3. Fibre Biology (How Fibre Properties are Determined)

This chapter outlines the properties of cotton fibre, its development, and key factors that influence the development of the fibre.

The Cotton Fibre

Cotton fibres form from single cells that begin their development on the seed coat of unfertilised seeds (ovules) just prior to flowering. A mature or fully ripened cotton fibre consists of about 96% pure cellulose (a naturally occurring crystalline carbohydrate polymer). In nature, the function of cotton fibres on the seed in wild species may be related to seed dispersal to new locations by floating on water, and protection against herbivores and extreme climate conditions. The fibre itself consists of a primary and secondary cell wall. The primary wall is covered with a cuticle consisting of mainly wax and consists of fibrils (very small fibres) placed on a wide angle to the axis (approximately horizontal) which adds little to fibre strength. The secondary wall which makes up 90% of fibre weight consists of cellulose fibrils arranged in a layered helical structure. This layer contributes greatly to the tensile properties of the cotton fibre.

Cotton Fibre Development

Cotton fibre development can be divided into four phases: initiation, elongation, secondary wall thickening, and maturation. These phases will be discussed in more detail below.

Fibre Initiation

Fibre initiation on an ovule starts one to two days before flowering, beginning at the chalazal (round) end of the seed and moving towards the micropylar (pointy) end of the seed (see Figure 3.1). The time for initiation sometimes takes up to three days from one end to of the seed to the other. On the day of flowering most of the fibre cells on the seed coat have swelled into small balloons (Figure 3.1), although some fibres can still be initiated four to five days later. This ballooning stage is considered critical to determining fibre perimeter. Following this initial burst of fibre initiation a second set of fibres are initiated on the seed. These develop into the fuzz left on cotton seed following ginning. The majority of fibres that initiate remain as fuzz (up to 80%).

The number of fibres initiated can vary between 12,000 and 20,000 per seed and is also variety dependant. There is little understanding of the effects of plant stress on fibre initiation although stress is known to reduce the number of fruit, ovules per fruit and seeds per ovule.

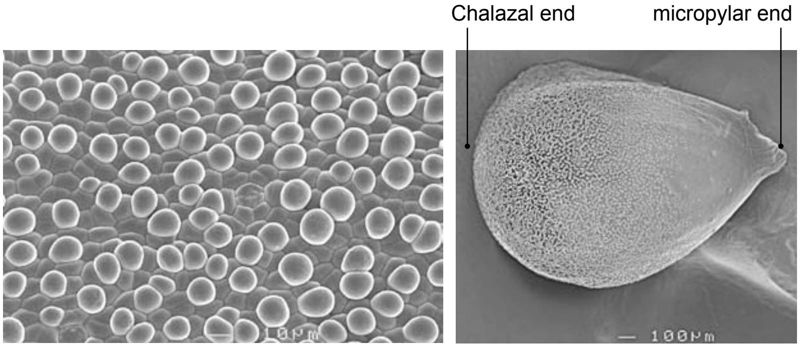

Figure 3.1: Fibres initiating on a seed in the boll at flowering. Note that fibres at the chalazal (round) end of the seed are initiated first. (Photos: Rosemary White, CSIRO).

Fibre Elongation

Fibre elongation (Figure 3.2) does not start until flowering despite some fibres having been initiated a few days before this. From flowering fibres elongate for up to 25 days, reaching variable lengths. The elongation period and the rate of fibre elongation in this period determine the final length of fibres (the reason for differences between varieties). This is well illustrated by Pima which has a longer fibre elongation period and long fibre length. Across the seed, average fibre length decreases from the chazal (round) end of the seed to the micropyle (pointy) end.

Elongation is the onset of a process in which fibre length increases 1000 to 3000 times the diameter of the cell. The tubular hair cells that form consist of a very thin cuticle, a thin primary wall (only about 30% cellulose), a cytoplasmic layer and a large vacuole (lumen) (Figure 3.3). The rapid expansion of the fibre cell is controlled by internal water pressure (turgor), which stretches the primary wall like an inflating balloon. To enable this massive extension, the cell must be able to incorporate both expansion and new growth of cell wall material. New growth occurs especially at the fibre tip but diffuse growth occurs over its entire surface. This prodigious growth of the fibre cell can only result from: considerable metabolic activity; a fast and consistent uptake of large amount of substrate into the cell; and formation of a strong primary wall.

The large and vigorous demand on the plant during fibre lengthening makes this process very sensitive to stress. The environment therefore plays an important role in whether fibre length reaches the genetic potential (determined by variety). Firstly, to maintain turgor, the cell must have ready access to potassium, solutes and water to regulate osmosis into the vacuole and produce the turgor pressure essential for fibre elongation. Severe water stress or potassium deficiency will reduce turgor pressure and result in shorter fibres. Temperature also plays an important role in regulating the rate of fibre elongation and influencing the duration of fibre elongation. Cool temperatures may reduce the rate of elongation but this effect will often be compensated by having a longer fibre elongation period.

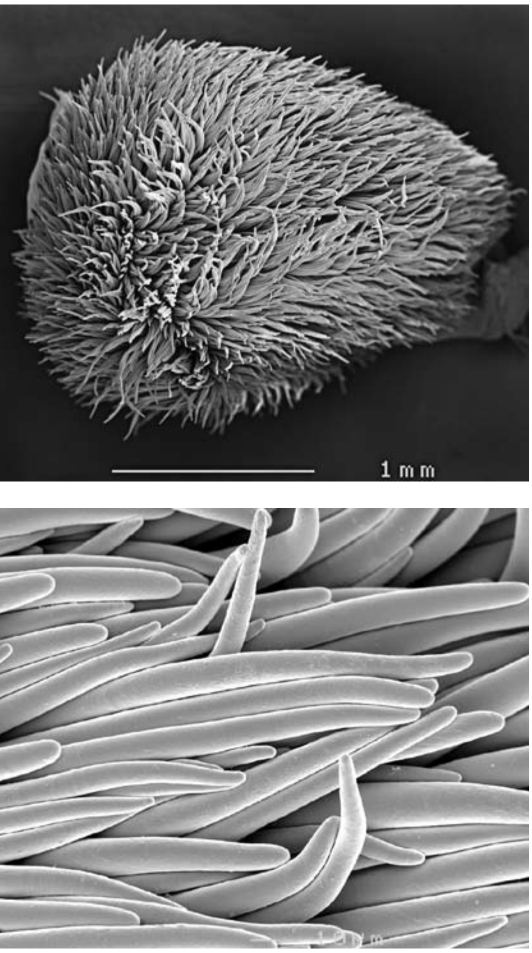

Figure 3.2: Fibres beginning their elongation. (Photos: Rosemary White, CSIRO).

High temperatures and stress however, may reduce fibre length as the elongation period is shortened and access to substrates is limited.

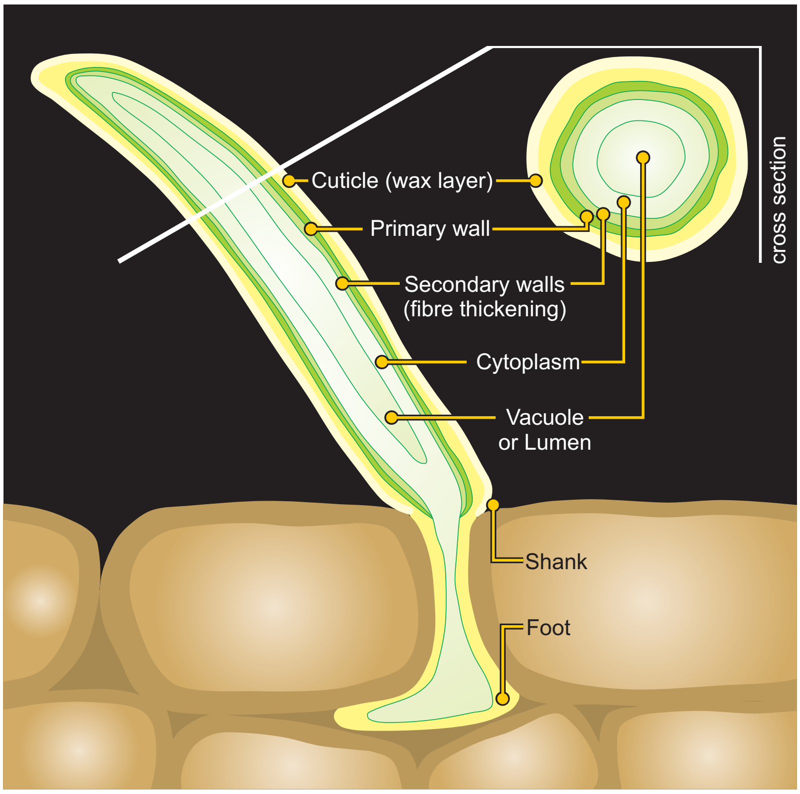

Figure 3.3: A diagrammatic representation of the internal structure of an individual fibre attached to the wall of a seed.

Fibre Thickening

Fibre thickening is sometimes referred to as the secondary wall formation phase. It is the phase where cellulose is laid down in winding sheets on the inner surface of the primary wall of the fibre cell. As a result the cytoplasm is pushed towards the interior of the cell and the vacuole (lumen) is reduced in size. More than 90% of the fibre weight is made up of the secondary wall. Fibre thickening occurs over a period of approximately 40 days but this can vary depending on cotton species, variety and environment. Some overlap of up to 5 to 10 days occurs between the end of the fibre elongation and the start of the fibre thickening phases.

Photosynthesis is the process by which plants convert carbon dioxide and water using light of the day and chlorophyll present in the leaves to produce carbohydrates for energy needed by the plant (e.g. glucose), and cellulose used for the formation of structural components contained within the plant. A further by-product is oxygen. Hence the degree of deposition of cellulose in the fibre cell is significantly affected by factors that affect photosynthesis. As cotton plants are subjected to fluctuations in the levels of photosynthesis and growth on a daily basis, the production of secondary wall in the fibre forms growth rings like a tree (Figure 3.4). However, unlike a tree where growth rings are deposited on outside of last year's growth, a cotton fibre's growth rings are deposited on the inside of the previous day's growth. A fibre growth ring is made up of two layers: the compact layer that is laid down during the day; a porous layer that is laid down at night. Improved photosynthesis during the day will mean that there is a greater chance that the fibre growth ring for that day will be also thicker.

Cotton growth rings

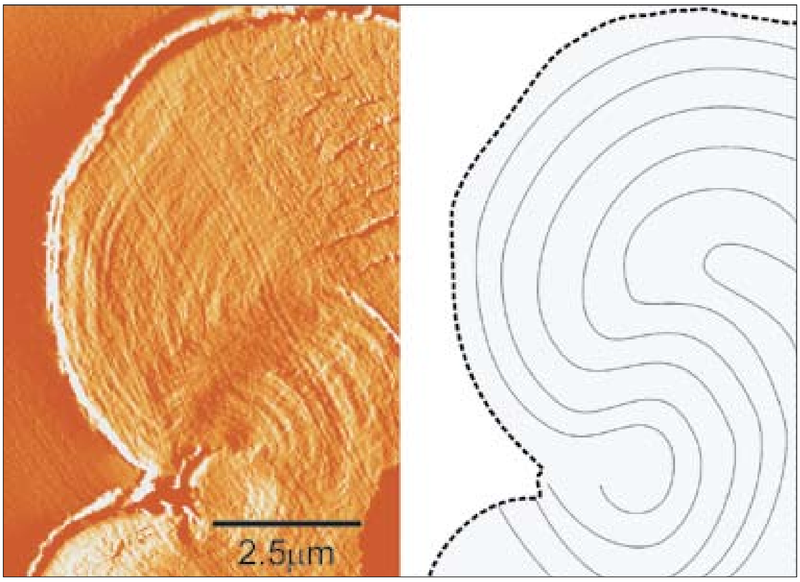

Figure 3.4: A cross section of a fibre showing concentric rings (reproduced with permission from Maxwell et al. (2003).

Fibre maturity is a term that is used to refer to the degree of development or thickening of a fibre (which contributes to the Micronaire measurement incorporated in HVI (High Volume Instrument) testing). The thicker the layers of cellulose during fibre thickening the more mature the fibre. Insufficient supplies of carbohydrate for cellulose production will cause fibres to be more immature. Fibre maturity is an important property for both the physical and chemical processing properties of cotton fibres. Immature fibre is more prone to nep formation and do not take up as much dye as mature fibres. A nep is an entanglement of fibres resulting from mechanical processing (see chapter on importance of quality).

HVI (High Volume Instrument)

HVI (High Volume Instrument) lines are assembled and automatically linked fibre testing instruments that enable quick, objective measurement of fibre quality characteristics of cotton. HVI lines currently measure colour grade, length, Micronaire, strength, length uniformity index. Manual classers still largely determine the leaf, extraneous matter and preparation grades of cotton.

Immature fibre results from effects on photosynthesis during secondary wall thickening. Some reasons for this include:

- Early termination of leaf function (e.g. early defoliation or frost).
- Excessive internal competition within the plant for carbohydrates from photosynthesis needed for boll growth. This is often associated with high boll loads.
- Late season cloudy and/or cool temperatures reducing photosynthesis.
- Water stress causing reductions in leaf area or direct reductions as a result of leaf stomates closing reducing transpiration and then photosynthesis.
- Premature senescence caused by nutrient deficiency (such as potassium, phosphorus, nitrogen, etc.) as a result of high boll load. The loss of leaf area can reduce photosynthesis.

The strength of cotton fibres is related to the degree of wall thickening. Importantly however, substantial differences in strength of fibres will depend on the chemical structure or the cellulose being laid down in the secondary wall. The longer the cellulose molecule chains that are laid down the stronger the fibre. It is analogous to the length of fibres needed for yarn strength (longer fibres mean stronger yarn (see yarn production chapter). The different fibre strength in varieties is related to composition of the cellulose.

Micronaire, Fineness, Fibre Maturity, Linear Density and Fibre Perimeter?

When these terms are used in FIBREpak they will use these following definitions (also see Figure 3.5).

Fibre Linear Density or Fibre Fineness – Cotton fineness is described in terms of linear density or weight per unit length of fibre, the unit for which is usually milligrams per kilometre (mtex) or μg/m. FIBREpak will use the term linear density.

Fibre Maturity – The degree of wall thickening increases as the fibre matures. Historically maturity ratio was assessed under the light microscope by counting the proportions of mature and 'immature' fibres in a sample swollen in concentrated caustic soda. The scale for this ratio has a theoretical range between 0.2 and 1.2, where cotton samples with a value greater than 0.85 are regarded as mature, and samples with a value less than 0.85 are immature. More recently with the advent of fibre cross-section and image analysis techniques the degree of wall thickening (denoted θ - theta) has been used as reference measure of fibre maturity. The degree of thickening is defined as the ratio of the cell wall area to the area of a circle with the same perimeter as the fibre cross-section (Figure 3.5). The value has a theoretical range of between 0.0 and 1.0. An empirical scaling factor is used to convert theta values to maturity ratio values.

Fibre Perimeter – Refers to the perimeter of the cross-section of a fibre. The perimeter is often considered to be genetically determined. It is an important property that contributes to differences in fibre linear density and the number of fibres that exist in the yarn cross section.

Micronaire – Airflow measurement based on the pressure difference obtained when air is passed through an accurately weighed plug of cotton fibres. The method measures specific surface area (surface area per unit mass) and reflects a combination of the sample's linear density and fibre maturity. Reducing fibre linear density or fibre maturity (e.g. by reducing cell wall thickness) results in more fibres in the plug increasing airflow resistance lowering Micronaire. FIBREpak will not use the term Micronaire when fibre linear density or fibre maturity are discussed specifically.

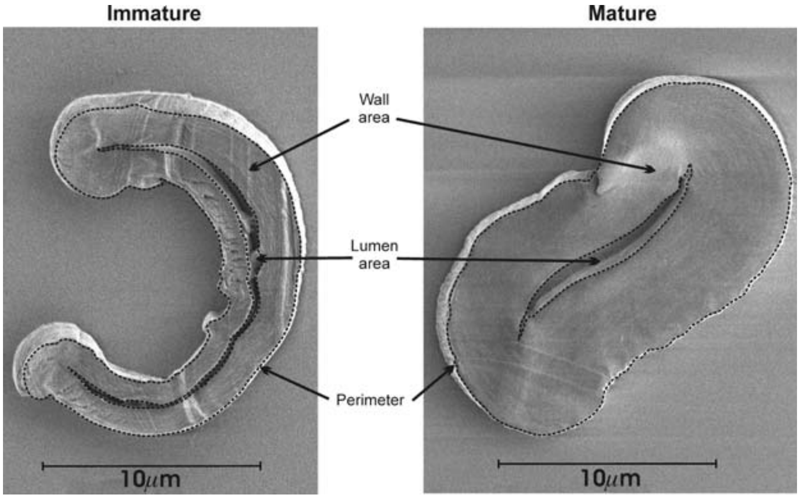

Figure 3.5: Fibre cross sections showing fibre perimeter and differences in wall area that lead to differences in fibre maturity. Units are micrometres. (Photos: CSIRO).

Fibre Maturation

As a boll matures the seed coat oxidises (turns black) and the lint cells (fibres) lose water causing the vacuole (lumen) to collapse and the fibre to die. The fibres are no longer cylindrical or tubular in structure, rather they become twisted ribbon-like (crimped) structures (Figure 3.6) with a kidney (bean) shaped cross section (Figure 3.5).

Fibres can have few to many twists that can change direction at frequent intervals along their length. Twist in a fibre is influenced by fibre maturity (secondary wall thickness), the size of vacuole (lumen) remaining, as well as the perimeter of the fibre. The direction of the twist in the fibre reflects the orientation of the microfibrils laid down during secondary wall thickening.

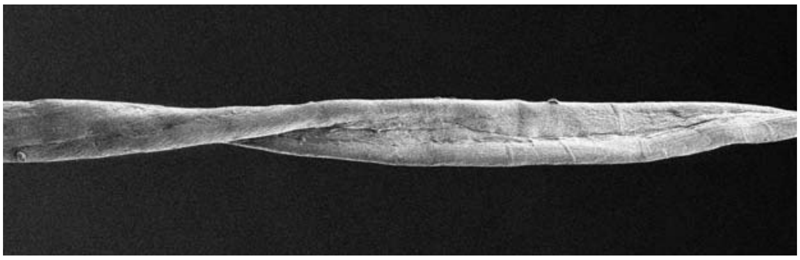

Figure 3.6: A mature cotton fibre showing fibre twists (convolutions). (Photo: Margaret Pate, CSIRO).

Mature fibres are easily detached from the seed and only fuzz remains. The presence of fuzz is genetically controlled, and in some instances no fuzz is present and the seed is naked (e.g. Pima). During fibre development the fibre base spreads out broadly into a flattened foot into the surrounding cells on the surface of the seed to anchor the fibre to the seed (Figure 3.3). However, the diameter of the fibre at the base near the seed is less. This allows the fibres to break close to the seed coat and be easily removed during ginning. This point, where the secondary wall is thinnest is sometimes referred to as the shank and is where most fibres break during ginning. Varieties can differ in the force required to separate the fibre from the seed at this point of attachment and this can be a significant factor in determining the quality of fibre resulting from the ginning process.

Figure 3.7 shows the timing of fibre elongation and fibre thickening. Fibre length is determined and finalised in the first one-third of boll development time (250 day degrees or about 20 days at normal temperature). Fibre thickening which effects Micronaire is then determined in the last two-thirds of boll development (from 250 to 750 day degrees, or about days 20 to 60 from flowering). Fibre maturing and drying occurs between about 650 and 750 day degrees from flowering.

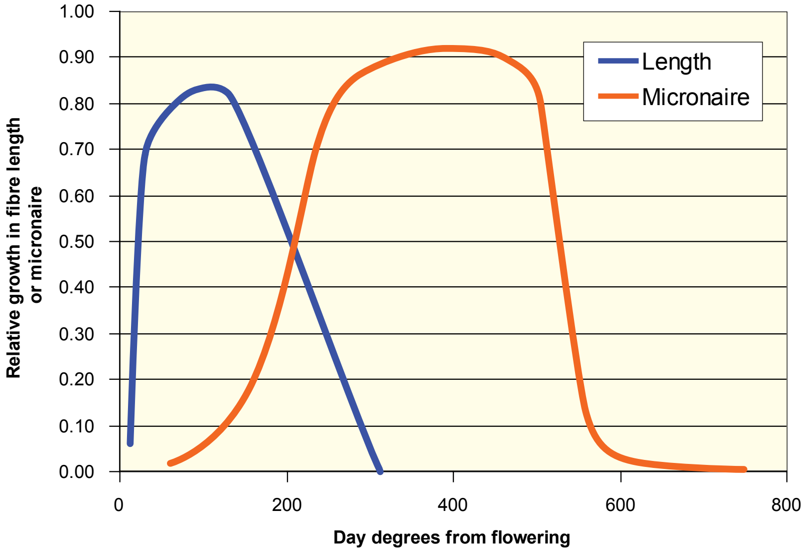

Figure 3.7: Stages of fibre development within a single boll.

Cotton Fibre Quality and its Relationship to Yield

Fibre properties can be strong yield components. It stands to reason that if a plant has more, longer or heavier fibres then it should have a higher yield. We see in the example given in Table 3.1 that longer and more mature or coarse fibres (those with greater linear density) contribute to higher yields even when boll number and seeds/boll remain equal. So it may appear that achieving high yields and quality together seems straightforward. However, the problems breeders face is that improved fibre quality attributes are often genetically associated with lower yield. This is especially the case when breeders select for long, strong and fine fibres. The cause of this negative association is not well understood. It could be genetic, or simply related to how the fibre develops and grows relative to the rest of the plant.

Table 3.1: Fibre quality attributes are strong yield components. Note that changes in fibre length (A to B), fibre linear density (often referred to as fineness) (B to C) and fibres/seed (C to D) can lead to changes in yield even when boll size and number remain similar.

Component	**A**	**B**	**C**	**D**
bolls/m (no)	100	100	100	100
seeds/boll	30	30	30	30
fibres/seed (no)	15,000	15,000	15,000	**18,000**
length (inch)	1.15	**1.20**	1.20	1.25
uniformity (%)	82	82	82	82
linear density (ug/m)	170	170	**190**	**160**
yield (kg lint/ha)	1645	1716	1918	2019

Breeders continue to scan large populations of cotton in order to identify instances where the negative relationship between quality and yield is less evident. This provides opportunities for progress on improving combinations of high yield and improved fibre quality. Understanding the linkages between yield and fibre quality is a subject of current intensive research. With these efforts breeders will continue to progress improved yield and fibre quality combining traditional breeding with biotechnology traits and tools.

Further Reading

Benedict CR, Smith RH, Kohel RJ (1973) Incorporation of 14C-photosynthate into developing cotton bolls, *Gossypium hirsutum* L. Crop Sci. 13, 88-91.

Schubert AM, Benedict CR, Berlin JD, Kohel RJ (1973) Cotton fiber development – kinetics of cell elongation and secondary wall thickening. Crop Sci. 13, 704-709.

Basra AS (1999) Cotton Fibres: Developmental Biology, Quality Improvement, and Textile Processing. (Haworth Press, United States of America).

Maxwell JM, Gordon SG, Huson MG (2003) Internal structure of mature and immature cotton fibers revealed by scanning probe microscopy. Textile Research Journal 73:1005-1012.

Constable GA and Bange MP (2007) Producing and preserving fiber quality: from the seed to the bale. In Proc. 4th World Cotton Conf. (Lubbock, USA).