

2.1 Introduction

The properties of textile fibres are in many cases strongly affected by the atmospheric moisture content. Many fibres, particularly the natural ones, are hygroscopic in that they are able to absorb water vapour from a moist atmosphere and to give up water to a dry atmosphere. If sufficient time is allowed, equilibrium will be reached. The amount of moisture that such fibres contain strongly affects many of their most important physical properties. The consequence of this is that the moisture content of all textile products has to be taken into account when these properties are being measured. Furthermore because the percentage of moisture that can be retained by fibres is quite high (up to 40% with some fibres), the moisture content can have a significant effect on the mass of the material. This factor has a commercial importance in cases where material such as yarns and fibres is bought and sold by weight.

2.2 Effect of moisture on physical properties

The physical properties of fibres can be affected by their moisture content. In general the fibres that absorb the greatest amount of moisture are the ones whose properties change the most. Three main types of properties are affected.

2.2.1 Dimensional

The mass of the fibres is simply the sum of the mass of the dry fibre plus the mass of the water. The absorption of moisture by fibres causes them to swell, because of the insertion of water molecules between the previously tightly packed fibre molecules. Because the fibre molecules are long and narrow most of the available intermolecular spaces are along the length of the molecules rather than at the ends, so that the swelling takes place mainly in the fibre width as shown in Table 2.1. Nylon is a notable exception to this.

Table 2.1 The swelling of fibres due to moisture absorption [2]

Fibre	Transverse swelling		Longitudinal swelling (%)	Volume swelling (%)
	Diameter (%)	Area (%)		
Cotton	20, 23, 7	40, 42, 21		42, 44
Mercerised cotton	17	46, 24	0.1	
Viscose	25, 35, 52	50, 65, 67, 66, 113, 114	3.7, 4.8	109, 117, 115, 119, 123, 126, 74, 122, 127
Acetate	9, 11, 14, 0.6	6, 8	0.1, 0.3	
Wool	14.8-17	25, 26		36, 37, 41
Silk	16.5, 16.3-18.7	19	1.3, 1.6	30, 32
Nylon	1.9-2.6	1.6, 3.2	2.7-6.9	8.1-11.0

Table 2.1 is a summary of measurements made by different workers so that there is a certain amount of discrepancy among them. Because of the non-circular cross-section of a number of fibres, most notably cotton, the percentage change in cross-sectional area is a better measure than change in diameter. The change in volume of a fibre is linked to the changes in its length and cross-sectional area by simple geometry. The change in volume is also linked to the amount of water that has been absorbed. The swelling of fibres is a continuous process which takes place in step with their increasing moisture content. From this it follows that the swelling increases with the relative humidity of the atmosphere, the shape of the curve linking swelling to relative humidity being similar to that linking fibre regain with relative humidity [1].

Fabrics made from fibres that absorb large amounts of water are affected by the swelling. When such a fabric is soaked in water the increase in width of the fibres leads to an increase in diameter of the constituent yarns. Depending on the closeness of spacing of the yarns this can lead to a change in dimensions of the fabric. However, on subsequent drying out the structure does not necessarily revert to its original state. This behaviour is responsible for the dimensional stability problems of certain fabrics. Advantage is taken of fibre swelling in the construction of some types of waterproof fabrics whose structures are designed to close up when wetted, so making them more impermeable to water.

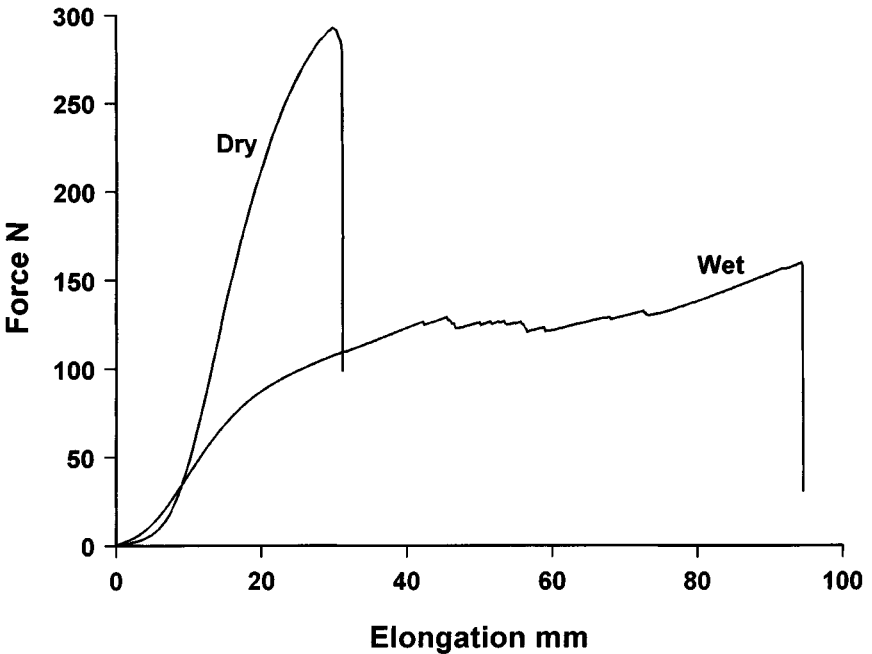
2.2.2 Mechanical

Some fibres, such as wool and viscose, lose strength when they absorb water and some, such as cotton, flax, hemp and jute, increase in strength.

Furthermore the extensibility, that is the extension at a given load, can increase for some fibres when they are wet. Figure 2.1 shows the loss in strength and the gain in elongation of a sample of wool tested when wet compared with a similar sample tested when dry. These changes in strength and extension have consequences for many other textile properties besides tensile strength. Some properties such as fabric tearing strength are ones that are obviously likely to be affected by fibre strength, but for other ones such as crease resistance or abrasion resistance the connection between them and changes in fibre tensile properties is less apparent. It is because of these changes in properties that textile tests should be carried out in a controlled atmosphere.

2.2.3 Electrical

The moisture content of fibres also has an important effect on their electrical properties. The main change is to their electrical resistance. The resistance decreases with increasing moisture content. For fibres that absorb water the following approximate relation between the electrical resistance and the moisture content holds for relative humidities between 30% and 90% [3, 4]:



2.1 The strength of wet and dry wool.

$$RM^n = k$$

where R = resistance,

M = moisture content (%),

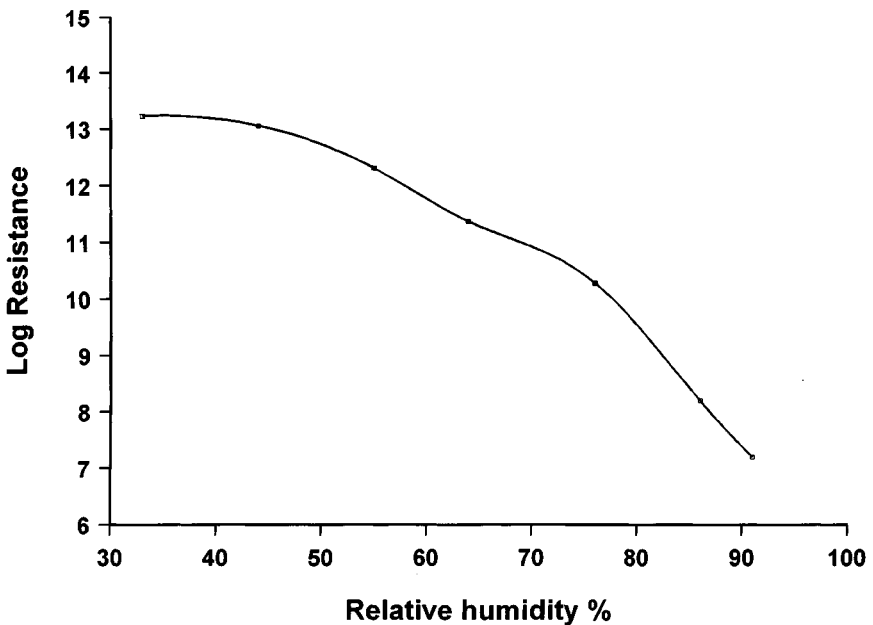
and n and k are constants.

The changes in resistance are large: there is approximately a tenfold decrease in resistance for every 13% increase in the relative humidity. Figure 2.2 shows the change in resistance with relative humidity for a sample of nylon [4]. This fall in resistance with increasing moisture content means that static electrical charges are more readily dissipated when the atmospheric relative humidity is high.

The relative permittivity (dielectric constant) of fibres increases with increasing moisture content in those fibres that absorb moisture [1]. Water itself has a much higher permittivity than the material making up the fibre and so as moisture is absorbed by the fibre the overall value is influenced by this, which will therefore affect any capacitance measurements, such as for evenness, which are made on textile materials.

2.3 Atmospheric moisture

The moisture content of textile materials when they are in equilibrium with their surroundings is determined by the amount of moisture in the air.

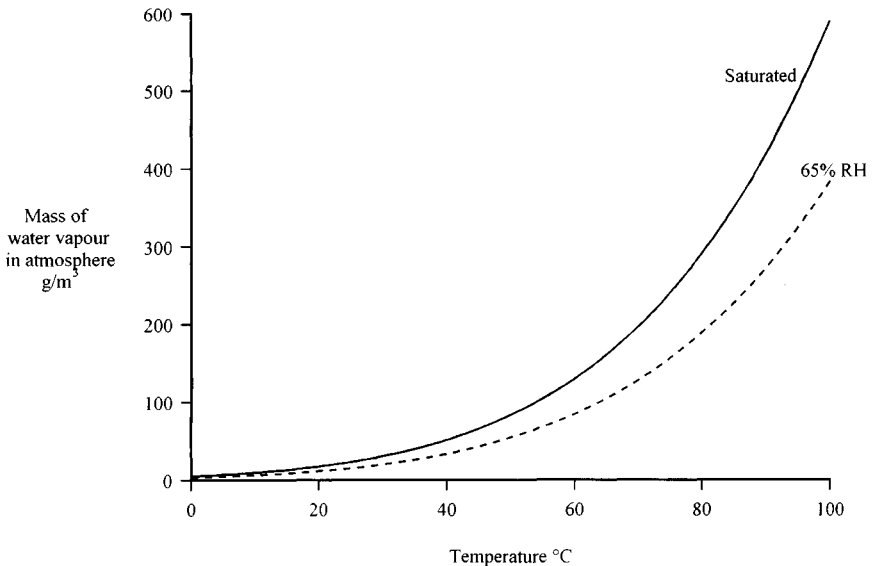


2.2 The change in resistance of nylon with relative humidity.

Therefore the moisture content of those materials that absorb water can vary from day to day or from room to room. The atmospheric moisture level is normally expressed in terms of relative humidity and not absolute water content.

2.3.1 Vapour pressure

Water molecules evaporate from the bulk at a rate determined by the exposed surface area and the temperature. Eventually the space above the surface reaches a stage when as many molecules are condensing back onto the surface as are evaporating from it. The space is then saturated with vapour. The amount of water held at saturation depends only on the temperature of the air and its value increases with increasing temperature as shown in Fig. 2.3. The pressure exerted by the water vapour is known as the saturated vapour pressure and is independent of the volume of space existing above the surface. If the vapour pressure in the space is kept higher than the saturated vapour pressure, water will condense back into the bulk. If, however, the vapour pressure is kept lower than the saturated vapour pressure, water will continue to evaporate from the surface until all the water has gone or the vapour pressures are equal. The total pressure above a surface is the pressure of the air plus the saturated vapour pres-



2.3 The mass of water vapour in the atmosphere (RH = relative humidity).

sure. For example at 20°C the saturated vapour pressure of water is 17.5 mmHg, if the atmospheric pressure is 760 mmHg then the pressure of the air above a water surface is 742.5 mmHg (Dalton's law of partial pressures).

2.3.2 Relative humidity

The amount of moisture that the atmosphere can hold increases with its temperature so that warmer air can hold more water than cold air. The converse of this is that when air containing moisture is cooled, a temperature is reached at which the air becomes saturated. At this point moisture will condense out from the atmosphere as a liquid: this temperature is known as the dew point.

When considering the effects of atmospheric moisture on textile materials the important quantity is not how much moisture the air already holds, but how much more it is capable of holding. This factor governs whether fibres will lose moisture to or gain moisture from the atmosphere. The capacity of the atmosphere to hold further moisture is calculated by taking the maximum possible atmospheric moisture content at a particular temperature and working out what percentage of it has already been taken up. This quantity is known as the relative humidity (RH) of the atmosphere and it can be defined in two ways. In terms of the mass of water vapour in the atmosphere:

$$\text{RH} = \frac{\text{mass of water vapour in given volume of air}}{\text{mass of water vapour required to saturate this volume at the same temperature}} \times 100\%$$

Alternatively it can also be defined as the ratio of the actual vapour pressure to the saturated vapour pressure at the same temperature expressed as a percentage:

$$\text{RH} = \frac{\text{actual vapour pressure} \times 100\%}{\text{saturated vapour pressure}}$$

The absolute humidity is defined as the weight of water present in unit volume of moist air measured in grams per cubic metre.

It is important to note that the relative humidity of the atmosphere changes with temperature even when the total quantity of water vapour contained in the air remains the same. The dotted line in Fig. 2.3 shows the increase in the mass of water vapour contained in the atmosphere with increasing temperature for a constant relative humidity of 65%.

The amount of moisture contained by fibres that are in equilibrium with the atmosphere is dependent on the relative rather than the absolute humidity.

2.3.3 Standard atmosphere

Because of the important changes that occur in textile properties as the moisture content changes, it is necessary to specify the atmospheric conditions in which any testing is carried out. Therefore a standard atmosphere has been agreed for testing purposes [5] and is defined as a relative humidity of 65% and a temperature of 20 °C. For practical purposes certain tolerances in these values are allowed so that the testing atmosphere is RH 65% \pm 2%, 20 \pm 2 °C. In tropical regions a temperature of 27 \pm 2 °C may be used.

2.3.4 Measurement of atmospheric moisture

There are a number of different instruments for measuring the moisture content of the atmosphere, known as hygrometers or psychrometers.

Wet and dry bulb hygrometer

If the bulb of a glass thermometer is surrounded by a wet sleeve of muslin in an atmosphere that is not saturated, water vapour will evaporate into the air at a rate proportional to the difference between the actual humidity and 100% humidity. Owing to the latent heat of evaporation, heat is drawn from the thermometer bulb, thus cooling it. This cooling effect has the consequence that the temperature indicated by a wet bulb thermometer is lower than the air temperature. By mounting two identical thermometers together, one with a wet sleeve and one with a normal bulb, the two temperatures can be read directly. The relative humidity can then be calculated from the temperature difference between the two readings. The value is usually read from appropriate tables. The rate of evaporation of water is also governed by the speed of the airflow past the wet bulb. Therefore for accurate work the rate of airflow past the thermometer bulbs has to be controlled as still air conditions are difficult to achieve in practice. The sling and the Assmann type hygrometers are two instruments in which the flow of air is controlled.

Sling or whirling hygrometer

This instrument works on the same principle as above but the two thermometers are mounted on a frame with a handle at one end. This allows them to be rotated by hand at a speed of two or three revolutions per second, so giving an air speed of at least 5 m/s past the thermometers. After half a minute of rotation, temperature readings from the two thermometers are taken and the procedure is then repeated until the readings have reached minimum values.

Assmann hygrometer

This is a more sophisticated instrument than the sling hygrometer in that a fan is used to draw air across the thermometer bulbs at a constant pre-determined speed. The temperatures are read when they have reached a steady value.

Hair hygrometer

Human hair increases or decreases in length as the humidity of the surrounding air increases or decreases. By attaching a bundle of hairs to a suitable lever system, the relative humidity of the atmosphere can be indicated directly and, if required, recorded on a chart. The accuracy of this method is limited to within 3 or 4% of the true value for the range of relative humidities between 30% and 80%. A combined temperature and humidity recording instrument is often used in laboratories and is known as a thermo-hygrograph. The hair hygrometer requires frequent calibration and has a slow response to changes in atmospheric conditions.

2.4 Regain and moisture content

The amount of moisture in a fibre sample can be expressed as either regain or moisture content. Regain is the weight of water in a material expressed as a percentage of the oven dry weight:

$$\text{Regain} = \frac{100 \times W}{D} \%$$

where D is the dry weight and W is the weight of absorbed water.

Moisture content is the weight of water expressed as a percentage of the total weight

$$\text{Moisture content} = \frac{100 \times W}{D + W} \%$$

Regain is the quantity usually used in the textile industry.

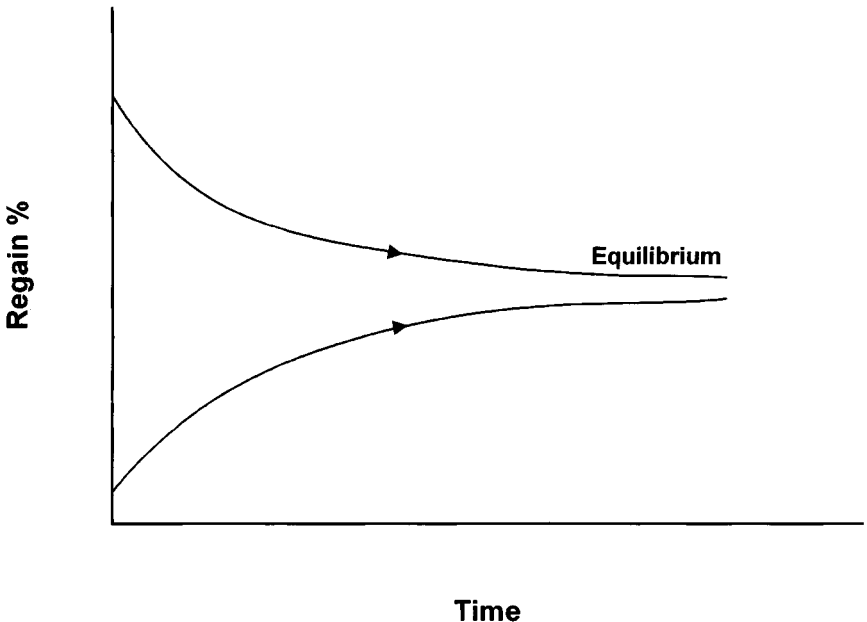
2.4.1 Regain – humidity relations of textiles

Hysteresis

If two identical samples of fibre, one wet and one dry, are placed in a standard atmosphere of 65% RH, it might be expected that they would both eventually reach the same value of regain. However, this is not the case as the one that was originally wet is found to have a higher regain than the

one that was originally dry; this is shown diagrammatically in Fig. 2.4. This difference is due to hysteresis between moisture uptake and moisture loss.

If the regain of a fibre that absorbs moisture is plotted against the atmospheric relative humidity as in Fig. 2.5 it is found to have an S-shaped curve and not a straight line relationship. If the relationship is plotted for decreasing relative humidity, that is when the fibres are drying out, it is found that the curve is different from that plotted for increasing relative humidity. It is this difference between the curves which is responsible for the difference in equilibrium regain values shown in Fig. 2.4. The dotted line in Fig. 2.5 at 65% relative humidity cuts the absorption and desorption curves at different values of regain. A sample that absorbed moisture in an atmosphere of 65% RH and reached equilibrium at the lower value of regain would then follow an intermediate path as it dried out. This phenomenon, which can result in two different values of regain at the same relative humidity depending on whether the sample is gaining or losing water, is important when samples are being conditioned. It is necessary for reproducibility of moisture content for a sample to approach equilibrium in the standard testing atmosphere from the same direction every time. Where this factor is important the samples are dried in an oven at a low temperature (50°C) before conditioning in the standard atmosphere.

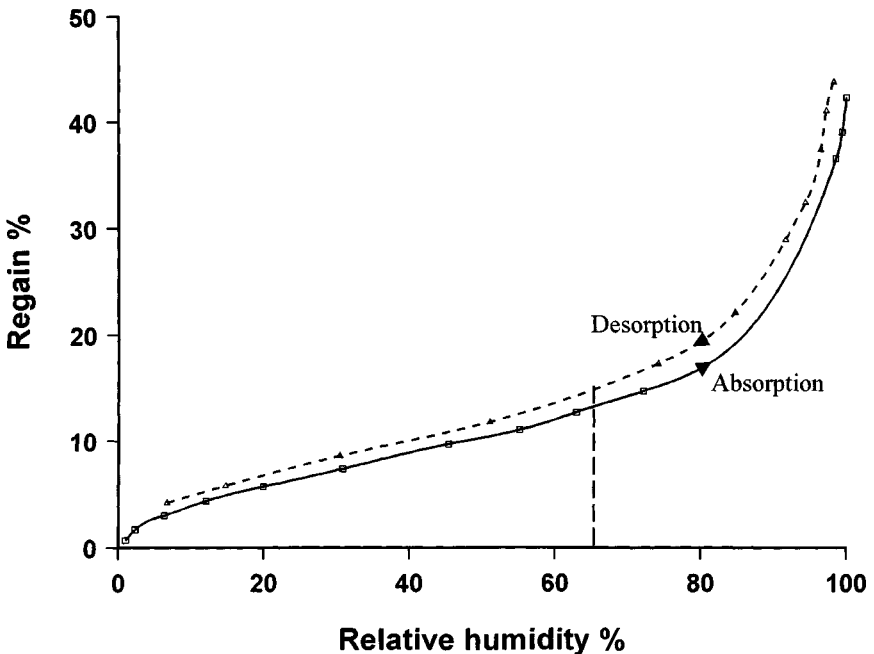


2.4 The hysteresis in moisture absorption.

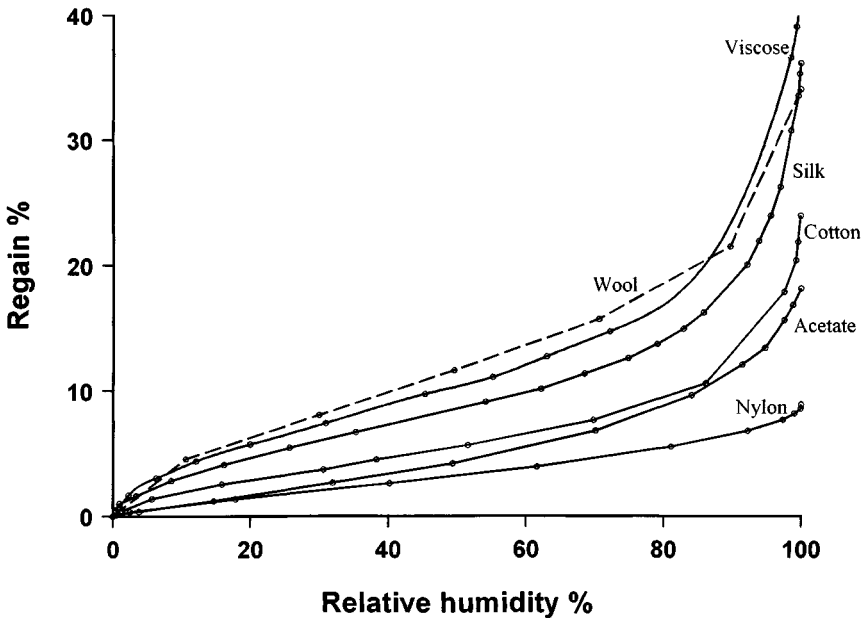
2.4.2 Factors affecting the regain

Different fibre types absorb different amounts of moisture depending on their affinity for water as shown in Fig. 2.6 [6–10]. For a given fibre type the moisture content is governed by a number of factors:

- 1 **Relative humidity.** The higher the relative humidity of the atmosphere, the higher is the regain of textile material which is exposed to it.
- 2 **Time.** Material that is in equilibrium at a particular relative humidity which is then moved to an atmosphere with a different relative humidity takes a certain amount of time to reach a new equilibrium. The time taken depends on the physical form of the material and how easily the moisture can reach or escape from the individual fibres. For example the British Standard for count testing [11] suggests a period of one hour for yarn in hank form to reach equilibrium, but three hours for yarn on packages.
- 3 **Temperature.** For practical purposes the temperature does not affect the regain of a sample.
- 4 **Previous history.** The moisture content of textile materials in equilibrium with a particular relative humidity depends on the previous history of the material. For example the hysteresis effect as mentioned above



2.5 A plot of regain versus relative humidity for viscose fibres.



2.6 A comparison of the moisture uptake of fibres.

means that it will have a different moisture content depending on whether it was previously wet or dry. Processing of the material can also change its regain value by altering its ability to absorb moisture. The removal of oils, waxes and other impurities can also change the regain by removing a barrier on the fibre surface to the flow of moisture vapour. For example the standard regain value for scoured wool is 16% and that for oil combed tops is 19%.

2.4.3 Methods of measuring regain

To measure the regain of a sample of textile material it is necessary to weigh the material, dry it and then weigh it again. The difference between the masses is then the mass of water in the sample.

$$\text{Regain} = \frac{\text{mass of water} \times 100\%}{\text{oven dry mass}}$$

Regain is based on the oven dry mass, which for most fibres is the constant mass obtained by drying at a temperature of $105 \pm 2^\circ\text{C}$. Constant mass is achieved by drying and weighing repeatedly until successive weighings differ by less than 0.05%. The relevant British Standard [12] specifies that successive weighings should be carried out at intervals of 15 min when

using a ventilated oven, or at 5 min intervals if using a forced air oven. The exceptions to the above conditions are: acrylic fibres which should be dried in a normal oven at $110 \pm 2^\circ\text{C}$ for 2 h and chlorofibres which should be dried at $77 \pm 2^\circ\text{C}$ to constant mass.

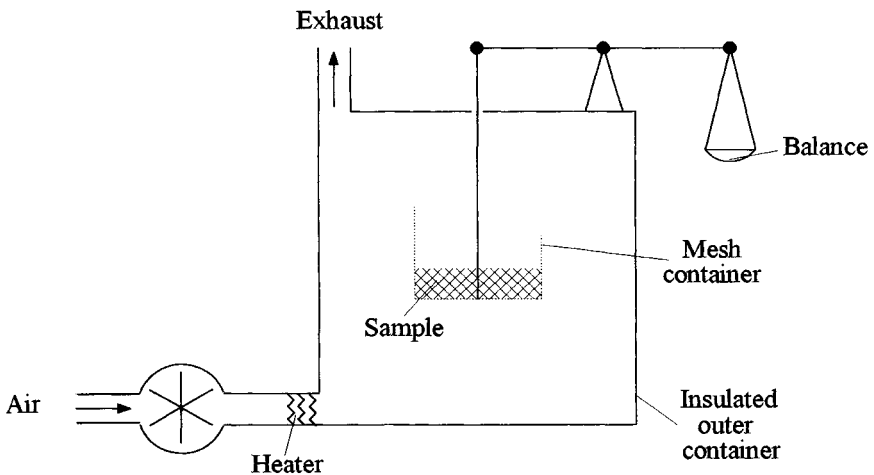
Conditioning oven

A conditioning oven, as shown in Fig. 2.7, is a large oven which contains the fibre sample in a mesh container. The container is suspended inside the oven from one pan of a balance, the mechanism of which is outside the oven. This ensures that the weight of the sample can be monitored without the need to remove it from the oven. A continual flow of air at the correct relative humidity is passed through the oven which is maintained at 105°C .

The main advantage of using a conditioning oven for carrying out regain determinations is that all the weighing is carried out inside the oven. This means that the sample does not gain moisture as it is taken from the oven to the balance. The oven is also capable of drying large samples. The use of a conditioning oven to dry a sample is the correct standard procedure; any other method of sample drying has to be checked for accuracy against it.

The method is based on the assumption that the air drawn into the oven is at the standard atmospheric conditions. If this is not the case then a correction has to be made based on the actual temperature and relative humidity of the surrounding air.

The basis of the recommended correction [13] is to add the following percentage to the dry weight of the sample



2.7 A conditioning oven.

$$\text{Percentage correction} = 0.5(1 - 6.48 \times 10^4 \times E \times R)\%$$

where R = relative humidity %/100,

E = saturation vapour pressure in pascals at the temperature of the air entering the oven (taken from a table of values).

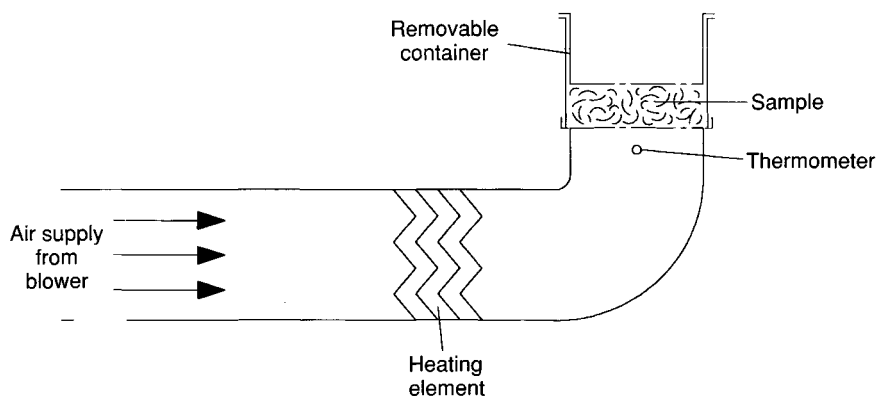
Rapid regain dryer

The rapid regain type of dryer represents a quicker way of drying fibre samples. The basis of this type of dryer is that the hot air is blown directly through the sample to speed up the drying process.

There are a number of different versions of this instrument, but in all cases the sample being dried has to be removed from the output end of the hot air blower and weighed on a separate balance. In some instruments a removable sample container which has interchangeable end caps is used. One end cap is a perforated one for use when the air is being blown through and the other end caps are a pair of solid ones which are placed on the container when it is removed from the heater for weighing.

The WIRA improved rapid regain dryer, shown in Fig. 2.8, uses a powerful blower to force air through the sample in order to give more rapid drying. Because of the high volume of heated air which can be passed through the instrument a large sample can be dried. This can either be weighed in its container or removed from the container and weighed separately.

The CSIRO (Commonwealth Scientific and Industrial Research Organization) direct reading regain dryer is similar in principle but has a vertical column with a removable sample container at the top. There is also



2.8 The WIRA process dryer.

a dedicated balance which forms part of the equipment and is calibrated to give the regain figure directly. Alternatively a balance may be connected to a computer which will calculate the regain from the weight. In order to achieve this the original sample is placed on the balance which is then zeroed before drying. As the sample then dries out, the balance indicates percentage regain.

When an external balance is used to weigh heated samples certain precautions have to be made:

- 1 The balance should be enclosed.
- 2 The time for weighing should not exceed 20s from removal of the sample from the dryer.
- 3 A buoyancy correction should be determined by using a dummy sample of steel wool which is weighed when cold and then reweighed after heating for a set time (5 or 15 min).

Electrical methods

The electrical properties of fibres change quite markedly with their moisture content so that the measurement of resistance or capacitance changes can be used to give an indirect method of regain determination.

The resistance change is a more suitable basis for an instrument as there is a greater change in the resistance of fibres with moisture content than there is in the capacitance. Furthermore the weight and distribution of material between the plates of a capacitor must be closely controlled in order to give reproducible results.

The great advantages that electrical methods possess over drying and weighing methods are the speed and ease of reading, the fact that they can be calibrated directly in regain units and the ease with which instruments can be made portable.

The disadvantages of electrical methods are the need to recalibrate them as they are indirect methods, the variations in readings due to packing density, the possible presence of dyes, antistatic agents and also variations in fibre quality.

In a typical electrical resistance measuring instrument, two electrodes are pushed into a package of yarn and the resistance between the electrodes is measured by suitable electronics, the answer being displayed on a scale which is directly calibrated in regain values. Different electrode sets are used for different packages, for example long thick prongs for bales and short needle like probes for yarn packages. The instrument usually has to be calibrated for the type of probe, the type of fibre and the expected regain range.

2.5 Correct invoice weight

When textile materials are bought and sold by weight, it is necessary for there to be agreement between buyer and seller on the exact weight that has to be paid for. This value can vary considerably with the moisture content of the material which in turn varies with type of material, the atmospheric moisture content at the time and how wet or dry the material was before it was packed, among other factors. The buyer certainly does not wish to pay for excess water at the same price per kilogram as the textile material. A 'correct invoice weight' is therefore determined according to [12]. In this procedure the consignment is considered to contain a percentage of water known as the standard regain allowance and the weight of the consignment is calculated as if it contained this amount of water.

When a consignment of textile material is delivered and weighed, a sample is taken from it on which tests are made which enable the correct invoice weight to be calculated. Samples of at least 200g are selected according to adequate sampling procedures and immediately stored in airtight containers so that no moisture is lost. The samples are weighed and then the oven dry weight is determined as described above. In some cases other non-textile materials, such as oils, grease, wax and size, are removed before drying.

If M = mass of consignment at time of sampling, D = oven dry mass of sample, S = original mass of sample and C = oven dry mass of the consignment:

$$C = M \times \frac{D}{S}$$

To the oven dry mass is added an official allowance for moisture depending on the nature of the material. This regain allowance, sometimes called the 'official' or 'standard' regain, is set out in BS 4784. These values are only approximately the regains the materials would have when in equilibrium with the standard atmosphere and represent agreed commercial numbers for the purposes of determining quantities such as consignment weights, yarn counts and percentage compositions which vary with moisture content.

The regain allowances vary depending on what physical state the material is in, for example woollen yarn 17%, worsted yarn 18.25%, oil combed tops 19%, wool cloth 16%.

$$\text{Correct invoice weight} = C \times \left(\frac{100 + R_1}{100} \right)$$

where R_1 = commercial moisture regain.

Table 2.2 Regain allowances. Note that regain values depend on the form of the material

Fibre type	UK regain (%)	US regain (%)
Man-made fibres		
Acetate	(9)	6.5
Acrylic	2	1.5
Nylon 6, 6 and 6	(6.25)	4.5
Polyester	(1.5)	0.4
Polypropylene	(2)	0
Triacetate	(7)	3.5
Viscose	(13)	11
Natural fibres		
Cotton – natural yarn	8.5	7
Linen fibre	12	12
Linen yarn	12	8.75
Silk	11	11
Wool – worsted yarn	18.25	13.6
Wool – fibre clean scoured	17	13.6

Figures in brackets commercial allowances for cleaned fibres.

Source: taken from [12] and [13].

If the samples are dried after cleaning a different set of allowances is used for moisture and oil content, etc:

$$\text{Correct invoice weight} = C \times \left(\frac{100 + R_2 + A_2 + B_2}{100} \right)$$

where R_2 is the moisture regain which may differ from R_1 , A_2 is the allowance for natural grease and B_2 is the allowance for added oil. In most cases an overall allowance is given which includes the values for moisture and natural and added fatty matter.

In the case of a blend the overall allowance is calculated from the fraction of each component in the blend multiplied by its regain value, for example: 50/50 wool / viscose (dry percentages)

$$\frac{50 \times 17}{100} + \frac{50 \times 13}{100} = 8.5 + 6.5 = 15\%$$

Regain values vary slightly from country to country. For instance, the USA has a single value of 13.6% for wool in all its forms but has separate values for natural cotton yarn (7.0%), dyed cotton yarn (8.0%) and mercerised cotton yarn (8.5%), although there is no value laid down for raw cotton. Therefore the appropriate standard should be consulted for the correct commercial regain figures. Table 2.2 is intended only as a guide.

Table 2.3 The relative humidity of air over saturated solutions of salts at 20°C

Saturated salt solution	Relative humidity (%)
Potassium sulphate	97
Potassium nitrate	93
Potassium chloride	86
Ammonium sulphate	81
Sodium chloride	76
Sodium nitrite	66
Ammonium nitrate	65
Sodium dichromate	55
Magnesium nitrate	55
Potassium carbonate	44
Magnesium chloride	33
Potassium acetate	22
Lithium chloride	12
Potassium hydroxide	9

2.6 Control of testing room atmosphere

Testing laboratories require the atmosphere to be maintained at $65 \pm 2\%$ RH and $20 \pm 2^\circ\text{C}$ in order to carry out accurate physical testing of textiles. The temperature is controlled in the usual way with a heater and thermostat, but refrigeration is necessary to lower the temperature when the external temperature is higher than 20°C as is usually the case in summer. The tolerances allowed on temperature variation are quite difficult to meet. The relative humidity is controlled by a hygrometer which operates either a humidification or a drying plant depending on whether the humidity is above or below the required level. Double glazing and air locks to the doors are usually fitted to the laboratory in order to reduce losses and to help to keep the atmosphere within the tolerance bands. Adequate insulation is necessary on all external surfaces as the high moisture content of the atmosphere can cause serious condensation on cold surfaces. Only large organisations may be able to afford a fully conditioned testing laboratory. If one is not available, testing should be carried out in a room in which ambient conditions are as uniform as possible throughout the year in order to cut down on variations in measurements due to atmospheric variation.

Cabinets that control the atmosphere of a relatively small volume can be obtained commercially. These may be used to condition samples before testing, the actual tests being carried out in a normal atmosphere straight after removal from the conditioned atmosphere. The relative humidity of a small enclosed volume of air, such as a desiccator, may be controlled by the

presence of a dish containing a saturated solution of certain salts such as those listed in Table 2.3 [14].

References

1. Morton W E and Hearle J W S, '*Physical Properties of Textile Fibres*', 3rd edn, Textile Institute, Manchester, 1993.
2. Preston J M and Nimkar M V, 'Measuring the swelling of fibres in water', *J Text Inst*, 1949 **40** P674.
3. Hearle J W S, 'The electrical resistance of textile materials: I The influence of moisture content', *J Text Inst*, 1953 **44** T117.
4. Cusick G E and Hearle J W S, 'The electrical resistance of synthetic and cellulose acetate fibres', *J Text Inst*, 1955 **46** T699.
5. BS EN 20139 Textiles. Standard atmospheres for conditioning and testing.
6. Urquhart A R and Eckersall N, 'The absorption of water by rayon', *J Text Inst*, 1932 **23** T163.
7. Urquhart A R and Eckersall N, 'The moisture relations of cotton VII a study of hysteresis', *J Text Inst*, 1930 **21** T499.
8. Speakman J B and Cooper C A, 'The adsorption of water by wool I Adsorption hysteresis', *J Text Inst*, 1936 **27** T183.
9. Hutton E A and Gartside J, 'The moisture regain of silk I Adsorption and desorption of water by silk at 25 °C', *J Text Inst*, 1949 **40** T161.
10. Hutton E A and Gartside J, 'The adsorption and desorption of water by nylon at 25 °C', *J Text Inst*, 1949 **40** T170.
11. BS 2010 Method for determination of the linear density of yarns from packages.
12. BS 4784 Determination of commercial mass of consignments of textiles Part 1 Mass determination and calculations.
13. ASTM D 1909 Table of commercial moisture regains for textile fibres.
14. The *WIRA Textile Data Book*, WIRA, Leeds, 1973.

7.1 Introduction

It has been known for a long time that fibres take up moisture from the air. Leonardo da Vinci (1452–1519) has, in his notebooks, two drawings of self-indicating balances with cotton on one pan and wax on the other; the increased weight of the cotton in a damp atmosphere alters the setting of the balance so that it can be used 'for knowing the quality and density of the air and when it will rain'. Earlier, Nicholas of Cusa (1401–1463) had measured the increase in weight of wool for the same purpose. The first detailed investigation of the subject was carried out by Schloesing [1] in 1893. Between 1924 and 1932, Urquhart and his collaborators conducted an investigation of the absorption of cotton, rayons and acetate that will remain a classic of painstaking experiment.

The property of absorbing moisture is a valuable feature of clothing materials. Apart from its direct utility in keeping the skin dry, the absorption of water causes the fabric to act as a heat reservoir, protecting the body from sudden changes of external conditions. However, it may be a disadvantage in drying the hygroscopic fibres that it is necessary to remove the absorbed moisture that is not present in the non-hygroscopic synthetic fibres.

The absorption changes the properties of fibres. It causes swelling to occur, which alters the dimensions of the fibre, and this, in turn, will cause changes in the size, shape, stiffness and permeability of yarns and fabrics, The mechanical properties and the frictional properties are altered, so affecting the behaviour of the fibres in processing and in use. Wetting and drying may lead to permanent set or creasing. The moisture condition of the material is one of the most important factors in determining its electrical properties; 'static' is much less likely to occur in damp conditions.

The above examples show the technological importance of moisture absorption in fibres. There is also a direct commercial interest. In 100 kg of raw cotton, for example, there may be up to 12 kg of water. Since it is expensive to pay for this at the price of raw cotton, it must be allowed for in calculating the weight to be charged.

7.2 Definitions

7.2.1 Humidity

The *absolute humidity* h of an atmosphere is defined as the mass of water in unit volume of air. The dampness of the air is also indicated by the *vapour pressure* p that

is, the partial pressure of the water vapour in the atmosphere. The most convenient term is the relative humidity H , given by:

$$H = 100 \left(\frac{h}{h_s} \right) \quad (7.1)$$

where h_s is the absolute humidity of saturated air at the same temperature. At ordinary air temperatures, this ratio differs inappreciably from the corresponding ratio of vapour pressures.

Since the properties of fibres vary with the moisture condition, testing should be done under controlled conditions. For this purpose, a *standard temperate atmosphere* is defined as one of 65% r.h. and 20 °C¹. The permitted tolerances for testing are $\pm 2\%$ r.h. and ± 2 °C. An uncontrolled indoor atmosphere is usually drier than this.

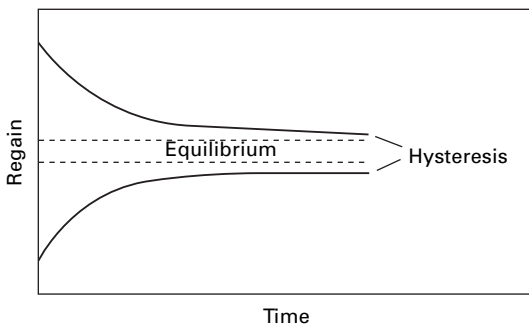
7.2.2 Equilibrium

When a textile material is placed in a given atmosphere, it takes up or loses water at a gradually decreasing rate (Fig. 7.1) until it reaches equilibrium, when no further change takes place. This is a dynamic equilibrium, which occurs when the number of water molecules evaporating from the specimen in a given time becomes equal to the number condensing and being absorbed.

7.2.3 Regain and moisture content

The amount of water in a specimen may be expressed in terms of either the regain or the moisture content:

$$\text{regain} = \frac{\text{mass of absorbed water in specimen}}{\text{mass of dry specimen}} \times 100\% = R \quad (7.2)$$



7.1 The approach to moisture equilibrium, with hysteresis depending on whether sample is gaining or losing water.

¹ In tropical and sub-tropical countries, 27 °C may be used as a secondary standard.

$$\text{moisture content} = \frac{\text{mass of absorbed water in specimen}}{\text{mass of undried specimen}} \times 100\% = M \quad (7.3)$$

The two are simply related, for, if the dry mass = D and the mass of absorbed water = W , we have:

$$R = \frac{100 W}{D} \quad (7.4)$$

$$M = \frac{100 W}{D + W} = \frac{100 W/D}{1 + W/D} = R \frac{1 + R}{100} \quad (7.5)$$

7.2.4 Recommended allowance

For commercial transactions, a set of values of recommended allowance² has been agreed on. The mass of a consignment of a textile material on which the charge is to be based is known as the *correct invoice mass* and is equal to the mass that the consignment would have if its regain were the recommended allowance.

It should be noted that the values of the recommended allowances are chosen purely for convenience, since they are near the values found in practice and are not the regains in a standard atmosphere. The values of the recommended allowances are included in [Table 7.3](#).

7.3 Measurement of regain

7.3.1 The gravimetric method

The gravimetric method is the basic method of measuring regain or moisture content, and any indirect method must be calibrated by it. The sample to be tested is weighed, dried and then weighed again. The regain R is calculated as follows:

$$\text{mass of undried specimen} = W + D = m_1$$

$$\text{mass of dried specimen} = D = m_2$$

$$R = \frac{100 W}{D} = 100 \frac{(m_1 - m_2)}{m_2} \% \quad (7.6)$$

No difficulty is involved in the first weighing, except that care should be taken that the regain of the sample does not change before or during the weighing. The determination of the dry weight does involve certain difficulties.

7.3.2 Difficulties involved in drying the specimen

To obtain the most accurate results, the sample should be dried by exposing it in an enclosed space containing an efficient drying agent, such as phosphorus pentoxide,

²Commercial regain in the United States

at room temperature. The high affinity of the drying agent for water results in complete drying of the specimen, and, since the temperature is not raised, other changes in the specimen are not likely to occur. This method, however, has the disadvantage that it is extremely slow. Davidson and Shorter [2] found that a period of from 4 to 6 weeks was necessary to dry 8 g specimens of cotton. This slowness renders the method impracticable except for very special investigations.

The usual method in practice is to dry the specimen in an oven at about 110 °C. The raising of the temperature of the air lowers its relative humidity, since, although the absolute humidity of the air changes very little, the saturation humidity increases enormously. Water must then evaporate from the specimen until it reaches equilibrium. Since all chemical processes are more rapid at higher temperatures, this does not take long.

However, the relative humidity in the oven is not zero. If the air outside the oven has a relative humidity of 50% at 20 °C, when it is heated to 110 °C its relative humidity will be 0.8%. The moisture that is left in equilibrium with this humidity is known as the *residual regain* and is the first inherent source of error in the oven method. It results in a measured value of the regain that is too low, since the loss of weight on drying is not as great as it should be.

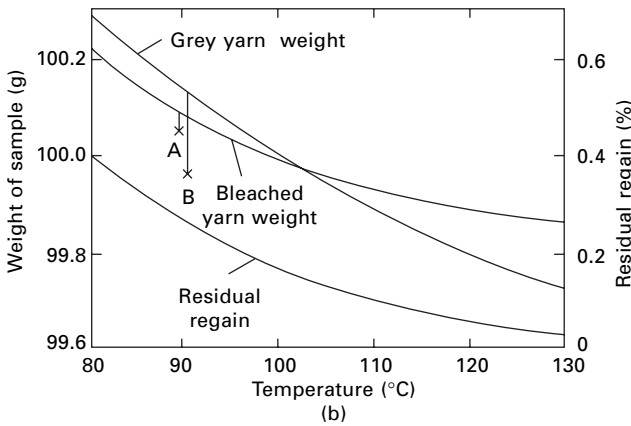
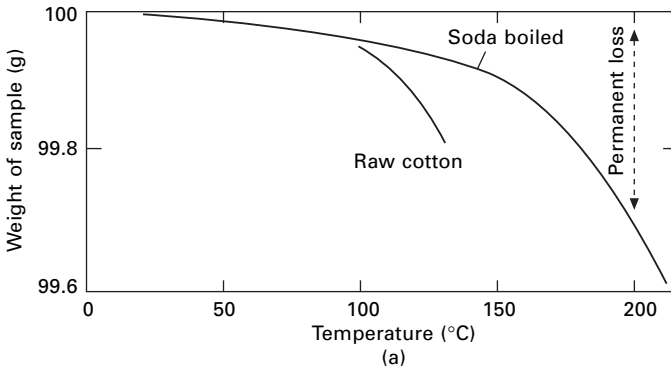
The heating of the specimen may cause substances other than water, for example, oils and waxes present as impurities, to be driven off from the sample. This is known as *permanent loss* and is the second inherent source of error in the oven method. It causes the measured loss of weight to be greater than it should be and thus gives a high value of the regain. Figure 7.2 illustrates the two sources of error. Figure 7.2(a) shows the permanent loss of soda-boiled and unbleached cotton after 3 h heating, dry, in a vacuum. Figure 7.2(b) shows the residual regain in cotton due to a water vapour pressure of 8 mm of mercury (1.07 kPa) at various temperatures. The change of weight of bleached cotton follows this curve closely, but the raw cotton shows a greater change in weight owing to the permanent loss. The amount of permanent loss can be shown by allowing the specimen to reabsorb water and then drying again at 90 °C; for bleached cotton, this shows little difference from the previous value, but the value for raw cotton is almost 0.2% lower than the previous value owing to the permanent loss in the first drying to 130 °C.

The amounts of error due to these causes will vary with the conditions but they may both be of the order of 0.2% in the value of the regain. The true dry weight is given by:

$$\text{true dry weight} = \text{oven-dry weight} - \text{residual regain} + \text{permanent loss}$$

7.3.3 Experimental practice

For commercial and routine testing, a special oven is usually used. It contains a basket in which about 1 kg of material can be placed and weighed *in situ*. The material is then dried until its weight becomes constant in a current of heated air. The dry sample is weighed with the air current switched off. Stephenson [3] has described the experimental errors that may occur:



7.2 (a) Permanent loss on heating 100 g of dry cotton for 3 h *in vacuo*. (b) Change in weight of samples of cotton dried at water vapour pressure of 8 mm of mercury (1.07 kPa). Points A and B are for material dried at 130 °C, allowed to reabsorb water at room temperature, and then dried at 90 °C. From Davidson and Shorter [2].

- The differing density of hot and cold air will affect the buoyancy of the specimen.
- Convection currents may affect the balance, but this can be minimised by a well-designed oven.
- Absorption may occur during weighing, after the air current has been switched off.

The errors should not total more than 0.1% in the value of the regain. Balls [4] found that random errors in routine oven-testing amounted to $\pm 0.2\%$ in the regain value for cotton at 10% regain.

More rapid tests may be made by using an apparatus in which a stream of hot air is blown through a container holding the specimen. The container can be removed and closed for weighing. In another instrument, a standard weight of material is used, and, after drying, the regain is directly indicated on a scale.

Laboratory tests are usually made on smaller samples, which are placed in weighing bottles. For the most accurate work, they are dried in a desiccator with a drying agent.

A more rapid method is to dry them in a small chemical oven at 110 °C. The bottles are removed from the oven, stoppered up and cooled before being weighed. The errors liable to occur in this method are:

- absorption of moisture before the stopper is replaced;
- enclosure of hot air in the container, giving it added buoyancy (the amount of the error due to this cause will depend on the relative size of container and sample);
- convection errors, which should be negligible if the bottle is cooled;
- diffusion of moisture into the bottle, which can be prevented by a good seal.

Stephenson [3] estimates that the errors due to these causes may be between 0.2 and 0.8% in the value of the regain.

Table 7.1 gives a comparison of results obtained by LeCompte and Lipp [5] when using various methods for determining moisture in wool. They conclude that toluene distillation (Section 7.3.4) is the most accurate method in this case. Impurities accounted for less than 0.01% in the water distilled over.

The techniques involved in obtaining accurate relations between equilibrium regain and relative humidity have been reviewed by McLaren and Rowen [6].

7.3.4 Other direct methods

Another method of determining the water in the material is by heating the sample with toluene (boiling point 111 °C) and measuring the amount of water that distils over and is collected in a receiver. The toluene used should be saturated with water. The method is not open to the error of residual regain, since a fresh atmosphere of toluene is continually being supplied. Errors due to permanent loss can be checked by analysis of the water collected.

Van Lamoen and Borsten [7] have described a method for the titration of water, which they consider to be superior to the use of drying ovens, though the reagents are relatively expensive.

7.3.5 Indirect methods

Methods based on the variation of the electrical properties of fibres have been used to indicate their moisture condition.

Table 7.1 Regain determination for wool [5]

Method	Average	Range of values of regain % in three tests
Vacuum oven over P ₂ O ₅	7.13*	0.22
Conditioning oven 110 °C	7.16	0.19
USDA suction drier 150 °C	7.27	0.15
Forced-draught drier	7.33	0.16
Toluene distillation	7.77	0.17

*Still falling at 0.05% per day at end of test.

The Shirley Moisture Meter [8] was, at one time, widely used for the measurement of electrical resistance of cotton, and, although it is no longer manufactured, its essential features could be reproduced in other equipment. As illustrated in Fig. 7.3, an electronic circuit measures the resistance between the inner and outer electrodes of the cone, which is pressed onto the sample of fibre. Other types of electrode may be used for material in other forms. Because of the rapid variation of electrical resistance with moisture content, the method is sensitive. The resistance values depend on fibre type and are sensitive to temperature, additives, contact pressure and material form, but, if a resistance meter is properly calibrated for the test, it gives an accurate measure of resistance. Instruments based on the variation of dielectric constant are also available, but they suffer from the disadvantages that the weight and distribution of material between the plates of the condenser must be controlled and that the variation of dielectric constant with moisture content is much less than the variation of resistance. The capacity method has been extensively used in process-control applications, but, where it can be applied, a resistance method is better.

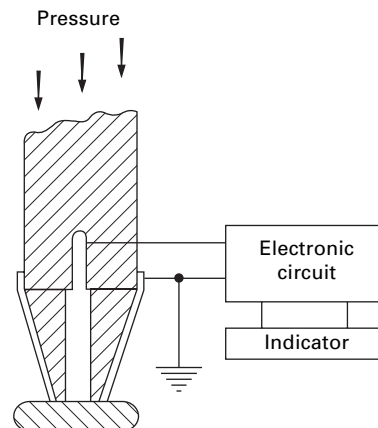
Another indirect method of measuring regain is to shake up a known weight of the sample with calcium carbide in a closed container. This reacts with the water and generates acetylene; measurement of the pressure indicates the regain.

The Shirley Moisture Regain Indicator may also be mentioned. A prepared sample of material is hung on a balance, and, as the relative humidity changes, its weight changes, and the regain is directly indicated on a scale. This may be placed in a spinning room and used for calculating the dry or standard weights of the material being processed.

7.4 Relation between regain and relative humidity

7.4.1 General

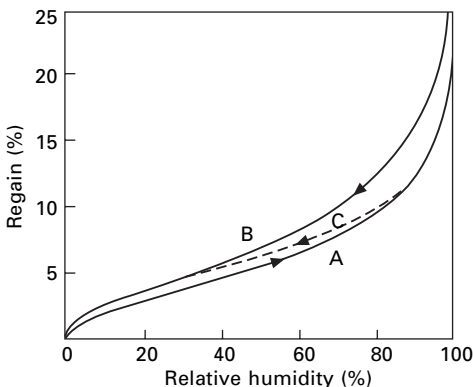
There is hysteresis in the relation between the regain of a textile material and the relative humidity of the atmosphere with which it is in equilibrium. This is illustrated



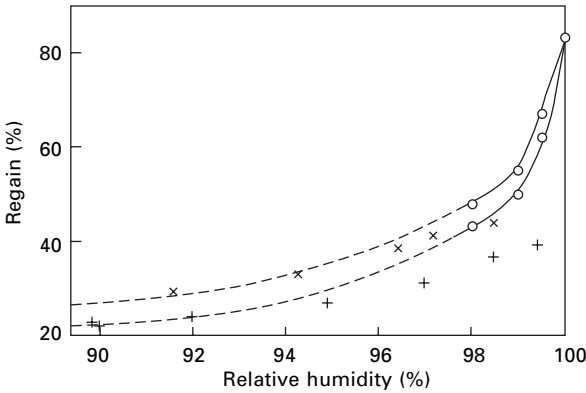
7.3 Basic features of Shirley Moisture Meter.

in Fig. 7.1, which shows the approach to equilibrium in the same atmosphere of two specimens initially at different regains. The specimen that originally had the higher regain also has the higher regain at equilibrium. Depending on its previous history, the specimen may come to equilibrium anywhere in a range of metastable states and does not come to a true thermodynamic equilibrium. In relating regain to relative humidity, it is usual to plot two curves (Fig. 7.4). The first curve A, commonly called the absorption isotherm, is a plot of equilibrium regains at successively higher humidities of a specimen initially bone-dry; the second curve B, the desorption isotherm, is a plot for a specimen initially wet, at successively lower humidities. The nomenclature is unfortunately in confusion. *Desorption* always refers to the loss of water, but the terms *sorption*, *absorption* and *adsorption* are used variously by different authors for the uptake of water or for the whole general phenomenon. Adsorption is, however, best reserved for a specialised meaning implying a particular mechanism of attachment of the water molecules.

The curves usually have the sigmoidal shape shown in Fig. 7.4: a rapidly increasing regain at low humidities, followed by an almost linear portion, and then a more rapid rise at high humidities. The two curves must join at the origin, but Urquhart and Eckersall's experiments [9] indicated that they were separate at 100% r.h. Wetting the specimen caused the values to lie on a higher curve than could be reached by exposure in a saturated atmosphere. Ashpole [10] has disputed this view and produced experimental results indicating that there is a rapid rise in the absorption curve near the saturation point (Fig. 7.5). Experiments are difficult near saturation, since the rapid rise in the absorption means that a large amount of water has to be taken up under a small vapour pressure gradient when conditioning is very slow, while, if there are any temperature fluctuations, it is easy for supersaturation and condensation to occur. Ashpole devised the technique of enclosing the specimen in waxed gauze surrounded by a cellophane membrane and placing this in a solution of sugar of the concentration needed to give the required humidity. This reduces the distance over which diffusion has to occur and so hastens the attainment of equilibrium. By special precautions, temperature fluctuations were kept below 10^{-4} °C. At the highest humidities,



7.4 Typical curves of regain of soda-boiled cotton against relative humidity: A, absorption; B, desorption; C, intermediate [9].



7.5 Hysteresis loop for viscose rayon near saturation. o Ashpole’s experimental values [10]; + absorption; x desorption values found by Urquhart and Eckersall [9].

Ashpole found that the regain varied continuously with time, and, to allow for this, he extrapolated back to zero time. This effect casts some doubt on the validity of his results, and the exact form of the curves near saturation remains uncertain.

The two curves are the limiting equilibrium values. Equilibrium can be attained at any point between them by taking the specimen through a suitable chain of humidities. The curve C in Fig. 7.4 shows a typical result for the desorption of a specimen that had previously been absorbing. The intermediate curves are also sigmoidal in shape.

Taylor [11, 12] has shown that hysteresis occurs even in cycles at low relative humidities. The results given in Table 7.2 show that at about 1% r.h. the hysteresis due to desorption from 4% r.h. may be only a little less than half the hysteresis due to desorption from saturation.

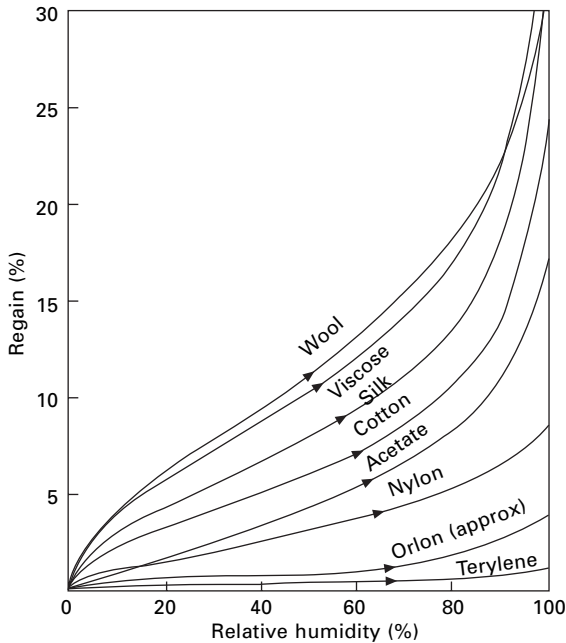
7.4.2 Comparison of various materials

Figure 7.6 shows the relations between regain and relative humidity for various textile fibres, and Table 7.3 gives values of regains at 65% r.h. and the widths of the hysteresis loops.

Cotton shows the typical behaviour. There are small differences between cottons of different origins, for example, at 57.6% r.h. Urquhart and Williams [25] found

Table 7.2 Hysteresis in cycles at low regains [11, 12]

Material	r.h. (%)	Absorption regain (%)	(Desorption regain – absorption regain) (%)	
			cycle 0–4% r.h.	Cycle 0% r.h. to saturation
Viscose rayon (Fibro)	0.85	0.95	0.23	0.49
	1.7	1.38	0.14	0.69
	4	2.19	–	0.69
Cotton	1.7	0.66	0.036	0.095
	4	1.07	–	0.159



7.6 Regain versus relative humidity for cotton [13], viscose rayon [14], acetate [14], silk [15], wool [16], nylon [17], *Terylene* polyester (PET) [18] and *Orlon* acrylic [18].

absorption regains ranging from 6.76% for a Texas cotton to 7.19% for a Peruvian cotton. After soda-boiling to remove impurities, the difference between these two cottons decreased to 0.12%. Processing, especially wet processing, may cause large changes in the amount of moisture absorbed. There are two principal effects: a removal of highly absorbing non-cellulosic impurities; and a change in the internal arrangement of the cellulose molecules. Heating the sample dry lowers the curve of regain against relative humidity, but wet heating raises it. Mercerisation without tension can increase the regain at a given relative humidity to 1.5 times its previous value; mercerisation under tension does not cause such a large increase [19].

A sample of cotton straight from the boll of the cotton plant or immediately after hot-wet processing shows a desorption curve higher than the usual one (Fig. 7.7). This is known as the *primary desorption curve*. Once the material has been dried below 50% r.h., it follows the usual curves. The intermediate curves for cotton are very long, as shown in Fig. 7.8. For example, if absorption is started from 10% r.h. on the desorption curve, the absorption curve will not be joined below 80% r.h. To be sure of getting on either the absorption or the desorption curve, it is necessary to start from almost complete dryness or wetness, respectively.

The effects of processing were shown to a marked extent by experiments by Gu [26] on naturally coloured green cotton, which contained 14.19% of fat, lignin and pectin, compared with 1.8% in white cotton. The moisture regain of the green cotton was 3.87% and of white was 8.6%. After treatments in NaOH solutions of varying

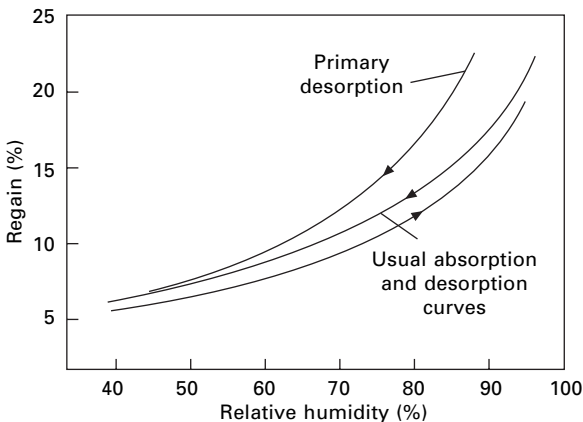
Table 7.3 Moisture absorption of fibres. Based on data by Ford [19] and other workers

Material	Recommended allowance or commercial regain or conventional allowance* (%)	Absorption regain at 65% r.h. 20 °C** (%)	Desorption regain minus absorption regain at 65% r.h. 20 °C** (%)
Cotton [13]	8.5	7–8	0.9
Mercedised cotton [20]	–	up to 12	1.5
Hemp [21]	12	8	–
Flax [21]	12	7	–
Jute [22]	13.75	12	1.5
Viscose rayon [14]	13	12–14	1.8
Secondary acetate [14]	9	6, 6.9	2.6
Triacetate	–	4.5	–
Silk [15]	11	10	1.2
Wool [16]	14–19	14, 16–18	2.0
Casein [23]	–	14	1.0
Nylon 6.6, Nylon 6 [17]	5 ³ / ₄ or 6 ¹ / ₄	4.1	0.25
Polyester [18]	1.5 or 3	0.4	–
Acrylic	–	1–2	–
Modacrylic	–	0.5–1	–
Polyvinyl alcohol [18]	–	4.5–5.0	–
Polylactic acid [24]	–	0.4–0.6	–
Para-aramid (Kevlar, Twaron)	–	low modulus 7 to high modulus 1.2	–
Meta-aramid (Nomex)	–	5	–

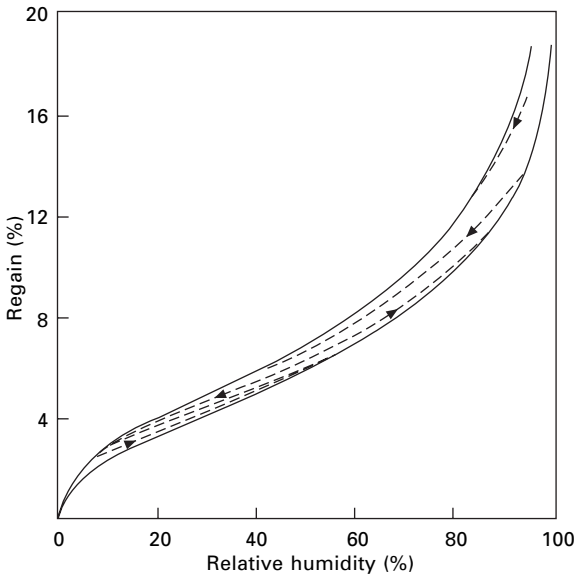
Polyethylene, polypropylene, polyvinyl chloride, carbon, glass and ceramic fibres have zero moisture absorption.

*As given in BS 4784:1973; other standardising organisations may quote different values.

**The earlier measurements were at 70 °F (21.1 °C).



7.7 Primary desorption curve of raw cotton from boll. From Urquhart and Eckersall [9].



7.8 Intermediate curves for raw cotton. The outer full lines are for absorption and sorption between 0 and 100% rh; The inner dashed lines are for absorption and desorption between intermediate humidities. From Urquhart and Eckersall [9].

strengths at different temperatures and for different times, the regain of the green cotton increased to 7.53–8.69%.

Viscose rayon has regain values that can be obtained by multiplying the regain values for cotton at the same humidity by an almost constant factor. For a particular specimen of viscose rayon, the figures were [14]:

r.h. (%)	5	20	40	60	80
Regain of viscose rayon/regain of cotton	1.99	2.13	2.08	2.03	1.98

For other specimens of viscose rayon, this ratio, which is often called the *sorption ratio* of the material, may not be as close to 2 as the values quoted, but it is a general feature of cellulosic fibres that their sorption ratios remain almost constant over the whole range of humidity.

Taylor's results [11] (Table 7.2) show that, although the absorption regain of viscose rayon is twice that of cotton, the difference between the desorption and absorption regains at low humidities is four times that of cotton. Above 30% r.h., this behaviour is reversed and cotton shows the greater hysteresis, in proportion to its regain.

Acetate has a curve of a different shape and does not show a rapid rise of regain at low humidities. The regains are lower than those of cotton, but the rate of change of regain with r.h. in the practical range above 20% r.h. is about the same.

Wool has a regain curve close to that of viscose rayon but of slightly different

shape. In particular, at high humidities the regain of wool is lower. The type of wool and its processing also affect the regain values. For example, Speakman [16] found regains at 63.3% r.h. ranging from 13.97% for a merino wool to 14.54% for a Wensleydale. Nicholls and Speakman [27] have shown that acid-treated wool has a lower equilibrium regain; thus, at 53.8% r.h., untreated wool had a regain of 12.68%, but wool containing 40 milliequivalents of acid per gram of wool had regains ranging from 11.89% for sulphuric acid to 9.79% for picric acid.

Figure 7.9, from Speakman and Cooper [28], shows that the intermediate hysteresis curves for wool are shorter than those for cotton, a change of 18% r.h. being sufficient to pass between the main absorption and the main desorption curves. This range is independent of the value of the regain.

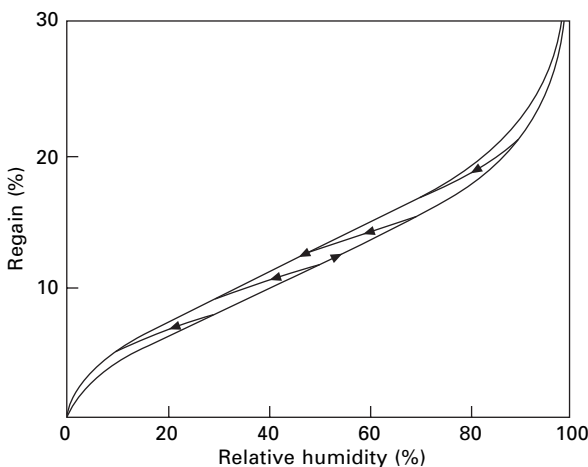
Casein fibres have regains very close to those of wool at the same humidity but show a rather large difference between absorption and desorption values [23].

Silk has a regain intermediate between cotton and wool. Silk gum has a high regain, and the degumming causes a reduction in regain at 65 r.h. from 10.65 to 9.9% [15].

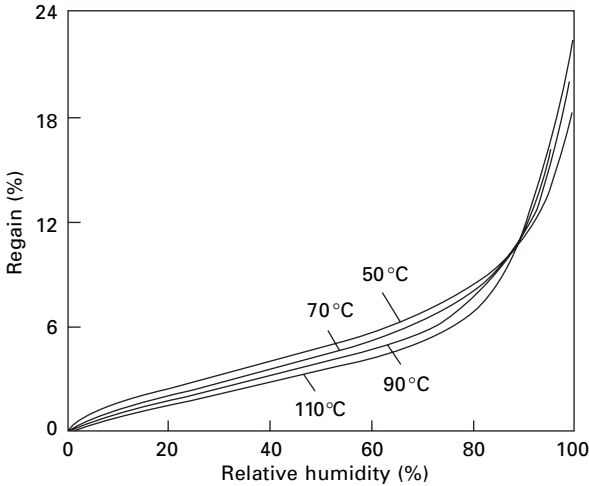
The synthetic fibres have low regains. Nylon has about half the regain of cotton. Some workers have suggested that hysteresis is absent, but Hutton and Gartside [17] showed that a small hysteresis definitely existed. At 80% r.h., they obtained regain values of 5.48% in absorption and 5.64% in desorption. Forward and Smith [29] have shown that the moisture absorption of undrawn nylon yarn can be appreciably altered by chemical treatment. Polyester (PET) fibres have a small regain. Many other polymer fibres have zero moisture absorption, as do inorganic fibres.

7.4.3 Influence of temperature

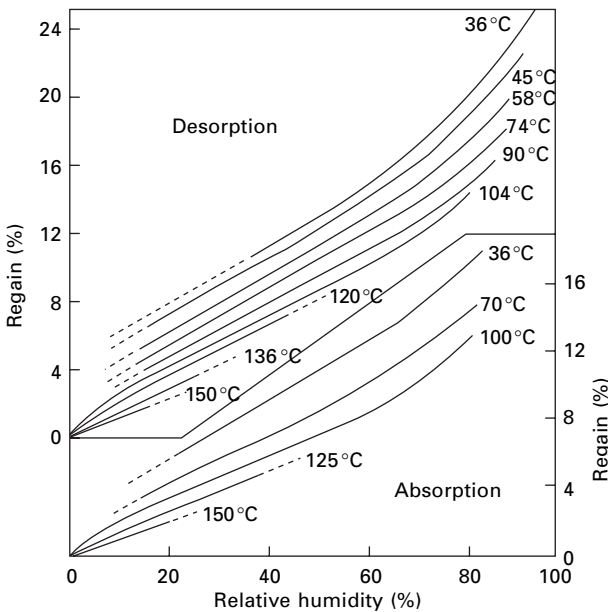
The curves of regain against relative humidity depend to a slight extent on temperature, the result being a family of isothermals. Figure 7.10 shows data for cotton. Except at



7.9 Intermediate curves for wool. The outer full lines are for absorption and sorption between 0 and 100% rh; the crossing lines are for absorption and sorption between intermediate humidifier From Speakman and Cooper [28].



7.10 Effect of temperature on absorption of cotton. From Urquhart and Williams [30].



7.11 Effect of temperature on absorption of wool. From Wiegerink [31].

high temperatures and humidities, the regain decreases as the temperature increases. This is the expected thermodynamic behaviour for an exothermic reaction such as absorption. The increase above 50 °C at high humidities is due to a change in the internal structure and is associated with the irreversible hysteresis effects.

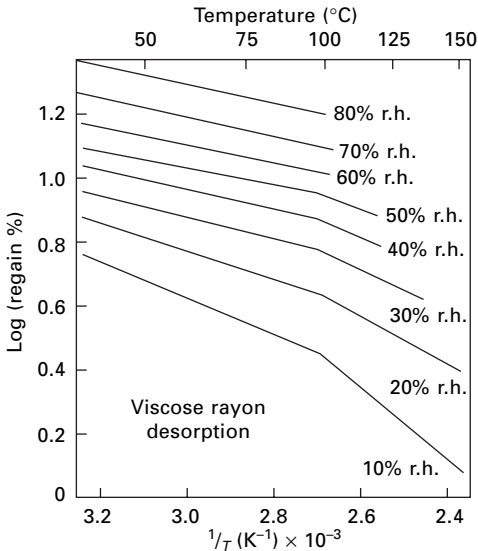
Wiegerink [31] tested a variety of fibres between 35 and 150 °C, and the curves for wool, shown in Fig. 7.11, are typical of his results. He found that when the logarithms

of the regains were plotted against the reciprocal of temperature, straight lines were obtained, with a change of slope at about 100 °C. Figure 7.12 illustrates this for viscose rayon. Darling and Belding [32] tested the same materials at low temperatures, but, owing to the slowness of conditioning, they were able to test only at a limited set of conditions. Their results indicate that the linear relations cease to apply below 20 °C. Below about 0 °C, the regain decreases. Values for the regain at 70% r.h. are given in Table 7.4.

7.4.4 Effect of stresses

The swelling of fibres during absorption means that the application of stresses will change the regain. Table 7.5 shows the increases in regain due to the application of a tension to filaments that were reported by Treloar [33, 34].

By contrast, the lateral compression of fibres, such as would come from applying tension to a twisted yarn, would lower the regain. For example, Nickerson [35] states



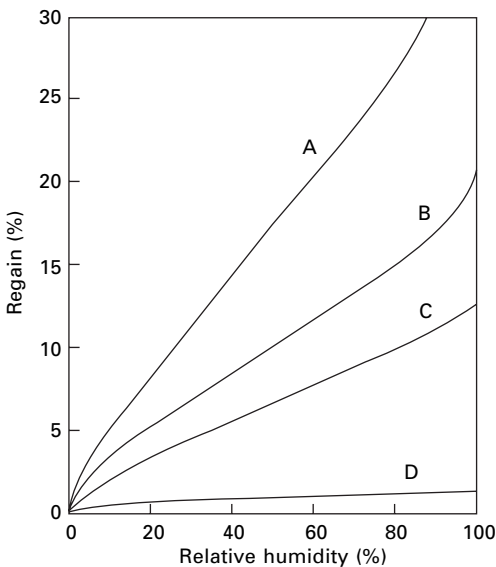
7.12 Effect of temperature on absorption of viscose rayon. T is absolute temperature in Kelvin (K). From Wiegerink [31].

Table 7.4 Change of regain with temperature [32]

Temperature (°C)	Regain at 70% r.h.			
	Cotton	Wool	Viscose rayon	Secondary acetate
-29	8.5	17	16	7.9
-18	9.8	18	17	9.6
4	9.7	17.5	17	9.0
35	7.8	15	14	7.1
71	6.7	13	12	6.2

Table 7.5 Effect of axial applied stress on moisture absorption at 75.5% r.h., 25 °C. From Treloar [33, 34]

Isotropic cellulose		Oriented cellulose		Horsehair	
Stress (MPa)	Increase in regain (%)	Stress (MPa)	Increase in regain (%)	Stress (MPa)	Increase in regain (%)
5.7	0.2	10.2	0.1	25.8	0.14
10.2	0.4	17.7	0.4	47.3	0.28
13.6	0.6	35.6	1.1		
27.4	1.5				
40.5	1.1				



7.13 Absorption of spruce wood under stress: (A) material completely free of stress; (B) natural sorption, including internal restraints on swelling of block of wood; (C) volume of block of wood held constant, but allowing swelling into void spaces in wood cells; (D) wood cell walls (internal and external) held at constant volume.

Curve B is experimental; remainder are calculated. From Barkas [36].

that the application of 60% of its breaking load to a cotton yarn lowered the regain from 8.78 to 8.19%. Barkas [36] has studied this effect in wood, and the curves in Figure 7.13 show the large changes that can occur when severe restraints are applied.

7.5 References

1. T. Schloesing. *Compt. Rend.*, 1893, **116**, 808.
2. G. F. Davidson and S. A. Shorter. *J. Text. Inst.*, 1930, **21**, T165.
3. M. Stephenson. *J. Text. Inst.*, 1938, **29**, T297.

4. W. L. Balls. *J. Text. Inst.*, 1950, **41**, T127.
5. G. LeCompte and H. H. Lipp. *Amer. Dyest. Rep.*, 1949, **38**, 484.
6. A. D. McLaren and J. W. Rowen. *J. Polymer Sci.*, 1951, **7**, 289.
7. F. L. J. van Lamoen and H. Borsten. *Tex.*, 1953, **12**, 861.
8. E. H. Jones. *J. Sci. Instrum.*, 1940, **17**, 55.
9. A. R. Urquhart and N. Eckersall. *J. Text. Inst.*, 1930, **21**, T499.
10. D. K. Ashpole. *Proc. Roy. Soc.*, 1952, **A212**, 112.
11. J. B. Taylor. *J. Text. Inst.*, 1952, **43**, T489.
12. J. B. Taylor. *J. Text. Inst.*, 1954, **45**, T642.
13. A. R. Urquhart and A. M. Williams. *J. Text. Inst.*, 1924, **15**, T138.
14. A. R. Urquhart and N. Eckersall. *J. Text. Inst.*, 1932, **23**, T163.
15. E. A. Hutton and J. Gartside. *J. Text. Inst.*, 1949, **40**, T161.
16. J. B. Speakman. *J. Soc. Chem. Industr.*, 1930, **49**, 209T.
17. E. A. Hutton and J. Gartside. *J. Text. Inst.*, 1949, **40**, T170.
18. R. Hill (Editor). *Fibres from Synthetic Polymers*, Elsevier, Amsterdam, Netherlands, 1953.
19. J. E. Ford. *Fibre Data Summaries*, Shirley Institute, Manchester, 1966.
20. A. R. Urquhart and A. M. Williams. *J. Text. Inst.*, 1925, **16**, T155.
21. F. Howlett. *J. Text. Inst.*, 1942, **33**, T102.
22. A. Powrie and J. B. Speakman. *J. Text. Inst.*, 1943, **34**, T77.
23. R. L. Wormell. *New Fibres from Proteins*, Butterworths, London, 1954, p. 129.
24. D. W. Farrington, J. Lunt, S. Davies and R. S. Blackburn. in *Biodegradable and Sustainable Fibres*, R. S. Blackburn (Editor), Woodhead Publish Cambridge, 2055, p. 191.
25. A. R. Urquhart and A. M. Williams. *J. Text. Inst.*, 1926, **17**, T38.
26. H. Gu. *J. Textile Inst.* 2006, **96**, 247.
27. C. H. Nicholls and J. B. Speakman. *J. Text. Inst.*, 1954, **45**, T267.
28. J. B. Speakman and C. A. Cooper. *J. Text. Inst.*, 1936, **27**, T183.
29. M. V. Forward and S. T. Smith. *J. Text. Inst.*, 1955, **46**, T158.
30. A. R. Urquhart and A. M. Williams. *J. Text. Inst.*, 1924, **15**, T559.
31. J. G. Wiegerink. *Text. Res.*, 1940, **10**, 357.
32. R. C. Darling and H. S. Belding. *Industr. Engng Chem.*, 1946, **38**, 524.
33. L. R. G. Treloar. *Trans. Faraday Soc.*, 1952, **48**, 567.
34. L. R. G. Treloar. *Trans. Faraday Soc.*, 1953, **49**, 816.
35. R. F. Nickerson in *Matthews' Textile Fibers* H. R. Mauersberger (Editor), 6th edition, Wiley, New York, 1954, p. 212.
36. W. W. Barkas. *The Swelling of Wood under Stress*, Svenska Träforskningsinstitutet Meddelande 61, Stockholm, 1950, p. 35. (See also: W. W. Barkas. *The Swelling of Wood under Stress*, HMSO, London, 1949.)