A Review of the Prediction of Textile Wear Performance with Specific Reference to Abrasion

by

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ABSTRACT

The current position of the laboratory measurement and prediction of wear, particularly that relating to abrasion, of textile fabrics is reviewed. Topics covered include the nature of wear in textiles, abrasion mechanisms, abrasion testers and testing and their inter-correlations and correlations with wear, factors affecting abrasion resistance and wear trials.

INTRODUCTION

The development of laboratory tests, capable of determining the ‘wear resistance’ and ultimate durability of a textile article in consumer use accurately and reliably, has provided the technologist with a complex and seemingly insoluble problem. In the first recorded attempt, as far back as 1858, Alcan and Tresca tried to simulate ‘wear’ on cotton fabrics by means of an instrument which brushed the test samples in one direction. Later workers, Whatmough and Myers for example, produced refined and modified testers based on similar actions. From these early prototypes, a host of machines were developed in the first thirty five years of this century. All had the same basic principle; to simulate ‘wear’ by means of abrading the test fabric with an abradant, such as emery, until a predetermined end point was reached, usually the appearance of a hole. These laboratory tests, however, proved unsuccessful in predicting fabric behaviour during actual use and workers began to realise that the mechanisms involved were far more complex than first imagined.

Such was the importance attached to the problem of wear prediction that national bodies in both the United States and the United Kingdom devoted much time to discussing its nature and laboratory simulation. Opinions from many delegates, representing all sides of the textile industry, were heard at the Annual Conference of the Textile Institute in 1937. In a much publicised and controversial paper, Peirce was moved to state:

"The textile technologist has a conditioned reflex to the word ‘wear’ that sets him automatically to the design of a machine to grind a hole in cloth with emery"

and concluded:

"imitative tests are a delusion and a snare".

The period since has seen a proliferation of studies and publications dealing with various aspects of wear and the accurate prediction of fabric
performance by laboratory tests. Consideration has been given to machine
design and action, microscopic studies (comparisons) of fibres taken from
textiles used by consumers and those subjected to laboratory tests, attempted
correlation of results obtained from the numerous methods developed — the list
becomes endless. It is disconcerting, therefore, that in 1969 Hamby could write:
"We appear to be no closer today to predicting fabric performance than we have
been for the past several years", a sentiment re-echoed some ten years later by
Taylor in a rather pessimistic view of the ability and worth of laboratory tests in
assessing fabric performance, though he concluded: "tests will continue to be
made in the belief that it is better to have some results than to be without".

This review is not meant to form a historic documentary, rather is it
intended to present the current knowledge and thinking on 'wear' and its
laboratory simulation. Ample reference to general reviews on the subject written
during the last forty years is given in the bibliography, though the reader
should be warned that some may be dated and that several express contradictory
view points.

SERVICEABILITY, WEAR AND ABRASION

Although several writers have adequately defined and explained the
terms 'serviceability', 'wear' and 'abrasion', it is not out of place to remind the
reader briefly of their meaning and inter-relation⁴,⁷,⁸,¹⁷,²¹,²³,³⁴,³⁵,⁴²,⁴³,⁴⁴.

The concept of serviceability is simple; an article must fulfil the functions
required of it by the customer and in doing so it is said to be 'serviceable'. The
serviceable life of an article, therefore, is its life up to the time that it fails in one
essential performance factor⁴³, be it often rather subjectively in the eyes of the
consumer. Regrettably 'the article performing its required function' in the eyes
of the technologist and 'what the customer wants' are rarely synonymous. With
textile materials the requirements of the person who actually uses the item are
complex and not immediately apparent. One of the best examples to use is that
of clothing.

At the most basic level clothes should protect us from heat, cold, the
elements and injury or damage to delicate parts of our bodies. In clothing, the
technologist must consider those functions necessary for the garment to succeed
in these aims. A raincoat must obviously be waterproof, a sweater must retain
body heat. It is adornment, however, which is often the prime factor in the eyes
of the buyer, more especially in the realms of women's fashion. Style and colour,
in terms of what is fashionable, play an important role in determining whether a
garment is serviceable. Therefore, it may be discarded because it is out of fashion
even though it is still in a practically new condition.

Determination of serviceability by such fickle parameters confounds the
technologist in any attempt he may make at its prediction and he is forced to
confine his attention to the technical consideration. Even in cases, however,
where the physical (or technical) properties of the article are paramount, an example being certain types of army clothing where durability is the prime concern, the serviceable end point remains vague. Whereas one individual may discard a pair of trousers at the first sign of shine on the seat, another may consider this perfectly serviceable and only reject the article on the appearance of a hole. As Smith mused: "At what point does the consumer consider a textile apparel or home furnishing worn out". The subjective nature of the issue cannot be over emphasised and as personal judgement is individually unique, serviceability becomes an undefinable and vague term.

The assessment of a fabric's likely performance should be made in terms of those properties deemed relevant to its end use. The example of raincoats has already been cited; swimwear must be resistant to chlorinated water, "every day" garments should be easily laundered. For all textiles the "wear resistance" is considered since this ultimately determines the durability of the article in terms of physical and aesthetic properties.

Wear is the basic deterioration of the physical and aesthetic properties of a textile in use. Anderson has emphasised the ambiguous meaning applied to the term by many researchers in this field. To the laymen, wear is directly associated with abrasion leading to the gradual erosion and final appearance of an abraded hole. In fact, workers in the field used the terms 'abrasion' and 'wear' synonymously until the late thirties when Ball, Skinkle and Peirce differentiated, quite rightly, between the two, for abrasion forms only a part of the wear process.

Wear is the net result of a number of degradative agencies which may be classed as biological, chemical or mechanical. Biological wear, mainly confined to natural fibre, is the result of mildew, bacterial or insect attack. The devastation caused to wool by moth lava and carpet beetle or to cellulose by mildew is only too well known. Chemical degradation is due to the action of acids and alkali's as found in laundering processes and perspiration and also the effects of photodegradation. In general, chemical and biological attrition tend to weaken the fibre/fabric structure thus enhancing the action of the third agency, mechanical wear. Mechanical wear results from abrasive rubbing, crumpling, shearing, stretching, twisting and flexing; forces which lead to the gradual breakdown of fibre/fabric structure.

The formation of abraded holes form only one of the modes in which wear manifests itself. Of equal importance, in terms of customer satisfaction and rejection, are pilling, snagging, change in appearance, colour loss, wrinkling, formation of fabric shine, (i.e. mainly aesthetic qualities), seam failure, and dimensional change which are all the results of wear action. In fact, Mehta, in an article on wool durability, thought that too much emphasis in textile testing was placed on abrasion resistance, experience having shown that most customer complaints
concerned the more aesthetic qualities. Conversely, Manock\textsuperscript{309} reported that poor garment durability in terms of abrasion resistance was the major reason for customer dissatisfaction with mens' suits.

The term 'wear', therefore, encompasses a wide spectrum of properties and actions of which abrasion is only one aspect.\textsuperscript{5,7,13,17,23,34,53,73 - 77} The assessment of fabric performance becomes a monumental undertaking; furthermore, the assessment of all these factors by one machine sets an impossible task\textsuperscript{8, 13, 18, 19, 29, 44, 76, 79}. For the purpose of this review it is intended to consider wear in terms of durability and ignore the more aesthetic qualities previously mentioned.

A number of factors are involved in determining wear rate and pattern in textiles. Consider the instance of two consumers purchasing supposedly identical garments. Nevertheless, even at this very early stage, differences may have been introduced in the manufacturing process, for example during 'making up'. Even more important, the probability of both consumers treating the articles in the same manner throughout their serviceable lives is so minimal as to be virtually zero. The laundering (or dry-cleaning) process alone introduces many variables; e.g. severity, frequency, duration, temperature, machine action, chemical agents and their concentrations, and 'drying' action\textsuperscript{19,28,30 - 92}. The employment, hobbies, general activities and environment of the wearer are equally important\textsuperscript{8, 17, 93 - 96}, one can hardly compare the working life of a miner's garments to those of a doctor. Personal habits, physical build, biological functions, even temperament add further considerations\textsuperscript{42,48,96 - 99}, the list becomes endless.

When further extended beyond garments then the range of wear conditions become vast. Carpeting, curtaining, upholstery, sheeting, tarpaulins — in no two cases is the article treated in a like manner, the major wear action, whether chemical, biological or mechanical in nature being dependent on the conditions encountered in use\textsuperscript{38}.

The important thing to note is that the technologist is not only faced with a vague end point to an article's life but also with a vast array of variables which influence wear and the rate at which it occurs. In terms of apparel it becomes a very personal matter and accurate prediction of the performance of individual articles becomes an unobtainable goal. At best the technologist can lay down specifications which hopefully produces an article of acceptable serviceability to all consumers.

In attempting to predict textile performance in terms of durability, two basic modes of approach are used\textsuperscript{29}. Firstly, full scale wearer trials are used in which a textile's performance in actual use is monitored. Such a method is expensive and obviously takes long periods before results are obtained. Secondly, laboratory tests, based mainly on abrasion, are used which attempt to simulate or predict wear. The use of 'or' should be noted since a method need not
be exact in reproducing wear as long as the results may be reliably translated into fabric performance\textsuperscript{22}. Indeed, this forms the theoretical criterium of most mechanical methods.

Abrasion has been defined as "the progressive loss of substance from a material brought about by mechanical action"\textsuperscript{17} and has been cited as the most important single factor in determining 'wear' thus being used as a basis in the design of laboratory testing machines\textsuperscript{8, 17, 34, 55, 56, 76, 100 - 104}. Early attempts were made without real consideration to the phenomenon being measured and, as described in the introduction, tests simply involved rubbing away at a fabric specimen. As O’Brien\textsuperscript{2} stated in 1934 "... Only by accumulating data on wear of fabrics which have been into actual service will we be able to get anywhere". Since then, several researchers, notably Clegg\textsuperscript{56, 105}, have carried out examinations of worn textiles in an effort to gain some understanding of the mechanisms involved.

**THE NATURE OF WEAR IN USED TEXTILES**

Clegg\textsuperscript{56, 105} made a detailed microscopic study of fibres from a wide range of worn textile garments and products during and at the end of their useful lives. She found that mechanical action on fibres was the primary factor in wear and that this occurred in two major forms, abrasion and transverse cracking due to flexing, the relative amounts of which were dependent on the conditions encountered. Examination of fibres revealed extensive fibre fibrillation, transverse cracking and breakage. Intense abrasion occurred where fibres were held firmly and led to extensive cuticular damage and fibrillation. In fibres not held under tension but subjected to bending and flexing, break-down was due to transverse cracking. With the majority of articles a combination of flexing and gentle abrasion occurred which depended on the fibre position in the article. Thus the textile articles examined could be classified into one of the three major categories according to the damage type which predominated (i.e. intense abrasion with fibrillation, flexing and bending with transverse cracking or a combination of mild abrasion and flexing). Furthermore, Clegg reported that the mechanisms of breakdown for wool, silk, cotton, rayon and flax were basically similar.

Anderson and Robinson\textsuperscript{107}, in an extensive study of worn wool garments, reported five types of fibre damage, dependent mainly on the position of the fibre in the article. The first action was one of cuticular damage and scale removal, further attrition resulted in extensive fibrillation and was most pronounced in regions of greatest wear. Fibrillated fibre ends were also common, probably the result of transverse fractures across the fibrils. Rounded fibre ends resulted from gentle abrasion of fibrillated ends. The least common type of damage was transversely fractured fibre ends due probably to tearing. Similar types of damage have been noted in other studies of wool\textsuperscript{108, 109}.
Crosslinking wool with formaldehyde drastically alters the mechanism\textsuperscript{110}. Little fibrillation is observed. Instead, transverse fracture and abrupt rupture occurs\textsuperscript{110}. It has been reported that the fibrillation observed in wool is a result of the preferential damage and removal of the non-keratinous 'cement' material (cell membrane complex) found between the cortical cells and that this region, although forming only a relatively small part of the wool fibre, is important in determining properties such as abrasion resistance\textsuperscript{27,38,97}.

A study of silk revealed\textsuperscript{111} that 'ribbon-like' fibrils were peeled from the fibre and fibrillation occurred at fibre ends, fibrillation being more severe when the fibre was wet.

Studies of cotton have revealed essentially different mechanisms operating when the cotton was wet and dry\textsuperscript{112-119, 121}. In the dry state, fibre 'smoothing', 'cracking', 'mashing' and 'bruising' have been reported, with small wedges and gouges pinched from the fibres, only slight fibrillation being observed. Eventual fibre rupture occurred as cracks linked up, the broken fibre ends consisting of a number of fingers\textsuperscript{112, 118}. When the cotton was wet, extensive fibrillation of fibres was observed, the hypothesis being that fibre swelling in water aided the fibrillating process\textsuperscript{47, 112, 114, 118}. Kirkwood\textsuperscript{115} studied fibres taken from military garments that had been subjected to actual combat conditions and found that fibre damage ranged in dimension from stringy fine fibrillation to somewhat more coarse fibrillar components. Fibres were also observed in which fibre deterioration via fibrillation was in progress prior to eventual fibre rupture. Dweltz and Sparrow\textsuperscript{121} reported of two principal directions of potential weakness in a cotton fibre, one along the spiral angle or the line of the spiralling fibrils, the other almost perpendicular to the spiral angle.

An area which has received considerable attention is the resin treatment and crosslinking of cotton for crease resist and permanent press finishes. Such treatments can seriously reduce the abrasion resistance of cotton fabrics and hence drastically shorten the life of a garment\textsuperscript{88, 125}. For treated fibres, the mechanism of fibre breakdown is fundamentally the same in both dry and wet conditions\textsuperscript{118}. Only slight 'ribbon-like' fibrillation occurs, damage being major cracks, clean fibre fracture and the removal of fibre chunks and fibril bundles\textsuperscript{112, 114, 118, 121}. Essentially the fibres behave in a brittle manner\textsuperscript{118}.

Very little has been reported on synthetic fibres in worn garments though fibrillation is observed in nylon; the fibres, however, are relatively thick and short when compared to cotton\textsuperscript{115}.

An examination of worn cotton fabrics revealed that, during wear, the yarn structure was first of all opened, after which the fibres were 'teased up', and then removed, resulting in yarn thinning\textsuperscript{123, 124}. Studies of wool trousers\textsuperscript{106, 107, 126} and cotton shirts\textsuperscript{56} showed that the number of fibre ends increased with length of service and that fibres were gradually broken down into smaller units. Anderson and Robinson\textsuperscript{107} concluded that garment thinning was
caused by the production and loss of short fibres that were removed from the fabric and not by a reduction in individual fibre diameter. Thus, the mechanism involved can be summed up as the gradual mechanical break-down of fibres accompanied by the teasing out and removal of short fibre lengths.

The wear occurring in shirts, sheets and trousers is well reported and, as expected, certain areas are subjected to more severe conditions and thus fail first. With trousering the knee, crotch and seat areas receive severest wear. In shirt, abrasion of collars and cuffs and tearing in the shoulder area represent the critical points. With sheeting, specific areas of wear are noted dependent on the body’s position in bed and eventual failure is usually by tearing.

Stoll, in an extensive study of army shirtings, broke down mechanical wear into constituent parts and found that it consisted of:

- 30% plain abrasion
- 20% edge abrasion and projection abrasion
- 20% flex and folding
- 20% tear
- 10% other mechanical action

and varied according to the specific area in the garment. As Hamby has pointed out, although such theory cannot automatically be applied to all textiles it does represent an attempt to scientifically analyse the problem.

A number of researchers have discussed the importance of the laundering process as opposed to the ‘wear’ encountered whilst in actual use. Laundering involves both chemical deterioration through bleaches and detergents and mechanical attrition in the washing and drying action. Considerable differences in opinions have been voiced on the subject. Several authors claim that chemical damage in laundering is minimal whilst some reports have found it to be a major factor. Lord has claimed that wear damage in laundering is the major action in the deterioration of polyester/cotton sheets, whereas Schimmel et al. and Sukharev and Kolchak found the wear on the bed to be the primary factor. A report on tea towels claimed that mechanical action in laundering was almost totally responsible for deterioration and not actual use.

According to studies on shirts, collar edge wear is dependent on mechanical attrition in laundering, the wear at collar folds arises mainly from personal use and that cuff wear arises from laundering and personal use.

Tumble drying is regarded by some as an important consideration...
and has been reported as the major factor in the wear of collar tips. Others dispute that tumble drying causes any appreciable damage to garments. Taylor and others have questioned whether the laundering process has any major affect on the durability of an article and there have even been reports of improved abrasion resistance following laundering. The situation is complex and far from clear involving many variables, though mechanical and chemical wear in laundering are factors which should be considered, especially in items liable to frequent washing and several reports have suggested improved laundry practice for maximum durability.

**ABRASION MECHANISMS**

As previously mentioned, abrasion is considered the most influential factor in wear and has been used as a basis for most laboratory machines aimed at assessing durability. Abrasion is essentially the action of rubbing away of a surface. With textile fabrics this may be due to either external surfaces in contact with the article or internal abrasion of the fabric by yarns or individual fibres rubbing against each other.

Backer proposes three mechanisms to explain the mechanical breakdown of fibre structures during abrasion by external forces, namely; 'frictional wear', 'cutting' and 'plucking' or 'snagging', the dominating element depending on the abradent, fibre behaviour and general conditions prevailing during abrasion.

'Frictional wear' may be considered the action of a smooth surface abradant, polished furniture forms a good example, and is dependent on the normal load applied. Two theories have been postulated and generally accepted to explain frictional wear; the adhesive theory of molecular welds between two contacting bodies and the external forces which must be applied for their rupture, and the abrasive or ploughing theory for the movement of a hard material across a relatively soft material with resultant damage to the soft surface in the form of surface ruts. Furthermore, frictional wear may be indirect through transmission of forces along the fibre axis with resultant individual fibre slippage in a yarn or the formation of stresses at specific points which in turn leads to fibre fracture.

'Cutting' occurs when the surface abradant is composed of sharp projections which are relatively small compared with the fibre/yarn surface. These tend to gouge into the fibre and cut, the action of emery provides a good example.

When the abradant protuberances are large relative to the yarn/fibre diameter, a 'plucking' action results which can cause immediate fibre slippage or rupture.
IMPORTANT FACTORS AND CONSIDERATIONS IN ABRASION TESTS

From the theories postulated by Backer\textsuperscript{52} it is immediately apparent that both the abradant type and pressure with which it is applied are important considerations in abrasion tests. A further four points should be added: the character of the mechanical motion employed in the test instrument, the sample mounting and tensioning, the removal of deritus and the determination of an end point\textsuperscript{150}. Gavan \textit{et al}\textsuperscript{151} have stated that any machine should incorporate the following eight principles if it were to have any chance of success:

1. The abrasive should be similar to that encountered in service.
2. Slippage between abrasive and specimen should take place at a speed comparable to service.
3. The pressure applied should be constant and not excessive.
4. Excessive heat should not develop.
5. Specimen and abrasive should be kept dry (unless the opposite is required).
6. Action of abradant should be constant throughout the test.
7. Some standard for measuring the consistency of the integrated action of the abradant should be employed.
8. An accurate and quantitative means of determining abrasion resistance must be used.

The type of abrasion predominating may be plane, flex, edge or a combination dependent on the character of motion, and machines specialising in each type have been developed\textsuperscript{6}.

The severity and nature of abrasion will vary with the abradant used, in fact reversals in fabric ranking by different abradants have been reported\textsuperscript{15,52,67,93,101,103,152--164}. The abradants most commonly incorporated in machines are standard fabrics, emery, steel plates or blades, sand and carborundum. Kawamura and Ikeda\textsuperscript{161--163} have studied the attrition of a steel blade, steel plate and emery. They reported that the emery cut and hooked the fabric dependent on grain size, the steel blade had a plucking/hooking action whilst the steel plate exhibited frictional wear due to axial stress. With fabric mainly frictional wear occurs, the coefficient of friction determining the rate of attrition\textsuperscript{159}. The action of emery has been reported as independent of applied finishes and fibre type\textsuperscript{101,163}, factors found to influence other abradants. Furthermore, the action of any of the abradants used must remain constant over both a long period when considering continual testing of routine fabrics and also over relatively short periods during the testing of an individual sample. Crawshaw \textit{et al}\textsuperscript{150} encountered difficulty in manufacturing carborundum paper which gave reproducible results. The same difficulty is reported for steel blades\textsuperscript{101}. The study of the gradual abrasion of abradants has received some
attention\textsuperscript{101,150,154,155,165–168}. Dweltz et al\textsuperscript{168} have studied the progressive abrasion of cloth and paper abradants. Germans\textsuperscript{169} has designed a tester where the abrasive was kept constant by its continual change, through use of a 'typewriter ribbon' form of mechanism. Even a steel blade, the action of which might be considered uniform after an initial 'break in' period, may be affected by the build up of fibre deritus which can act as an abradant\textsuperscript{35,101}.

The pressure with which any abradant is applied to the test fabric affects the severity and rate at which abrasion occurs\textsuperscript{17,32,75,101,144,154,161,162,169–171}. It has been shown that using different pressures can seriously alter the ranking of a set of fabrics when using a particular abradant\textsuperscript{32,75,101,160,161,162}. Furthermore, accelerated destruction of test samples through increased pressure or machine speed may lead to false conclusions on fabric behaviour during use\textsuperscript{32,38,39,42,52,75,93,155,172,173,174}. For instance, accelerated tests can cause temperature rises which can affect the physical properties of thermoplastic fibres\textsuperscript{39,161,165}. Accelerated tests give no time for relaxation of fibres and fabrics which might be expected during normal use\textsuperscript{32,52,75}.

The tension of the mounted test specimen must remain constant\textsuperscript{32,34,137,175} since this determines the degree of mobility under the applied abradant. The backing of the mounted specimen must also be considered\textsuperscript{13,170,176}, an inflated rubber diaphragm or foam being widely used, though the effect of different backings is not well reported.

The importance of the direction of application of abrasion and motion has been demonstrated. In many fabrics the abrasion resistance as measured in the warp direction differs from that of weft direction\textsuperscript{15,55,115,144,170,177–180}. A number of directional rubbing motions have been incorporated in machines, namely unidirectional, multidirectional and rotatory. Scheiffer\textsuperscript{180} used a mathematical model in arriving at a motion which gave a uniform action in all directions of the surface plane of a fabric, thus eradicating directional effects.

Finally, consideration must be given to assessment of the abrasion end point\textsuperscript{8,137}. Ideally any method should remove subjective operator assessment, visual techniques being a prime example, since these immediately introduce a variable human factor\textsuperscript{13,46,137,181}. Two basic approaches are used. Abrade the specimen until a pre-determined end point, such as destruction, and record the number of cycles or time required for this\textsuperscript{15}, or abrade for a set time or number of cycles and assess some aspect of the abraded fabric by visual (e.g. change in appearance) or physical methods (e.g. mass loss)\textsuperscript{15}. The former has disadvantages in that the test may be unduly long and it requires that the test be terminated precisely at the predetermined end point\textsuperscript{137}. The second method could present a problem in terms of assessing the abraded fabric. Handle\textsuperscript{8,152}, lustre\textsuperscript{8,152} and visual interpretation\textsuperscript{74,126,147,152,182,185,187} have been reported but as already stated are subject to operator bias. Assessment by physical or chemical analysis eliminates the human factor, and reported methods include mass
loss, tensile strength, bursting strength, air permeability, electrical capacitance, electrical conductance, electron absorption, light transmission, thickness, reflectance, light transmission, crease resistance, count of broken fibre ends, chemical fluidity and colour loss. Of the methods listed, tensile strength and mass measurements have gained popularity in standard tests, although on close examination, discrepancies are apparent in each method. For example, mass and thickness can increase during initial abrasion due to abradant deritus and fabric fuzzing, while air permeability can be effected by the deposition of debris in the fabric structure. Hamburger stated that strength measurements were the least objectionable methods provided they were used to assess the extent of damage from abrasion and not to reflect values of durability. None of the methods produce results which show a linear or direct comparison with one another. Neither, in general, is there a linear relationship between the measurements of any method and progressive amounts of abrasion, though a direct relationship is claimed between mass loss and abrasion as applied with an Accelerodor. Serious reversal of fabric ranking is reported between visual and physical methods of appraisal, the main problem appearing to be visual rejection of what is registered acceptable in physical tests. Again the human element becomes apparent. Balls recommended that the choice of the method of assessment should be made purely on its relative bearing to the end use of the tested fabric.

LABORATORY MACHINES AND METHODS

To list every abrasion machine developed, and over 100 have been reported, would be a daunting and fruitless task. Dawson described those developed prior to 1945, listing over 50. Further reviews have been given by Sulser, Scheiffer et al, Buist, Hall and Kaswell, and more recently, Piechottka. As is to be expected, many machines have vanished into obscurity, developed and discarded without adequate thought or knowledge. Several machines have gained recognition by national bodies and have been incorporated in standard abrasion test methods, the most widely adopted being those of the American and British standards organisations. Anderson has tabulated these more standard testers and their basic aspects and a revised and updated version of his work is given in Table 1. For more detailed information on machine design and individual test methods the reader should refer to the references quoted. Table 2 lists those machines reported on more recently or that have been fairly widely used but which, for lack of sufficient information and time, permit no further detailed comment.

With regard to the testers in Table 1, the following observations can be made. The Accelerodor is somewhat unique in its action, the sample being free
# TABLE 1

## DETAILS OF SOME ABRASION TESTERS IN COMMON USE

<table>
<thead>
<tr>
<th>Name</th>
<th>Motion</th>
<th>Sample Backing</th>
<th>Standard Abrasiv</th>
<th>Load</th>
<th>End Point Assessment</th>
<th>Design Ref.</th>
<th>Test Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Martindale</td>
<td>Lissajous figure plane abrasion 50 cycles/min</td>
<td>Foam</td>
<td>Worst cloth</td>
<td>5.83N (9 kPa) 7.78N (12 kPa)</td>
<td>Generally cycles to thread rupture or Mass loss</td>
<td>(79)</td>
<td>(200)</td>
</tr>
<tr>
<td>Bocking Fabric Tester (B.F.T.)</td>
<td>1. Flexing over bar</td>
<td>—</td>
<td>Steel blade</td>
<td>17.8N(4lb) load 17.8N(4lb) tension</td>
<td>Cycles to rupture</td>
<td>(201)</td>
<td>(42)</td>
</tr>
<tr>
<td></td>
<td>2. Unidirectional reciprocating over a ball</td>
<td>Resilient conducting pad</td>
<td>Ball bearing</td>
<td>6.7N (1½ lb)</td>
<td>Cycles to penetration (automatic electrical knock off)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Unidirectional plane abrasion</td>
<td>Resilient conducting pad</td>
<td>Stainless steel gauze</td>
<td>8.5N (2 lb)</td>
<td>Cycles to hole (electrical contact)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accelerator</td>
<td>Rotating impeller in abrasive lined cylinder 1500-3000 rev/min</td>
<td>—</td>
<td>Aluminium oxide (Grit 360 or 240) abrasive paper</td>
<td>—</td>
<td>Mass loss, Tensile strength loss or Visual</td>
<td>(192)</td>
<td>(202)</td>
</tr>
<tr>
<td>Taber</td>
<td>Rotatory in one plane so that multi directional abrasion is achieved 70 rev/min</td>
<td>Rubber mat</td>
<td>Abrasive wheel impregnated with grain or vitreal roughened by diamond cutting</td>
<td>1.22-9.81N (125-1000g)</td>
<td>Residual or % loss in breaking load Cycles to specific destruction</td>
<td>(203)</td>
<td>(204)</td>
</tr>
<tr>
<td>Stoll-Quartermaster</td>
<td>1. Unidirectional reciprocal folding and rubbing 115 double strokes/minute</td>
<td>—</td>
<td>Steel flex bar or blade</td>
<td>Bar tension such that rupture occurs above 500 cycles, Head load sufficient to prevent sample vibration</td>
<td>Cycles to rupture % loss in breaking load Visual rating</td>
<td>(190)</td>
<td>(205)</td>
</tr>
<tr>
<td></td>
<td>2. Uni-or multi directional plane abrasion, 115 strokes/min</td>
<td>Inflated rubber diaphragm</td>
<td>Abrasive paper</td>
<td>0-21.5N (0-2.2 kg)</td>
<td>Cycles to hole (electrical contact) Visual after specified cycles</td>
<td>(190)</td>
<td>(206)</td>
</tr>
<tr>
<td>Scheiffer</td>
<td>Abrasivand and sample rotate at about 250 rev/min one slightly faster than the other so that action is uniform in all directions in the plane of the surface of the specimen</td>
<td>—</td>
<td>Spring steel blade (other may be specified)</td>
<td>44.5N (4.54 kg) recommended for most textiles</td>
<td>Change in thickness Mass loss Cycles to specific failure</td>
<td>(166)</td>
<td>(207)</td>
</tr>
<tr>
<td>Wyzenbeck</td>
<td>Oscillating abrasive cylinder applied to sample in unidirectional movement 90 cycles/min</td>
<td>Sponge rubber pressure pad</td>
<td>Emery cloth</td>
<td>8.90N load (90g) 8.90N tension (90g)</td>
<td>Residual or % loss in breaking strength</td>
<td>(209)</td>
<td>(208)</td>
</tr>
<tr>
<td>Schopper</td>
<td>Circular, reversing every 500 cycles</td>
<td>Cloth underlay</td>
<td>Emery cloth</td>
<td>9.8N (100g)</td>
<td>Loss in bursting strength Cycles to hole</td>
<td>(210)</td>
<td>(211)</td>
</tr>
<tr>
<td>Frank-Hauser</td>
<td>Lissajous figure plane abrasion</td>
<td>Cloth underlay</td>
<td>Emery cloth</td>
<td>2.45N (200g)</td>
<td>Cycles to hole</td>
<td>(212)</td>
<td>(212)</td>
</tr>
<tr>
<td>Name and Origin</td>
<td>Comments</td>
<td>Reference</td>
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<tr>
<td>Shirley Bose Tester</td>
<td>Plane abrasion, sample held in clamp which reciprocates so that abrasion is equal in all directions. Abrasion is cloth covered (from state).</td>
<td>(15)</td>
<td></td>
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<tr>
<td>H. Baer and Co. Ltd</td>
<td>Development claimed to give constant uniform abrasive action over many tests for all types of fabrics.</td>
<td>(219)</td>
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<tr>
<td>Ivanov et al</td>
<td>Two mechanical abrasion devices developed in Russia, one for household fabrics and the other for protective clothing and industrial fabrics.</td>
<td>(219)</td>
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<tr>
<td>Izmay</td>
<td>Hungarian abrasion machine based on rotary action using a cloth abradant.</td>
<td>(216)</td>
<td></td>
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<tr>
<td>Kizlov et al</td>
<td>Russian mechanical device for testing abrasion of flax yarns.</td>
<td>(217)</td>
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<tr>
<td>L.I.N.R.A.</td>
<td>Machine developed to simulate both abrasion and flexing at the same time.</td>
<td>(218)</td>
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<tr>
<td>Sand Blast Method</td>
<td>Stream of sand granules blasted against fabric until hole forms in sample. Developed by U.S. Army.</td>
<td>(219)</td>
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<tr>
<td>Smith Sand Abrader</td>
<td>Stream of sand allowed to impinge at constant rate on cement block over which fabric sample reciprocates. Developed by U.S. Army.</td>
<td>(219)</td>
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<tr>
<td>Abruoflex</td>
<td>Specifically for asbestos textiles. Destructive action (abrasion, flexing and creasing).</td>
<td>(220)</td>
<td></td>
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<tr>
<td>Ringwear tester</td>
<td>Rotary action, sample being abraded on one plane against a standard wool fabric.</td>
<td>(221)</td>
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<tr>
<td>Usanov &amp; Sokolov</td>
<td>Apparatus for testing abrasion of clothing at collars and cuffs.</td>
<td>(222)</td>
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<tr>
<td>Usanov &amp; Bemalakaya</td>
<td>Pneumatic apparatus for testing flex abrasion of wool fabrics especially in trouser folds and pockets.</td>
<td>(223)</td>
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<tr>
<td>Vekassy</td>
<td>Equipment for flex abrasion of knitted goods.</td>
<td>(224)</td>
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<tr>
<td>Veer</td>
<td>Bending abrasion tester, mainly for industrial fabrics.</td>
<td>(225)</td>
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<tr>
<td>Zart</td>
<td>Apparatus for abrasion resistance testing of single fibres using Perlon wire abrasive.</td>
<td>(226)</td>
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<tr>
<td>Dimitrieva &amp; Mikhailovskaya</td>
<td>Reports on three Russian, the IT-3, IT-3M-1 and IT-1, and one Japanese, the Shimatzu abrasion testers.</td>
<td>(227)</td>
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<tr>
<td>Frecuко</td>
<td>Reports on TI-3M, Hervog Grieger and Duda Kryzma abrasion testers, the latter supposedly simulates hand movement.</td>
<td>(228)</td>
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<tr>
<td>Giindev</td>
<td>Bulgarian device for bagging and abrasion testing of garments.</td>
<td>(229)</td>
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<td>Gorski et al</td>
<td>Reports on Kovo and Peter abrasion tests.</td>
<td>(230)</td>
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<tr>
<td>Henso &amp; Jouhet</td>
<td>Device for testing resistance of fabric to repeated flexing and folding with no tension applied.</td>
<td>(231)</td>
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<tr>
<td>Taber Yarn Sheet abrader</td>
<td>Adoption of Taber abrader test to measure yarn instead of fabric abrasion.</td>
<td>(232)</td>
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<tr>
<td>Kawamura &amp; Ikeda</td>
<td>Apparatus for rapid evaluation of abrasive resistance of fibres.</td>
<td>(233)</td>
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<tr>
<td>ATIRA</td>
<td>Developed for rapid measurement of abrasion resistance.</td>
<td>(235)</td>
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<tr>
<td>Zwiegl</td>
<td>Abrasion resistance of yarns by rubbing them against a reciprocating cylinder covered with emery.</td>
<td>(234)</td>
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<tr>
<td>Schonfeld</td>
<td>Reports on three abrasion testers: 1. FF-23, a cloth abradant rubs specimen in linear figure 2. FF-22, both standard cloth abradant and sample rotate 3. Scheuermann Type 70, emery abradant applied in unidirectional rubbing action.</td>
<td>(235)</td>
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<tr>
<td>Walker Yarn abrader</td>
<td>Abrasion resistance of yarns in which damage is produced by rubbing yarn against itself.</td>
<td>(236)</td>
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<tr>
<td>Modified Martindale</td>
<td>Adaptation of Martindale which claims to simulate the LINRA wear tester.</td>
<td>(237)</td>
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<tr>
<td>Balella et al</td>
<td>Device consisting of two rods which move in varying directions and to which accessories may be added to simulate parts of the body. Tests are performed on finished garments. Claimed to simulate normal wearing conditions.</td>
<td>(238)</td>
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<tr>
<td>Benaquen S A &amp; J</td>
<td>Fabric passed through abrasion machine under negligible tension by rolling and unrolling between two rollers. At least one rotating abrasion cylinder is applied to the fabric between the two rollers which can be oscillated transverse to the direction of fabric motion.</td>
<td>(239)</td>
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<td>Montague Burton Ltd</td>
<td>Seam abrasion tester developed from the linear reciprocating fabric abrader of the same name.</td>
<td>(72)</td>
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<td>Charles Inc.</td>
<td>Fabric wear apparatus includes an axial member over which the fabric is clamped in a stretched condition and a shot member which is pressed against it.</td>
<td>(240)</td>
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<td>Ciboch</td>
<td>A flex abrasion testing instrument.</td>
<td>(241)</td>
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<tr>
<td>Clutett Peabody &amp; Co. Inc.</td>
<td>Clamped specimen subjected to a high velocity jet of air carrying grit particles. Time taken for break through is measured.</td>
<td>(242)</td>
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<tr>
<td>Damyanov &amp; Moskowka</td>
<td>Laboratory apparatus for measuring impact abrasion resistance of wool fabrics, simulating sudden fails.</td>
<td>(243)</td>
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<tr>
<td>Davis &amp; Buckley</td>
<td>Abrasion tester specifically for knitted goods. Sample rotates in a holder and is abraded by standard cloth which is rubbed across in a pendulum motion.</td>
<td>(244)</td>
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<tr>
<td>Swiss Standard method</td>
<td>Abrasion machine, somewhat similar to Accelerator.</td>
<td>(245)</td>
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<tr>
<td>Schoenert &amp; Scholast</td>
<td>For abrasion of flexible products in strip form comprising cylindrical array of emery covered abrading cylinders which can rotate, the abrading surfaces of which define a circular path over which the flexible fabric is constrained to pass.</td>
<td>(246)</td>
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<tr>
<td>Scout</td>
<td>Consists of steel cylinder covered with abrasive paper. The sample is mounted on an abrasive steel plate arm which abrades the sample surface.</td>
<td>(247)</td>
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<tr>
<td>W.I.R.A.</td>
<td>Circular specimen mounted in holder and rubbed over pads of abrader in multi- or unidirectional movement.</td>
<td>(248)</td>
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<tr>
<td>L.I.R.A.</td>
<td>Strip of fabric, held under tension, is rubbed by carborundum abrader which has reciprocating motion.</td>
<td>(249)</td>
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</table>

**TABLE 2**

**SOME OTHER TESTERS AND MORE RECENT DEVELOPMENTS**

*SAWTRI Special Publication - August, 1984*
to rotate within the impeller cylinder, the claim being that this allows fabric/fabric abrasion as well as fabric/abradant abrasion and as such could provide a better simulation of actual wear conditions\textsuperscript{152}. However, Galbraith \textit{et al}\textsuperscript{186} have noted the tendency for the fabric sample to ‘hang up’ on the rotor arm during the test thus giving rise to a false result.

The Stoll\textsuperscript{100} and Bocking Fabric Testers (BFT)\textsuperscript{201} are somewhat similar and consist of three separate tests which may be performed on the same machine with some small mechanical adjustment. Flexing and plane abrasion tests can be applied on both machines, on the BFT the third test consists of rubbing over a ball bearing somewhat similar to bursting simulation, whilst on the Stoll, edge abrasion can be performed. In both testers, end point is measured automatically by means of electric contact points. The BFT test provides for the results of the three different tests being combined into a ‘Duty Factor’ for the fabric\textsuperscript{42}. Stoll’s breakdown of importance of each test has already been mentioned. By including flexing, edge and plane abrasion the obvious claim for both machines is that they provide a more complete picture of fabric performance.

The Martindale\textsuperscript{79} and Frank-Hauser\textsuperscript{212} testers are similar in that they simulate plane abrasion using a Lissajous figure rubbing motion. The application of a mathematical model in the Scheiffer machine, to develop uniform motion over the specimen surface, has already been discussed\textsuperscript{180}.

**CORRELATIONS BETWEEN LABORATORY ABRASION TESTERS AND WEAR TESTS**

Before considering whether any one machine is capable of predicting fabric durability in wear it would be wise to consider the correlation found not only between different types of testers but also between identical models as used by different laboratories and operators.

On the basis of the results of a series of extensive trials, the Committee of Directors of Textile Research Associations\textsuperscript{197} (CDTRA) reported in 1964 that inter-laboratory correlation between machines of the same type under nominally identical conditions was likely to be very poor. Sturley\textsuperscript{198} has disputed the ‘sweeping statements’ in this report as made on the evidence given. In a similar trial Kemp\textsuperscript{199} reported good correlation between identical machines, though, again, the findings have been questioned, this time by Hamby\textsuperscript{5} who points out that the said correlations “left something to be desired”. An inter laboratory study of seven Accelerotors revealed reasonable accord between five of the machines\textsuperscript{167}, Briarl\textsuperscript{165}, Kagi\textsuperscript{250} and Mencke\textsuperscript{251} claiming this could be further enhanced by using a constant power motor drive. Considerable variation is reported between Taber\textsuperscript{253} and Wyzenbeek\textsuperscript{252} abraders as used at various stations, this in the former case being mainly attributed to non-uniformity of the abradant wheel. One of the main problems in any test is the bias introduced through individual operative techniques and these arise no matter how rigid a test procedure is laid down\textsuperscript{103,197,208}. 

14  \textit{SAWTRI Special Publication – August, 1984}
The lack of meaningful correlation between like machines does not bode well when the field is further widened to encompass different abrasion testers. As Taylor\(^6\) stated, "is it really to be expected that abrasives as diverse as emery cloth, corrugated plastic, worsted cloth, steel blades on edge and a blast of sand can all be used to determine the durability of, say, a cotton/polyester overall cloth". Reversals in fabric ranking by different abrasion testers has been widely reported\(7,9,13,48,59,82,93,103,116,153,187,197,228,237,254-260,264\). A most comprehensive study of bed sheets by Lord\(^9,116\) failed to find any correlation in fabric ranking as assessed by 15 of the most widely used testers. Beck et al\(^9\) found it impossible to convert the results of one machine into those of another. The inter-laboratory test results of the CDTRA\(^97\) indicated a correlation between the following machines under the stated conditions:

1. Linra, Scheifer (wool abrasive), Martindale (yarn break end point).
2. Boss (loomstate canvas abrasive), Stoll bar, Martindale (mass loss).
3. Stoll blade, BFT flex, BFT ball, Scheiffer (steel abrasive), Boss (mineral-khaki-dyed abrasive), Accelerator.

Tests were conducted on woven cotton, viscose rayon, and cotton/viscose rayon blend fabrics.

The CDTRA\(^97\) concluded that such differences appeared associated with the operating conditions of the machine, particularly with type of abradant and the pressure with which it was applied. Weiner and Pope\(^258,259\) found correlations between machines of similar actions and abradants thus a correlation was found between the Taber and Sand abrader, and between the BFT and Stoll flex testers but not between the two groups or other testers. Furthermore they reported that, of the abrasion mechanisms proposed by Backer\(^52\), the Stoll flex tester and BFT were primarily of the adhesive type whereas the Taber and Sand Blast testers were abrasive. They further theorized that the former group (adhesive) would be sensitive to lubricants applied to fabric samples whereas the latter (abrasive) would not. Kirkwood\(^115\) has further characterised the Accelerator as abrasive and the Scheiffer as adhesive, though also finding that the morphology of wear damage on individual fibres seemed to be little influenced by whether the abrasion tester used was adhesive or abrasive in nature. Elder and Mehta\(^255\) list the BFT as adhesive in nature and sensitive to the amount of applied resin whilst the Accelerator was abrasive and sensitive to both amount and type of resin, thus the ranking of fabrics could be contradictory for differing machines according to their various responses to resin types.

The ability of any one of the employed machine tests to predict wear is not good. Lord\(^9,116\) reported that none of the laboratory abrasion machines used in a study of bed sheets was capable of predicting wear, findings further
supported by the evidence of many researchers using other textiles. The CDTRA\textsuperscript{197} concluded its report on abrasion tests with the statement: "it cannot be assumed, without independent evidence, that the results obtained from a particular abrasion test are necessarily a reliable guide to behaviour in a particular practical situation". Such shortcomings have moved the British and American standard organisations to include warning notes in each test procedure to the effect that methods are only tentative and results need not reflect true fabric performance.

Several microscopic studies have been made of the fibre damage inflicted by the more standard abrasion testers using the recommended abradants. For wool, the Scheiffer abrasion tester reportedly smoothed the wool scales when using the recommended steel blade abrasive\textsuperscript{268}. Scheiffer and Krasny\textsuperscript{267} found that particles of wool, 10-20 nm in size were found on the blades following tests. Anderson and Robinson\textsuperscript{107} found that the Stoll flex abrasion test (steel bar) removed the wool scales and caused abrupt rupture of fibres. There was no fibrillation, though some longitudinal splitting of fibres was observed. The Stoll flat abrasion tester (steel wire mesh) removed the wool cuticle, and extensive fibrillation occurred before fibre fracture. Both the Accelerotor (corrugated metal liner) and the Martindale (standard wool cloth) caused severe fibrillation of the fibres, the fibrils tending to be rather thick in the case of the Accelerotor and thin with less cuticular damage for the Martindale. A reduction of the load applied in the Martindale test from the standard 600g weight to a 185g weight produced the best simulation of the morphological changes of actual wear. The fibrillation patterns observed were similar to those obtained with the higher load, but the cuticular damage was more representative and the ends of some broken fibres were rounded. Anderson and Robinson\textsuperscript{107} concluded that none of the abrasion machines reproduced exactly the fibre damage found in wear, the best replication being achieved by the Martindale with a standard wool cloth abradant under a load of 185g. Allen \textit{et al} \textsuperscript{27,97} have also recommended the Martindale as the breakdown of the nonkeratinous material in the wool fibre and subsequent fibrillation observed with this test closely resembled that found in fibres from worn garments. McCormac \textit{et al} \textsuperscript{172} recommend the Accelerotor on the grounds that it gave a realistic number of broken wool fibre ends for a given amount of abrasion.

Fujiwara and Kobayashi\textsuperscript{111} reported that flex abrasion of silk over a steel blade resulted in longitudinal splitting and fibrillation of fibre ends. Flat abrasion against an emery abradant tended to scrape and smooth the fibres; against a nylon cloth abradant flat abrasion produced similar results to flex abrasion when performed dry, and extensive fibrillation when wet.

With cotton, the Taber (rubber based wheel) and Scheiffer (steel blade) testers reportedly produced compressed and flattened fibrilled fibre ends\textsuperscript{115}. The
Stoll flex test (steel bar) caused transverse cracking, severe splintering and longitudinal splitting of fibres with fraying of broken fibre ends when applied to dry fibres and extensive fibrillation with no splitting when performed wet\textsuperscript{115,118,121,187,269}. Resin treated samples reportedly fracture abruptly in both dry and wet tests\textsuperscript{118,121,269}. Extensive mashing and cutting of both resin treated and untreated cotton fibres have been observed with Stoll flat abrasion (emery cloth), fibrillation occurring only in wet abrasion of untreated fibres\textsuperscript{187,269}. The Accelerotector (grit abrasive) reportedly pinched small wedges, removed ‘chip-like’ fragments and to some degree fibrillated untreated cotton fibres, with the removal of ‘shale-like’ flakes in the case of resin treated fibres\textsuperscript{118,121}. When performed wet, progressive fibrillation was observed with peeling away of the outer fibre layer in both untreated and resinated cotton although the degree of fibrillation was less and more ‘ribbon-like’ for the resin treated cotton\textsuperscript{118,121}. Steigler et al\textsuperscript{152} reported that the use of a non-grit abrasive in the Accelerotector tended to produce rounded fibre ends with no fibrillation.

Galbraith et al\textsuperscript{187} studied the effect of abrasion, as applied with the Accelerotector, Stoll (flat), and Scheiffer abrasion testers on the structure and properties of cotton and nylon fabrics. Progressive abrasion with the Accelerotector (grit abrasive and plastic liner) and Stoll (emery cloth) increased fabric thickness by causing fibre spreading and disarray in the yarn and by teasing out or cutting fibre ends from the yarn structure, the effect being more pronounced for the Accelerotector. The Scheiffer (steel blades) tended to compress and flatten the yarn structure and the degree of fibre teasing and cutting was much less than for the Accelerotector or Stoll.

None of the applied laboratory abrasion tests has replicated exactly the fibre damage found in actual wear of cotton\textsuperscript{121}, though several researchers have favoured the Accelerotector finding it the closest approximation\textsuperscript{115,121,155,228}. Galbraith et al\textsuperscript{187} recommended that the choice of laboratory test should depend on the predominant type of fibre damage found in actual use. Dowlen\textsuperscript{184} has recommended that despite the different types of fibre damage occurring in wet and dry tests on an Accelerotector, there is no benefit in applying alternate wet and dry tests to fabric samples and that dry tests alone should suffice.

Although abrasion tests fail to predict wear in general, there are specific cases reported where some success has been achieved. The Stoll flex abrasion test correlated well with actual service wear of shirts, particularly at the collar fold\textsuperscript{132,133,257,270}, but not of cuff wear\textsuperscript{257} or laundering\textsuperscript{80}. Stoll flat abrasion gave a good simulation of shirt cuff wear\textsuperscript{257} and the service life of sari’s\textsuperscript{272} and mens’ slacks\textsuperscript{277}. Elsewhere it has been reported, however, that fabrics with good Stoll flex and flat abrasion resistance failed readily in shirts\textsuperscript{88,271}. Several reports have shown that the Martindale could provide a useful and accurate guide to probable service wear in upholstery fabrics as used by the automotive and upholstery industries\textsuperscript{235,273,274}; a report on blazer fabrics, however, produced
glaring differences between Martindale laboratory and service wear evaluations. Close simulation of, and correlation with, service wear have been found in Accelerotor tests with respect to wear in shirt collars and cuffs. A combination of Accelerotor abrasion followed by a bursting or tensile strength test gave reasonable prediction of likely knee failure in boys jeans. The Accelerotor has reportedly correlated well with multiple wash tests in assessing laundry durability. Accelerotor ranking has given good agreement with the subjective evaluation of both a selection of nightgown and acetate fabrics.

The abrasion testers discussed so far are used for the abrasion testing of a wide range of textiles. Carpets form a well researched and documented field in their own right and as such merit a separate case study. Mention should be made, however, of testers developed specifically for testing floor coverings and which have proved useful in predicting, within certain limits, the performance of such products. Two such examples are the WIRA and WRONZ carpet testers.

The poor correlations obtained, in general, between fabric performance as assessed by laboratory tests and that found in consumer use, have led several researchers to question the value of such tests. Tyrer stated that abrasion tests could be useful in evaluating fabric behaviour provided results were interpreted in the light of considerable experience and combined with the information obtained from other performance and quality tests. Ball and Lomax recommend that abrasion tests should only be used to compare fabrics and not assess serviceability. Pritchard, in 1937, maintained that testing formed the only means by which bulk purchasers of textiles, such as the leading chain stores, could ensure uniformity in supplied fabrics and set and maintain standards. Parkinson has stated that tests are necessary for product evaluation, for maintaining checks on continuity of production and in the investigation of customer complaints. Peach has also emphasised the importance of the latter point. Tovey, although admitting that sudden fluctuations in test results of a production fabric probably indicated some marked changes in fabric properties, warned against translating this into the fabric's immediate rejection for its intended purpose. Some researchers have tried to set criteria and minimum standards of acceptability. Hunter and Smuts have given some reference values for the Martindale abrasion resistance of woven worsted fabrics. However, to date, a comprehensive reference publication covering various fibre, fabric and abrasion test machine types has not appeared. Many chain stores and retailers, whose reputations rely on claims of high quality, base their standards on knowledge accumulated over many years of trading. Weston, however, has reported of a large British institution, who, on questioned regarding the standards set for uniform fabrics, replied that they bore no relation to serviceability which was determined purely on working agreements made with their employees.
FACTORS AFFECTING ABRASION RESISTANCE

The abrasion resistance of a fabric is determined by several major factors: fibre properties, cloth and yarn structure and geometry, fabric finishes and, in the case of hydrophilic fibres, moisture content. Comprehensive reports, covering this topic extensively, have been given by McNally and McCord (208 references) and Galbraith, and it is intended to briefly summarise and, where necessary, update their work.

Fibre Properties

Hamburger stated that the mechanical visco-elastic properties of a fibre are of paramount importance since the abrasion resistance is, in essence, a measure of the ability of a structure, and thus the individual fibres, to absorb work. Thus, for a high abrasion resistance, five fibre properties were necessary: low modulus of elasticity, large immediate elastic deflection, high ratio of primary to secondary creep, high magnitude of primary creep and a high rate of primary creep. Hamburger proposed that the abrasion resistance of a material could therefore be predicted from the load elongation diagrams of conditioned specimens.

McNally and McCord theorized that elongation and elastic properties were more significant in determining abrasion resistance and also considered flexural and shear strength as important factors. Thus, an increase in durability is achieved through reduced stiffness and increased extensibility and work of rupture. From the hypothesis given, several researchers have advocated that mechanical properties, more especially the energy applied to rupture a fibre (energy rupture per unit mass) or the work done, may be used as an assessment of abrasion resistance, the Accelerator being cited as a useful machine for such measurements on fabrics. The basic drawbacks in such an approach are the assumptions that all the work applied by the Accelerator is used in abrasion, losses through heat being neglected, that it ignores time factor considerations in terms of life expectancy and that it requires standardisation of these machines.

Parisot has investigated load extension curves of single fibres and claimed that the chemical and mechanical components of wear resistance could be estimated. Such an approach neglects geometric factors and the determination of fabric abrasion properties from fibres is questioned, in fact many researchers dispute the validity of pure mechanical tensile tests as giving any assessment of likely fabric wear performance. As Elder has warned, abrasion is a dynamic process whilst mechanical properties are measured under quasi-static conditions.

The abrasion resistance of fibre types varies according to their particular mechanical properties. Nylon has been cited as most...
resistant to abrasion, and heads relative tables of merit which have been prepared for different fibre types. Despite widely differing mechanical properties, McNally and McCord55 have stated that wool and cotton are similar in terms of abrasion resistance. Morton and Hearle297, in a table of relative fibre abrasion resistance taken from the yarn flex abrasion results of several workers, found that this was not entirely true and that in some tests cotton performed better than wool and vice versa, though their relative performance in an actual wear trial on socks was similar.

Blends with synthetics have been studied and used to improve the abrasion resistance of natural fibres52, 59, 123, 163, 261, 298, 300, 302 - 310. Blends of wool/polyester and polyester/cotton are frequently used59, 82, 93, 119, 307 - 311. The improved abrasion resistance obtained through blending nylon and cotton131, 151, 299, 303, 304, however, is no compensation for the loss which occurs in yarn strength over that of the 100% cotton yarn19, 304. Wool/nylon blends show increased tenacity and yarn abrasion resistance172, 304 - 306 and as such, have found popularity in the carpet industry38. Tyrer39, however, reported that the results of abrasion tests had cast suspicions concerning the use of wool/nylon blends in socks where the nylon was thought to act as an abradant on the wool, thus shortening service life over 100% wool garments. Despite this report, socks of wool/nylon blends have proved satisfactory in consumer use and have become popular in the hosiery industry. Lord39 and Mehta and Thomas311 found that the improvement obtained in the abrasion resistance and durability of sheets through the use of cotton/synthetic blends, instead of all cotton, was negated, to some extent by an increased rate of fabric discolouration and pilling. It is also reported68 that although blending polyester with cotton improved the durability of shirts compared to that of 100% cotton, there was a decrease in customer satisfaction due to pilling.

Fibre shape, length and diameter are contributing factors in the cohesive forces of yarns and thus influence abrasion resistance55. Abrasion results in the gradual removal of fibres from yarns and resistance to abrasion thus shows a corresponding increase with fibre length41, 55, 312 - 322. Consequently filament yarns are more resistant than staple yarns of the same fibre type76, 77, 172, 236. With regard to fibre diameter it is reported that, although finer fibres form stronger yarns, moderately coarse fibre improves abrasion resistance up to an optimum diameter at which point increasing strains experienced in flexing and bending may counteract any further advantage55, 77, 312, 329. In addition, a reduction in the number of fibres in the yarn cross-section lowers fibre cohesion55. Barella and Manich329 reported that wool fibre flex life is a function of the fibre diameter. Work at SAWTRI has shown that the Martindale abrasion resistance of wool, wool blend and mohair fabrics improves with increasing fibre length and diameter316 - 328, 332. Allen et al 27 found, however, that for wool fabrics made from fibres of widely varying diameters, this parameter had little effect on Martindale.
abrasion resistance for fabrics of similar mass and construction. Hadley$^{331}$ found that, whereas the abrasion resistance of polypropylene increased with a decrease in filament diameter, that of polyester was independent of both filament diameter and tenacity.

McNally and McCord$^{55}$ have stated that flat, elliptical or hollow fibres might have improved abrasion resistance over round ones.

**Yarn and Fabric Construction**

Those yarn parameters reported to affect abrasion resistance are yarn twist, linear density and ply. Abrasion resistance reportedly increases with yarn twist$^{19, 20, 27, 47, 55, 77, 78, 170, 171, 236, 269, 313, 322, 333-336}$ to an optimum value past which additional twist results in a deterioration in abrasion resistance$^{27, 77, 170}$. It is postulated that the initial improvement is due to a tightening of the yarn structure preventing fibre removal. However, as twist further increases so does yarn rigidity with a corresponding reduction in fibre mobility which lowers the energy absorbing capability and hence abrasion resistance$^{27, 170}$.

Abrasion resistance is also reported to improve with increasing yarn linear density at a constant fabric mass$^{19, 55, 77, 104, 170, 334, 336}$. Backer and Tanenhaus$^{170}$ stated that abrasion resistance is related to the thickness or diameter of the exposed structure at the rubbing surface, though McNally and McCord$^{55}$ have pointed out that where serviceability is measured solely in terms of surface appearance heavy yarns do nothing to prevent the formation of objectionable fuzz. Abrams and Whitten$^{236}$ reported that fabrics constructed of a two-ply yarn had improved abrasion resistance over a fabric manufactured from a singles yarn of the same overall linear density; the improvement of the two ply yarn being attributed to a protecting influence of the second thread inhibiting fibre removal from the first, and vice versa$^{55, 187}$. Ruppernicker et al$^{330}$ reported, however, that the resistance to laundry wear of fabrics was improved if they were woven from a singles yarn instead of a plied yarn.

In terms of yarn produced by different spinning systems, cotton ring spun is reported to have marginally better abrasion resistance than open-end spun yarn$^{263}$. Lünenschloss$^{338}$ reported that the same was true of polyester but that the converse applied to acrylic yarns. Phillips$^{28}$ has reported that the abrasion resistance of woollen fabrics and yarns are generally lower than their worsted counterparts due mainly to the shorter fibre length and hence reduced fibre security found in the former.

Pick and end densities are important factors in the actual fabric construction, though their combined influence is complex. Moderate increases in picks and ends, that is to say, fabric density, improve abrasion resistance$^{20, 47, 55, 78, 104, 170, 177, 259, 339-340}$, applied stresses being dissipated over a greater number of yarn crown heads$^{170}$. However, an optimum value is reached beyond which fabric rigidity, reduced yarn mobility and increasingly

*SAWTRI Special Publication – August, 1984* 21
pronounced yarn crown heads lead to deterioration in abrasion resistance. Allen et al. reported improved Martindale abrasion resistance with increasing mass per unit area of woven wool fabrics; Smuts and Hunter have reported that the same was true of knitted wool fabrics. A high positive correlation was reported between the thread slippage force and abrasion resistance in any construction. The degree of crimp in either the warp or weft yarns determines which threads predominate at the surface and hence suffer maximum abrasion. It is, therefore, advantageous to protect the load bearing threads by raising the other threads through the use of increased crimp.

The importance of the weave pattern in determining fabric abrasion resistance is dependent on the degree of flexing and bending encountered during abrasion, direction of stress application and the abrasion encountered. Plain weave is reported to possess the highest resistance to plane flat abrasion, with good yarn binding and even distribution of the applied stresses. However, the same weave performs relatively badly in laundering. The yarn mobility introduced in sateen and twill weaves, through the use of floats, enhances the stress absorption capacity of the structure and becomes advantageous as the degree of flexing increases. The abrasion resistance is improved if the stress bearing threads, usually the warp, are protected by the floats from the weft yarns. Further maximum abrasion resistance is achieved when abrasion is applied along the direction of the float. Rupemicker et al. reported that in flex abrasion the converse was true, that is, maximum abrasion resistance was achieved when abrasion was applied perpendicular to the direction of the yarn float. The length of float is limited, however, as vulnerability to plucking and snagging increases with float length. Of the two methods available for protection of stress bearing threads, namely the use of crimp or floats, Backer and Tanenhaus found the latter more practical.

Mehta has argued that knitted goods are likely to be less resistant to abrasion than their woven counterparts of a similar mass, mainly because of basic structural differences. Whereas failure of a thread in a woven material passes unnoticed, in a knitted structure this could lead to the formation of a hole or ladder. Conversely, Elder hypothesised that the looser structure of knitted fabrics would enable them to more easily absorb the stresses applied in abrasion.

**Fabric Finishes and Treatments**

Lubricants and waxes of silicones and polyethylenes are reported to improve abrasion resistance by reducing friction and aiding yarn mobility. The effect is more pronounced in flex than flat abrasion. For softeners used in laundering, conflicting evidence is reported. Whereas Murray observed a reduction in abrasion resistance with...
softeners, a study by a committee of the AATCC\textsuperscript{350} reported improved resistance in shirting and tricot fabrics.

Mercerisation\textsuperscript{55,154}, carboxy methylation\textsuperscript{354}, cyanoethylation\textsuperscript{354}, treatment with liquid ammonia\textsuperscript{264}, and crosslinking with long carbon chain esters\textsuperscript{351} reportedly improve the abrasion resistance of cotton, whereas bleaching\textsuperscript{53,55,154} and acetylation\textsuperscript{354} have an adverse effect. For wool, treatment with chlorophenol\textsuperscript{110}, benzotriazole\textsuperscript{357} and shrinkresist shrinkproofing\textsuperscript{355} reportedly improve abrasion resistance, though the results of the latter process are somewhat variable\textsuperscript{27}. Allen and Leeder\textsuperscript{97} have discussed the effects of varying finishing and chemical treatments on wool, generally bleaching, dyeing, drying and setting have an adverse affect on abrasion resistance. They stated that improvements to abrasion resistance could be achieved by modifying the nonkeratinous cement material of the wool fibre and several such treatments have been reported\textsuperscript{37,38,336}.

An area which has received considerable attention is the resin treatment of cotton fabrics for improved crease recovery. Such resins crosslink the cotton fibres, improving elastic recovery but seriously reducing the tenacity and elongation. The latter lowers the energy absorbing capability of the fibres and thus reduces laboratory abrasion resistance\textsuperscript{17,19,26,55,98,154,175,358-362,366}. Several studies\textsuperscript{19,75,314,362}, however, report that mild abrasion, when restricted to friction, of resin treated cottons can give improved abrasion resistance over untreated fabrics; probably the result of the resin holding the yarn structure together and preventing fibre loss. This has been used as an argument against accelerated tests incorporating relatively high loads as results may not be a true reflection of actual relatively mild abrasion encountered in use\textsuperscript{75,362}. Wear trials have also produced conflicting evidence on this point. Whereas Gagliardi and Nueesse\textsuperscript{75} found that, despite laboratory evidence to the contrary, resin treated viscose rayon fabrics had improved wear performance over their untreated counterparts, Elder\textsuperscript{17} reported that resin treatment of rayons led to complaints of poor wear. Furthermore, it is reported that through careful choice of finishing treatment good crease resist properties can be obtained without detrimentally affecting abrasion resistance\textsuperscript{125,359,363-366}.

Moisture Content and Static

There have been no reports of moisture content having any marked effect on the abrasion resistance of hydrophobic fibres, but it is an important consideration for hydrophilic fibres\textsuperscript{19,47,55,80,90,113,355,367-370}. Morton\textsuperscript{47} stated that fibres are more readily damaged by abrasion when they are wet or moist. McNally and McCord\textsuperscript{35} theorized, however, that as the extensibility and breaking strength of cotton are higher in the wet state, the same would be true of the abrasion resistance. This has been verified by Caldwell\textsuperscript{19}, Haycock\textsuperscript{19} and
Dowlen in trials using an Accelerotor and by Reid et al in a study of tumble drying. Wake in a wear-trial on raincoats include, and deGruy et al, in a study using the stoll flex abrasion test, found the converse to be true. Parisot stated that cotton articles may be considered ‘worn out’ when the wet strength fell below the original dry strength.

Viscose rayons, which have a lower tensile strength when wet than when dry might be expected to have a lower wet abrasion resistance, and this has been observed.

Nhan and Denby, in a study using a Martindale tester, reported increasing wool abrasion resistance with increasing relative humidity (RH) (and thus moisture regain of the wool) include, the effect being more pronounced in the high relative humidity range (> 65%). At 100% RH, on wet fabrics, however, the abrasion resistance fell abruptly. Microscopic investigation of the fibres revealed that the type of damage predominating varied according to the RH and that at low humidities the wool fibre became brittle. Such a dependence on the moisture regain of the sample under test is also reported by Holme and Peppas.

A study by Rybol'chenko et al indicated that the abrasion resistance of man-made fibres was affected by the action of electrical charges and that when such charges were led away from the abrasion zone, abrasion resistance increased by some 30%.

**WEAR TRIALS**

Wear trials, by which textiles are monitored in actual conditions of consumer use, obviously provide a more exact replication of the forces of wear than mechanical testers. There are, of course, severe disadvantages to using such a system, primarily cost, planning and the time span involved before reliable results are obtained. It would be impossible, for example, to apply such a method to articles of fashion — they would be outdated before meaningful results could be obtained. Nevertheless, wearer trials are an important part of the testing arena. Tattersfield and Thomas have discussed their primary functions, namely to ascertain the suitability and potential of new fibre and fabric innovations, to establish standards and criteria for laboratory testing methods, and to detect and correct gross faults that may arise.

To many, even those connected with the industry, a wearer trial simply involves the distribution of articles to a selection of people, usually closely connected to their work, and then monitoring their performance over an ensuing period. Regrettably this type of approach, all too often used, is a gross over simplification and often gives rise to a false and meaningless set of results. A wearer trial requires a great deal of thought, forward planning and care in evaluation of results.

Weiner and Kennedy have reported on six basic designs of wear testing. the most popular being the ‘randomised’ and ‘incomplete’ block systems.
which allow for moderately small groups of testers and articles. The number of subjects should be sufficient both to produce representative results and allow for erroneous readings; as few as ten are reported as yielding realistic results. Test duration and result interpretation are equally important and regrettably subjective. Beaver has suggested three options:

1. Specified test duration followed by wear rating.
2. Wear life until specific failure of article (or percentage thereof).

Beaver recommends the second on the basis of its flexibility.

Assessment of wear performance usually requires that each participant in the test returns a questionnaire detailing their personal opinions of the garment and which also provides information to the researcher on the conditions to which each has been subjected. Alternately, visual or physical assessment may be made of the garment at the end of the trial period. One technique, claimed to eliminate subjective evaluation, relies on automatic photographic comparison with standards, but, in the main, wearer trials remain prone to personal bias when determining performance values. The selection of test subjects is, therefore, a prime concern, for they must be capable of making evaluations and reports, represent a fair consumer cross-section, be reliable in terms of carrying out instructions and in continuing the test to termination. Furthermore, as previously stated, personal habits are of paramount importance where severity and patterns of wear in garments are concerned. Thus, although the consumer wear trial would appear a reliable means of assessing performance, many pitfalls exist to trap the unwary.

Further detailed reference to full-scale wearer trial design, organisation and assessment as used by researchers is given in the bibliography.

Accelerated wear trials have been used, in an attempt to eliminate the time factor disadvantages of full scale consumer tests, whilst retaining some degree of replication of service conditions. Such tests have actually found more favour with textile products of long life span expectancy, carpets represent a good example, where wear trials would take a matter of years. In the case of carpets the accelerated wear test is achieved by subjecting samples to extreme volumes of pedestrian traffic.

The US Army, which through the Quartermaster Board pioneered American research in the field of wear, constructed an army style ‘combat course’ at Camp Lee, Virginia, for testing uniform fabrics. Garments were subjected to repeated circuits of the course by combat troops. Evaluation was by visual ranking or transmitted radiation (recorded as mass loss). The method was found to provide a good simulation of army service.
conditions, providing rapid results and was also useful in providing comparisons with mechanical abrasion testers developed by the Quartermaster Board, e.g. the Stoll.

The importance of the laundering process has been previously discussed and accelerated laundry tests, based on multiple washes, have been used by some researchers. The AATCC and British Standards handbooks only list laundry tests in connection with colour loss, crease and wrinkle recovery and dimensional stability and not in terms of durability. The ASTM handbook recommends a general laundry test with regard to care labelling of textiles which necessitates examination of many service parameters including durability; it is stated, however, that the test method is not intended as an index of wear life.

The mechanics of laundry wear are a combination of chemical and mechanical wear. The chemical wear is caused by detergents and bleaches, and the mechanical wear by fabric on fabric or machine abrasion and flexing and crumpling in the wash and tumble dry process. The method of analysis of tests include visual ranking against standards, residual breaking strength, residual abrasion resistance, dyeing techniques, mass loss, wash cycles to failure, chemical fluidity, and light transmission. Although a correlation was observed between identical new machines at various locations in the USA, a poor correlation is reported between different machine types and more importantly between identical machines of varying ages, machines tending to become damaged with use. Handy et al. reported that the results of multiple wash tests gave a good assessment of the durability of dress shirts and such tests have been recommended by some as giving reliable information about fabric performance in articles liable to frequent washing. Many researchers, however, advise that the use of wash tests solely is unsound due to wide fluctuations which occur in results, and dispute the significance of any results in terms of likely performance as they ignore the factors of wear in use.

Microscopic examination of cotton fibres, subjected solely to laundering, revealed extensive fibrillation whilst tumble drying tended to smooth and crack the fibres. The damage observed did not replicate exactly that found in fibres taken from worn garments.

CONCLUDING REMARKS

This review has attempted to present the current position of textile wear and performance prediction based upon published literature. Briefly the main points may be summarised as follows:

Consumers demand certain performance levels from textile articles although the expectations in terms of life and standards differ widely between
individual consumers. Discounting factors such as fashion, though important, over which technologists have no control, rejection may arise due to unsatisfactory or unacceptable performance in various respects besides structural failure, e.g. pilling, colour loss and creasing. Deterioration in appearance and physical properties is a direct result of wear through a combination of chemical, mechanical and biological attrition; the rate and type of wear being dependent on many environmental factors not least of which is the human element. In fact, in many instances, it is the wearer and not the garment which is responsible for supposedly premature garment failure or unsatisfactory performance. Technologists have attempted to predict likely performance through wear trials and mechanical laboratory tests. The former are not viable in routine testing due to excessive costs, planning and time. The latter are based on abrasive action, abrasion being cited as the single most important action in wear. Regrettably mechanical laboratory tests generally fail to predict fabric performance in use and agreement between machines tend to be poor.

Regrettably this review has presented a rather pessimistic view of the testing of textiles for durability. True, in areas where the variable factors may be reduced and relatively simple actions occur, such as automotive fabrics and the field of carpets, which have not been discussed in detail, some success has been met. For a vast range of textiles, however, the problem remains unsolved, and it would be hoped that this review has highlighted the many reasons why this is so.

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*SAWTRI Special Publication – August, 1984* 35


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