1
Introduction

1.1 Reasons for textile testing

The testing of textile products is an expensive business. A laboratory has to be set up and furnished with a range of test equipment. Trained operatives have to be employed whose salaries have to be paid throughout the year, not just when results are required. Moreover all these costs are non-productive and therefore add to the final cost of the product. Therefore it is important that testing is not undertaken without adding some benefit to the final product.

There are a number of points in the production cycle where testing may be carried out to improve the product or to prevent sub-standard merchandise progressing further in the cycle.

1.1.1 Checking raw materials

The production cycle as far as testing is concerned starts with the delivery of raw material. If the material is incorrect or sub-standard then it is impossible to produce the required quality of final product.

The textile industry consists of a number of separate processes such as natural fibre production, man-made fibre extrusion, wool scouring, yarn spinning, weaving, dyeing and finishing, knitting, garment manufacture and production of household and technical products. These processes are very often carried out in separate establishments, therefore what is considered to be a raw material depends on the stage in processing at which the testing takes place. It can be either the raw fibre for a spinner, the yarn for a weaver or the finished fabric for a garment maker. The incoming material is checked for the required properties so that unsuitable material can be rejected or appropriate adjustments made to the production conditions. The standards that the raw material has to meet must be set at a realistic level. If the standards are set too high then material will be rejected that is good enough for the end use, and if they are set too low then large amounts of inferior material will go forward into production.

1.1.2 Monitoring production

Production monitoring, which involves testing samples taken from the production line, is known as quality control. Its aim is to maintain, within known tolerances, certain specified properties of the product at the level at which they have been set. A quality product for these purposes is defined as one whose properties meets or exceeds the set specifications.

Besides the need to carry out the tests correctly, successful monitoring of production also requires the careful design of appropriate sampling procedures and the use of statistical analysis to make sense of the results.

1.1.3 Assessing the final product

In this process the bulk production is examined before delivery to the customer to see if it meets the specifications. By its nature this takes place after the material has been produced. It is therefore too late to alter the production conditions. In some cases selected samples are tested and in other cases all the material is checked and steps taken to rectify faults. For instance some qualities of fabric are inspected for faulty places which are then mended by skilled operatives; this is a normal part of the process and the material would be dispatched as first quality.

1.1.4 Investigation of faulty material

If faulty material is discovered either at final inspection or through a customer complaint it is important that the cause is isolated. This enables steps to be taken to eliminate faulty production in future and so provide a better quality product. Investigations of faults can also involve the determination of which party is responsible for faulty material in the case of a dispute between a supplier and a user, especially where processes such as finishing have been undertaken by outside companies. Work of this nature is often contracted out to independent laboratories who are then able to give an unbiased opinion.

1.1.5 Product development and research

In the textile industry technology is changing all the time, bringing modified materials or different methods of production. Before any modified product reaches the market place it is necessary to test the material to check that the properties have been improved or have not been degraded by faster production methods. In this way an improved product or a lower-cost product with the same properties can be provided for the customer. A large organisation will often have a separate department to carry out research

and development; otherwise it is part of the normal duties of the testing department.

1.2 Standardisation of testing

When a textile material is tested certain things are expected from the results. Some of these are explicit but other requirements are implicit. The explicit requirements from the results are either that they will give an indication of how the material will perform in service or that they will show that it meets its specification.

The implicit requirement from a test is that it is reproducible, that is if the same material is tested either at another time, or by another operator or in a different laboratory the same values will be obtained. In other words the test measures some 'true' or correct value of the property being assessed. If the test results vary from laboratory to laboratory then the test is not measuring anything real and it is pointless carrying it out. However, the values that are obtained from testing textile materials are not expected to be exactly the same, so that appropriate statistical criteria should be applied to the results to see whether they fall within the accepted spread of values.

The lack of reproducibility of test results can be due to a number of causes.

1.2.1 Variation in the material

Most textile materials are variable, natural fibres having the most variation in their properties. The variation decreases as the production progresses from fibres to yarns to fabrics, since the assembly of small variable units into larger units helps to smooth out the variation in properties. The problem of variable material can be dealt with by the proper selection of representative samples and the use of suitable statistical methods to analyse the results.

1.2.2 Variation caused by the test method

It is important that any variations due to the test itself are kept to the minimum. Variability from this source can be due to a number of causes:

1 The influence of the operator on the test results. This can be due to differences in adherence to the test procedures, care in the mounting of specimens, precision in the adjustment of the machine such as the zero setting and in the taking of readings.
2 The influence of specimen size on the test results, for instance the effect of specimen length on measured strength.

3 The temperature and humidity conditions under which the test is carried out. A number of fibres such as wool, viscose and cotton change their properties as the atmospheric moisture content changes.
4 The type and make of equipment used in the test. For instance pilling tests can be carried out using a pilling box or on the Martindale abrasion machine. The results from these two tests are not necessarily comparable.
5 The conditions under which the test is carried out such as the speed, pressure or duration of any of the factors.

It is therefore necessary even within a single organisation to lay down test procedures that minimise operator variability and set the conditions of test and the dimensions of the specimen. Very often in such cases, factors such as temperature, humidity and make of equipment are determined by what is available.

However, when material is bought or sold outside the factory there are then two parties to the transaction, both of whom may wish to test the material. It therefore becomes important in such cases that they both get the same result from testing the same material. Otherwise disputes would arise which could not be resolved because each party was essentially testing a different property.

This requires that any test procedures used by more than one organisation have to be more carefully specified, including, for instance, the temperature and humidity levels at which the test takes place. The details in the procedure have to be sufficient so that equipment from different manufacturers will produce the same results as one another. This need for standard written test methods leads to the setting up of national standards for test procedures so making easier the buying and selling of textiles within that country. Even so certain large organisations, such as IWS or Marks and Spencer, have produced their own test procedures to which suppliers have to conform if they wish to carry the woolmark label or to sell to Marks and Spencer.

Most countries have their own standards organisations for example: BS (Britain), ASTM (USA) and DIN (Germany) standards. The same arguments that are used to justify national standards can also be applied to the need for international standards to assist world-wide trade, hence the existence of International Organization for Standardization (ISO) test methods and, within the European Union, the drive to European standards.

1.3 Sampling

It is not possible or desirable to test all the raw material or all the final output from a production process because of time and cost constraints. Also

many tests are destructive so that there would not be any material left after it had been tested. Because of this, representative samples of the material are tested. The amount of material that is actually tested can represent a very small proportion of the total output. It is therefore important that this small sample should be truly representative of the whole of the material. For instance if the test for cotton fibre length is considered, this requires a 20 mg sample which may have been taken from a bale weighing 250 kg. The sample represents only about one eleven-millionth of the bulk but the quality of the whole bale is judged on the results from it.

The aim of sampling is to produce an unbiased sample in which the proportions of, for instance, the different fibre lengths in the sample are the same as those in the bulk. Or to put it another way, each fibre in the bale should have an equal chance of being chosen for the sample [1].

1.3.1 Terms used in sampling

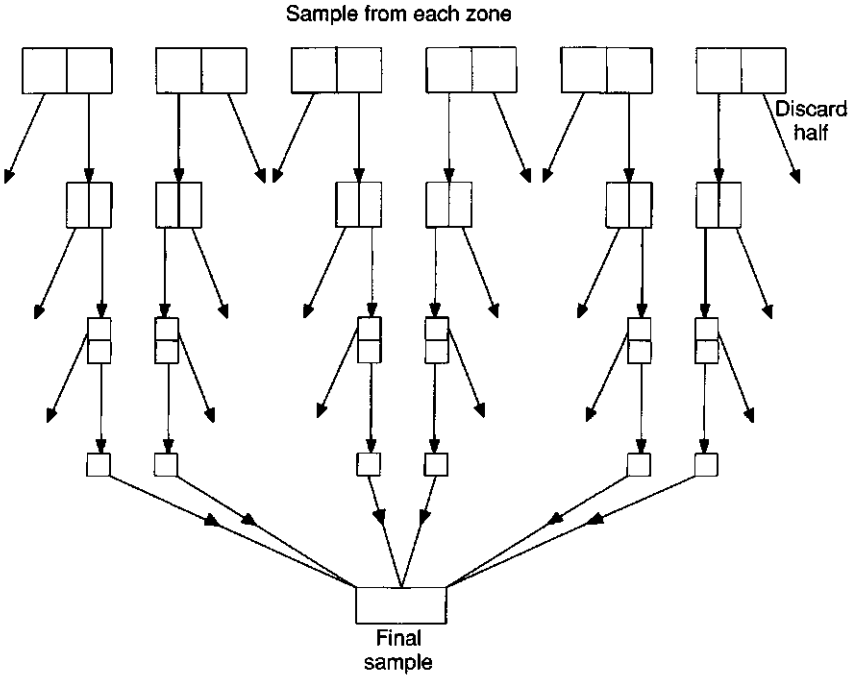
Several of the terms used in sampling have different meanings depending on whether wool or cotton, yarn or fibre is being sampled. This is due to the different representative organisations which have historically grown around each industry. The appropriate standard should always be consulted [1–4]:

- **Consignment**: this is the quantity of material delivered at the same time. Each consignment may consist of one or several lots.
- **Test lot or batch**: this consists of all the containers of a textile material of one defined type and quality, delivered to one customer according to one dispatch note. The material is presumed to be uniform so that this is the whole of the material whose properties are to be characterised by one set of tests. It can be considered to be equivalent to the statistical population.
- **Laboratory sample**: this is the material that will be used as a basis for carrying out the measurement in the laboratory. This is derived by appropriate random sampling methods from the test lot.
- **Test specimen**: this is the one that is actually used for the individual measurement and is derived from the laboratory sample. Normally, measurements are made from several test specimens.
- **Package**: elementary units (which can be unwound) within each container in the consignment. They might be bump top, hanks, skeins, bobbins, cones or other support on to which have been wound tow, top, sliver, roving or yarn.
- **Container or case**: a shipping unit identified on the dispatch note, usually a carton, box, bale or other container which may or may not contain packages.

1.3.2 Fibre sampling from bulk

Zoning

Zoning is a method that is used for selecting samples from raw cotton or wool or other loose fibre where the properties may vary considerably from place to place. A handful of fibres is taken at random from each of at least 40 widely spaced places (zones) throughout the bulk of the consignment and is treated as follows. Each handful is divided into two parts and one half of it is discarded at random; the retained half is again divided into two and half of that discarded. This process is repeated until about n/x fibres remain in the handful (where n is the total number of fibres required in the sample and x is the number of original handfuls). Each handful is treated in a similar manner and the fibres that remain are placed together to give a correctly sized test sample containing n fibres. The method is shown diagrammatically in Fig. 1.1. It is important that the whole of the final sample is tested.



1.1 Sampling by zoning.

Core sampling

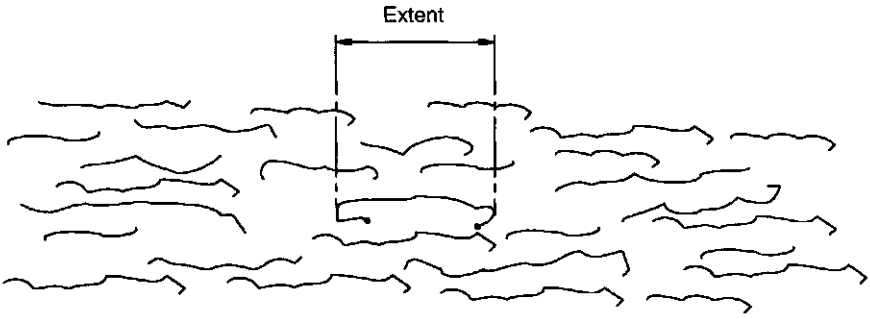
Core sampling is a technique that is used for assessing the proportion of grease, vegetable matter and moisture in samples taken from unopened bales of raw wool. A tube with a sharpened tip is forced into the bale and a core of wool is withdrawn. The technique was first developed as core boring in which the tube was rotated by a portable electric drill. The method was then developed further [5] to enable the cores to be cut by pressing the tube into the bale manually. This enables samples to be taken in areas remote from sources of power.

The tubes for manual coring are 600 mm long so that they can penetrate halfway into the bale, the whole bale being sampled by coring from both ends. A detachable cutting tip is used whose internal diameter is slightly smaller than that of the tube so that the cores will slide easily up the inside of the tube. The difference in diameter also helps retain the cores in the tube as it is withdrawn. To collect the sample the tube is entered in the direction of compression of the bale so that it is perpendicular to the layers of fleeces. A number of different sizes of nominal tube diameter are in use, 14, 15 and 18 mm being the most common the weight of core extracted varying accordingly. The number of cores extracted is determined according to a sampling schedule [6] and the cores are combined to give the required weight of sample. As the cores are removed they are placed immediately in an air-tight container to prevent any loss of moisture from them. The weight of the bale at the time of coring is recorded in order to calculate its total moisture content.

The method has been further developed to allow hydraulic coring by machine in warehouses where large numbers of bales are dealt with. Such machines compress the bale to 60% of its original length so as to allow the use of a tube which is long enough to core the full length of the bale.

1.3.3 Fibre sampling from combed slivers, rovings and yarn

One of the main difficulties in sampling fibres is that of obtaining a sample that is not biased. This is because unless special precautions are taken, the longer fibres in the material being sampled are more likely to be selected by the sampling procedures, leading to a length-biased sample. This is particularly likely to happen in sampling material such as sliver or yarn where the fibres are approximately parallel. Strictly speaking, it is the fibre extent as defined in Fig. 1.2 rather than the fibre length as such which determines the likelihood of selection. The obvious area where length bias must be avoided is in the measurement of fibre length, but any bias can also have effects when other properties such as fineness and strength are being mea-



1.2 The meaning of extent.

sured since these properties often vary with the fibre length. There are two ways of dealing with this problem:

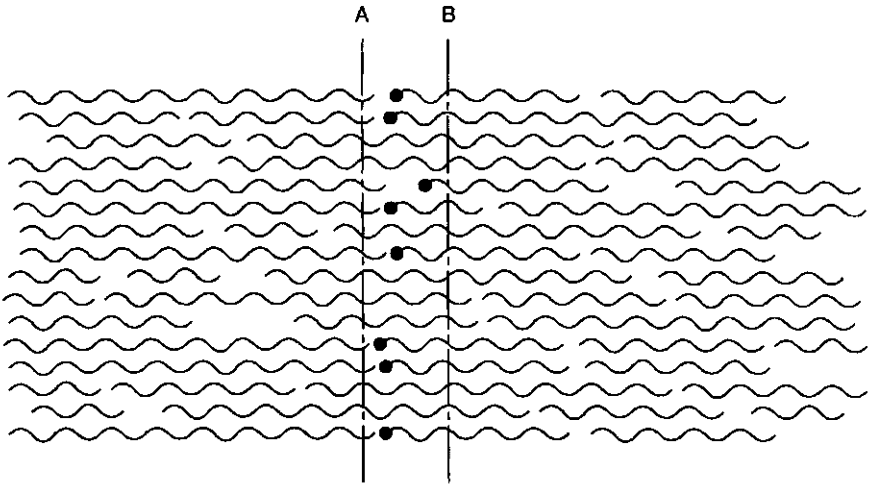
1 Prepare a numerical sample (unbiased sample).
2 Prepare a length-biased sample in such a way that the bias can be allowed for in any calculation.

Numerical sample

In a numerical sample the percentage by number of fibres in each length group should be the same in the sample as it is in the bulk. In Fig. 1.3, A and B represent two planes separated by a short distance in a sample consisting of parallel fibres. If all the fibres whose left-hand ends (shown as solid circles) lay between A and B were selected by some means they would constitute a numerical sample. The truth of this can be seen from the fact that if all the fibres that start to the left of A were removed then it would not alter the marked fibres. Similarly another pair of planes could be imagined to the right of B whose composition would be unaffected by the removal of the fibres starting between A and B. Therefore the whole length of the sample could be divided into such short lengths and there would be no means of distinguishing one length from another, provided the fibres are uniformly distributed along the sliver. If the removal of one sample does not affect the composition of the remaining samples, then it can be considered to be a numerical sample and each segment is representative of the whole.

Length-biased sample

In a length-biased sample the percentage of fibres in any length group is proportional to the product of the length and the percentage of fibres of

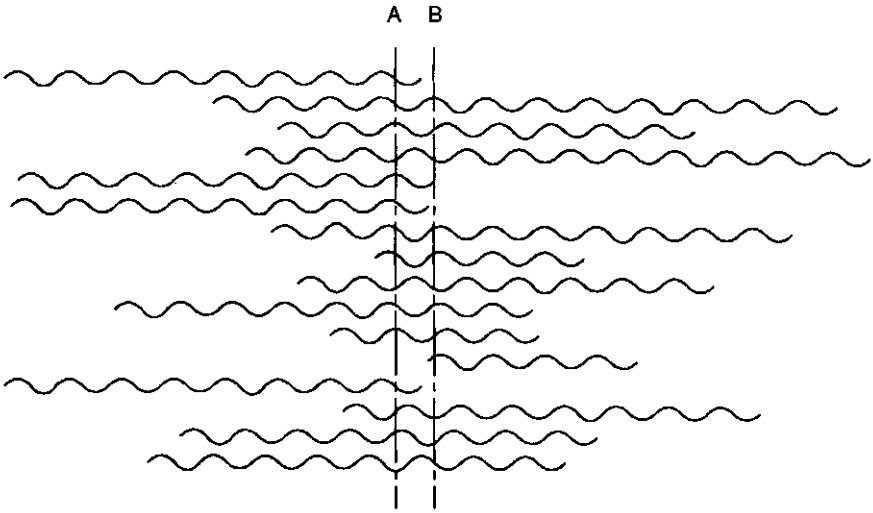


1.3 Selection of a numerical sample.

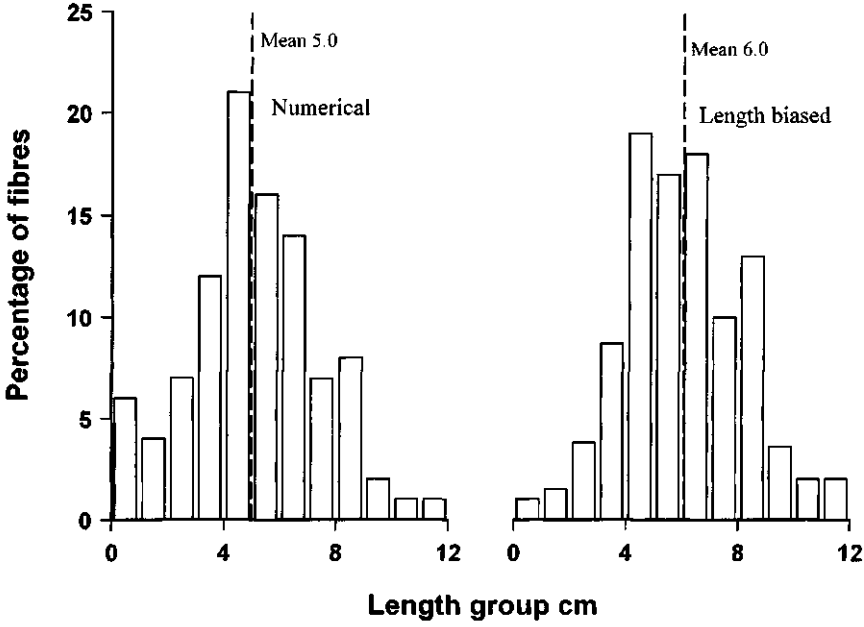
that length in the bulk. The removal of a length-biased sample changes the composition of the remaining material as a higher proportion of the longer fibres are removed from it.

If the lines A and B in Fig. 1.3 represent planes through the sliver then the chance of a fibre crossing these lines is proportional to its length. If, therefore, the fibres crossing this area are selected in some way then the longer fibres will be preferentially selected. This can be achieved by gripping the sample along a narrow line of contact and then combing away any loose fibres from either side of the grips, so leaving a sample as depicted in Fig. 1.4 which is length-biased. This type of sample is also known as a tuft sample and a similar method is used to prepare cotton fibres for length measurement by the fibrograph. Figure 1.5 shows the fibre length histogram and mean fibre length from both a numerical sample and a length-biased sample prepared from the same material [7].

By a similar line of reasoning if the sample is cut at the planes A and B the section between the planes will contain more pieces of the longer fibres because they are more likely to cross that section. If there are equal numbers of fibres in each length group, the total length of the group with the longest fibres will be greater than that of the other groups so that there will be a greater number of those fibres in the sample. Samples for the measurement of fibre diameter using the projection microscope are prepared in this manner by sectioning a bundle of fibres, thus giving a length-biased sample. The use of a length-biased sample is deliberate in this case so that the measured mean fibre diameter is then that of the total fibre length of the whole sample. If all the fibres in the sample are considered as being



1.4 Selection of a tuft sample.



1.5 Histograms of length-biased and numerical samples.

joined end to end the mean fibre diameter is then the average thickness of that fibre.

Random draw method

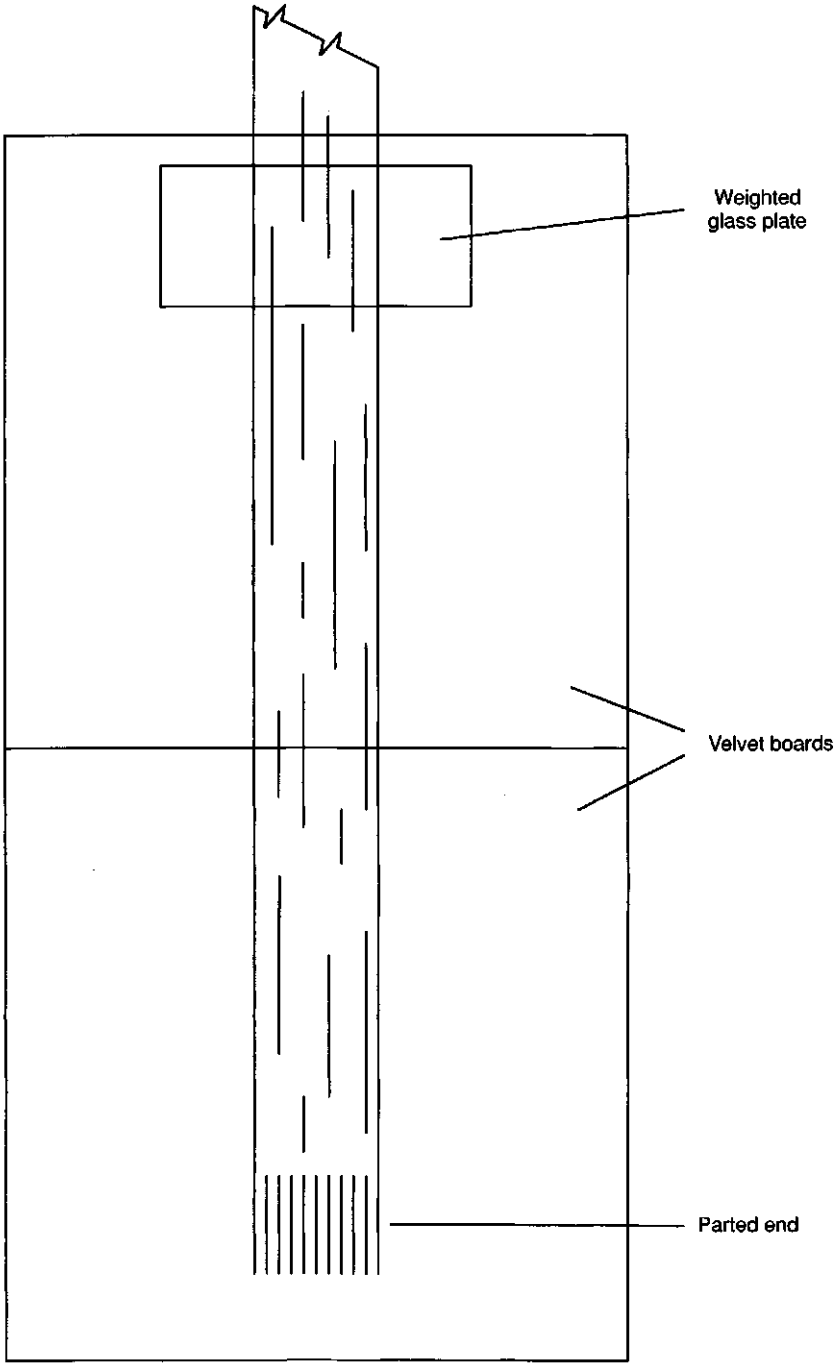
This method is used for sampling card sliver, ball sliver and top. The sliver to be sampled is parted carefully by hand so that the end to be used has no broken or cut fibres. The sliver is placed over two velvet boards with the parted end near the front of the first board. The opposite end of the sliver is weighed down with a glass plate to stop it moving as shown in Fig. 1.6. A wide grip which is capable of holding individual fibres is then used to remove and discard a 2 mm fringe of fibres from the parted end. This procedure is repeated, removing and discarding 2 mm draws of fibre until a distance equal to that of the longest fibre in the sliver has been removed. The sliver end has now been 'normalised' and any of the succeeding draws can be used to make up a sample as they will be representative of all fibre lengths. This is because they represent a numerical sample as described above where all the fibres with ends between two lines are taken as the sample. When any measurements are made on such a sample all the fibres must be measured.

Cut square method

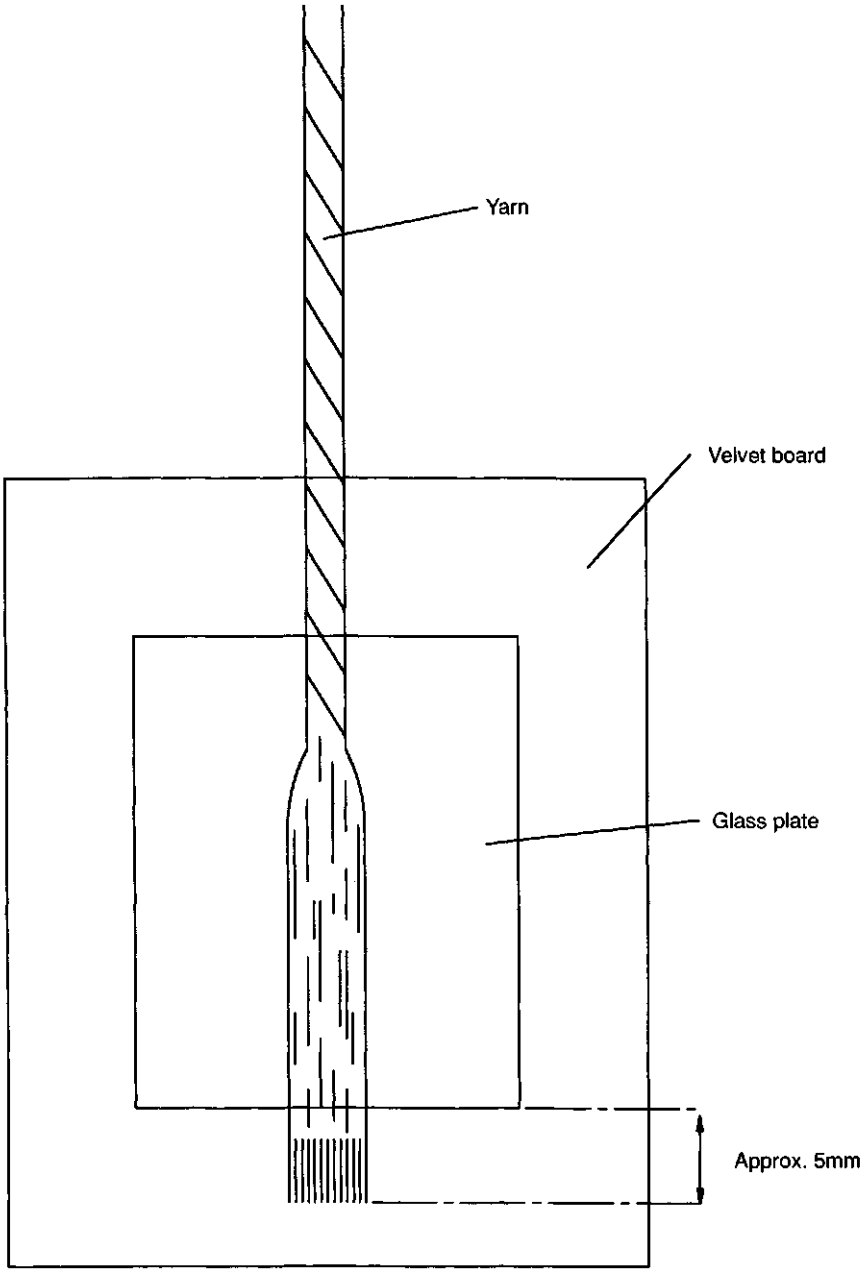
This method is used for sampling the fibres in a yarn. A length of the yarn being tested is cut off and the end untwisted by hand. The end is laid on a small velvet board and covered with a glass plate. The untwisted end of the yarn is then cut about 5 mm from the edge of the plate as shown in Fig. 1.7. All the fibres that project in front of the glass plate are removed one by one with a pair of forceps and discarded. By doing this all the cut fibres are removed, leaving only fibres with their natural length. The glass plate is then moved back a few millimetres, exposing more fibre ends. These are then removed one by one and measured. When these have all been measured the plate is moved back again until a total of 50 fibres have been measured. In each case once the plate has been moved all projecting fibre ends must be removed and measured. The whole process is then repeated on fresh lengths of yarn chosen at random from the bulk, until sufficient fibres have been measured.

1.3.4 Yarn sampling

When selecting yarn for testing it is suggested [8] that ten packages are selected at random from the consignment. If the consignment contains more than five cases, five cases are selected at random from it. The test



1.6 The random draw method.

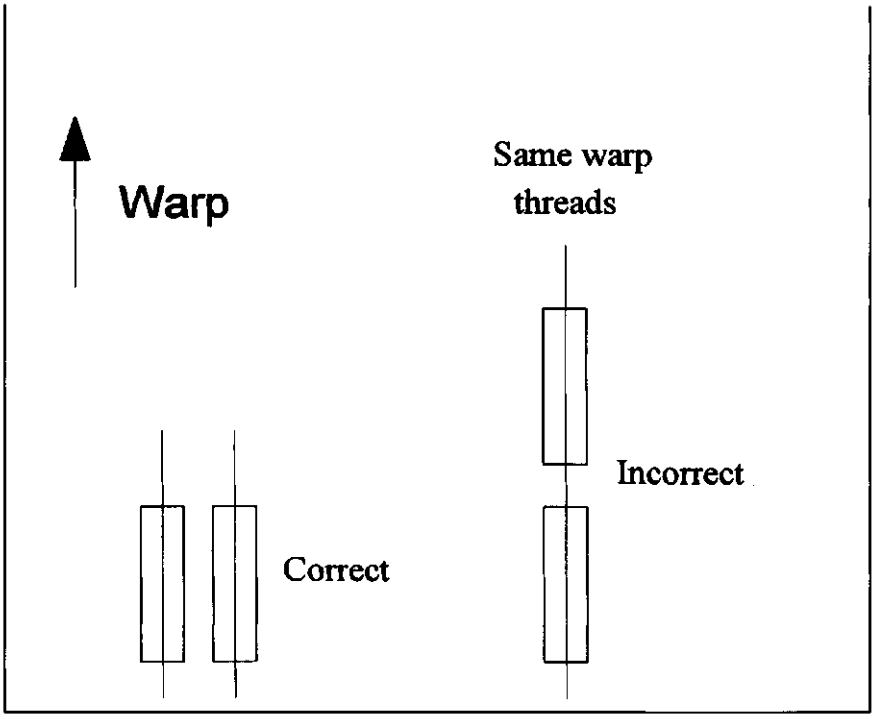


1.7 The cut square method.

sample then consists of two packages selected at random from each case. If the consignment contains less than five cases, ten packages are selected at random from all the cases with approximately equal numbers from each case. The appropriate number of tests are then carried out on each package.

1.3.5 Fabric sampling

When taking fabric samples from a roll of fabric certain rules must be observed. Fabric samples are always taken from the warp and weft separately as the properties in each direction generally differ. The warp direction should be marked on each sample before it is cut out. No two specimens should contain the same set of warp or weft threads. This is shown diagrammatically in Fig. 1.8 where the incorrect layout shows two warp samples which contain the same set of warp threads so that their properties will be very similar. In the correct layout each sample contains a different set of warp threads so that their properties are potentially different depending on the degree of uniformity of the fabric. As it is the warp direction in this case that is being tested the use of the same weft threads is not



1.8 Fabric sampling.

important. Samples should not be taken from within 50 mm of the selvedge as the fabric properties can change at the edge and they are no longer representative of the bulk.

1.4 Measurement

The process of measurement can be defined as a quantitative comparison between a predefined standard and the object being measured. This definition shows that there are two parts to the measuring process: the comparison, which is the process that is usually thought of as measurement, and the predefined standard, which is the part that is easily overlooked. When an object is weighed in the laboratory on a single pan balance it gives a reading of the mass of the object and so the balance is the local standard. However, what is actually taking place is a comparison of the mass of the object with that of the international standard kilogram. The validity of the measurement relies on there being a clear link between the balance that is in use and the international standard. In other words the balance needs to be calibrated with standard masses that have themselves been calibrated against other masses that in turn have been calibrated against the international standard. This link needs to be documented at each calibration step as to when it was carried out and to what limits of accuracy it has been made so that the calibration of a given instrument can be traced back to the international standards. It is also important that this calibration is carried out at regular intervals as instrumental readings can change over time because of wear of mechanical parts and ageing of electronic circuits. Besides regular calibration being good laboratory practice it is specifically demanded by ISO 9000.

The actual process of measurement is always subject to errors which can be defined as the difference between the measured value and the 'true' value. However, the 'true' value of any parameter can never be known because the value can only be obtained through measurement and any measurement can only be an estimation of the value, subject to unknown errors.

The term **precision** as used by metrologists [9] means the same as repeatability. It is defined as the quality that characterises the ability of a measuring instrument to give the same value of the quantity measured. In other words it is an indication of how well identically performed measurements agree with each other. A measurement of a property may return a value of 2.9347, which because of the number of figures after the decimal point may impress with its precision. If the measurement is then immediately repeated by the operator on the same object a value of 2.8962 may be obtained, when it will be seen that the number of figures represents a spurious precision and that the actual precision is much less. The precision

of any measurement can only be obtained by making a number of identical measurements and estimating the dispersion of the results about the mean. The standard deviation or coefficient of variation of a set of results is used as a measure of this. A single measurement is always of an unknown precision, although in general the precision of particular test procedures is known through repeated testing in a single laboratory.

However, a result may be very precise in that every time the measurement is made the same number is obtained but it may vary from the 'true' value due to systematic errors.

Accuracy may be defined as conformity with or nearness to the 'true' value of the quantity being measured. This can only be obtained by calibration of the measuring system against the appropriate standards at suitable intervals.

Sensitivity is defined as the least change in the measured quantity that will cause an observable change in the instrument reading. The sensitivity of a measuring instrument can be increased by amplifying the output or by using a magnifying lens to read the scale. Without an accompanying increase in the accuracy of the calibration and a reduction in sources of variation this may mean no more than an amplification of the errors as well.

1.4.1 Statistical terms

Most measurements in textile testing consist of a set of repeat measurements that have been made on a number of identical individuals constituting a sample taken from the bulk of the material. Certain statistical measures are used to describe the average of the results and their spread. A short guide to the terms employed is given below. For a more comprehensive explanation a textbook of statistics should be consulted [10–12].

Arithmetic mean or average

The arithmetic mean is the measure most commonly chosen to represent the central value of a sample. It is obtained by adding together the individual values of the variable x and dividing the sum by the number of individuals n. It is represented by the symbol $\bar{x}$:

$$\bar{x} = \frac{x_1 + x_2 + x_3 + \ldots + x_n}{n}$$

Standard deviation

The standard deviation is the most widely used measure of the dispersion or spread of results about the mean value. The symbol σ is used for the

standard deviation of the universe (population) containing all the possible measurements that could be made of the variable in question. The symbol s is generally used for the estimated value of the standard deviation from a sample which has been taken from the universe

$$s = \sqrt{\left[\frac{\sum(x - \bar{x})^2}{n - 1}\right]}$$

The units that the standard deviation is measured in are the same as those of the mean.

Coefficient of variation

A standard deviation of 1 for a property that has a mean value of 10 is far more significant than a standard deviation of 1 for a property with a mean value of 100. Because of this the coefficient of variation (CV) is often used as a measure of dispersion: it is the standard deviation expressed as a percentage of the mean. Therefore in the above example the first result would have a CV of 10% and the second result would have a CV of only 1%.

$$\text{CV} = \frac{\text{standard deviation} \times 100}{\text{mean}} = \frac{s}{\bar{x}} \times 100\%$$

Standard error of the mean

The standard error of the mean is a measure of the reliability of the mean value obtained from a sample of a particular size. It is the standard deviation of the means that would be obtained if repeated samples of the given size were measured:

$$\text{Standard error of mean} = \frac{\sigma}{\sqrt{n}}$$

where σ is standard deviation of the parent universe. In the case of a sample the standard error of the mean has to be estimated by using the standard deviation of the sample s in place of σ.

The standard error can be used to place confidence limits on the mean that has been measured. For example there is a 95% probability that the population mean lies within $\pm(1.96 \times$ standard error) of the measured mean value. This relationship only holds when the standard error has been calculated from the standard deviation of the parent universe σ or when the sample is large. For small samples where s has been used to calculate the standard error, the value of 1.96 should be replaced by the appropriate value of t obtained from statistical tables.

1.4.2 Determination of number of tests

In any test the number of individuals to be tested will depend on the variability of the material and the accuracy required from the measurement [1, 13]. If the material is repeatedly sampled at random and the test performed on n selected items each time, in 95% of cases the mean value which is calculated will be within $\pm(2C/\sqrt{n})\%$ of the population mean, where C is the coefficient of variation of the property being tested and n is the number of test specimens. The values of $(2C/\sqrt{n})\%$ are the confidence limits of error. For many standard tests the coefficient of variation is known approximately so that the number of tests necessary to achieve given confidence limits of error can then be calculated. For instance if the coefficient of variation for a yarn strength test is 10% and the number of tests carried out n is 5, there is a 95% chance that the mean value will lie within ±8.9% of the population mean. If the number of tests is increased to 10, then there is the same chance that the mean will lie within ±6.3% of the population mean, and if the number of tests is increased to 50, then it is likely that the mean will lie within ±2.8% of the population mean.

The use of the coefficient of variation in the above formula assumes that the error, in the form of the standard deviation, is proportional to the mean value. For example in the above case of yarn strength if the mean value was 10 N then the standard deviation would be 1 N, whereas if the mean value was 100 N then the standard deviation would be 10 N. With some measurements the error is relatively independent of the magnitude of the mean. If this is the case then the actual standard deviation should be used instead of the coefficient of variation so that in 95% of cases the measured mean value will lie within $\pm 2S/\sqrt{n}$ of the population mean, where S is the standard deviation.

1.4.3 Use of computers

The incorporation of computers and microprocessors has brought great changes to the instrumentation used for testing textiles. Their use falls into two main categories: recording and calculation of results and automation of the test procedure. Both of these uses may be found in the most advanced instruments.

Recording of results

In these applications the computer is usually connected via an analogue to digital converter to an existing instrument from where it collects the data that would previously have been written down on paper by the operator. The advantages of such an installation are as follows:

1 In the case of a graphical output the whole of the curve is recorded numerically so that results such as maxima, areas under the curve and slopes can be calculated directly without having to be read from a graph. This allows a more consistent measurement of features such as slopes which would previously have been measured by placing a rule on the graph by eye. However, it is important in such applications to be clear what criteria the computer is using to select turning points in the curve and at what point the slope is being measured. It is useful to have visual checks on these points in case the computer is making the wrong choice.
2 The ability to adjust the zero level for the instrument automatically. This can be done, for instance, by taking the quiescent output as being the zero level and subtracting this from all other readings.
3 The ability to perform all the intermediate calculations together with any statistical calculations in the case of multiple tests.
4 The ability to give a final neatly printed report which may be given directly to a customer.

It is important, however, to be aware of the fact that the precision of the basic instrument is unchanged and it depends on, among other things, the preparation and loading of the sample into the instrument by the operator and the setting of any instrumental parameters such as speed or range.

Automation of the test procedure

In such applications use is made of electronic processing power to control various aspects of the test rather than just to record the results. This means that steps such as setting ranges, speeds, tensions and zeroing the instrument can all be carried out without the intervention of an operator. The settings are usually derived from sample data entered at the keyboard. In the case of yarn-testing instruments the automation can be carried as far as loading the specimen. This enables the machinery to be presented with a number of yarn packages and left to carry out the required number of tests on each package.

The automation of steps in the test procedure enables an improvement to be made in the repeatability of test results owing to the reduction in operator intervention and a closer standardisation of the test conditions. The precision of the instrument is then dependent on the quality of the sensors and the correctness of the sample data given to the machine. The accuracy of the results is, however, still dependent on the calibration of the instrument. This is a point that is easily overlooked in instruments with digital outputs as the numbers have lost their immediate connection with the physical world. If the machine fails in some way but is still giving a numerical output, the figures may still be accepted as being correct.

To be generally acceptable automated instruments have to be able to carry out the test to the appropriate standard or have to be able to demonstrate identical results to those that have been obtained with the standard test method.

It is still possible even with advanced automation for results to be incorrect for such simple reasons as wrong identification of samples or failure to condition samples in the correct testing atmosphere.

1.4.4 Types of error

Errors fall into two types.

Bias or systematic error

With this type of error the measurements are consistently higher or lower than they should be. For instance if a balance is not zeroed before use then all readings taken from it will have the same small amount added to or subtracted from them. This type of error cannot be detected by any statistical examination of the readings. Systematic errors can only be eliminated by careful design of the tests, proper calibration and correct operation of the instruments.

Precision or random error

This type of error is present when repeated measurements of the same quantity give rise to differing values which are scattered at random around some central value. In such cases the error can be estimated by statistical methods.

1.4.5 Sources of error

Errors of both types can arise from a number of causes:

1 **Instrument reproducibility**: even when an instrument is correctly calibrated, mechanical defects can influence the readings unless they are taken in exactly the same fashion as the calibration values. Mechanical defects such as slackness, friction and backlash can cause measurements to vary. These effects can depend on the direction that the mechanism is moving so that the error may be different when the reading is increasing from that when it is decreasing. Electrical and electronic instruments can suffer from drift of settings over a period of time owing to an increase in temperature of components.
2 **Operator skill**: a great many tests are based on personal manipulation of the apparatus and visual reading of a resultant indication. An op-

erator may be called on to prepare a sample, load it into the instrument, adjust readings such as zero and maximum, and to take a reading from a scale. Each manipulation, adjustment and reading involves an uncertainty which can depend on the skill and the conscientiousness of the individual operator. The ideal in instrument and test method design is to reduce the amount and scope of operator intervention.

3 **Fineness of scale division**: a fundamental limit is set to the precision of a measurement by the instrument scale which is necessarily subdivided at finite intervals. It carries with it an immediate implication of a minimum uncertainty of one half of the finest scale division. In the case of a digital scale the last digit of the display sets the limit to the precision in a similar manner as it has by its nature to be a whole digit. The final digit implies that it is plus or minus half of what would be the next digit. However, digital scales usually read to more figures than the equivalent analogue scale.

4 **External factors**: these may come from sources outside the actual instrument such as line voltage fluctuations, vibration of instrument supports, air currents, ambient temperature and humidity fluctuations and such diverse factors as variation in the sunlight intensity through windows.

The above uncertainties in the measurement of textile properties derive from the measurement process. In addition to these uncertainties, textile materials also exhibit variation in properties throughout their bulk. These can be quite considerable in magnitude, particularly in the case of yarns and fibres. This variability, in a similar manner to the errors described above, falls into two types: systematic, as is the case when the properties of a fabric vary from the edge to the centre, and random, when the variability has no pattern. The effect of this is to add to the errors from the measurement itself to give a larger overall error from which it is difficult to separate out the variability of the material from the experimental error. Therefore, because of all the above sources of variation, the appropriate statistical analysis of results has a great importance in textile testing.

1.4.6 Repeatability and reproducibility

The true accuracy of a test method can only be gauged by repeated testing of identical material both within the same laboratory and between different testing laboratories that possess the same type of equipment. International round trials [14–17] are organised by sending out sets of test samples, all produced from the same batches of material, to participating laboratories and asking them to test the samples in a prescribed manner. The results are then correlated and the within (repeatability) and between (reproducibility) laboratory variations calculated. The variation between

laboratories is always greater than the variation found within a single laboratory.

BS 5532 [18] defines repeatability and reproducibility as follows.

Repeatability

1 *Qualitatively*: the closeness of agreement between successive results obtained with the same method on identical test material, under the same conditions (same operator, same apparatus, same laboratory and short intervals of time).
2 *Quantitatively*: the value below which the absolute difference between two single test results obtained in the above conditions may be expected to lie with a specified probability. In the absence of other indication, the probability is 95%.

Reproducibility

1 *Qualitatively*: the closeness of agreement between individual results obtained with the same method on identical test material but under different conditions (different operators, different apparatus, different laboratories and/or different times).
2 *Quantitatively*: the value below which the absolute difference between two single test results on identical material obtained by operators in different laboratories, using the standardised test method may be expected to lie with a specified probability. In the absence of other indication, the probability is 95%.

Errors involved

In order to understand the difference between repeatability and reproducibility the error in the test result can be considered to be due to two components [14]:

1 A random error (standard deviation σ_r) which occurs even when the same operator is using the same apparatus in the same laboratory. The variance of this σ_r^2 is called the within-laboratory variance and is assumed to have the same value for all laboratories.
2 An error (standard deviation σ_L) due to the difference that occurs when another operator carries out the test in a different laboratory using a different piece of identical apparatus. The variance of this σ_L^2 is called the between-laboratory variance.

The total error in a result that combines several sources of error can be obtained by adding together their variances. The numerical values for

repeatability and the reproducibility are then given by substituting a value of 2 for n in the above equation for confidence limits:

$$\text{Repeatability} = \frac{2}{\sqrt{2}}\sigma_r$$

$$\text{Reproducibility} = \frac{2}{\sqrt{2}}(\sigma_L^2 + \sigma_r^2)^{1/2}$$

1.4.7 Significant figures

The numerical expression of the magnitude of a measurement may contain some figures that are doubtful. This can arise either from an estimation between the scale divisions by the operator or, in the case of a digital readout, from the uncertainty in the choice of the last figure by the machine. For instance in the case of a measurement of length by a rule that is graduated in millimetres, the rule might show that the length is definitely between 221 mm and 222 mm. Estimation by the person making the measurement might put the value at 221.6 mm. The figures 221 are exact but the final digit (6) is doubtful because it is only estimated. However, all four figures are regarded as significant because they convey meaningful information. This can be seen if it is imagined that the true value is actually 221.7 mm; the error would then be 0.1 mm but if the figures had been taken to the nearest whole millimetre (222) the error would have been 0.3 mm.

Significant figures, therefore, include all the exact figures followed by one doubtful one. Any zeros before the figures are not included in the number of significant figures and zeros after the figures are included only if they are considered to be exact regardless of the position of the decimal point. Zeros that are only there to position the decimal point are not regarded as significant; for example, 540,000 has only two significant figures. If it is necessary to express the fact that some of the zeros are significant, it is better to write the number as, for instance, 5.40×10^5. Zeros after a decimal point should be included only if they are significant. For instance the value 3.0 has two significant figures.

Unless otherwise indicated the uncertainty in any written measurement of a continuous variable is taken to be plus or minus half a step of the last significant figure. For instance 25.4 mm is taken to mean 25.4 ± 0.05 mm but 25.40 mm would be taken to mean 25.40 ± 0.005 mm.

The number of significant figures written down only concerns the reading of figures from instruments. It is an entirely separate issue from how many of the figures are meaningful which can only be decided from repeat tests as described above.

Rounding off

When further calculations are carried out on measured values the number of figures in a result may increase but in general the number that are significant does not increase. Retaining these figures in the final result gives a misleading impression of the precision of the result. The discarding of any figures beyond the significant ones is known as rounding off.

The convention for rounding off is that the last figure to remain is left unchanged if the amount to be discarded is less than 0.5, but it is increased by one if the amount to be discarded is greater than 0.5. For example: 6.854 would be rounded to 6.85 to three significant figures or 6.9 to two significant figures. Note that the rounding up or down is done only in one stage, not firstly to 6.85 and then to 6.8.

If the amount to be discarded is exactly 0.5 of a step then the rounding is to the nearest even figure in the last place, the idea being that this gives a random choice with as many results being rounded up as are rounded down. For example 6.85 would be rounded down to 6.8 whereas 6.95 would be rounded up to 7.0.

When carrying out calculations involving results with different numbers of significant figures, the number of figures in the result is governed by the contribution with the largest error. For example in addition or subtraction:

$$2.71 + 11.814 = 14.52$$
$$6.4 + 123.625 + 5.7165 = 135.7$$
$$2000 + 2{,}400{,}000 = 2{,}400{,}000$$

In each case the result is governed by the number whose concluding figure is the furthest to the left. In the case of simple multiplication or division the result should not in general be credited with more significant figures than appear in the term with the smallest number of significant figures. For example:

$$63.26 \times 0.0217 = 1.37$$
$$0.356 \times 0.6149 = 0.219$$

In case of doubt the mathematical operations can be carried out on the results for the implicit range of values.

Any rounding off must be carried out only on the final result after all the calculations have been made.

General reading

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