48 and about 0.90 in water and soap, are remarkably high, and they clearly indicate the existence of very intimate contact between the fibres and the glass surface. (It may be recalled for comparison that the corresponding value of μ_T in air, but at room temperature, was only 0.52).

In contrast the values of the with-scale coefficient have been found to be only slightly affected by increasing the temperature. Thus for example even at 60°C. μ_R in water (0.45 cp.) was found to be only 0.32 compared with 0.18 at 20°C.

This observation is in line with the previous results which showed repeatedly that in the case of with-scale motion conditions approaching fluid film lubrication persist even at exceedingly low values of ZN/P.

3. EFFECT OF pH.

The influence of pH in friction was studied at room temperature using a series of unbuffered solutions, viz. sulphuric acid, boric acid, water, sodium bicarbonate and sodium carbonate.

As indicated in Fig.26 the against-scale coefficient was found to be highest in strongly acid media (μ_T = 1.15 at pH 0.3), then to decrease with increasing pH to μ_T = 0.68 round neutrality and finally to gradually rise again to 0.95 at pH 11.6. By comparison the variations ~~with~~ of the with-scale coefficient with pH were found to be small, the corresponding values being 0.24 in acid, 0.18 in water and 0.32 in sodium carbonate.

These observations are in broad agreement with the data published by other workers on friction under static conditions or at very slow velocities, e.g. Mercer found (23), in the case of wool rubbed against horn, at pH 1.3 μ_T = 0.72 and μ_R = 0.32, these values falling to 0.66 and 0.30 respectively at pH 4.0, whilst at pH 10.8 the coefficients were 0.66 and 0.25 respectively.
The more recent work of Mercer and Makinson (43) also showed a similar dependence of friction on pH, the values of the coefficients being considerably higher with especially clean fibres (e.g. $\mu_T > 1$) than with contaminated surfaces.

The fact that the values of the with-scale coefficients are relatively little affected by pH further supports the view that the with-scale friction, by virtue of the favourable scale configuration, almost invariably occurs under conditions approaching fluid film lubrication. It is probably for this reason therefore that the pH of the fluid, which may affect the nature of the fibre surface, is of little consequence for the with-scale friction.

The positions is, however, quite different in the case of the against-scale friction, for in unthickened solutions friction occurs well to the left of the region of fluid film lubrication, as indicated by μ vs. ZN/P diagram (Fig.20). Under such conditions the magnitude of the coefficient reflects the degree of separation of the rubbing surfaces, and so it would appear that the pH of the medium may affect the fibre surface in a manner that will determine the degree of contact between the fibres and the glass surface. This would, of course, be similar in effect to the influence that the high temperature has on the against-scale friction in unthickened media, as suggested earlier.

The mechanism through which both the pH and the temperature influence the against-scale friction under boundary conditions is clearly of great interest. The matter has not, however, been pursued beyond the above observations.

SUMMARY.

Frictional phenomena are commonly divided into three types: solid, boundary and fluid film friction. The last seemed of particular interest in connection with the problem of friction of animal fibres, because of the analogy which was observed between the configuration of the scales on these fibres and the geometrical characteristics of bearings. Since in the problems of fluid film lubrication geometrical similarities imply a similarity of frictional behaviour, it was thought that the frictional properties of animal fibres may follow the pattern of the frictional phenomena occurring in bearings.

It was therefore suggested that the frictional asymmetry of animal fibres arises in consequence of the characteristic cuticular scale structure of the fibres, and that the difference in the magnitude of the against-scale and the with-scale coefficients is due to the difference in the ease of formation of fluid film between the surfaces according to the direction of rubbing. Thus it was shown that on rubbing from tip to root (i.e. against the scales) the slope of the scales opposes this process, which leads therefore to an imperfect separation of the surfaces and so to a relatively high coefficient of friction. On the other hand, on rubbing from root to tip (i.e. with the scales) the fluid film formation is promoted by the

slope of the scales, the surfaces are therefore separated more efficiently and this results in a relatively low coefficient of friction.

The experiments on the frictional behaviour of animal fibres which have been carried out were designed to examine this hypothesis in detail by a thorough investigation of the effect on animal fibre friction of those factors which are of primary importance in connection with fluid film lubrication, viz. viscosity of the fluid (Z), speed of rubbing of the surfaces (N) and the pressure between them (P).

These investigations have demonstrated a striking adherence of the frictional behaviour of animal fibres to the friction vs. ZN/P relation, which adherence reveals a remarkable resemblance to the frictional phenomena occurring in bearings, thus indicating the correctness of the assumption.

The experiments have also substantiated several predictions made on the basis of the hypothesis, e.g. as regards the relative position of the minima on the friction vs. ZN/P curves for the against- and with-scale motion; also regarding the magnitude of the frictional coefficient of the fibres and the effect of viscosity on the differential frictional effect; and also as regards the frictional behaviour of the fibres in air.

Subsequent results on the effect of temperature and pH on friction have also been found in agreement with the previous findings. Moreover, the experiments on felting of wool, which were designed to provide a further check on the present theory and which will be discussed in the last section, corroborated the present theory in a remarkable manner.

It is felt, therefore, that all these experiments provide convincing evidence in favour of the present theory of the nature of the frictional asymmetry of animal fibres.

II. FELTING BEHAVIOUR OF ANIMAL FIBRES IN RELATION TO THEIR FRICTIONAL PROPERTIES.

1. Applicability to Felting of the Lubrication Theory of Animal Fibre Friction.

In the discussion on the mechanism of the felting process in Chapter 1 it has been shown that the felting power of animal fibres arises fundamentally in consequence of their frictional asymmetry; with all other factors beingconstant, the rate of felting is proportional to the magnitude of the differential frictional effect ($\mu_T - \mu_R$).

The present experiments on friction provided a wealth of information on the variation of the differential frictional effect with viscosity, speed and load. The data have already been presented in a concise form in Fig. 39 which showed the variations of ($\mu_T - \mu_R$) with ZN/P. Thus as indicated the differential frictional effect rises steeply from a low value in air (0.12) to ($\mu_T - \mu_R$) = 0.49 in water and then it falls gradually again to a very low value (0.09) as ZN/P increases.

These data refer, of course, to the friction of fibres against glass, but assuming that the same phenomena occurs in fibre to fibre friction (the basis of this assumption having been indicated when the present theory was first postulated in Chapter 3), then the felting power should be expected to vary with ZN/P in the same sense as does the differential frictional effect.

The matter was examined by carrying out felting measurements using wool fibres under conditions when speed and load (and temperature) were maintained constant whilst the viscosity of the fluid was varied. The results obtained have been presented in Table 17 and Figs. 32 and 33 for felting determinations over a viscosity range from 1.0 to approx. 40.0 cp. at five different pH values. As will be seen from these data, at every pH value, examined, felting power decreases until it is practically completely inhibited as the viscosity rises to about 25-30cp.

In order to indicate clearly the relation between the felting power and the differential frictional effect in respect of viscosity the felting curve and the $(\mu_T - \mu_R)$ curve have been plotted together in Fig.40. The felting data are taken from Table 17 and represent the felting power of wool at pH 5.9 in solutions of 1.0, 5.1, 11.0, 23.0 and 42.0 cp. In air no felting occurs under the conditions of present experiments and so the corresponding value is plotted as 0.04 g./cc. The values for the differential frictional effect are those obtained under 5 g. load and at 42 cm./sec. in neutral sucrose solutions of various viscosities, from 1.0 to 40 cp. (cf. Figs.11,12 or 16,17),

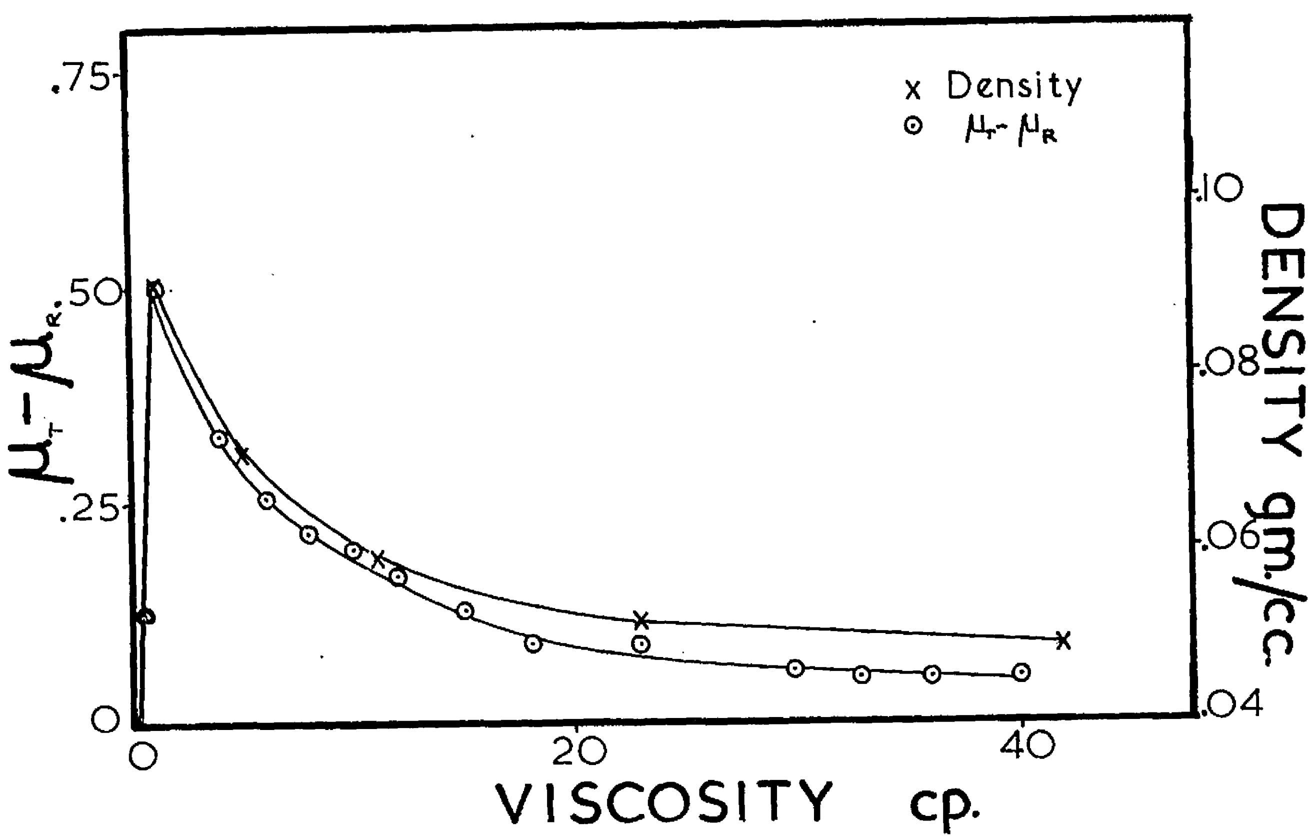


FIG. 40. VARIATION OF DIFFERENTIAL FRICTIONAL EFFECT AND OF FELTING POWER WITH VISCOSITY.

and they also include the value for the friction in air, from Table 12a.

As is evident from Fig.40 there is a complete parallelism between the felting power and the differential frictional effect in their relation to viscosity.

In view of this remarkable correspondence the following conclusions emerge:

(1) The present theory of animal fibre friction is further corroborated, for the dependence of friction on viscosity of the fluid has again been demonstrated and this time by means of an entirely different type of experiment. It may be expected that just as the viscosity influences felting so will the speed and the load in accordance with the ZN/P relation.

(2) The frictional phenomena occurring in the felting process are very similar to those observed in the experiments on friction against a glass surface. It would appear that the friction of human hair against glass is of the same nature as the friction between wool fibres. This is, of course, in complete agreement with the assumption which was made in Chapter 3 when the hypothesis was put forward.

(3) Further evidence is provided for the fundamental dependence of felting power on the differential frictional effect. It is clear that the existence of a differential frictional effect is the first essential condition for felting to take place.

Lastly, mention must be made of the practical offshot of these observations, namely the investigations into the problem of controlling the felting shrinkage of woollen goods in washing and laundering by means of adjusting the viscosity of the detergent solution so as to reduce the differential frictional effect to a low value.

As has already been indicated in Chapter 7 the method seems to hold considerable promise and may prove to be of practical importance.

2. EFFECT OF TEMPERATURE.

The experiments on the influence of temperature in felting were designed to parallel broadly those carried out on the temperature effect inn friction witht the view of establishing some correlation between those phenomena in respect of temperature.

(a) In the first series of experiments the felting power of wool was determined in unthickened solutions of sulphuric acid, soap and borax, the tempyerature being varied in each solution from 20 to 60°C. As has already been shown in Table 20 and Fig.35, in all media the felting power increases linearly with temperature.

In order to indicate the parallelism between these results and the differential frictional effect the felting data for acid and soap have been presented in Table 25 together with the corresponding results on the variation of the differential frictional effect with temperature (from Fig.25), the borax being omitted as no frictional data for this medium are available.

These comparative results have been plotted in Fig.41 for sulphuric acid and in Fig.42 for soap.

As will be evident from these diagrams there is a close correspondence between the felting and the differential frictional effect curves, in both sulphuric acid and soap. It would appear, therefore, that, in these ~~circum~~-

DIFFERENTIAL FRICTIONAL EFFECT				FELTING POWER			
H_2SO_4		Soap		H_2SO_4		Soap	
Temp. °C.	$\mu_T - \mu_R$	Temp. °C.	$\mu_T - \mu_R$	Temp. °C.	g/cc.	Temp. °C.	g/cc.
20	0.83	19	0.72	20	0.117	20	0.106
27	0.90	27	0.72	30	0.135*	30	0.118
35	0.92	40	0.75	40	0.140	40	0.130
40	1.03	50	0.76	50	0.158	50	0.134
50	1.15	55	0.77	60	0.165	60	0.149

TABLE 25. COMPARATIVE VALUES OF DIFFERENTIAL FRICTIONAL EFFECT AND FELTING POWER IN SULPHURIC ACID AND SOAP.

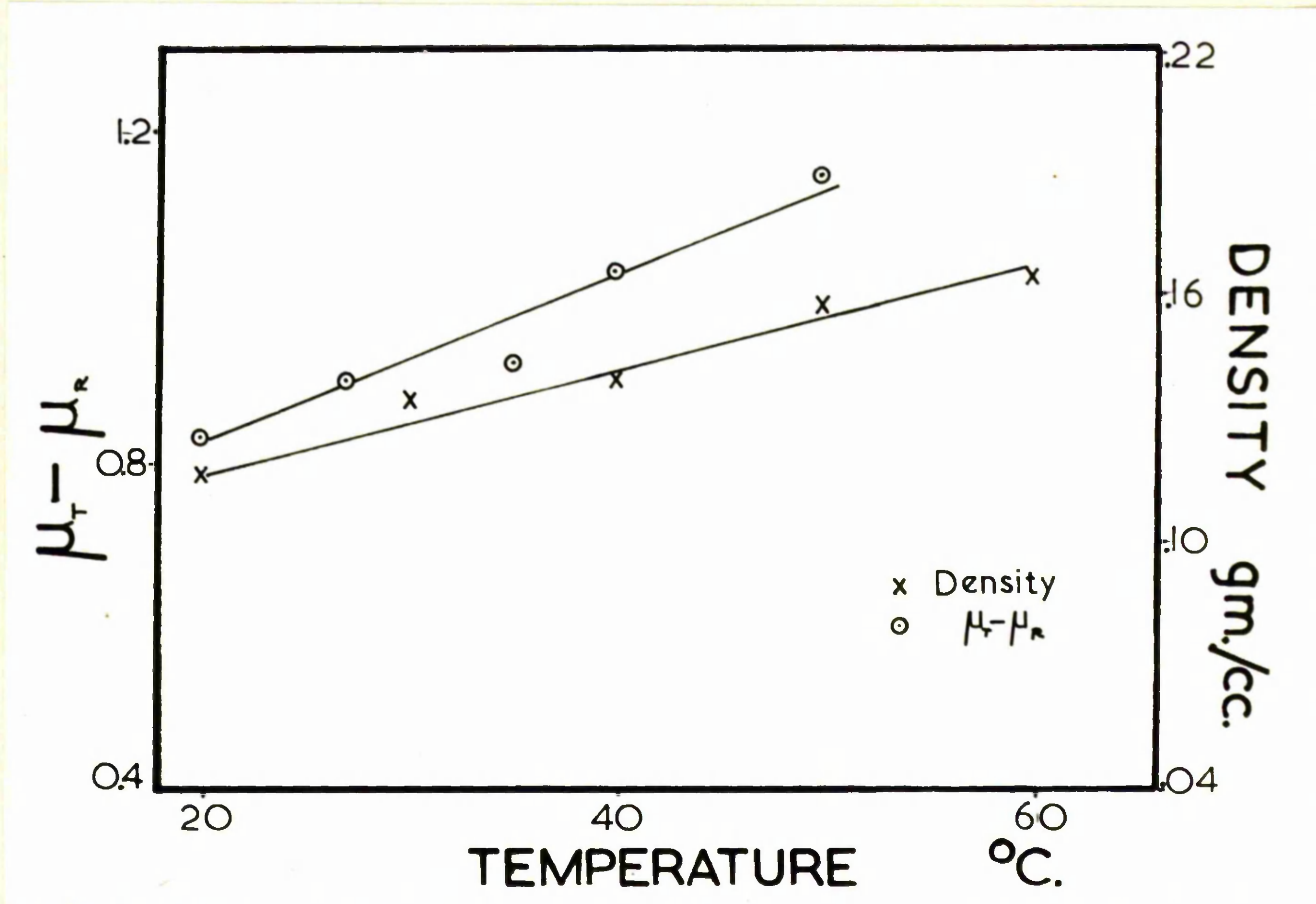


FIG. 41. EFFECT OF TEMPERATURE ON DIFFERENTIAL FRICTIONAL EFFECT AND FELTING POWER IN SULPHURIC ACID.

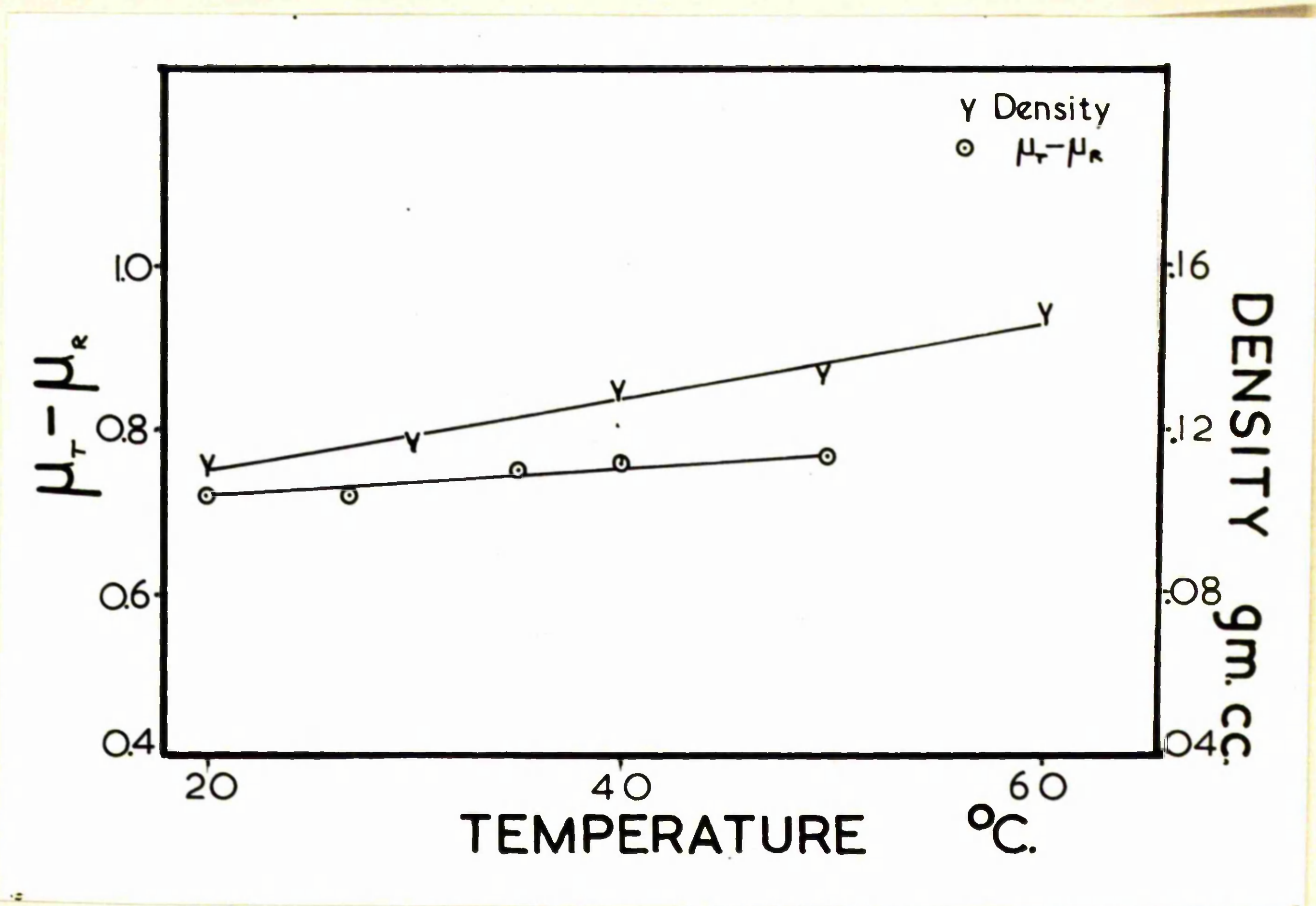


FIG. 42. EFFECT OF TEMPERATURE ON DIFFERENTIAL FRICTIONAL EFFECT AND FELTING POWER IN SOAP SOLUTION.

instances, the influence of temperature on the felting power of wool depends primarily on its effect on the differential frictional effect of the fibres.

The present felting results agree with those of Mercer (22) which showed a similar effect of temperature in the felting of woollen yarns in buffered solutions at pH 4.0, 7.2 and 9.2.

On the other hand Speakman, Menkart and Liu reported (19) that in the case of woven cloth felting reached a maximum at 35-37°C. in soap and borax, although in sulphuric acid it continued to increase with increasing temperature up to 60°C.

The reason for this discrepancy is not clear but it was suggested by Speakman et al. (ibid.) that the influence of temperature in felting is due to its effect on the elastic properties of the fibres. They also thought that in the woven fabrics these properties are of greater importance than in yarns or in loose fibre mass, since in fabrics the fibres are more likely to migrate by alternate extension and contraction. Consequently the effect of temperature may be expected to be different according to the state of aggregation of the fibres.

(b) The second series of experiments on the effect of temperature in felting dealt with the determinations of felting power at various temperatures in thickened solutions of different viscosities.

The results, which have been presented in Table 22 and Fig.37, show that at any given viscosity the felting power depends on the temperature, ie. at any given viscosity the higher the temperature the higher the felting power.

By reference to Fig.36 (which gives the temperature - viscosity relation of the solutions used) and to Fig.37 (where the density vs. viscosity data for the same solutions have been plotted) it is possible to derive more information from these experiments regarding the felting vs. viscosity relation at various temperatures and the felting vs. temperature relation at various viscosities.

In Table 26 are given the values of density at various viscosities, ~~viz~~ at 25, 35, 45 and 60°C. These have been obtained by finding from Fig.36 the viscosities corresponding to these temperatures and then reading off from Fig.37 the respective densities at these viscosities.

The data in Table 27 have been derived in a similar manner for the variation of felting power with temperature at various viscosities, viz. 10, 12.5, 15 ~~and~~ 20 cp. and 40 cp.

25°C.		35°C.		45°C.		60°C.	
Visc. cp.	Density g./cc.	Visc. cp.	Density g./cc.	Visc. cp.	Density g./cc.	Visc. cp.	Density g./cc.
20	0.067	15	0.083	10	0.093	10	0.106
40	0.058	20	0.078	15	0.092	12.5	0.103
		40	0.065	20	0.086	15	0.100
				40	0.070	20	0.092
						40	0.077

TABLE 26. VARIATION OF FELTING POWER WITH VISCOSITY AT VARIOUS TEMPERATURES.

10 cp.		12.5 cp.		15 cp.		20 cp.		40 cp.	
Temp. °C.	Dens. g/cc.	Temp. °C.	Dens. g/cc.	Temp. °C.	Dens. g/cc.	Temp. °C.	Dens. g/cc.	Temp. °C.	Dens. g/cc.
46	0.090	36	0.081	30	0.072	21	0.053	20	0.045
50	0.097	41	0.090	34	0.082	24	0.062	30	0.063
80	0.115	73	0.107	61	0.100	43	0.085	45	0.070

TABLE 27. VARIATION OF FELTING POWER WITH TEMPERATURE AT VARIOUS VISCOSITIES.

The data showing the density vs. viscosity relation (Table 26) have been plotted in Fig.43 which gives the equal temperature curves for 25, 35, 45 and 60°C.

As will be observed, at every temperature, felting power decreases as the viscosity of the fluid increases, which is in full agreement with the earlier observations on the effect of viscosity on felting and is no doubt due to the influence of viscosity on the differential frictional effect. That this is so is indicated by the similar slope of the curves at all temperatures.

The density vs. temperature relation has been plotted in Fig.44 which shows the equal viscosity curves for 10, 12.5, 15, 20 and 40 cp. It is clear from this diagram that at every viscosity felting power is dependent on temperature, the felting power increasing remarkably with increasing temperature.

These observation do not correspond to the frictional behaviour of the fibres, as established in Chapter 5 when it was shown (4a) that the coefficients of friction are independent of temperature provided the viscosity of the fluid (and all other factors) are constant.

Clearly, therefore, a new important factor or factors affect the felting power of wool fibres, and it must be through them that the temperature effect operates under conditions of constant viscosity.

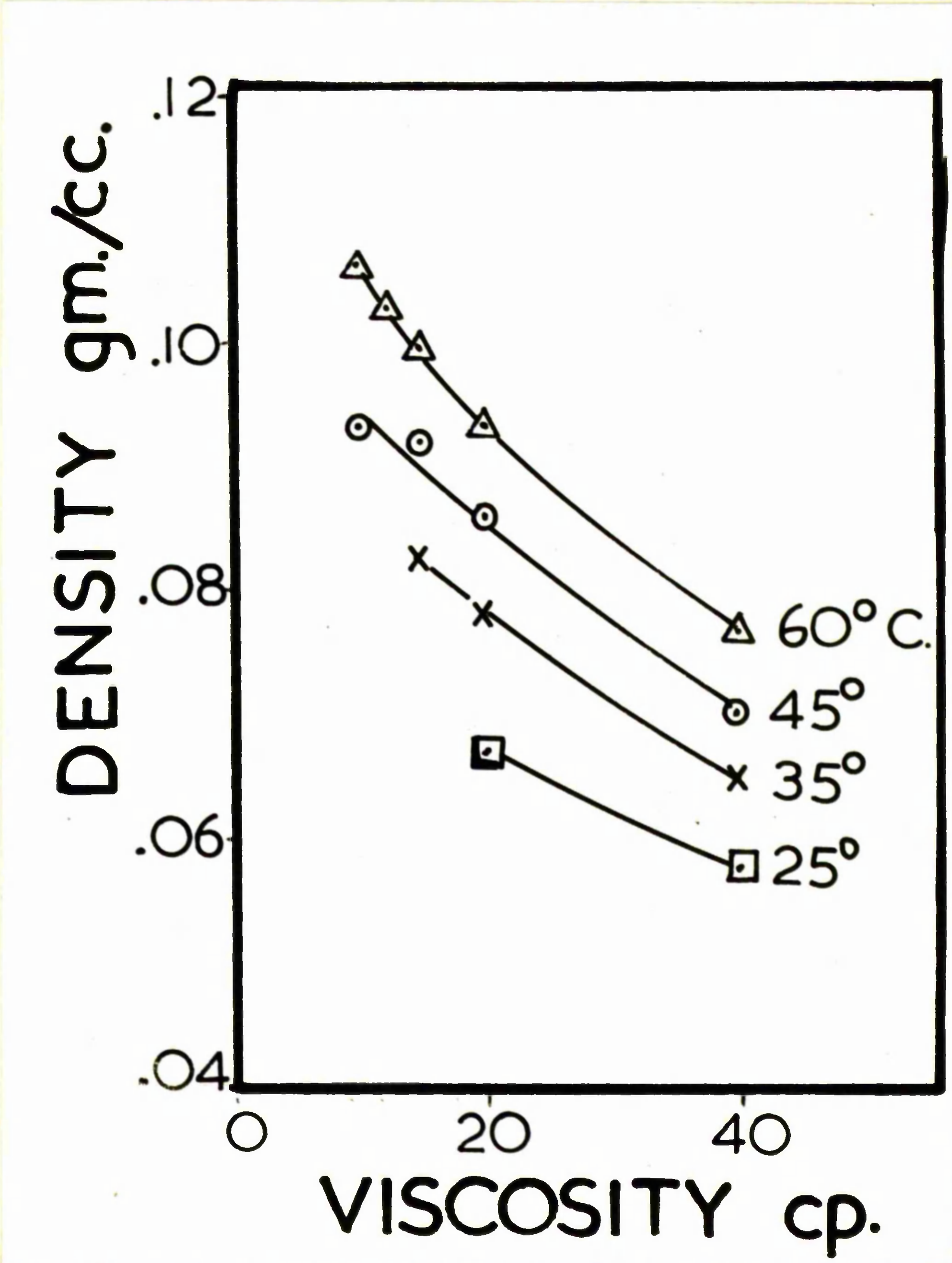


FIG. 43. FELTING POWER VS. VISCOSITY - EQUAL TEMPERATURE CURVES.

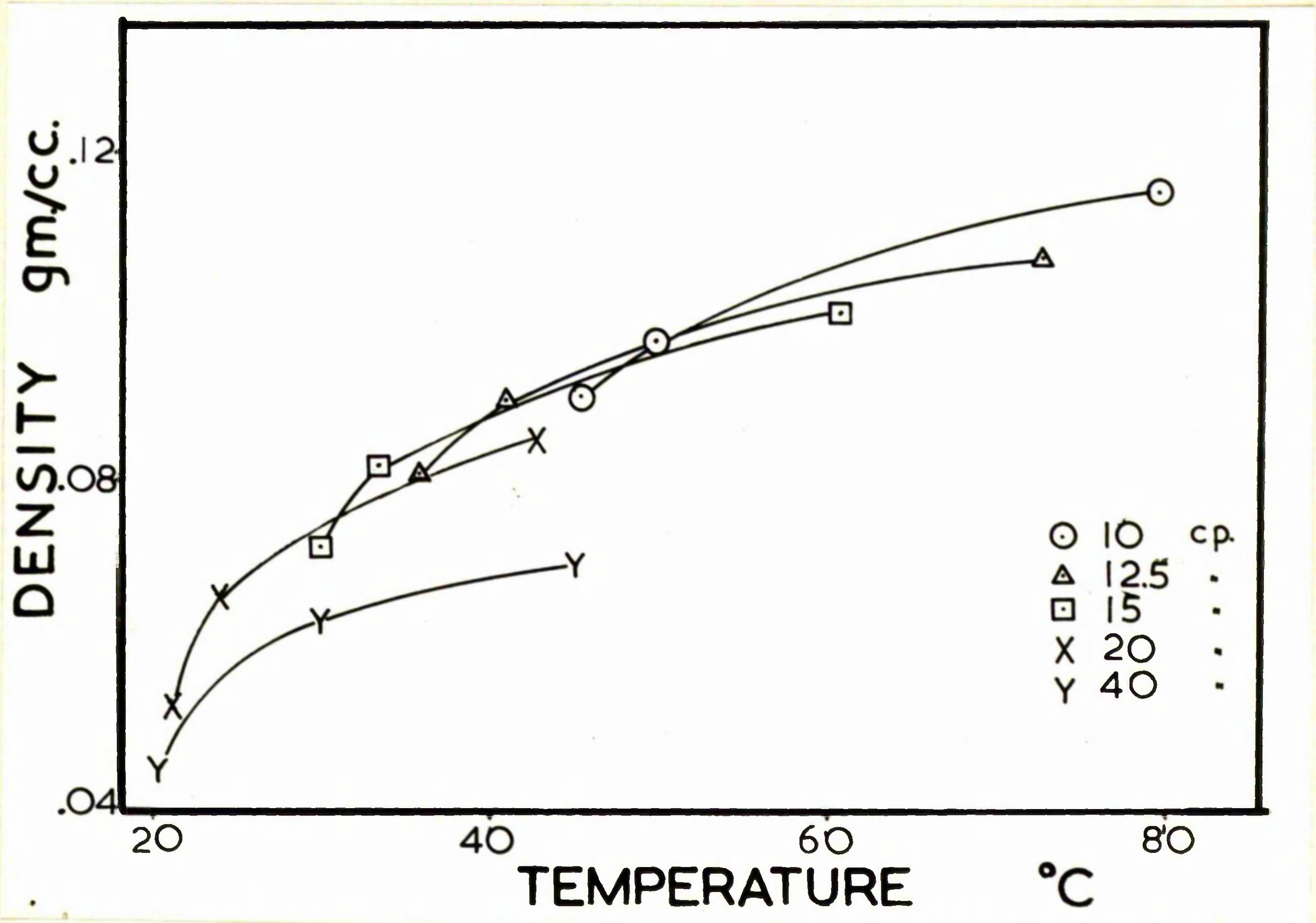


FIG. 44. FELTING POWER VS. TEMPERATURE - EQUAL VISCOSITY CURVES.

The matter, though obviously of great importance for the fuller understanding of the phenomenon of felting, has not yet been examined further. It is most probable, however, that the reason for the temperature effect under these conditions lies in the influence of temperature on the elastic properties of the fibres, as has been suggested by Speakman and his collaborators (19), and possibly also on their rigidity; these properties would be influenced by temperature so as to promote the fibre migration and the entanglement of the fibre mass.

3. EFFECT OF pH.

The influence of pH of the fluid on the felting power of wool has been studied using both unbuffered (Table 18) and buffered (Table 19)& Fig.34) solutions.

The present experiments confirmed the results of Speakman, Stoot and Chang (18) and Mercer(22), and they show that felting power which is highest in acid media decreases as the pH increases down to the neutral region and then increases again on the alkaline side of the pH range.

The felting behaviour and the frictional properties of animal fibres appear to correspond to each other very closely as will be observed from Fig.45. On this diagram the felting data (Table 18) and the corresponding values of the differential frictional effect (Table 13), both referring to the same unbuffered solutions, are plotted together. The parallelism between the two curves is clear.

These observations indicate therefore that as regards the pH of the medium the rate of felting is affected through the changes in the magnitude of the differential frictional effect.

However, the possibility must not of course be excluded that, as in the case of the temperature effect, the pH also influences felting power through its effect on

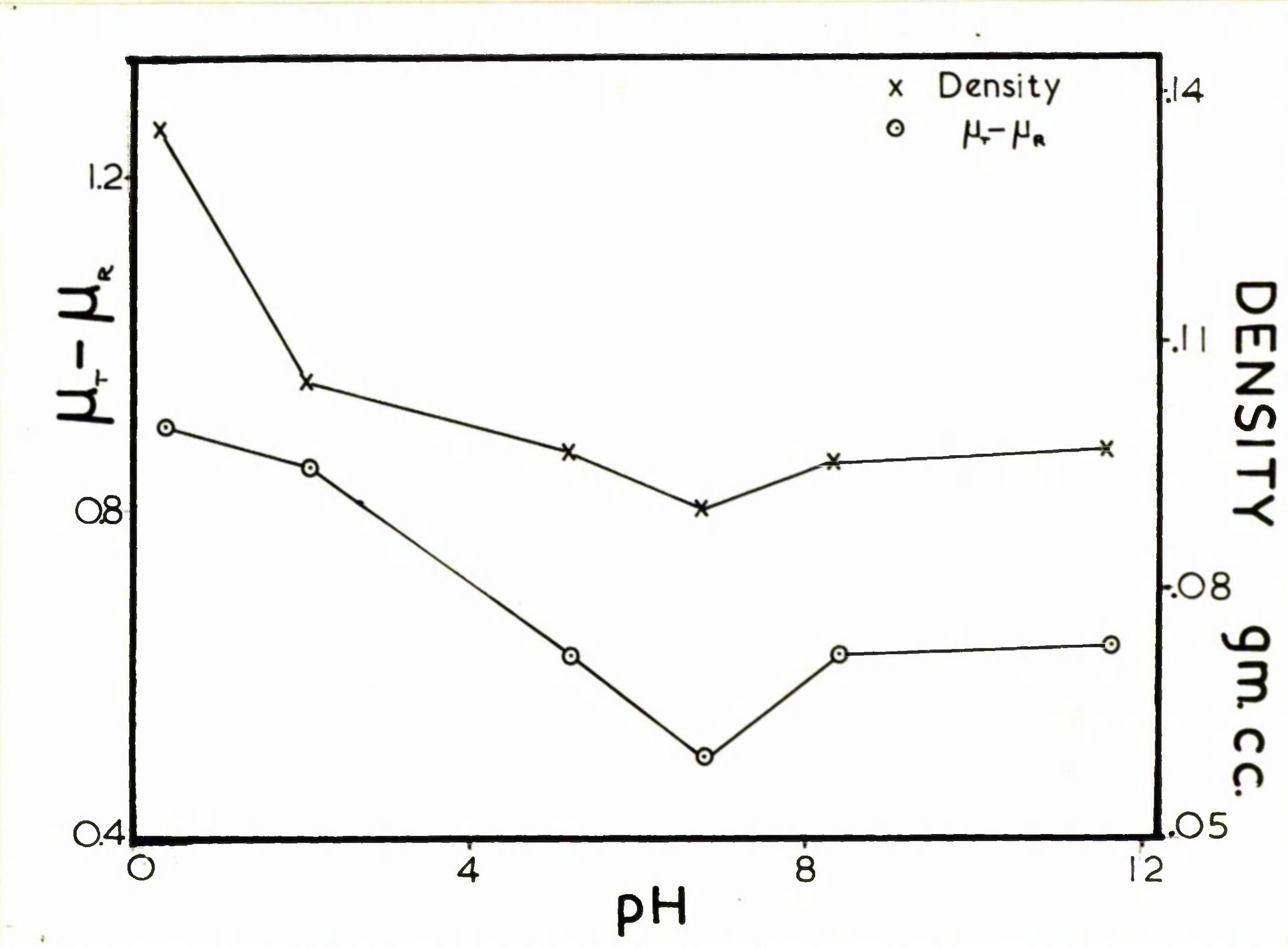


FIG. 45. INFLUENCE OF pH ON DIFFERENTIAL FRICTIONAL EFFECT AND FELTING POWER.

other fibre properties as well.

The likelihood of this possibility was shown by Speakman and his collaborators' work (18) which indicated that some of the pH effects can in fact be interpreted on the basis of the changes occurring in the elastic properties of the fibres.

Further evidence is provided by the present experiments (Figs.32 and 33) which show that even in very viscous solutions, when the differential frictional effect is very small, the felting power in acid solutions is appreciably higher than at other pH values and at similar viscosities.

(4) THE FELTING POWER - DIFFERENTIAL FRICTIONAL EFFECT RELATION.

One of the underlying themes of this work has been the relation between the differential frictional effect and the felting power of animal fibres, and it has been shown in many instances that, with all other factors constant, the felting power is proportional to the differential frictional effect.

These observations have now been summarized in Table 28 and Fig.46 which show the variation of felting power with the differential frictional effect under the influence of viscosity, pH and temperature, respectively, each set of experimental points thus representing an independent series of experiments.

It is evident that these points give rise to a straight line which shows that under these conditions of experiment felting power is directly proportional to the magnitude of the differential frictional effect.

EFFECT OF VISCOSITY			EFFECT OF pH			EFFECT OF TEMPERATURE					
						H_2SO_4			Soap		
Visc. cp. cp.	$\mu_T-\mu_R$	g/cc.	pH	$\mu_T-\mu_R$	g/cc.	Temp. °C.	$\mu_T-\mu_R$	g/cc.	Temp. °C.	$\mu_T-\mu_R$	g/cc.
1.0	0.50	.090	0.3	0.90	.136	20	0.83	.117	20	0.71	.106
5.1	0.30	.071	2.1	0.85	.106	30	0.91	.135	30	0.73	.118
11.0	0.16	.059	5.2	0.62	.097	40	1.06	.140	40	0.75	.130
23.0	0.09	.052	6.8	0.50	.090	50	1.16	.158	50	0.76	.134
42.0	0.07	.049	8.4	0.62	.096						
			11.6	0.63	.097						

TABLE 28. SUMMARY OF RESULTS SHOWING THE RELATION BETWEEN THE DIFFERENTIAL FRICTIONAL EFFECT & FELTING POWER.

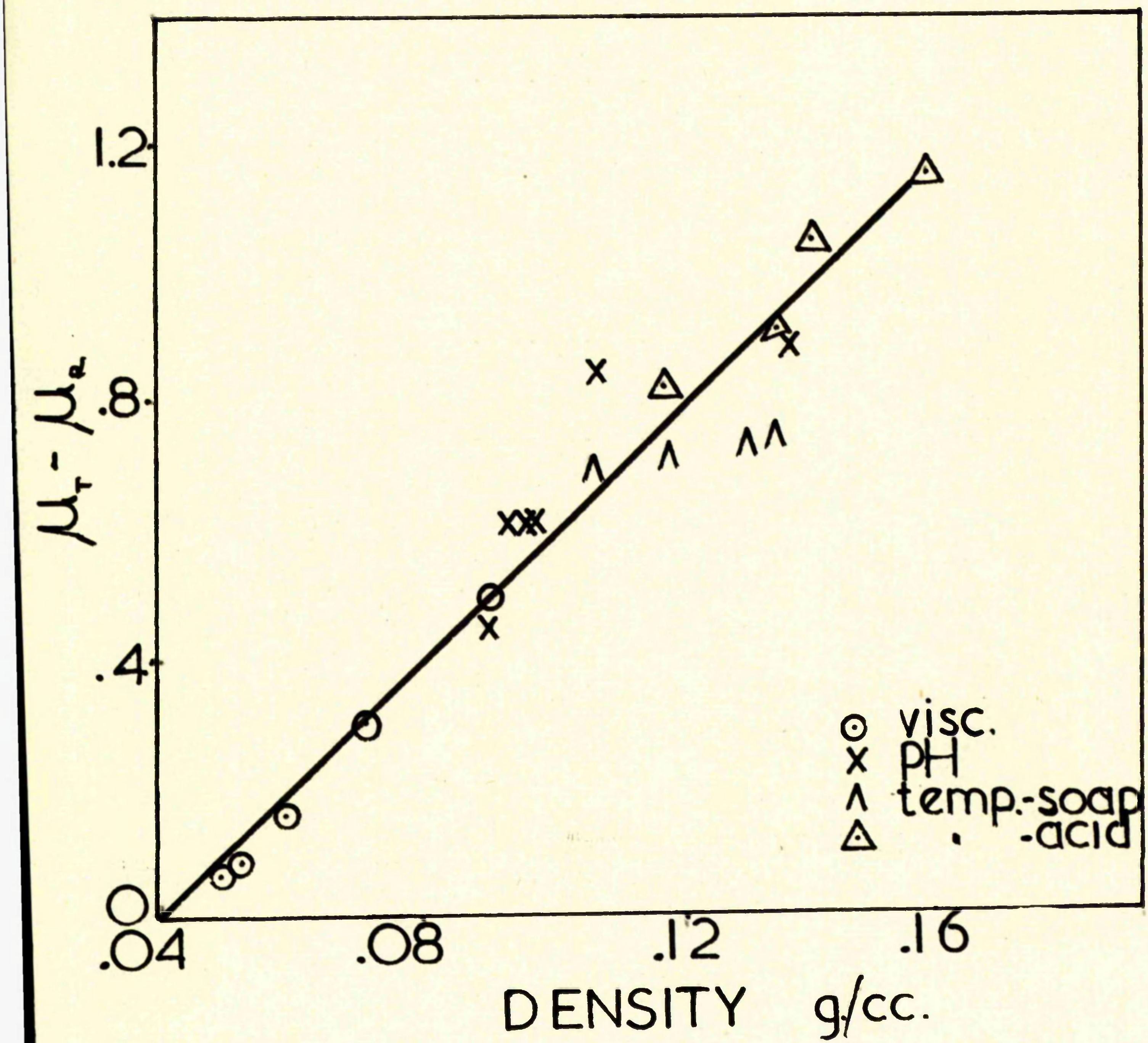


FIG. 46. DIFFERENTIAL FRICTIONAL EFFECT VS. FELTING POWER UNDER THE INFLUENCE OF VISCOSITY, TEMPERATURE AND pH.

SUMMARY.

The examination of the felting properties of wool fibres has been carried out with the view of correlating the felting behaviour of animal fibres with their frictional properties which were determined previously.

(1) The primary aim of these investigations has been the testing of the applicability to felting of the lubrication theory of friction of animal fibres, as postulated earlier.

Since, with other factors constant, felting power is proportional to the differential frictional effect, it was thought that the changes in the magnitude of the differential frictional effect due to variations in viscosity, speed and pressure should be reflected in the intensity of the felting power of wool.

The matter has been examined by investigating the effect of viscosity of the fluid on felting power; speed and pressure being kept constant. The experiments have in fact revealed that felting power changes with viscosity in the same sense as the differential frictional effect. This observations is considered as a very important corroboration of the lubrication theory of friction of animal fibres.

(2) The felting properties of wool have also been investigated in relation to temperature. Experiments

in unthickened solutions of sulphuric acid and soap show that the effect of temperature on felting in these media is directly related to the effect of temperature on the differential frictional effect.

It has also been found, through experiments on felting in thickened solutions, that this is not the only manner in which felting is affected by temperature. Thus it has been observed that at constant viscosity felting power still increases with increasing temperature.

It appears, therefore, that some other factor or factors (probably fibre elasticity and rigidity), apart from the differential frictional effect, play an important part in felting.

(3) The pH effect in felting has been found to correspond to the influence of pH on the differential frictional effect. It is thought, however, that as in the case of the temperature effect, the changes of other fibre properties caused by the pH may also be responsible for the variation of felting power with pH.

(4) It has been shown by plotting felting power against differential frictional effect, the experimental points being derived from the previous results on the effect of viscosity, pH and temperature, that with other factors constant, felting power is directly proportional to the differential frictional effect.

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BIBLIOGRAPHY.

1. Encyclopaedia Britannica, 14th Edition, vol.9, p.154
2. Monge, Ann. de Chimie, 1790, 6, 300
3. Jotemps, Farby and Girod, quoted in 'Wool - Study of the Fibre', H.M.S.O. 1929
4. Bowman, 'Structure of Wool Fibre', 1885, p.231
5. Witt, 'Chemische Technologie der Gespinstfasern', 1888
6. Zacharias, Z. f. Farbenindustrie, 1904, p.251 & 308
7. Justin Mueller, Koll. Z. 1909, 36, 66
8. Rinaldi, Jour. Soc. Dyers & Cols. 1920, 36, 151
9. Ganswindt, Melliand Textilber. 1922, 3, 84
10. Becke, Ibid. 1923, 4, 175
11. Ditzel, Deutsche Wolle Gewerben, 1891, No.1
12. Löbner, 'Studien und Forschungen uber die Wolle', 1898
13. Fiske, Text. Worl Jour. 1919, p.33
14. Reiser, 'Appretur der Wolle Gewebe', 1921, p.110
15. Shorter, Jour. Soc. Dyers & Cols. 1923, 39, 270
16. Arnold, Leipz. Monats. f. Textilind. 1929, 44, 463
17. Speakman and Stott, Jour. Text. Inst. 1931, 22, T339
18. Speakman, Stoot and Chang, ibid. 1933, 24, T273
19. Speakman, Menkart and Liu, ibid. 1944, 35, T41
20. Bohm, Nature 1945, 155, 547 and Jour. Soc. Dyers & Cols. 1945, 61, 278
21. Martin, Jour. Soc. Dyers & Cols. 1944, 60, 325
22. Mercer, J. Coun.Sc.Ind.Res.(Australia) 1942, 15, 285
23. Mercer, ibid. 1945, 18, 188
24. Speakman and Sun, Jour. Text. Inst. 1936, 27, T171

25. Boxser, Am. Dyestuff Rep. 1938, 27, 12

26. Nitschke, Melliand Textilber. 1942, 23, 434

27. Milton Harris, Am. Dyestuff Rep. 1945, 34, P72

28. Götte and Kling, Koll. Z. 1933, 62, 213

29. Schofield, Jour. Text. Inst. 1938, 29, T239

30. Whewell, Eid, Kokman and Lui, Jour. Soc. Dyers & Cols. 1943, 59, 233

31. Whewell, Text. Merc. 1946, Nov. 15th

32, Whewell and Messiha, Text. Rec. 1947, 65, 48

33. Speakman, Jour. Text. Inst. 1941, 32, T83

34, Cunliffe, ibid. 1936, 27, P53

35. Reumuth, Melliand Textilber. 1933, 14,23

36. Shorter, Jour. Soc. Dyers & Cols. 1945, 61, 172

37. Martin, ibid. 1945, 61, 173

38. Menkart and Speakman, Nature 1947, 159, 460

39. Reumuth, 'Textile microscopy in Germany', U.S.Dept. of Commerce, 1947

40. Hoffmann, Jahrb. Landw. 1925, 61, Pt.5

41. Speakman, Chamberlain and Menkart, Jour. Text. Inst. 1945, 36, T91

42. Bowden and Leben, Proc. Roy. Soc. A, 1939, 169, 371

43. Mercer and Makinson, Jour. Text. Inst. 1947, 38, T227

44. Gralen and Olofsson, Proc. Swedish Inst. for Text. Res. 1947, No.3

45. Lipson, Nature 1945, 156, 268

46. Martin and Mittelmann, Jour. Text. Inst. 1946, 37, T269

47. Bosman and van Wyk, Onderstepoort J. 1941, 16, 543

48. Freney, 'Fibrous Proteins', Symposium of Soc. Dyers & Cols. May 1946

49. Tomlinson, Phil. Mag. 1929, 7, 905

50. Lipson and Howard, Jour. Soc. Dyers & Cols. 1946, 62, 29

51. Mercer and Rees, Nature 1946, 157, 589 and Aust. J. of Expt.Biol. & Med.Sci. 1946, 24,147

52. Thomson and Speakman, Nature, 1946, 157, 804

53. Menkart and Speakman, ibid. 1945, 156, 143

54. Makinson and Mercer, Jour. Text. Inst. 1946, 37, T180

55. Freney, Deane and Anderson, Nature 1946, 157, 421

56. Whewell, Rigelhaupt and Selim, Nature, 1944, 154, 772

57. Ishida, Text. J. Australia, 1946, 21, 1

58. Speakman and Whewell, Jour. Text. Inst. 1945, 36, T48

59. Hall, Hicking and Pentecost, B.P. 464, 505

60. King and Galley, B.P. 417,719

61. Freney and Lipson, Counc.Sci.Ind.Res.Australia, 1940, Pamphlet No.94

62. Middlebrook and Phillips, Jour. Soc. Dyers and Cols. 1941, 57, 137

63. McQueen and DuPont, U.S.P. 2,406,958

64. Kline and DuPont, B.P. 572,041

65. Alexander and Wosley Ltd., B.P. 586,020

66. Baldwin, Barr and Speakman and I.C.I. Ltd., B.P.567,501

67. Barr and Speakman, Jour. Soc. Dyers & Cols. 1944, 60,335

68. Menkart and Speakman, ibid. 1947, 63, 322

69. Powers, Ind. Eng. Chem. (Ind. Edition) 1945, 37,188

70. Anderson, Nature,1946, 158, 554

71. Freney and Harris, Nature, 1946, 157, 664

72. Makinson, Jour. Text. Inst. 1947, 38, T332

74. Roberts, Text. Res. 1945, 15, 46

75. Geiger, J.of Res. Natl. Bur. Stds. 1944, 22, 127

76. Zahn, Melliand Textilber. 1943, 24, 157

77. Frölich, Spöttel and Tänzer, Wollkunde, 1929

78. Bristow, Proc. Roy. Soc. A. 1947, 189, 88

79. Barker and Marsh, 'Wool: A Study of the Fibre', H.M.S.O. 1929, p.146

80. Skinkle and Morrison, Am. Dyestuff Rep. 1935, 24, 27

81. Adderley, Jour. Text. Inst. 1922, 13, T249

82. Morrow, Jour. Text. Inst. 1931, 22, T425

83. Schmeidhäuser and Stoll, Kleipzig's Textil Zeit. 1938, 41, 103

84. Henning, Melliand Textilber. 1937, 18, 945

85. Boswall, 'Theory of Film Lubrication', 1928, Longman, Green & Co.,London

86. Hersey, 'Theory of Lubrication', 1936, John Wiley & Co., New York

87. Osborne Reynolds, Phil. Trans. Roy. Soc. 1886, 177, 157

88. Clower, 'Lubricants and Lubrication', 1939, McGraw Hill Book Co.,New York

89. Beauchamp Tower, Proc. Inst. Mech. Eng. (a) 1883, p.632, (b) 1884, p.29, (c) 1885, p.58

90. Bowden, Gregory and Tabor, Nature 1945, 156, 97

91. Beeck, Givens and Smith, Proc. Roy. Soc. A, 1941, 177, 90 and 103

92. Demeulemeester and Nicoloff, L'Ind.Text. 1932,49, 565

93. Bates et al. 'Polarimetry, Saccharimetry and the Sugars', U.S. Dept. of Comm. 1942

94. Creely and LeCompte, Am. Dyestuff Rep. 1940, 29, 387

95. Bowden and Hughes, Proc. Roy. Soc. A, 1939, 172, 263

96. Bowden and Tabor, ibid. 1938, 169, 371

97. Bowden and Ridler, ibid. 1936, 154, 640

98. Thomson and Logan, J. Roy. Tech. Coll.Glasgow 1940, 4, 696

99. Matthew, ibid. 1940, 4, 360

100. Bowden, Stone and Tudor, Proc. Roy. Soc. A, 1946, 188, 329

101. Bowden, Moore and Tabor, J. App. Phys. 1943, 14, 80

102. Sackmann, Burwell and Irvine, ibid. 1944, 15, 459

103. Hardy, 'Collected Works', Cambridge University Press, 1936

104. Beare and Bowden, Phil. Trans. 1935, 234A, 329

105. Langmuir, J. Franklin Inst. 1934, 218, 143

106. Bowden and Leben, Phil. Trans. 1940, 239A, 1

107. Hughes and Whittingham, Trans. Far. Soc. 1942, 38, 9

108. Frewing, Proc. Roy. Soc. a, 1942, 181, 23

109. Isemura, Bull. Chem. Soc. Japan, 1940, 15, 467

110. Bowden, Gregory and Tabor, Nature, 1945, 156, 97

111. Forrester, Proc. Roy. Soc. A, 1946, 187, 439

112. Karelitz, Proc. Special Conf. on Friction and Surface Finish, Mass. Inst. Tech. 1940

113. Kingsbury, Jour. Am. Soc. Naval Eng., 1897, 9, 267

114. Michell, Zeit. Math. Phys. 1905, 52, 123

115. Sommerfeld, ibid. 1904, 50, 97

116. Harrison, Trans. Camb. Phil. Soc. 1919, 22, 373

117. Stanton, 'Friction', Longman, Green & Co., London, 1923.
