Article

Fractal Dimensions of Cell Wall in Growing Cotton Fibers

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Abstract: In this research, fractal properties of a cell wall in growing cotton fibers were studied. It was found that dependences of specific pore volume (P) and apparent density (ρ) on the scale factor, $F = H/h$, can be expressed by power-law equations: $P = P_0 F^{(D_v - E)}$ and $\rho = \rho_0 F^{(E - D_\rho)}$, where h is minimum thickness of the microfibrillar network in the primary cell wall, H is total thickness of cell wall in growing cotton, $D_v = 2.556$ and $D_\rho = 2.988$ are fractal dimensions. From the obtained results it follows that microfibrillar network of the primary cell wall in immature fibers is loose and disordered, and therefore it has an increased pore volume ($P_0 = 0.037 \text{ cm}^3/\text{g}$) and low density ($\rho_0 = 1.47 \text{ g/cm}^3$). With enhance days post anthesis of growing cotton fibers, the wall thickness and density increase, while the pore volume decreases, until dense structure of completely mature fibers is formed with maximum density (1.54 g/cm^3) and minimum pore volume ($0.006 \text{ cm}^3/\text{g}$). The fractal dimension for specific pore volume, $D_v = 2.556$, evidences the mixed surface-volume sorption mechanism of sorbate vapor in the pores. On the other hand, the fractal dimension for apparent density, $D_\rho = 2.988$, is very close to Euclidean volume dimension, $E = 3$, for the three-dimensional space.

Keywords: cotton fibers; growth; cell wall; specific pore volume; apparent density; fractal dimension

1. Introduction

Cotton is known to be an important source of natural cellulose [1]. In particular, cotton is a source of long natural textile fibers, while short cotton fibers (linters) and residues (e.g., fluff) are used to produce micro- and nano-cellulose, cellulose derivatives, special paper, and many other products.

Cotton cellulose is biosynthesized in living cells—short and thin fibers (seed-hairs), as follows. After flowering cotton flower, a seed boll is formed, in which the seed-hairs, i.e., immature cotton fibers, begin to grow out from these seeds [2]. The growth and development of cotton fibers take place in two main stages [3,4]. In the first stage, 15–20 days post anthesis (DPA), a thin primary cell wall is biosynthesized; furthermore, immature fibers lengthen extremely to 25–30 mm due to growth mechanism by stretching without change in thickness of the primary cell wall. Electron microscopy studies showed that the primary cell wall of the fibers consists of microfibrillar network with a thickness (h) of about $0.1 \text{ }\mu\text{m}$, which is embedded in a hydrophobic lipid matrix [5,6].

In the second stage, 20–60 DPA, the hydrophobic matrix is gradually destroyed; in addition, thick layers of cellulose microfibrils are biosynthesized and form the secondary cell wall. As a result, the total thickness (H) of cell wall increases extremely and reaches $4\text{--}6 \text{ }\mu\text{m}$ in mature cotton fibers. Taking into consideration a significant increase in the scale factor ($F = H/h$) during formation of the cell wall, the fractal approach can be used to predict some properties of the growing fibers.

Previously, the fractal theory was applied to analyze the porous structure of various materials [7–10]. In particular, for cellulose it was found that the process of nitrogen sorption by pores of various sizes can be described by a fractal with dimension from 2.1 to 2.5 [11]. The relationship between cumulative volume and pore radius in cellulose fibers had fractal dimension of 2.8–2.9 [12], whereas the

dependence of specific pore volume on radius of microcrystalline beads is expressed by a power-law equation with fractal dimension of about 2.9 [13].

The main objective of this research is to apply the fractal approach to the formation process of the cell wall in growing cotton fibers.

2. Materials and Methods

Fibers of cotton variety Acala H-23, species of *G. hirsutum*, were collected after 10 to 70 DPA. To remove lipids, the selected cotton samples were extracted with benzene-ethanol mixture according to TAPPI T-204 standard procedure. The lipid-free cotton fibers of the same DPA were taken to prepare ca. 50 cross-sections. These cross-sections were then examined using a Zeiss Axio Lab 5 microscope at magnification of 2500 to measure the thickness of cell wall. The arithmetic mean of the thickness value was calculated with a relative standard deviation $\pm 10\%$.

Sorption of hexane vapor by cotton fibers was measured at 25 °C with the use of *vacuum Mac-Ben apparatus* having helical spring quartz scales [14]. The specific pore volume (P , cm^3/g) of the fibers was calculated by the equation:

$$P = V/m, \quad (1)$$

where V is the total volume of pores (cm^3) measured at relative vapor pressure $P/P_0 = 0.98$; and m is the mass of the dry sample (g).

From the results of determination of specific pore volume, the apparent density of the samples can be obtained, as follows:

$$\rho = [P + V_c]^{-1}, \quad (2)$$

where $V_c = d^{-1}$ is the specific volume of cotton fibers having an average specific gravity $d = 1.55 \text{ g/cm}^3$.

3. Results

The studies have shown that dependence of cell wall thickness (H) on days post anthesis (DPA) has S-shape (Figure 1). With an enhance DPA from 20 to 50 days, the thickness, H , in growing cotton fibers increases rapidly, until it reaches its maximum value.

Figure 1. Dependence of cell wall thickness on days post anthesis (DPA) of cotton fibers.

Thickening of the cell wall with increasing DPA leads to a decrease in specific pore volume (P), but to enhance in apparent density (ρ) of cotton fibers (Table 1).

Table 1. Characteristics of cotton fibers of various age.

DPA	H, μm	F	P, cm^3/g	ρ , g/cm^3
20	0.1	1	0.034	1.473
25	0.4	4	0.023	1.498
30	1.0	10	0.013	1.519
40	2.5	25	0.010	1.527
50	4.3	43	0.007	1.534
60	4.7	47	0.006	1.536
70	4.8	48	0.006	1.537

Since the minimum thickness of the cell wall corresponds to the thickness of the microfibrillar network in the primary cell wall ($h \approx 0.1 \mu\text{m}$), a scale factor F can be calculated from the ratio $F = H/h$ (Table 1).

According to theory, the fractal dimension (D) can be determined from power-law dependence of the structure or property on the scale factor [10,15,16]. Therefore, in this study, the specific pore volume in growing cotton fibers was expressed as a power-law function of the scale factor, F [10,14]:

$$P = P_0 \cdot F^{(D_v - E)}, \quad (3)$$

where P_0 is the specific pore volume of immature cotton fibers having the primary cell wall only, D_v is the fractal dimension; $E = 3$ is the Euclidean dimension.

Similarly, the dependence of the apparent density on the scale factor, F, is the following [7,14]:

$$\rho = \rho_0 \cdot F^{(E - D_\rho)}, \quad (4)$$

where ρ_0 is apparent density of immature cotton fibers having the primary cell wall only, D_ρ is fractal dimension.

After logarithmization of the Equations (3) and (4), the linear graphs were drawn (Figures 2 and 3).

Figure 2. Linearized dependence of P on F in double logarithmic coordinates.

Figure 3. Linearized dependence of ρ on F in double logarithmic coordinates.

From these graphs, the constants and fractal dimensions were calculated:

For dependence of P on F : $P_o = 0.037 \text{ (cm}^3/\text{g)}$ and $D_v = 2.556$.

For dependence of ρ on F : $\rho_o = 1.474 \text{ (g/cm}^3)$ and $D_\rho = 2.988$.

4. Discussion

From the obtained results it follows that microfibrillar network of the primary cell wall in immature fibers is loose and disordered, and therefore it has an increased pore volume ($P_o = 0.037 \text{ cm}^3/\text{g}$) and low density ($\rho_o \approx 1.47 \text{ g/cm}^3$).

In the process of growth and development of cotton fibers, the biosynthesized dense and ordered microfibrillar bundles forming the secondary cell wall are wound on the primary wall. As a result, with enhanced DPA of growing cotton fibers, the wall thickness and density increase, while the pore volume decreases, until structure of completely mature fibers is formed with maximum density (1.54 g/cm^3) and minimum pore volume ($0.006 \text{ cm}^3/\text{g}$).

The fractal dimension for specific pore volume, $D_v = 2.556$, indicates the mixed, surface-volume, sorption mechanism of sorbate vapor in the pores. On the other hand, the fractal dimension for apparent density, $D_\rho = 2.988$, is very close to Euclidean volume dimension, $E = 3$, for the three-dimensional space.

5. Conclusions

In this research, it was shown that an enhance of days post anthesis (DPA) of growing cotton fibers leads to rapid increase in thickness and apparent density of cell wall, until the maximum value of these characteristics is reached. On the other hand, an increase of DPA causes rapid decrease in specific pore volume of cell wall until it reaches its minimum value. Fractal dimensions of growing cotton fibers have been studied. It was found that such characteristics of the fibers as specific pore volume and apparent density are power functions of the scale factor. As a result, with a rise in the scale factor, the apparent density increases, while the specific pore volume decreases. Thus, as cotton fibers grow and develop, their structure becomes more ordered. The obtained value of fractal dimension for specific pore volume, $D_v = 2.556$, evidences the mixed surface-volume sorption mechanism of sorbate vapor in the pores, while fractal dimension for apparent density, $D_\rho = 2.988$, is very close to Euclidean volume dimension $E = 3$.

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