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DETERMINATION OF MATERIAL HYGROSCOPIC PROPERTIES THAT AFFECT INDOOR AIR QUALITY

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ABSTRACT

Moisture-associated air quality problems frequently stem from the proliferation of microbes on hygroscopic bodies within a space. Airborne microbe concentrations can be diminished by regulating material moisture content. Knowledge of material hygroscopic behavior is necessary for this strategy to be effective. Hygroscopic materials recurrently associated with moisture-related building problems were tested. The objective was to determine material moisture content as a function of relative humidity, temperature, and time. Samples were exposed to controlled conditions in an environmental chamber and massed in situ to determine moisture content based on dry mass.

Results show that samples of fiberglass duct lining, polyester filter material (both from a veterinary hospital known to have an air quality problem), cotton cloth, and jute-backed nylon carpet can absorb sufficient moisture to support microbial growth. The experimental system used determined material moisture content to within 0.001 [moisture mass]/[dry sample mass] and sorption rate to within 0.01 lb/h (0.005 kg/h). It is concluded that fiberglass duct lining is unsafe in a microbial context unless organic materials are precluded from the HVAC system.

INTRODUCTION

In buildings, moisture-associated air quality problems commonly stem from the proliferation of microbes on moist hygroscopic surfaces within the HVAC system. In residences, fungus is more commonly found on carpeting and furnishings. Fungus growth can be prevented by keeping these materials dry through the use of controlled humidity. The most beneficial humidity setpoint will maintain a safe moisture content of less than 0.10 lb/lb (Block 1953, 1987) in fungus-susceptible materials. It will also prevent condensation, maximize comfort, minimize energy consumption, and may inhibit infectious microbial transmission.

Problems encountered in attempting to properly control indoor relative humidity are (1) performing an accurate moisture load calculation for proper selection and operation of equipment, and (2) selection of the most beneficial indoor relative humidity setpoint. A useful moisture load analysis requires accurate knowledge of the hygroscopic behavior of the structure so that sorption processes and the moisture content of potentially fungus-supporting materials can be predicted. Researchers involved with indoor humidity problems have stated or shown that a lack of material hygroscopic property data is a major problem in their work (Fairey and Kerestecioglu 1985; Kerestecioglu 1986; Kusuda 1983; Miller 1984).

The sorption behavior of hygroscopic materials found in the building environment is not adequately defined to predict material moisture content or indoor relative humidity. Available hygroscopic property data do not satisfy the rigorous models being developed by researchers.

TABLE 1

Samples tested to determine hygroscopic behavior in this study (A, B,__ , C-Clean, D-Dirty).

#	Sample
	Fiberglass
1C	clean unused
1D	sample from VMTH[a] duct lining
	Polyester filter material
2C	low efficiency (e = 20%), clean
2D	low efficiency from VPFQ[b]
3C	medium efficiency (e = 35%), clean
3D	medium efficiency from VMTH[a] HVAC intake
	Pressed paper ceiling tile
	clean unused
4A	front 0.055 in. section
4C	center 0.070 in. section
4B	back 0.070 in. section
	sample from VMTH[a]
4D	front 0.110 in. section
5	Urethane foam, fine cell
6	Carpet, 100% nylon, jute backed 60 oz/sq yd
7	Carpet pad, rubber-urethane composite 35 oz/sq yd
8	Shirt, 100% cotton
9	Shirt, 90% polyester — 10% cotton

a — veterinary medicine teaching hospital
b — apartment complex rental office

EXPERIMENT

The main experimental system consisted of an environmental chamber, a microprocessor-based digital process controller, and an electronic balance. The chamber was instrumented with two 24-gauge copper-constantan thermocouples (one each for dry- and wet-bulb) and two NBS specification 150 mercury-in-glass thermometers (±0.1°C).

The selected sample materials (Table 1) are linked to some aspect of moisture-related building problems. Samples of fiberglass duct lining and polyester filter material from the intake of a veterinary medical teaching hospital's (VMTH) HVAC system were tested. This building was known to have had an air quality problem. Filter samples from an apartment rental office (VPFQ) were also tested. Wood was not tested because an adequate body of data exists in the literature. The pressed paper ceiling tiles were sectioned because of sample non-homogeneity, and also because the front and back of the tiles may be exposed to different ambient conditions when installed.

Tests were performed to accurately determine equilibrium moisture content (u_e) as a function of relative humidity and temperature, and to approximately determine sorption time constant. Tests exposed the samples to known stable environmental conditions. Material moisture content was determined by massing the sample in situ as the test proceeded. Moisture content is defined as the ratio of moisture mass to dry solid mass. The sample is "dry" when it is free from water

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TABLE 2A

Important parameters of the samples tested, I-P units.

Sample	error in u_e $w(u_e)$ ±[lb/lb]	sample mass m [lb_m] × E3	error in m w(m) ±[g] × E3	density p [lb/ft^3]	surface/volume 1/R [1/ft]
1C fiberglass	0.001	29.41	0.02	2.43	240
1D VMTH fiber	0.004	8.00	0.02	3.62	79.1
2C low poly	0.002	35.56	0.04	0.50	42.5
2D VPFQ poly	0.002	41.42	0.04	0.59	42.5
3C med poly	0.005	6.59	0.02	0.60	35.1
3D VMTH poly	0.003	12.85	0.02	0.76	32.9
4A tile front	0.001	23.35	0.02	21.0	436
4C tile center	0.001	49.54	0.02	13.7	348
4B tile back	0.002	80.7	0.1	19.4	348
4D tile VMTH	0.001	122.4	0.1	21.4	218
5 urethane	0.002	15.96	0.02	1.30	62.2
6 carpet	0.001	560.0	0.4	13.2	68.4
7 padding	0.001	582.5	0.4	11.8	97.4
8 100% cot	0.001	313.7	0.2	12.4	300
9 90% poly	0.001	357.8	0.2	18.5	400

TABLE 2B

Important parameters of the samples tested, SI units.

Sample	error in u_e $w(u_e)$ ±[kg/kg]	sample mass m [g]	error in m w(m) ±[g]	density p [kg/m^3]	surface/volume 1/R [1/m]
1C fiberglass	0.001	13.34	0.01	38.9	787
1D VMTH fiber	0.004	3.63	0.01	58.0	260
2C low poly	0.002	16.13	0.02	8.0	139
2D VPFQ poly	0.002	18.79	0.02	9.5	139
3C med poly	0.005	2.99	0.01	9.6	115
3D VMTH poly	0.003	5.83	0.01	12.2	107
4A tile front	0.001	10.59	0.01	336	1430
4C tile center	0.001	22.47	0.01	219	1140
4B tile back	0.002	36.61	0.05	311	1140
4D tile VMTH	0.001	55.54	0.05	343	715
5 urethane	0.002	7.24	0.01	20.8	204
6 carpet	0.001	254.0	0.2	211	224
7 padding	0.001	264.2	0.2	189	320
8 100% cot	0.001	142.3	0.1	199	980
9 90% poly	0.001	162.3	0.1	296	1300

retained in capillaries, in solution, on fiber or cell walls, or by physical adhesion to solid surfaces; not chemically bound water (Luikov 1966). Sample dry mass was determined first so that volatile substances were driven off. Sorption hysteresis of the shirts and the capillary diffusion behavior of fiberglass were also investigated.

THEORETICAL APPROACH

Physical absorption occurs at the solid-vapor interface between the moisture in contact with the solid and airborne water vapor (Harter 1963). This process occurs spontaneously without the addition of energy (Bullock and Threlkeld 1986). The moisture absorbed on the solid is bound to it by capillary attraction; this force causes its vapor pressure to be lower than the vapor pressure of free water at the same temperature. At equilibrium, the vapor pressure of the absorbed water is equal to the vapor pressure of the surrounding air, which is proportional to relative humidity and temperature. The surface tension of the absorbed moisture exerts a force on vapor molecules at the solid-vapor interface, tending to increase their vapor pressure so that condensation occurs at the surface, even though the bulk vapor pressure of the surrounding air may be well below the vapor pressure of free water (Carrier Corp. 1929; Harter 1963). In a capillary-porous body the surface tension force, and thus absorption capability, is inversely proportional to capillary diameter (Luikov 1966). Thus, sorption is a highly material-dependent phenomenon.

The heat and mass transfer occurring at the surface of the body is modeled here as a low-intensity drying process. The conditions considered are drying at constant temperature, humidity, and pressure. This is a quasi-stationary heat and mass transfer process described by the following expressions for the initial constant rate drying period (Luikov 1966):

$$\frac{du}{dt} = \frac{q}{pR} \tag{1}$$

where

q = drying intensity [$lb_m/ft^2 \cdot h$], [$kg/m^2 \cdot s$]
R = volume to surface ratio [ft^3/ft^2], [m^3/m^2]
p = body density [lb_m/ft^3], [kg/m^3]

The drying intensity is equal to the density of moisture flow at the surface of the body. The constant drying process as described by Equation 1 is no longer applicable when a certain critical moisture content, U_{cr} (critical mean volumetric

TABLE 3

Maximum observed equilibrium moisture content of samples tested (listed by u_e, [lb/lb] = [kg/kg]).

Sample	u_e	rh [%]	T[F]	T[C]
1D VMTH fiberglass	0.540	99.1	71.4	21.9
3D VMTH polyester	0.402	99.0	63.9	17.7
8 100% cotton	0.137	99.3	71.9	22.2
6 carpet	0.100	94.0	119.2	48.4
3C medium polyester	0.093	96.0	119.6	48.7
2D VPFQ polyester	0.080	99.3	67.4	19.7
4D VMTH tile	0.060	99.3	67.4	19.7
5 urethane foam	0.052	99.3	67.4	19.7
4A tile front	0.050	99.3	67.4	19.7
4B tile back	0.045	99.3	67.4	19.7
4C tile center	0.044	99.3	67.4	19.7
2C low polyester	0.040	99.3	67.4	19.7
7 rubber-urethane	0.038	94.0	119.2	48.4
1C fiberglass	0.035	99.0	64.4	18.0
9 90% polyester	0.013	99.3	71.9	22.2

TABLE 4

Observed moisture content of samples at typical occupied space condition (listed by u_e, [lb/lb] = [kg/kg]).

Sample	u_e	rh [%]	T[F]	T[C]
3D VMTH polyester	0.081	76.4	68.8	20.4
8 100% cotton	0.057	65.0	69.1	20.6
6 carpet	0.024	54.2	66.7	19.3
1D VMTH fiberglass	0.023	74.7	69.3	20.7
4C tile center	0.017	54.2	66.7	19.3
4B tile back	0.017	54.2	66.7	19.3
7 rubber urethane	0.017	54.2	67.4	19.7
2D VPFQ polyester	0.016	54.2	66.7	19.3
4D VMTH tile	0.015	54.2	66.7	19.3
3C medium polyester	0.014	54.2	66.7	19.3
2C low polyester	0.012	54.2	66.7	19.3
5 urethane foam	0.012	54.2	66.7	19.3
4A tile front	0.011	54.2	66.7	19.3
9 90% polyester	0.006	65.0	69.1	20.6
1C fiberglass	0.005	65.0	70.0	21.1

TABLE 5A

Experimentally determined drying intensity, I-P units.

Sample	$q \times 10^4$ [lb/ft^2 · hr]	$w_q \times 10^4$ ±[lb/ft^2 · hr]
VMTH fiberglass	29.6	0.03
carpet	10.2	0.05
VMTH polyester	6.170	0.004
VMTH tile	5.52	0.02
100% cotton	5.511	0.006
rubber-urethane	3.175	0.003
fiberglass	2.355	0.002
tile front	2.345	0.002
medium polyester	2.266	0.002
tile back	1.953	0.009
tile center	1.329	0.002
urethane foam	1.045	0.001
VPFQ polyester	1.103	0.004
90% polyester	0.540	0.001
low polyester	0.414	0.002

TABLE 5B

Experimentally determined drying intensity, SI units.

Sample	$q \times 10^3$ [kg/m^2 · hr]	$w_q \times 10^3$ ±[kg/m^2 · hr]
VMTH fiberglass	131.7	0.1
carpet	45.7	0.2
VMTH polyester	27.44	0.02
VMTH tile	24.54	0.07
100% cotton	24.51	0.03
rubber-urethane	14.12	0.02
fiberglass	10.47	0.01
tile front	10.43	0.01
medium polyester	10.08	0.01
tile back	8.68	0.04
tile center	5.911	0.009
urethane foam	4.647	0.004
VPFQ polyester	4.91	0.02
90% polyester	2.402	0.004
low polyester	1.841	0.009

moisture content), and u_{cr} (critical surface moisture content) are reached (Luikov 1966). u_{cr} and the time required to reach equilibrium, t_{cr}, depend on the volume-to-surface ratio of the body:

$$\text{if } R \text{ is large} \quad \frac{du}{dt} << 1$$

$$\text{if } R \text{ is very large} \quad \frac{d^2u}{dt^2} < 0 \text{ and } u_{cr} > u_{initial}$$

The falling rate drying period, $t > t_{cr}$, is adequately described by an exponential relationship,

$$u = A\,exp(-kt) + B \tag{2}$$

where

A, B, and k are experimentally determined constants, u is moisture content [mass H_2O]/[mass solid], and t is time [h].

RESULTS

Of the samples tested, only the used fiberglass duct lining from VMTH, the used polyester filter material from VMTH, and the 100% cotton shirt exceeded the critical 0.10 lb/lb moisture content necessary for microbial survival. The jute-backed 100% nylon carpet sample was found to have an equilibrium moisture content of 0.100 lb/lb at 120°F (48.9°C) and 99.3% RH.

The duct from which the VMTH fiberglass and filter samples were taken brought in outdoor air from an area near covered outdoor dog pens. Microscope examination (60x) of the used fiberglass and filter samples revealed soil particles and bits of dried leaves and grass. A light micrograph (30x) of the latex-covered jute carpet backing showed that the latex is non-uniform and is an ineffective moisture barrier. Results are summarized in Tables 2, 3, 4, and 5.

An initially dry, clean fiberglass sample immersed to a depth of 0.75 in (2 cm) showed undetectable capillary diffusion at 30×. It was observed that liquid water did not rise into the fiberglass over a period of 18 days. However, when the sample was initially wet to a height of 2 in (5 cm) and then immersed to 0.5 in (1 cm), the 2 in (5 cm) wetted area was maintained over a 10-day test period at 65% RH, 70°F (21°C). Upon removal from the water, the sample dried to 0.005 lb/lb moisture content in 7 hours at 65% RH, 70°F (21°C).

The behavior of the 100% cotton and 90% polyester samples after wetting to ue = 0.62 lb/lb was also investigated. Equilibrium for both samples was reached in 42 hours. Neither sample experienced hysteresis due to the imposed high initial moisture content.

DISCUSSION

Used (soiled) samples consistently had a higher moisture content than the unused member of a used-unused sample pair. Calculations show that the deposited material in the

VPFQ polyester filter material had an effective moisture content of 0.32 lb/lb at 99.3% RH, 67.4°F (19.7°C). This deposited material is responsible for 50% of the moisture absorbed by the filter at these conditions. The VMTH fiberglass sample moisture content was from 10 to 40 times greater than that of the clean sample at the same conditions. This trend was also evident in the tile samples but to a lesser degree.

Results indicate that cotton and polyester will not have a higher equilibrium moisture content after being wet and then allowed to dry at room conditions than if they are completely dried first before being allowed to come to equilibrium at room conditions.

Fiberglass behaves hydrophobically when at low moisture content. At high moisture content, the water retained on and between the fibers attracts water with sufficient force to replace water lost to evaporation at room conditions. This means that dry fiberglass duct lining in contact with liquid water (for example, a condensate drip pan) will remain dry above the water line, but any section of lining that becomes wet will remain wet as long as part of it remains in contact with liquid water.

The equilibrium moisture contents and drying intensities determined can be directly applied to a building moisture mass balance model in order to predict indoor relative humidity and material moisture content (West and Hansen 1989). Data for additional materials are needed for a complete analysis.

Although the experimental design is simple, the need for precise control of environmental conditions over long test times (up to 16 hours per data point) results in a time-absorbing and delicate procedure. The use of automatic controls and data acquisition is recommended.

CONCLUSIONS

1. Clean fiberglass will not absorb sufficient airborne moisture to support microbial growth. Results show that its maximum hygroscopic moisture content is 0.052 lb/lb at 99.9% RH, 64.4°F (18.0°C). This is well below the required 0.10 lb/lb for growth reported necessary by Block (1953, 1987).
2. Cotton cloth can absorb sufficient moisture from the air to support microbial growth. Results show that an equilibrium moisture content of 0.10 lb/lb is attained at 92% RH, 72°F (22°C).
3. Organic materials attached to fiber strands in microbially contaminated polyester filter material and fiberglass can increase hygroscopicity 2 to 10 times that of clean materials. Results show this increase is enough to allow microbial growth in relative humidities greater than 90% in the material as a whole. Additionally, the organic matter itself appears to absorb sufficient moisture to support microbial growth at relative humidities greater than 60%.
4. Clean fiberglass does not absorb a measurable amount of liquid water by capillary diffusion when initially dry. However, when initially wet, capillary diffusion can proceed at a rate adequate to maintain maximum wetability at 60% RH, 70°F (21°C).
5. Cotton and polyester clothing material do not exhibit the degree of sorption hysteresis necessary to maintain higher than 0.10 lb/lb moisture content at 70% RH, 68°F (20°C). The sample materials can be safely dried indoors within 42 hours from a moist condition (u_e = 0.62 lb/lb).
6. The proliferation of microbes in the HVAC fiberglass duct lining sample obtained from a veterinary medical teaching hospital (which is known to have an air quality problem) exists due to two major factors: i) deposits of fine soil, parts of dried leaves and grass, and microbial matter on the fiberglass increases its ability to absorb moisture from the air tenfold over clean fiberglass; and ii) standing water in condensate drip pans maintains high lining moisture content by capillary diffusion.
7. Fiberglass duct lining is not a safe material to use inside HVAC system components, unless (i) a high-efficiency filter is installed at all air intakes to prevent buildup of organic materials, and (ii) the fiberglass does not contact liquid water. The conditions are easily met with minimal attention in the HVAC system design phase. If they are not maintained, even temporarily, microbial habitability will increase due to increased moisture retention. Remedial measures are very costly in terms of both economics and health. Although "drying out" of contaminated ductwork may kill or deactivate fungi, the residual organic material provides not only substrate for renewed growth, but moisture as well.
8. The experimental apparatus and procedure used in this work are ample for precise and accurate determinations of hygroscopic properties as applied to buildings and residences. Material moisture content can be determined to within 0.001 [moisture mass]/[dry sample mass] and sorption rate to within 0.01 lb_m/h (0.005 kg/h) over the range 20% to 100% RH (±2.5%) and 45°F (7°C) to 120°F (50°C), (±1°F, ±0.5°C).

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DISCUSSION

Carl N. Lawson, LRW Engineers Inc., Tampa, FL: Did you notice any reaction with duct liners or fiberglass duct that was moisture-laden after it was exposed to heat?

M.K. West, University of Florida, Gainesville, FL: No. The liner was exposed to 250°F, 5% RH before any moisture-laden heat exposure was maintained. This was done to determine dry mass and to drive off VOCs. Exposure to 120°F, 80+% RH lasted only several hours. Apparently this procedure limited an increased growth reaction since none was noticed. However, the focus of the observations made was the materials themselves and not reactions—thus a subtle reaction may have escaped observation.