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Dynamic moisture sorption behavior of cotton fibers with natural brown pigments

**Özgür Ceylan · Florence Goubet ·
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Abstract The moisture sorption behavior of white and naturally colored cotton fibers is studied by dynamic vapor sorption. Dark brown and brown fibers show a higher sorption capacity compared to beige and white fibers. The differences in sorption capacity are found to be related to the maturity and crystallinity index of the fibers. All fibers exhibited sorption hysteresis to varying degrees throughout the full relative humidity range. The variations in hysteresis behavior are mainly attributed to the differences in crystallinity index of the fibers. In addition the monolayer and polylayer moisture content is analyzed using the Hailwood Horrobin model. Monolayer sorption is most closely related to the crystallinity index and, to a lower extent, maturity of the fibers. For beige and white fibers monolayer sorption remains almost constant, whereas for darker fibers it shows a substantial increase with increasing color difference. In contrast, polylayer sorption shows a general increasing trend over the whole studied color spectrum.

Also a noticeable relationship was found between the total hysteresis and the monolayer sorption. Yet such relation was less evident for polylayer sorption. This study contributes to the better understanding of the dynamic moisture sorption behavior of white and naturally colored cotton fibers. This improved understanding is important for optimal application of naturally colored cotton fibers in novel materials.

Introduction

Increasing environmental concerns have stimulated the demand for organic textile products. Naturally colored cotton, comprising fibers with natural pigments, are considered potential eco-friendly materials because they reduce the need for costly and harmful textile processes such as bleaching, dyeing, and other finishing procedures. Also many qualities of colored cotton are considered to be insect and disease-resistant thus require less pesticide during growth (Dickerson et al. 1999). Other claimed properties include poor flammability as a lower limited oxygen index (Parmar and Chakraborty 2001).

As many commercial and technical performance aspects of cotton fibers are influenced by their response

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towards atmospheric humidity, a study on the moisture sorption is also of high interest for naturally colored fibers. The rapid sorption of water into the fiber internal structure is required for technical applications where high absorbency is required (Bredereck and Hermanutz 2005). However the hydrophilic nature of cotton fibers is a major problem for possible fiber reinforced composite applications. The water uptake involves dimensional changes and thus affects the fiber matrix adhesion which may reduce the mechanical strength of the composites (Kohler et al. 2006a, b). An understanding of the interaction of water with the cotton fiber structure is therefore crucial for the interpretation and prediction of the fiber performance in its end-use. In addition, new insights into this phenomenon are required to provide new opportunities to tailor moisture management properties of cotton fibers by means of plant breeding or other fiber modification techniques during growth.

The mechanism of moisture sorption in cotton fibers is very complex due to the continuous nanostructural changes associated with the dynamic behavior of the cell wall components and their structural properties (Xie et al. 2010a). Dynamic vapor sorption (DVS) is a well-suited technique to study the moisture sorption and the interaction of water molecules with a compound (Markova et al. 2001). The technique provides highly reproducible data and accurate isotherms over a wide relative humidity (RH) range at different user-set temperatures (Hill et al. 2009). Previous research reported on the sorption behavior of cotton fibers harvested at different stages in their development process (days post anthesis, DPA). The sorption mechanism during the elongation phase of the fiber was found to be significantly different from the one during the secondary cell wall synthesis (Ceylan et al. 2012). This knowledge will be further deepened on fully grown naturally colored cotton fibers in the present paper.

Fully grown cotton fibers consist of highly ordered less accessible crystalline regions and less ordered more accessible amorphous regions with different abilities to act as sorption sites (Siroka et al. 2008). Moisture is mainly absorbed in the amorphous regions of the fiber while in the highly ordered crystalline regions, water can only access the surfaces, but not penetrate into the crystallites (Gehlen 2010). Various models have been proposed to explain sorption isotherms of cellulosic materials (Brunauer et al.

1938; Taylor 1954; Hill 1950; Barrer 1947; Young and Nelson 1967; Kohler et al. 2006a, b; Kohler and Ausperger 2003). The Hailwood and Horrobin model (HH model) is a simple solid-solution model which was originally developed to describe sorption properties of cotton and was extensively used to investigate the sorption behavior of fibrous polymers and wood (Siau 1983; Yasuda et al. 1994; Watt and D'Arcy 1976; Bradbury 1963; Wangaard and Granados 1967; Xie et al. 2010a, b; Hailwood and Horrobin 1946). The HH model implies the formation of a solid solution where water absorbed by cotton can exist in two forms, namely, water of hydration corresponding to water molecules that are hydrogen bonded to the cell wall polymeric OH groups (monolayer water) and dissolved water corresponding to water molecules that are less constrained, but nonetheless are located within the cell wall micro voids (polylayer water) (Zaihan et al. 2009). The details of the model have been described by (Skaar 1972) and recently by (Hill et al. 2009).

The main objective of the present paper is to examine the sorption behavior of fully grown white and naturally colored fibers of different shades using DVS. Therefore the moisture sorption capacity as well as the hysteresis behavior in relation to maturity and crystallinity of the fibers are studied extensively. Moreover the HH model is used to evaluate the sorption kinetics of the fibers. The relationship between cotton and moisture is vitally important to such diverse characteristics as comfort, garment care, tensile strength or fiber matrix adhesion in composites. Thus the aim is to gain insights in the moisture sorption mechanisms of raw white and naturally colored cotton fibers to develop routes that improve or tune the moisture management properties of naturally colored cotton fibers, as relevant for an optimal future material benefit.

Experimental

Materials

White and different shades of naturally brown colored cotton (Gossypium hirsutum) fibers were supplied by Bayer CropScience N. V. (Ghent, Belgium). The plants were grown in similar conditions and harvested when mature. All fibers were used as received, without

any pre-treatment. Cotton fiber properties were determined in Cirad (Montpellier, France). A high volume instrument (HVI) is used to obtain micronaire values of cotton fibers. Micronaire is a measure of the cotton fiber's resistance to air flow per unit mass, and thus is an indicator of fiber fineness and/or fiber maturity (El Mogahzy and Broughton 1992; Rodgers et al. 2010). The maturity ratio of the fibers was determined using an advanced fiber information system (AFIS). The system quantifies circularity (θ) and cross-sectional area of the fiber by analyzing the light scattered at a 40° angle as fibers flow perpendicularly to the light beam with the help of a high-velocity air flow (Paudel et al. 2013). The maturity ratio is calculated from the Lord equation below (Lord and Heap 1988):

Maturity Ratio $= (N-D)/200 + 0.7$

where N is percentage of normal fibers ($\theta \geq 0.5$) and D is the percentage of dead fibers ($\theta \leq 0.25$).

Methods

UV–vis spectrophotometer

UV–vis spectra of fibers were recorded with a Perkin–Elmer Lambda 900 spectrophotometer, which is a double-beam spectrophotometer. For the reflection measurements on fibers an integrated sphere (Spectralon Labsphere 150 mm) was used. The spectra were recorded from 380 to 780 nm with a data interval of 5 nm.

The CIE Lab values were calculated based on the measured reflectance spectra using OPTI-LAB software for D65 illumination and a 2° observer. The color differences (ΔE^*) of the naturally colored cotton lines compared to a reference white fiber were calculated according to:

$$\Delta E = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$$

where L^*, a^* and b^* are the lightness, green–red coordinate and blue–yellow coordinate, respectively.

Dynamic vapor sorption

Dynamic vapor sorption (DVS) measurements were conducted in a Q-5000SA instrument (TA-instruments, Zellik, Belgium). All measurements were performed at 23 ± 0.1 °C. Deliquescent salts (sodium bromide and potassium chloride) were used to verify the humidity of the instrument.

4 mg of cotton fibers were rolled into a small ball and placed in the quartz sample pans. At the start of each moisture sorption cycle, the fibers are dried at 0 % RH until the weight change is stabilized to be less than 0.05 % for a period of 15 min. After the stabilization, the moisture sorption cycle was started and the humidity was increased stepwise, with steps of 10 % RH from 5 % till 95 %. The desorption isotherm, from 95 % till 5 % was recorded as well. At every RH, the equilibrium moisture concentration (EMC) is monitored after reaching equilibrium, or thus when the weight change is less than 0.05 % over a time period of 15 min. The coefficient of variation which is the percentage ratio of standard deviation and the mean, is between 1.5 and 2.5 % on the EMC-values for all experiments.

HH model

According to the HH model the total moisture content of material at any humidity during sorption can be calculated by the equation below (Hill et al. 2009):

$$M = Mh + Md$$

$$M = \left(\frac{1800}{W}\right) * \left[\frac{(K1 * K2 * h)}{(100 + K1 * K2 * h)}\right] + \left(\frac{1800}{W}\right) * \left[\frac{(K2 * h)}{(100 - K2 * h)}\right]$$

where M is the equilibrium moisture content, h is the % RH, M_h is the % moisture content from the monolayer sorption, M_d is the % moisture content due to the polylayer sorption, K1 is the equilibrium constant of monolayer water formed from dissolved water and cell walls, K2 is the equilibrium constant between water vapor and dissolved water, and W is the molecular weight of the cell wall polymer per sorption site. The values of K1, K2, and W are determined by plotting h/M against h with a polynomial equation:

$$\frac{h}{M} = A + Bh - Ch^2$$

where A, B, C are regression coefficients and linked to K1, K2, and W values by the following relationships using linear least square method:

$$A = \left(\frac{W}{18}\right) \times \left[\frac{1}{K2 * (K1 + 1)}\right]$$

$$B = \left(\frac{W}{1800}\right) \times \left[\frac{K1 - 1}{K1 + 1}\right]$$

$$C = \left(\frac{W}{180000}\right) \times \left[\frac{K2}{K1 + 1}\right]$$

Hysteresis

The total hysteresis value was calculated by subtracting the area under the normalized sorption curve from the area under the normalized desorption curve using Microcal Origin 6.0 software (Microcal Software, Inc., Northampton, MA, USA).

X-ray diffraction

The X-ray diffraction (XRD) patterns were measured for raw cotton fibers with an X-ray diffractometer (Thermo Fisher Scientific Inc, Waltham MA, USA) using CuKα radiation ($\lambda = 1.5406$ Å) at 40 kW and 20 mA. Scattered radiation was detected in the range of $2\theta = 5$–40°, at a scan rate of 2°/min. The crystallinity index (C_I) was calculated by the equation below (Morais Teixeira et al. 2010):

$$CI(\%) = \left(1 - \frac{Iam}{I200}\right) * 100$$

where I200 is the height of the 200 peak ($2\theta = 22.6^{\circ}$) and Iam is the intensity minimum between the 200 and 110 peaks ($2\theta = 18^{\circ}$). I200 represents both crystalline and amorphous material while Iam represents the amorphous material.

Results and discussions

Sorption isotherms of cotton fibers

The response of the fiber samples to a step change in RH in the sample chamber produces an asymptotic curve when plotted as moisture content against time, Fig. 1a. When exposed to an atmosphere at constant RH for an infinite time, the cell wall of the fiber has an associated moisture content which is in equilibrium with the atmosphere. The moisture content at this point, where the dynamic equilibrium occurs, is referred to as the equilibrium moisture content (EMC) (Hill et al. 2010). The EMC value at each interval is plotted against the RH to draw the equilibrium isotherm shown in Fig. 1b.

Although there are significant differences in the total amount of moisture present in different samples at a given RH, all of the cotton fibers under investigation exhibit an S-shape curve with a distinct hysteresis (Hill et al. 2009; Xie et al. 2010a; Okubayashi et al. 2004). This finding is in line with our previous work on developing cotton fibers in which indeed fully grown fibers show a type II-isotherm according to International Union of Pure and Applied Chemistry (IUPAC) classification, which describes the adsorption on macro-porous and non-porous adsorbents with strong adsorbate-adsorbent interactions (Sangwichien et al. 2002). Many factors influence the moisture sorption properties of cotton fibers, of which OH accessibility is a significant component (Zaihan et al. 2009). Thus the structural properties of fibers which may affect the availability and accessibility of OH groups are to be looked at. This is done by studying both the effect of maturity and crystallinity.
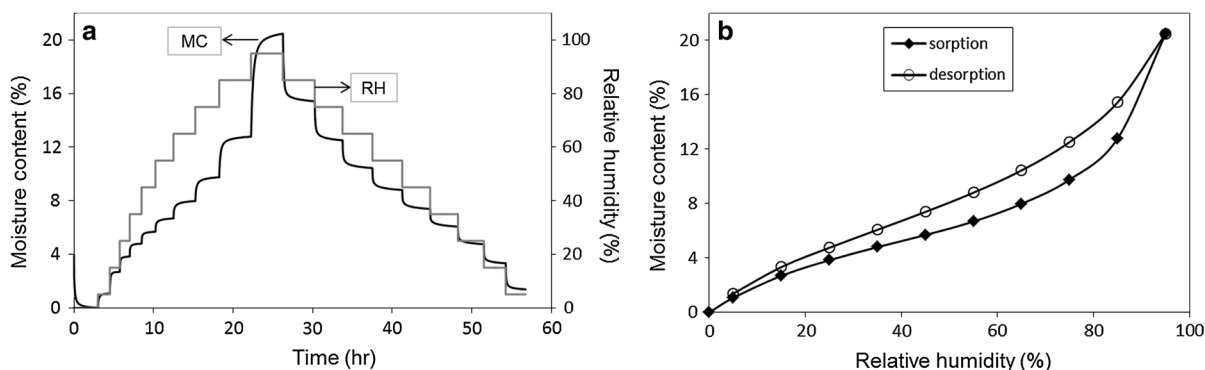

Fig. 1 Change in moisture content as a function of time (**a**) and equilibrium moisture content as a function of relative humidity (**b**) for cotton fibers

Table 1 EMC at 95 %, hysteresis, micronaire, maturity ratio, and crystallinity index data of studied cotton fibers ranked according to the variation in shade (ΔE calculated using Line 20 as reference)

Variety	EMC at 95 % RH (%)	Hysteresis	ΔE	Color	Micronaire	Maturity ratio	Crystallinity index (%)
Line 1	21	122	37	Dark Brown	2.5	0.72	70
Line 2	21	128	36	Dark Brown	2.3	0.7	68
Line 3	23	192	33	Dark Brown	2.3	0.71	61
Line 4	22	126	33	Dark Brown	2.2	0.71	71
Line 5	18	139	31	Dark Brown	2.7	0.75	77
Line 6	24	136	31	Dark Brown	2.1	0.68	65
Line 7	23	182	29	Brown	2.2	0.72	62
Line 8	21	149	29	Brown	2.4	0.69	72
Line 9	20	148	28	Brown	2.3	0.73	70
Line 10	20	106	26	Brown	2.5	0.73	77
Line 11	18	124	22	Brown	4	0.85	79
Line 12	21	158	22	Brown	3.7	0.83	69
Line 13	20	94	20	Beige	2.8	0.72	78
Line 14	17	111	16	Beige	4.9	0.79	81
Line 15	23	94	14	Beige	2.3	0.71	76
Line 16	18	116	10	Beige	4	0.81	79
Line 17	17	80	5	White	3	0.81	81
Line 18	20	114	2	White	3.9	0.79	76
Line 19	17	113	2	White	5.6	0.88	80
Line 20	17	92	0	White	4.1	0.84	81

Effect of maturity and crystallinity index on sorption capacity and hysteresis

Table 1 lists the EMC at 95 % RH and the total hysteresis for all studied fibers. In addition the ΔE, the maturity data measured by HVI (micronaire) and AFIS (maturity ratio) as well as the crystallinity index are given for each fiber type. The samples provide a range of maturity and crystallinity index values. The micronaire and maturity ratio ranged from 2.1 to 5.6 and 0.68 to 0.85 respectively, while the crystallinity index varied between 61 and 81 %.

The adsorbed water in the dark brown, brown, beige and white fibers produced an average EMC of 22, 20, 19 and 18 % respectively, at the highest RH of 95 %. The EMC of white cotton fibers is noticeably lower than those of the naturally colored cotton fibers. This may be explained by the differences in maturity and crystallinity index values of the fibers. The maturity and crystallinity index values tend to decrease with increasing color, Fig. 2a–c, meaning naturally colored cotton fibers have a less developed structure compared to white fibers. A cotton fiber is composed of a primary wall, a winding layer and a secondary wall with a closely packed parallel micro fibril arrangement (Xie et al. 2010b; Krakhmalev and Paiziev 2006). A less developed structure for cotton fibers corresponds to a lower degree of secondary cell wall development thus higher quantities of non-cellulosic primary cell wall components per unit of mass (Abidi et al. 2007). This results in a loose and more open arrangement of micro fibrils thus a higher number of accessible OH groups per unit volume. As cotton fiber absorbs water, it increases in volume to accommodate the water molecules. This dimensional change of the cell wall involves expansion of the non-cellulosic matrix in which the micro fibrils are embedded. The EMC of the fibers at any given RH is thus closely related to the pressure exerted upon the matrix by the cell wall (Xie et al. 2011). Therefore less mature cotton fibers having a less dense non-cellulosic matrix exhibit higher levels of sorption, as confirmed by the inverse correlations observed between color, maturity and cristallinity index data versus EMC at 95 % RH, Fig. 2c–e. In line with the results in Table 1 and Fig. 2, previous literature also suggested differences in the main
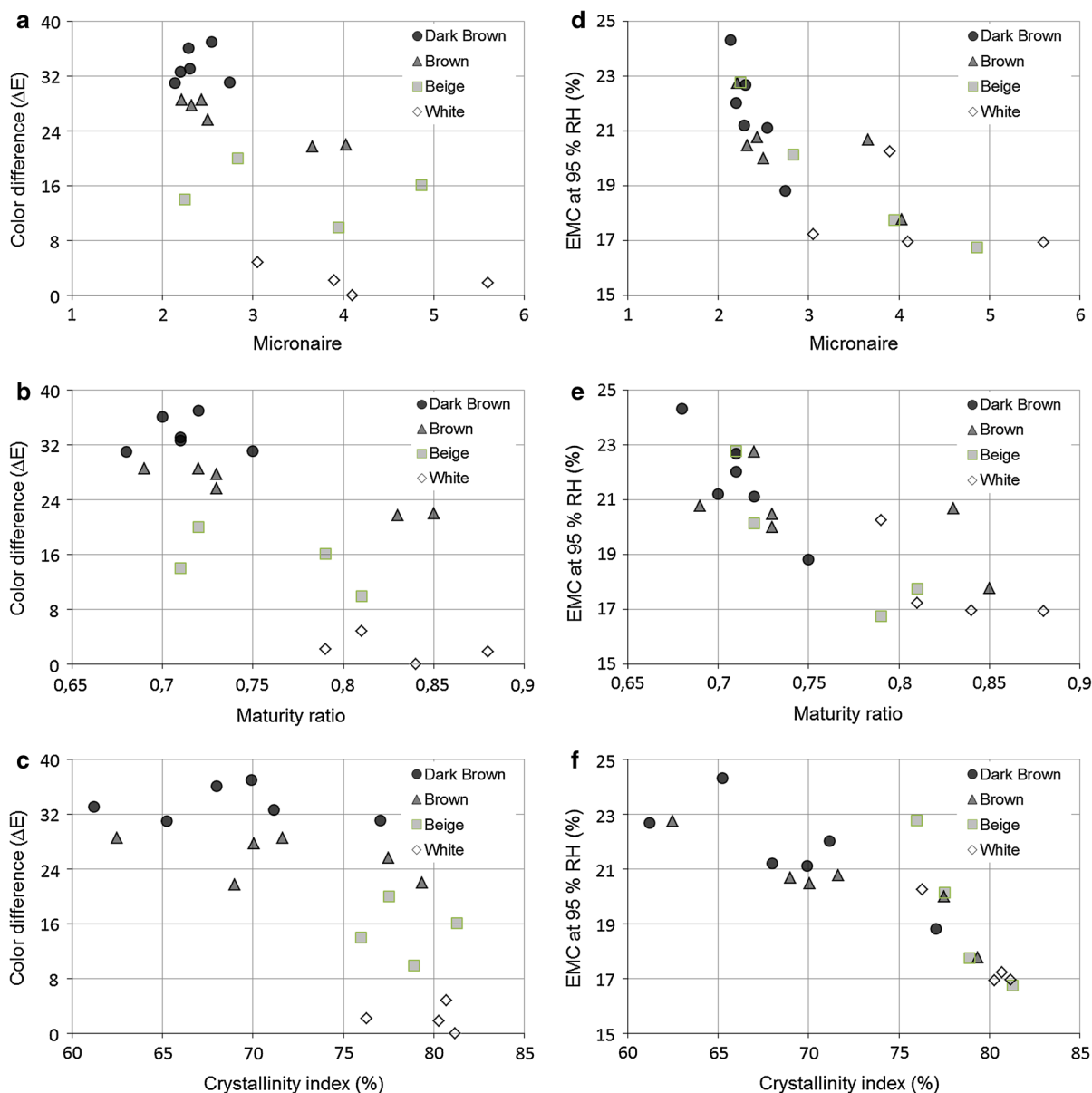
Fig. 2 Combined plots of micronaire, maturity ratio, crystallinity index as a function of color difference (ΔE) (**a–c**) and EMC at 95 % RH (**d–f**) for cotton fibers of different shades

constituents of colored cotton fibers (Corradini et al. 2009; Morais Teixeira et al. 2010; Pan et al. 2010). The content of constituents was not obviously distinct among the varieties with same color, but significantly different among different fiber color types. The wax content of white fibers was the lowest and increased with color depth with the highest wax content for the dark brown fibers (Pan et al. 2010). Moreover the

colored cotton fibers have higher amounts of low crystalline non-cellulosic (lignin and hemicellulose) matrix than the white fibers (Corradini et al. 2009). The cellulose content of white cotton on the other hand was found to be the highest, while that of dark brown cotton was significantly lower than white one. The relatively lower amount of cellulose is assigned to the presence of flavonoid pigments. The carbohydrates

which could have been used for cellulose synthesis may have been consumed in the synthesis of flavonoid pigments (Dutt et al. 2004; Morais Teixeira et al. 2010). Thus an increase in color (increasing ΔE) may lead to a decrease in maturity and crystallinity index and thus a concomitant increase in EMC at 95 % RH as shown in Fig. 2.

Apart from differences in the sorption capacity, there were also differences in the hysteresis behavior of the fibers. The dark brown and the brown fibers exhibit the highest values of total hysteresis and the white and beige ones the lowest values. These differences in the overall sorption hysteresis may be explained by the variations in the structural deformation of cell wall during sorption. Hysteresis behavior is recently linked to the ability of the matrix to deform in response to the adsorption or desorption of water molecules into or out of the glassy materials (Lu and Pignatello 2002, 2004). For these materials micro capillaries are expanded during sorption due to incoming water molecules thus resulting in the creation of new internal surfaces. On desorption, however, there is a time lag between the departing of water molecules and the rearrangement of the matrix to its original configuration. As presented in Table 1, the crystallinity index, and thus the internal stability, of the dark brown and the brown fibers is lower compared to the beige and white fibers. Therefore the extent of sorption and cell wall deformation would be greater for dark brown and brown fibers. An inverse correlation, Fig. 3a, is evident between the total hysteresis and the crystallinity index data of the fibers. This is in line with the results reported on the moisture sorption of cellulose powders with varying crystallinity (Mihranyan et al. 2004). The correlation between the maturity and hysteresis data, Fig. 3b, c, is much less explicit. This suggests the ability of moisture to penetrate the structure and cause a deformation of the internal surfaces is more related to the degree of crystallinity than to the maturity (Mihranyan et al. 2004). As to further assess the effect of the structural differences on the sorption behavior of cotton fibers the sorption kinetics are to be looked at as well.

Sorption kinetics

Increasing the RH in each step of the sorption cycle results in a new equilibrium condition within a specific time period for every sample. Dividing the increment
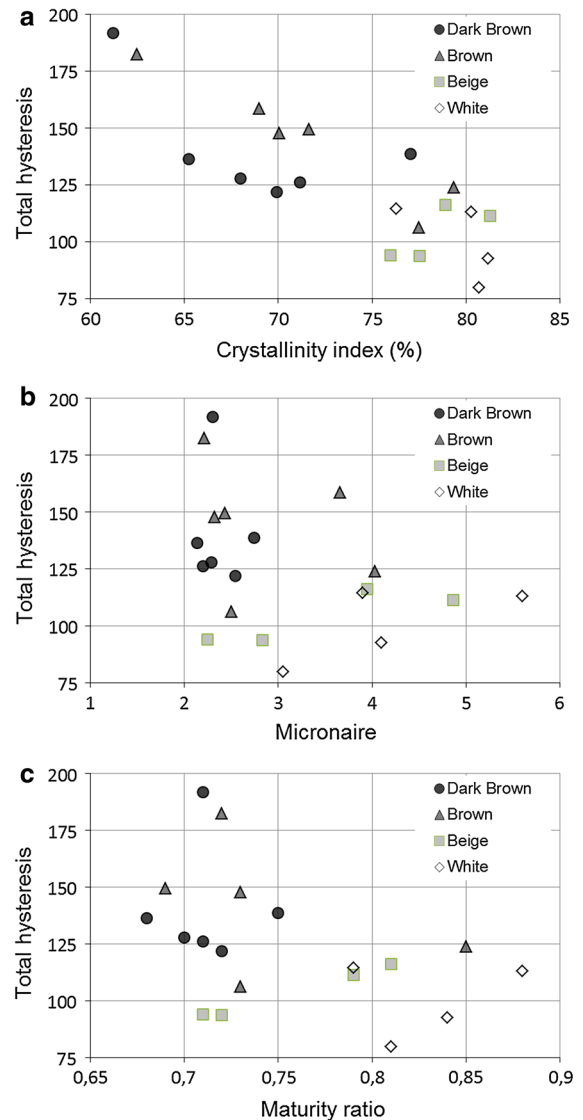

Fig. 3 Combined plots of crystallinity index (**a**), micronaire (**b**) and maturity ratio (**c**) as a function of total hysteresis for cotton fibers of different shades

or decrement of the moisture content at any RH by the time taken to reach the new EMC gives the sorption rate of materials (Xie et al. 2010a). The sorption rate of all studied cotton fibers displayed a "w" shape, Fig. 4, meaning that the fibers exhibited relatively higher sorption rates at both low and high RH ranges than in the middle RH range during the sorption process. This is similar to other cellulosic materials (Xie et al. 2011). At the highest RH, fibers of all shades showed a similar increase in sorption rates, although the rise for dark
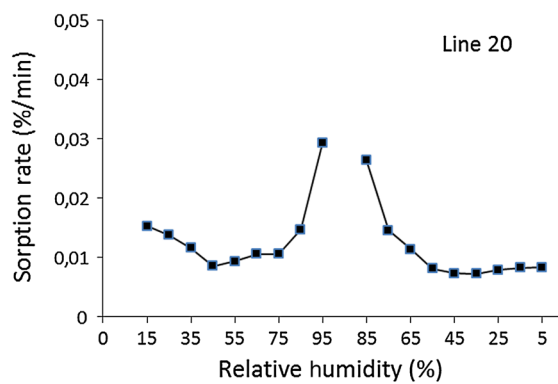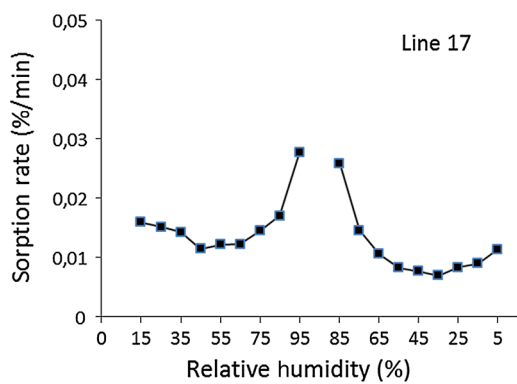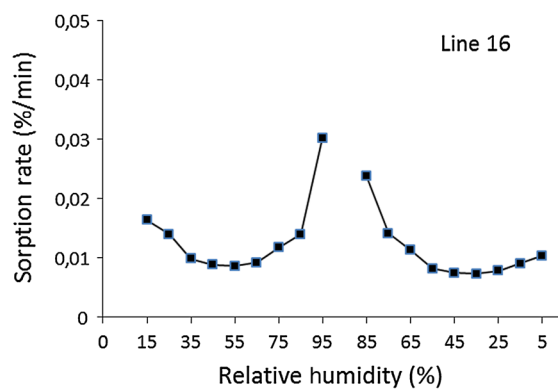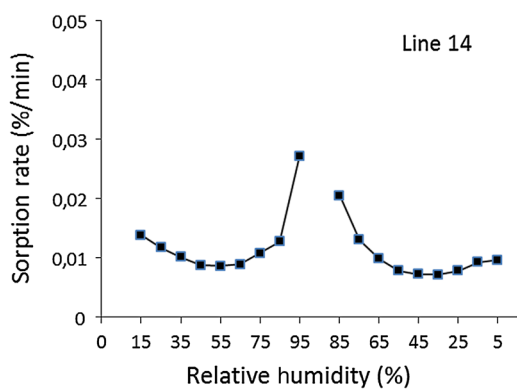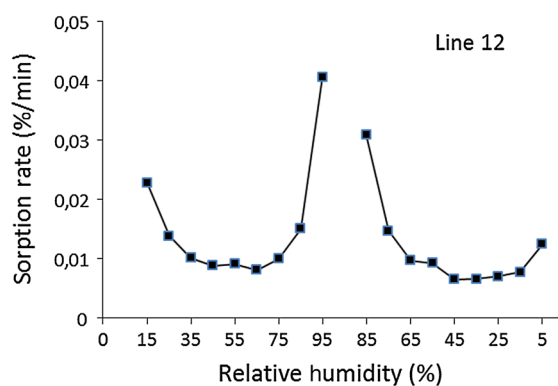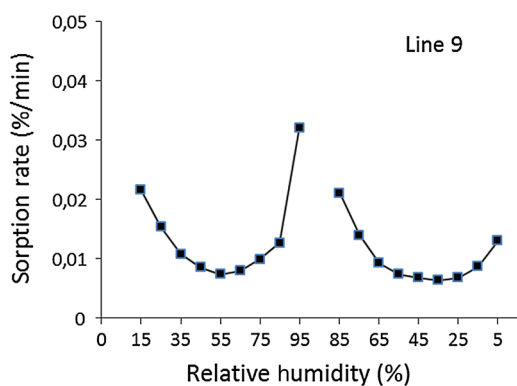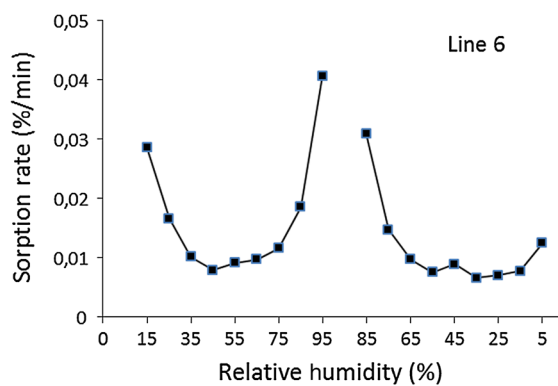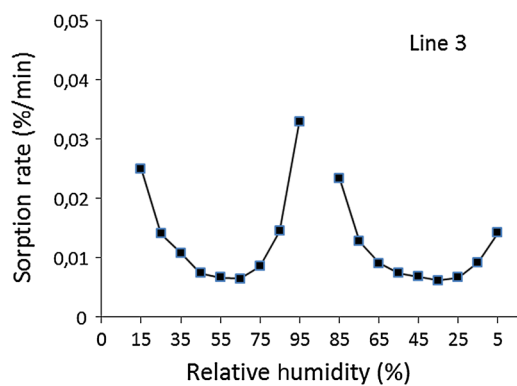
◀ **Fig. 4** Sorption rate within a set of RH during sorption process selected cotton fibers of different shades (Line 3 and 6 *Dark Brown*, Line 9 and 12 *Brown*, Line 14 and 16 *Beige*, Line 17 and 20 *White*)

brown and brown fibers was relatively higher than other fibers. At the lower end of the hygroscopic range, however, the differences in sorption rates were more pronounced, being highest for dark brown, relatively lower for brown, and lowest for beige and white fibers. The lower sorption rate of the white and beige fibers can mainly be attributed to their higher cellulose content with a high degree of crystallinity. This together with the low level of non-cellulosic constituents indeed limits the availability and accessibility of OH groups per unit volume. For dark brown and brown fibers on the other hand, a high proportion of non-cellulosics and the less crystalline cellulose content results in a loose and more open arrangements of the micro fibrils thus a more accessible structure for moisture sorption. The differences in sorption behavior are further examined using the HH model.

The HH model assumes the existence of an ideal solid solution consisting of unhydrated polymer, hydrated polymer (hydration water) and dissolution water (polylayer water). Thus it allows separating the total moisture content into a monolayer water and a polylayer water. An optimal fit between the experimental and calculated EMCvalues is aimed for, Fig. 5. Although Fig. 5 illustrates only some selected lines, the degree of fit with the experimental sorption isotherms is very good for all fibers under investigation, as clear from the high coefficient of determination values (>0.95). At low RH's monolayer water formation is dominant for all fibers due to possible interactions with available OH groups. Once all available sites are occupied, the monolayer water formation reaches an asymptote and thereafter polylayer sorption becomes dominant. The relationship between color differences, maturity, crystallinity index data of the fibers and the water content associated with monolayer and polylayer sorption is analyzed in Fig. 6.
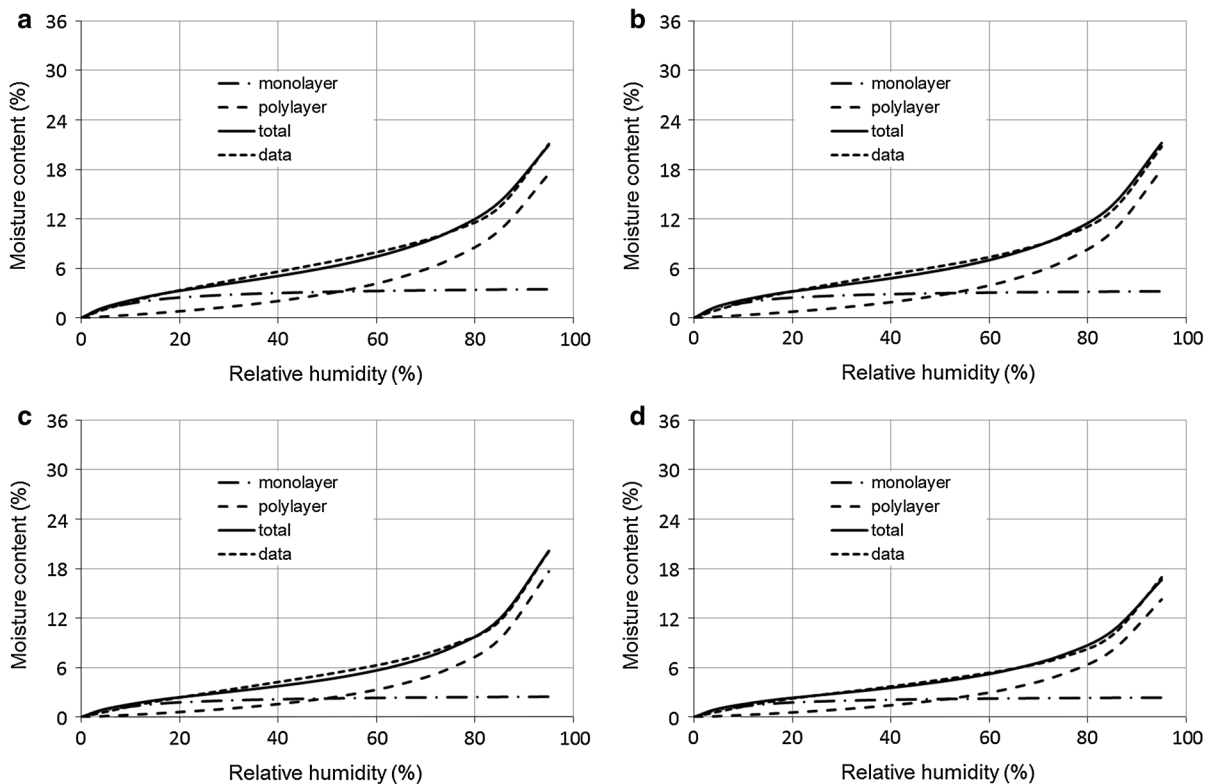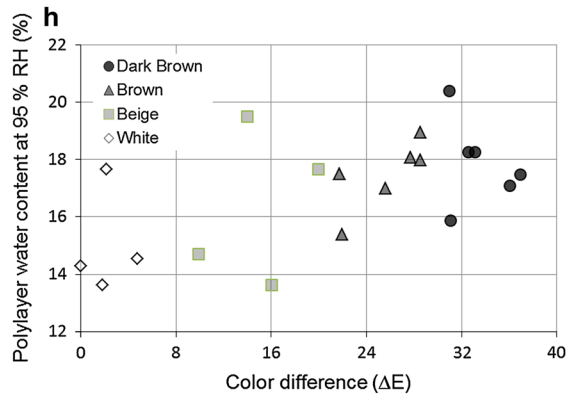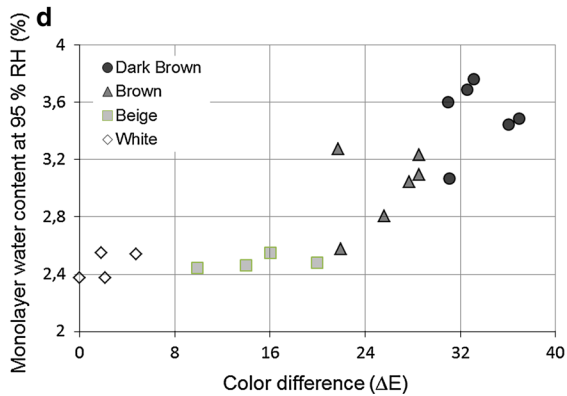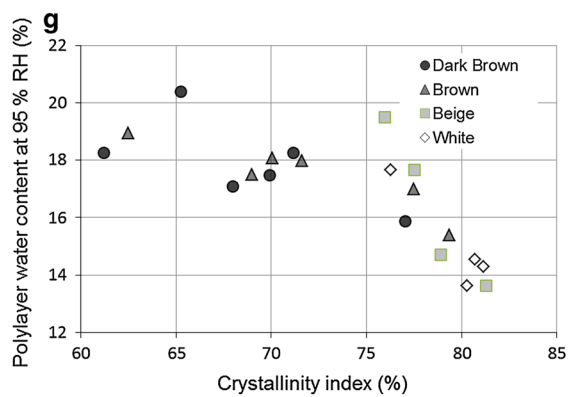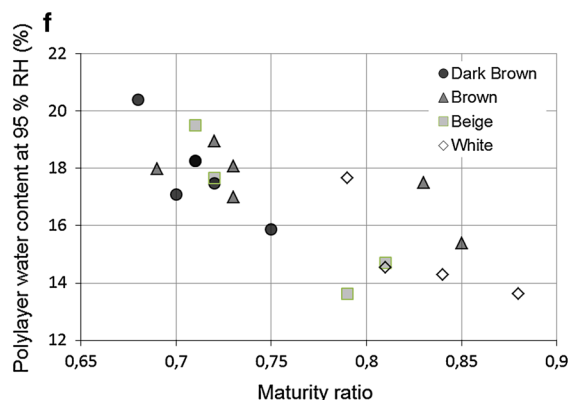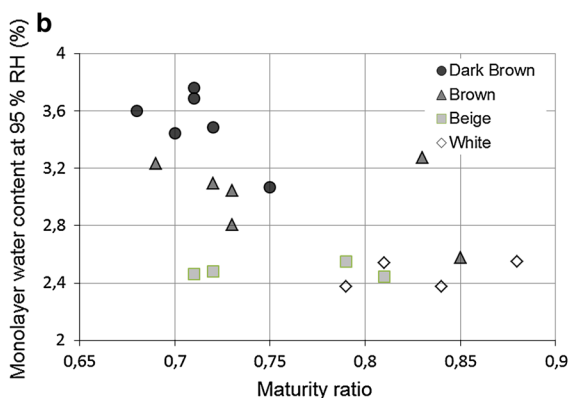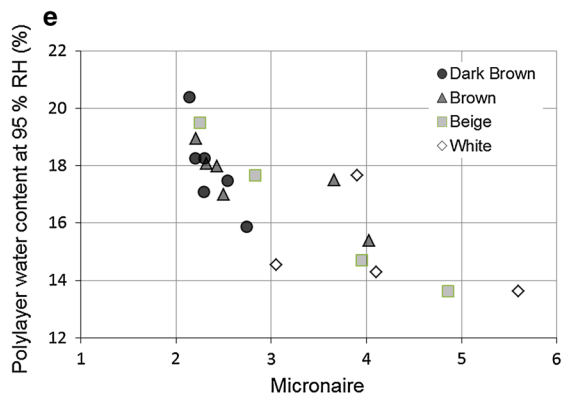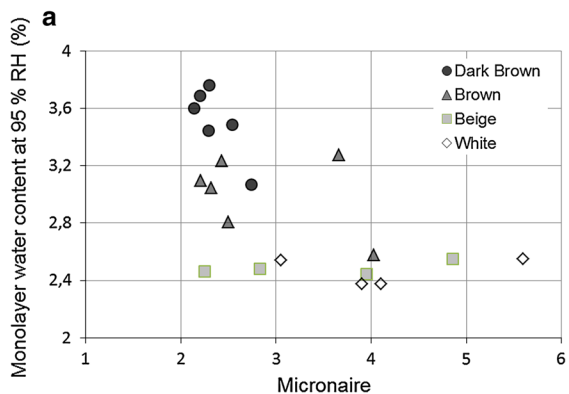

Fig. 5 The monolayer, polylayer and total sorption calculated using the HH model, through the relative humidity run compared to the experimental moisture content (data) for selected cotton fibers of different shades (**a**) Line 1, (**b**) Line 7, (**c**) Line 13, (**d**) Line 20
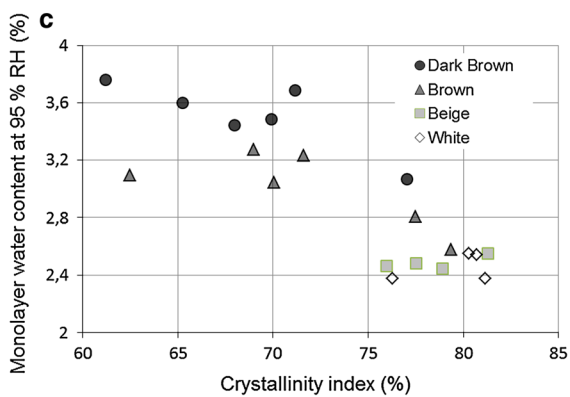
◄ **Fig. 6** Monolayer and polylayer water content at 95 % RH calculated using the HH model as a function of, micronaire, maturity ratio, crystallinity index and color difference

In general both monolayer and polylayer water content are decreasing with increasing maturity and crystallinity index values. The decreasing trend in polylayer water is observed through the entire maturity, Fig. 6e, f, as well as crystallinity index range, Fig. 6g, and is likely to be less dependent on color differences, Fig. 6h. Polylayer sorption is mainly associated with the water formation in the cell wall capillaries. The monolayer sorption on the other hand most closely related to the crystallinity index, Fig. 6c and, to a lesser extent, maturity of the fibers, Fig. 6a, b. The amount of monolayer sorption is dependent on the variations in water binding sites of the fibers which are presumably related to the different types of external or internal surfaces as well as the proportion of amorphous and crystalline regions (Kachrimanis et al. 2006). It is well known that cellulose as found in cotton is highly crystalline and therefore not accessible to water due to hydrogen bonds between cellulose molecules in the crystalline form (Skaar 1972). Thus moisture sorption mainly occurs in amorphous regions and at the surface of crystalline regions (Kongdee et al. 2004; Joly et al. 1996). With decreasing crystallinity index, therefore the accessible fraction of cotton fiber will increase and result in a higher water sorption into the fiber structure. Also fibers with low maturity have a higher monolayer sorption as the amount of low crystalline non-cellulosic constituent that are more hygroscopic and have a relatively high surface area will be higher in the fiber composition. Noteworthy is

the difference in monolayer water content of the cotton fibers of different shades as presented in Fig. 6d. A substantial increase is observed with increasing color difference for dark brown and brown fibers while no significant variation is noted for white and beige fibers in monolayer water. This can be attributed to the differences in availability and accessibility of OH groups in the fibers. As white and beige fibers have a better developed structure the number of accessible OH groups is lower compared to dark brown and brown fibers. Possibly a large enough variation is needed to obtain a difference in monolayer sorption thus showing no difference between the white and beige samples but yet a difference between the brown and dark brown fibers. Also interactions between the pigments in colored fibers and moisture may partly cause the difference in monolayer sorption although these pigments are essentially unknown (Corradini et al. 2009).

The total hysteresis is substantially higher for fibers with a higher monolayer sorption namely dark brown and brown fibers, Fig. 7. The extent of hysteresis is mainly influenced by the composition of cellulosic materials due to the structural and conformational rearrangements, which can change the accessibility of sorption sites (Al-Muhtaseb et al. 2004). The higher hysteresis behavior of fibers with a higher monolayer sorption can thus be attributed to the higher accessibility and relatively stronger interactions between fiber and water in monolayer sorption. Yet such relation was less evident for polylayer sorption probably due to the weaker interactions with hydrophilic sites. These results are in agreement with previous literature on
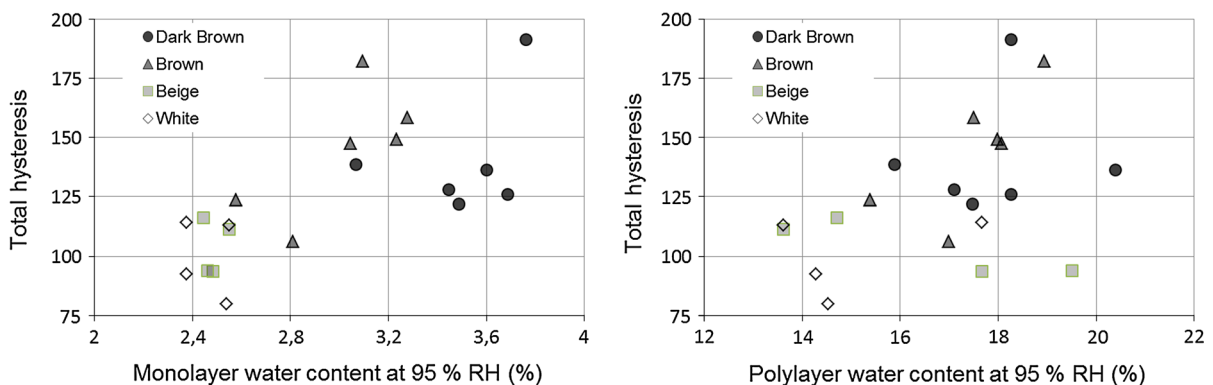

Fig. 7 Monolayer and polylayer water content at 95 % RH calculated using the HH model as a function of total hysteresis

developing cotton fibers where it was stated that an increase in monolayer sorption results in a gradual increase in degree of hysteresis.

Conclusions

Dynamic vapor sorption (DVS) can be used to gain valuable information concerning the sorption behavior of white and naturally colored cotton fibers. Significant differences were observed in sorption capacity and sorption rate as well as hysteresis behavior of cotton fibers with different shades. It is likely that the differences in sorption capacity are closely related to the maturity and crystallinity index of the fibers while the variations in hysteresis behavior are mainly attributed to the differences in crystallinity index. The variations in sorption rate of fibers at the lower end of the hygroscopic range are attributed to the differences crystallinity of the fibers.

The HH model was used to accurately fit the experimental measurements. The monolayer sorption was found to be most closely related to the crystallinity index and, to a lesser extent, maturity of the fibers. The substantial increase in monolayer sorption for dark brown and brown fibers is attributed to the higher availability and accessibility of OH groups in these fibers. On the other hand polylayer sorption was less dependent on color differences. Also a more noticeable relationship was found between the total hysteresis and the monolayer sorption most likely due to relatively stronger interactions between fiber and water in monolayer sorption.

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