Microbial Growth on Textiles: Conflicting Conventions

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Abstract—Conditions suitable for microbial activity on textiles are often described in parameters that do not correspond to the terminology, data, or theories of moisture absorption and desorption of textile fibers and fabrics. Current and historic wet processes of textile technology are profoundly affected by the chemical and physical properties of the textiles, including their potential as nutrient sources for microbial growth.

Especially for hygroscopic fibers, a continuing confusion about the nature of hysteresis exists. The *equilibrium* moisture regains and moisture contents are achieved at vastly different rates. Mathematical formulae used to consider the multi-layer absorption and desorption are complex. Commercial regain rates were established to regulate the practical and economic ramifications of the inherent tendency of fibers to absorb moisture. Studies of the propensity of these fibers to support microbial growth show a much higher threshold of Relative Humidity than articulated in museum literature; textile testing laboratory conditions also (65% RH) contradict museum rules. Complex changes in strength and dimension—swelling, hygral expansion, and shrinkage, also accompany changes in the moisture regain of fibers, yarns, and fabrics. Microbial growth can and does occur on textiles, but the actual condition for growth within museums and private collections may be less straightforward and less well defined than assumed.

1. Introduction

At what point does a textile risk being damaged by biodeterioration? When will microbial damage occur? For which fibers? Under what conditions? These are basic questions that textile conservators need to know in order to maintain the condition of antique textiles stored in museum collections. Current museum specifications for environmental conditions of 45–50% Relative Humidity and 20° C conflict with data and information from the history of the textiles themselves, from textile technology, textile chemistry, and textile commerce.

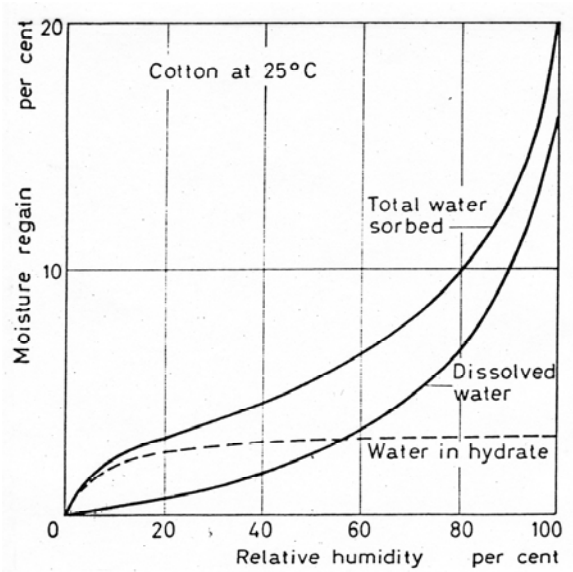
This problem may be illustrated with Edgar Degas's 1872–3 oil painting of jacketed gentlemen at the *New Orleans Cotton Exchange*. This commodity market was established to facilitate the financial transactions associated with the sale of ginned cotton. Ginned cotton, the raw fiber, is the seed hair less the seed itself. Compacted into bales of cotton, each weighing about 480 pounds (218 kilograms), this ginned cotton was shipped down the Mississippi River through New Orleans. From 1866 through 1872, over six million cotton bales were transferred through New Orleans—a city then with no air conditioning and a relative humidity that fluctuated between 64% and 84% RH (HMSO, 1958).

Yet, microbial damage did not play a major role in this commerce: the long sea voyage from New Orleans to English cotton mills did not affect the raw cotton significantly. Harvesting is best when the humidity is close to 60% RH. Textile technologists determined that the ginning process leaves the cotton with a moisture regain of about 6% (Martin, 1965). Compressing the cotton into a dense bale might have enhanced moisture uptake by capillary action, had not the primary wall impeded this wicking. The outer, primary wall of unscoured raw cotton contains water repellent waxes and pectins; these are dissolved only by scouring. Consequently, moisture diffuses through the bale slowly: it takes 40 days for 50% of the bale's cotton to reach the higher moisture equilibrium, and 240 days for 90% of the cotton (Crank, 1960, 85). The presence of high humidity was itself not the sole precondition for mold growth. In predicting microbial activity on textiles, four textile conventions conflict with those used in museum practice: terminology and formulae, data and theories, conditions and processing, and commercial values.

2. Terminology and Data

Moisture Regain is the most commonly used term to express the quantity of moisture in a fiber or textile. Moisture regain describes the conditioned fiber by its relationship to the 'oven-dry' weight of the fiber. This 'dry basis' capacity for moisture absorption varies with the chemical structure of the fiber, but generally takes the shape of a sigmoid curve for hygroscopic fibers. Urquhart proposed that this moisture regain from the dry state was actually composed of two parts: water molecules chemically bound to the fiber and loosely bound (van der Waals forces) for dissolved water. (see fig. 1).

Figure 1: Urquhart's explanation of the absorption curve (Urquhart, 1960, 16).



When careful experiments were conducted on desorption equilibria, values different from those in the absorbing mode were found. This peculiar discrepancy is known as hysteresis. At very, very low relative humidities (1.8% R.H. for scoured cotton), the two curves join. At saturation (100% R.H.) they do not meet precisely. Both the absorption and desorption curves can be—and are—described in terms of the 'dry weight' basis moisture regain. (see fig. 2). Urquhart and his coauthor found the curves were boundaries during cycling from high relative humidity to low relative humidity and interim transitions led to crossings. Setting up conditioning at a low relative humidity far away from the final desired equilibrium is suggested (Urquhart and Williams, 1924).

It is also possible to calculate the amount of moisture based on the mass of moist material. This is known as the 'wet' or 'as received' basis. It is possible to convert between moisture content and moisture regain by simple arithmetic (ASTM, D 1776–98).

Where R = moisture regain % and M= moisture content %:

R = [(M/100-M) x 100]

M = [(R/100+R) x 100]

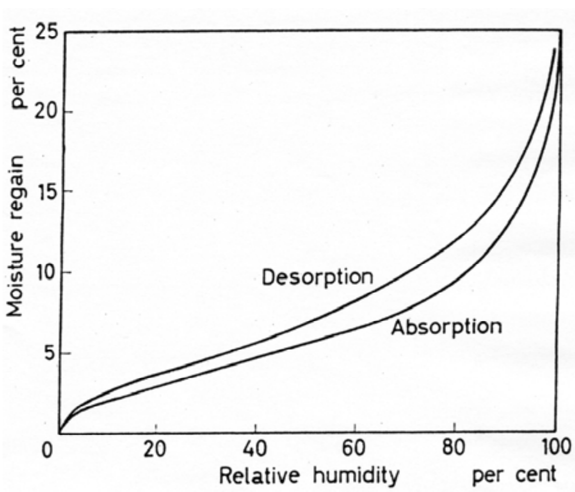


Figure 2. Urquhart's Sorption isotherm for Cotton (dried and scoured) when at 25^{o} C (77^{o} F) (Urquhart, 1960, 19)

Thus, for any given hygroscopic fiber or textile assembly, in equilibrium with a particular relative humidity and temperature, there are two values, absorption and desorption, which can be expressed two ways, as moisture regain or moisture content. As a result, there are four potentially 'correct' equilibrium percentage values at any relative humidity and temperature: along the lower absorption curve, the value can be read as moisture regain or moisture content; and along the higher, desorption curve, as moisture regain from the moist state, or moisture content from the wet state. Table 1 shows values from the dry, absorption state, in moisture regain and its equivalent moisture content and also values for both from the moist, saturated state. These four sets of numbers for various fibers, while different, express only two values: the same equilibrium point on the lower absorption curve and on the higher absorption curve. (ASTM D1776-98; Fusek, 1985).

Fiber (den/fil)	Moisture Regain From (oven) dry*	"Moisture Content" from Oven dry	"Moisture Regain" From moist state**	Moisture Content From moist state
Cotton (1.5)	7.43	6.91	9.05	8.30
Viscose Rayon (1.7)	13.30	11.74	15.40	13.34
Cellulose acetate (4.0)	4.99	4.75	8.43	7.77
Wool (3.5)	13.01	11.51	16.90	14.46
Silk (1.0)	9.39	8.58	11.89	10.63
Poly (propylene) (4.5)	0.92	0.91	1.46	1.44
Kevlar Aramid (1.4)	3.97	3.822	5.85	5.53

*equilibrium moisture regain ** equilibrium moisture regain calculated from the wet side

Table 1.Equilibrium Moisture Regain at 70ºF (21ºC) and 65% RH (after Fusek, 1985)

The data associated with these terms can be reconfigured to focus, for example, on the drying of textiles and other engineering theories. Instead of plotting the curve against relative humidity, it is possible to use temperature—or to alter the curve altogether by plotting moisture values against the partial pressure of water vapor. Textile technologists prefer the convention of moisture regain vs. relative humidity since the temperature variants are stable through the 20–80% RH range, textile engineers who deal with the drying of textile find moisture regain vs. the partial pressure of water vapor, or changes in moisture regain across changes in temperature at certain partial pressures more pertinent to their concerns (Urquhart and Williams, 1924; Rice, 1957; Keey, 1993).

3. Conditions and Processing

Because some of this research work dates back to the 1920s, it is tempting to consider these efforts lacked the precision and accuracy now available. However, Fusek confirmed this data when he revisited the values for natural fibers and developed values for newer synthetic fibers. Nonetheless, his equilibrium moisture regains at 21° C and 65% RH are startling for another reason (see Table 2).

Fiber (den/fil)	Time: from DRY to 65% RH (in hours)	Time: from WET to 65% RH (in days)
Cotton (1.5)	1.5	99
Viscose Rayon (1.7)	2.0	71
Cellulose acetate (4.0)	3.4	88
Wool (3.5)	2.5	103
Silk (1.0)	5.0	39
Poly (propylene) (4.5)	2.0	51
Kevlar Aramid (1.4)	5.0	0.7

Table 2.Equilibrium Moisture Regain at 70ºF (21ºC) and 65% RH (after

From a desiccated 'oven-dry' state, equilibrium can be reached in mere hours. Yet, from the moist, wet condition, equilibrium for fibers is reached in days, weeks, or even months. He found that the first order diffusion rate constants for moisture absorption for dry fibers are significantly higher than the evaporation rate constant for wet fibers. He confirmed that water is gained by diffusion quickly and absorption slowly by a dry fiber. On the other hand, wet fibers desorb in three ways: by evaporation from the surface, diffusion to the surface, and lastly, by desorption of the water (Fusek, 1985).

As a general rule, Fusek found hydrophobic fibers like polyester and nylon had a lower level of hysteresis than those of cotton or wool. It is also possible to alter the curves by chemical wet processing. Mercerization permanently raises the moisture isotherms of cotton (Urquart and Williams, 1924). During the different manufacturing processes, moisture levels and relative humidities are manipulated in order to alter the physical or working properties of fibers (see Table 3). Except for spinning cotton, optimum working relative humidities remain above 50% (Townsend, 1966 and von Bergen, 1969).

Operation	Cotton	Man-made Fibers	Wool
Opening and Picking	50-60%	50-55%	65-70%
Carding	50-55%	50-55%	60-75%
Combing	50-60%	50-60%	60-75%
Drawing	50-55%	50-60%	50-70%
Roving	50-55%	50-60%	--
Spinning	35-55%	35-60%	50-85%
Winding, Spooling	55-65%	50-65%	55-60%
Twisting	60-70%	50-65%	--
Warping	55-70%	50-65%	50-55%
Weaving	70-85%	55-70%	50-60%

Table 3: Recommended Relative Humidities During Textile Manufacturing Operations (Townsend, 1965; von Bergen, 1969)

Type of Fabric	Trace	Slight	Definite	Heavy
Grey Cotton	4 days	5 days	---	6 days
Mildly scoured cotton	26 days	42 days	58 days	>90 days
Thoroughly scoured cotton	45 days	55 days	>90 days	---
Cotton, mercerized as yarn, boiled with water after weaving	45 days	>90 days	---	---
Flax, woven from "twice boiled" yarns	25 days	32 days	38 days	54 days

---no data available, not applicable

Table 4: Level of Mold Growth on Cellulosic Fabrics in Days in an environment of 25° C. and 92% Relative Humidity (after Fargher, 1945)

For testing purposes, there is another convention. Traditionally, all textile testing laboratories are operated at standard atmosphere, 65% ± 2% relative humidity and 21°C ± 1°C

(70° F ± 2°F). Sometimes a special interior 'conditioning room' or chamber is built in order to house textile testing equipment. There is a protocol to bring any textile material to equilibrium with such conditions, prior to testing for particular physical properties like tensile strength or strain. When not otherwise specified, these are the standard measuring conditions found in the textile literature (ASTM D1776-98).

This returns us to our original question: when will microbial damage begin? For cotton, upper limits seem to depend upon the stage in the processing, the condition of foreign matter left in the fabric (Fargher, 1965; see Table 4). More thorough cleaning ('scouring') reduces the development of microbial growth, whether or not the cleaning composition contains antiseptic components. Wool technologists also found processing and cleaning agents affect the level of microbial damage. Tops—coils of wool not yet spun into yarn—and unscoured yarn are more susceptible to mildew at high humidities than the final scoured cloth. Soap residues enhance microbial growth preferentially. Some cleaning regimens retard the development of hyphae and conidia (Burgess, 1928 and 1929, see Table 5). Other textile technological factors that affect microbial development—beyond relative humidity—include the size and shape of the textile, its density, the inherent hygroscopicity of the textile, the temperature, the air circulation, as well as the overall average regain.

Commercially, there a practical agreement designating the proper moisture regain for various fibers and yarns because of the need for a standard convention. For hydrophilic commodities, like wool or cotton, adulteration can be water-related: it is quite easy to increase the weight of an absorbent commodity by sprinkling a little water on it or arranging the purchase to take place in a humid atmosphere. How much moisture would a "true weight" contain? Modern commercial regain values were established as early as 1875 in order to fix a contractual specification of moisture, an agreed value that can be measured and calculated. This textile convention, with very minor alterations, is still in place today. For example, silk has a 'Commercial Moisture Regain Value' of 11.0, wool, 13.6, cellulose acetate, 6.5. It is openly designated as 'purely arbitrary' and fixed expressly for commercial reasons! (ASTM, D-1909-96, Reapproved 2001)

Treatment	**1.5**	**2.5**	**3.5**	**4.5**	**5.5**	**6.5**	**8**	**9**
Ether	0	0	<	<	<	<	+	+
Ether & water	0	0	0	0	<	<	<	<
Alcohol	0	0	0	<	+	+	+	+
Alcohol & water	0	0	0	0	0	0	0	<
Soap	0	0	<	+	+	++	++++D	++++DD
Soap & water	0	0	0	<	<	<	<	+
No treatment	0	0	<	+	+	++	+++D	+++D
No treatment & water	0	0	<	<	<	<	+	+

0 is no growth at 80X magnification
< hyphae present
+ conidiophores present
++ conidiophores common
+++conidiophores abundant
++++ sample badly mildewed
D sample is slightly discolored
DD sample is badly discolored
-- no data. Penicillium was the fungal species used

Table 5:Level of Mold Growth on Worsted Wool Previously Treated Period of Incubation is in Weeks in Saturated, dark storage at 22° to 26° C (72° to 79° F).* (Burgess, 1929)

4. Microbiological Terminology and Conditions

Yet none of these conventions and standards that describe the boundaries for moisture in textile materials mesh with the basic quantitative term for moisture requirements for microbial activity. Quantitatively, microbiologists typically refer to the water activity (a_w) of a material, substrate, or environment. As a surface phenomenon, the water activity equals p/p_o, the vapor pressure of a solution (p) divided by the vapor pressure of water (p_o). In order to deter-mine the water activity level for a solid substrate like a fabric, the equation is more complex:

$$\ln a_w = \frac{-vm\theta}{55.5}$$

In this system, v is the number of ions formed by each molecule of the dissolved substance, m is the molar concentration of the dissolved substance, and θ is the molar osmotic coefficient. Water has an a_w value of 1.0. Other materials have lower values, depending upon the quantity of dissolved material and water. Microbial activity generally requires a_w values between 0.63 and 0.99 (Rose, 1981).

Because the water activity equals p/p_o, the vapor pressure of free water in a porous material relative to the vapor pressure of pure water, for a volume of air its a_w is equal to the value of the relative humidity. That is, a_w for water is 0.95 in 95% RH. Yet is not possible to predict the a_w or the free water associated with a particular material by using the ambient RH or even by designating the 'equilibrium relative humidity,' ERH, when a material is in equilibrium with its environment since moisture contents vary. An attempt to use an 'equilibrium moisture content' EHC, at a particular relative humidity, is confusing. For each textile fiber, with a specific processing, there will be two values at any given relative humidity and temperature, depending upon the use of the absorption curve or the desorption curve (Flannigan, 2001 and Florian, 1997). For microbes, their growth can be satisfactorily charted by plotting their reaction to a particular water activity level (in the ordinate) and temperature (in the abscissa).

5. Conclusion

The ambient conditions for textiles can be described in several ways, some are very precise, others are actually stipulated as 'arbitrary.' Textiles survive high humidity levels during processing and storage. The descriptive values used by microbiologists to map microbial activity are not correlated to textiles. Museum humidity levels are not correlated with textile manufacture, history, data, and practices.

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