Understanding Water:

The Physics of Moisture Dynamics

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Balanced Solutions

BEG
Building Engineering Group

Overview

- Moisture and Building Science
- Moisture storage in porous materials
- Moisture transport through porous materials
- Material performance thresholds
- Modeling

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Moisture Physics

- The Basics: The Moisture Balance
  - Wetting, Drying, Storage
- The Water Molecule
  - Phases, vapour pressure
- Porous Media – wood, concrete drywall
- Moisture Storage
- Moisture Transport – diffusion, capillary

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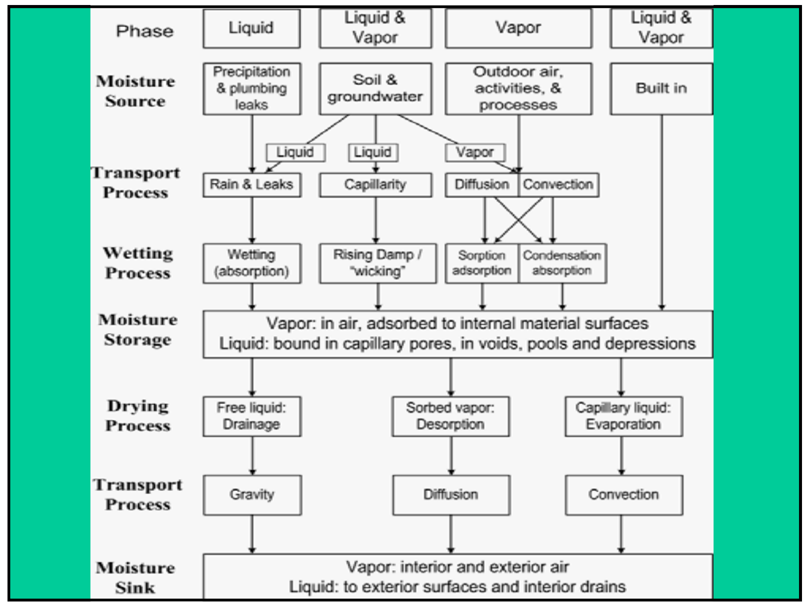
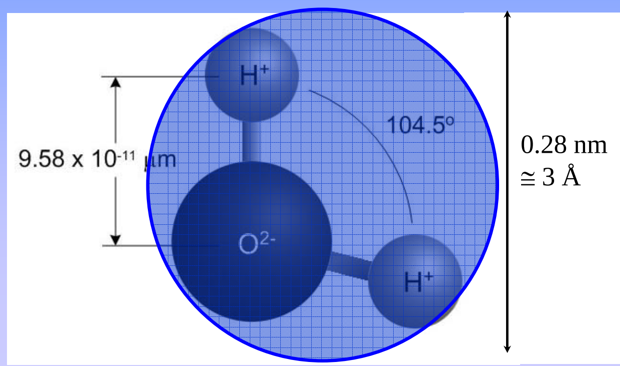


The Water Molecule

- Asymmetrical = polar
- Small: one billion = one foot



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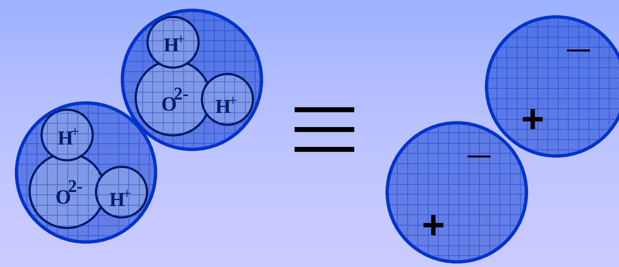
The Polar Molecule

- Hydrogen end is "more" positive
- Oxygen end is "more" negative



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Polar Implications

- Boiling point
  - higher than predicted
- Adsorption
  - water vapour sticks to surfaces
- Surface tension
  - liquid water sticks to itself and surfaces
- Surfactants
  - interact with water at surfaces

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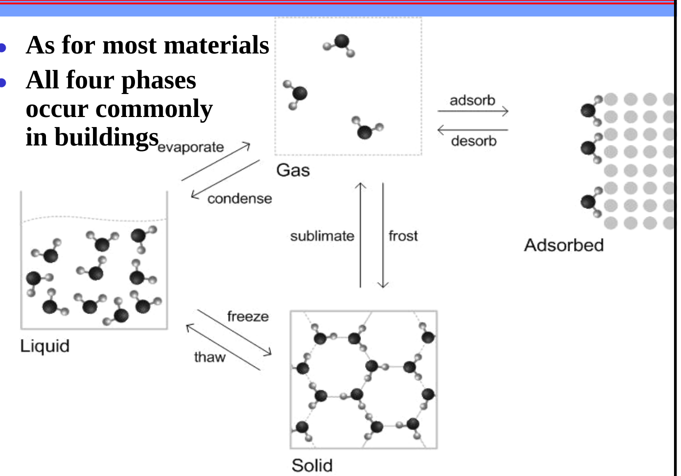
Moisture Phases

- As for most materials
- All four phases occur commonly in buildings



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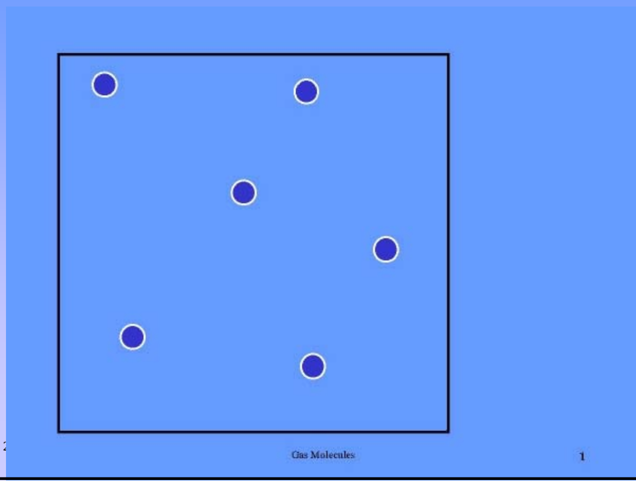
Moisture as a Gas (water vapor)



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Vapour Pressure

- For water vapour in a container
- Higher temperature
  - = more energy
  - = higher velocity
  - = harder collisions with wall (higher pressure)
- Greater number of molecules
  - = more collisions with walls (higher pressure)
  - = pressure simply another measure for moisture content

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Water Vapour in Air

- Water vapour exists in all air
- Air has a maximum vapour holding capacity
  - Capacity changes dramatically with temperature
  - When the maximum holding capacity is exceeded, condensation occurs
- These facts are summarized by the psychrometric chart

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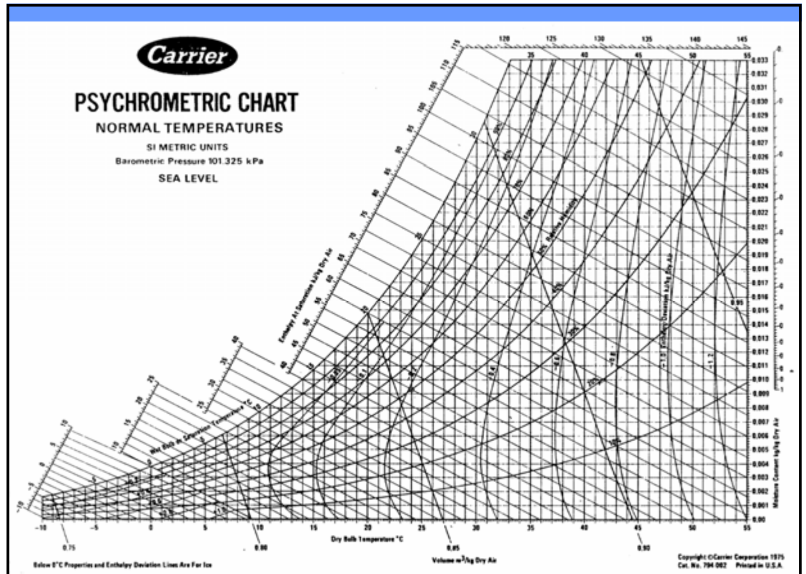
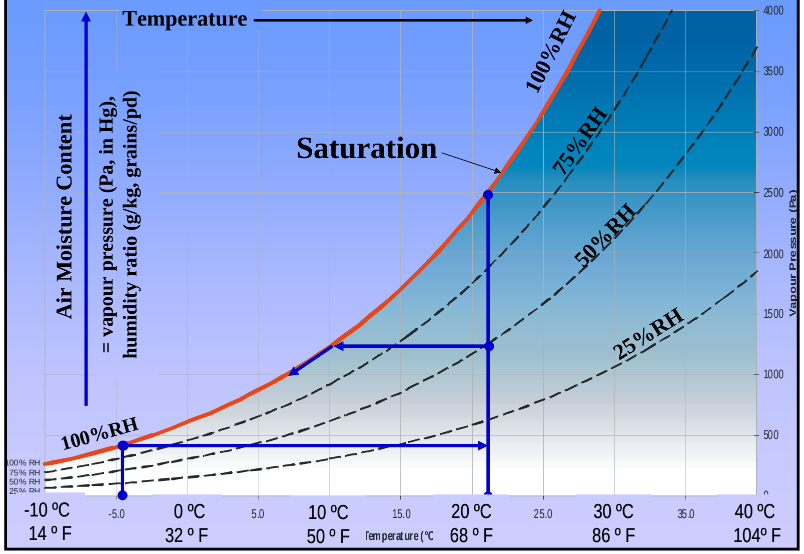
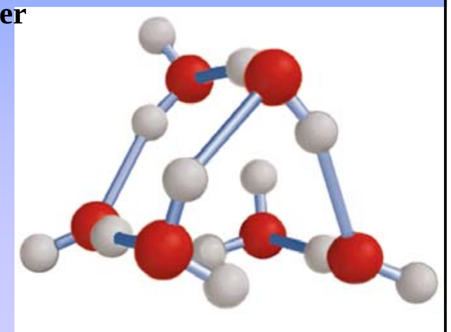


Psych Chart: Air Vapour Content vs Temperature



Moisture as a Liquid

- Polar molecules stick to each other
- Liquid water exists in clusters
  - e.g., $H_{120}O_{60}$ at room temperature
  - Clusters get smaller with higher temp



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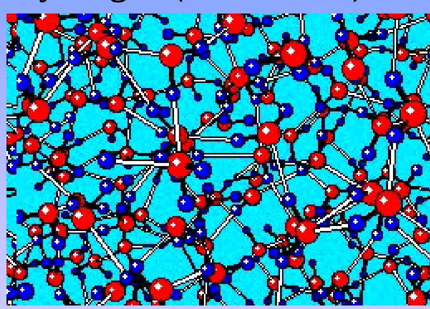
Vibrating Liquid Water

- Red= Oxygen (big, M=16)
- Blue = Hydrogen (small, M=1)



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Moisture as Liquid

- Single vapor molecule is small
- Liquid cluster is large
- Hence, Gore-Tex & Tyvek
  - Vapour molecules pass through small openings
  - Liquid molecules repelled by hydrophobic
  - E.g., try a pin hole in housewrap

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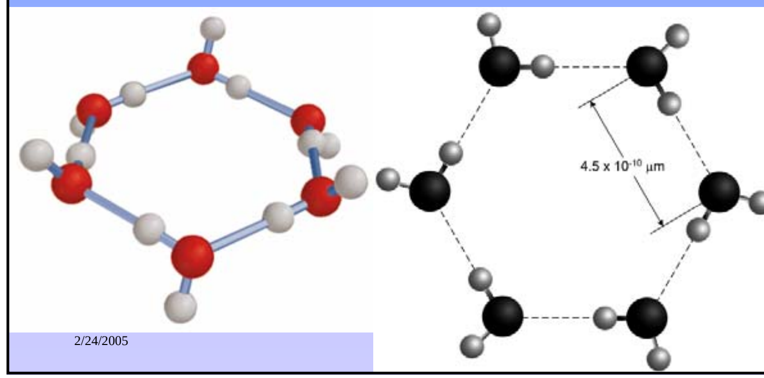
Moisture as a Solid

Canadian moisture jokes

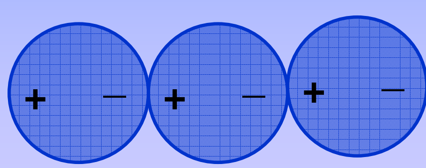
Ice : Moisture as Solid

- **Ice forms a crystal and expands as it freezes**
- **e.g., lower density by 9%**



Surface Tension

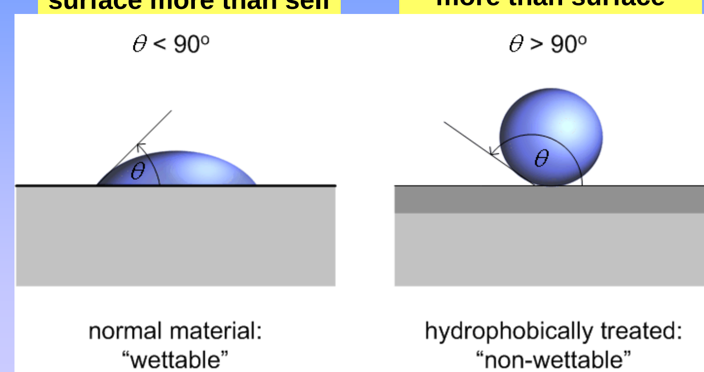
- **Water is attracted to self**
- **Creates a “membrane” or “surface film”**



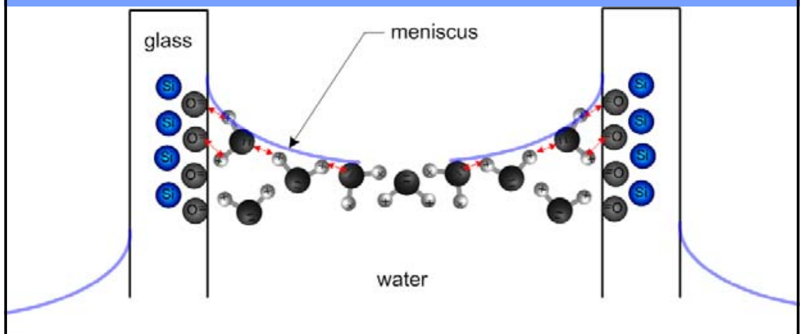
Surface Tension: Wettable

Water attracted to surface more than self

Water attracted to self more than surface



Capillary Suction Pressure



Silicon dioxide (glass) – attracts water
Result - meniscus, capillary suction

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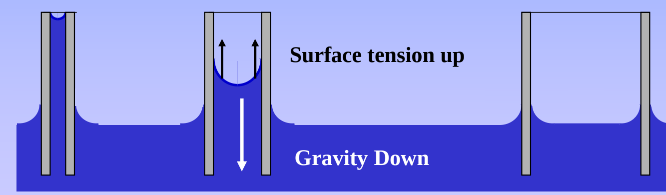
Capillary Pressures

- **Result of surface tension = attraction to surfaces**
  - **pressure varies with pore size**
  - **e.g., height rise in a glass tube**



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Surface Tension

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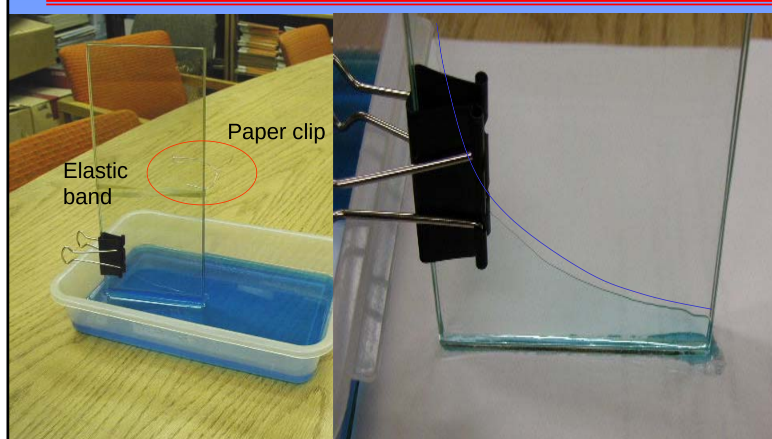
Capillary rise between plates



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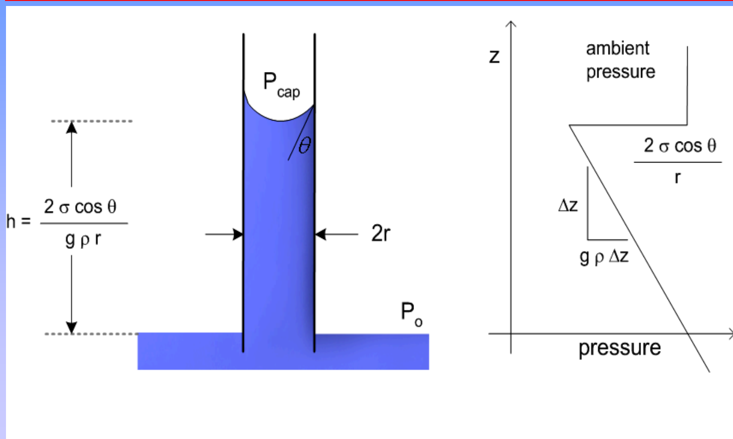
Calculating capillary rise



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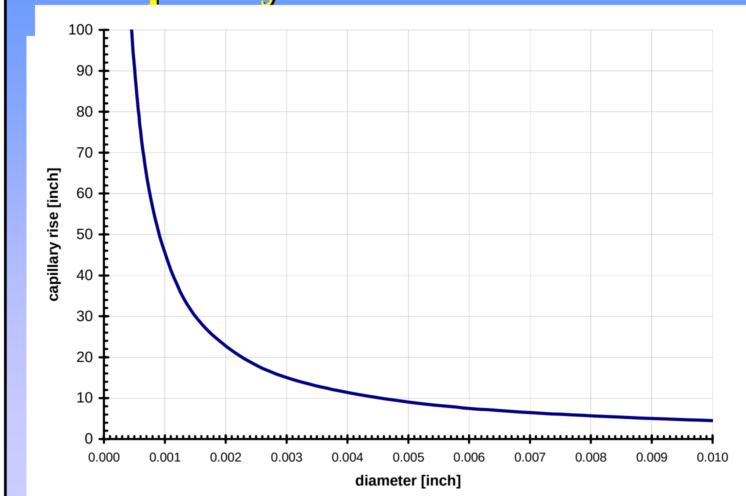
Capillary rise versus diameter



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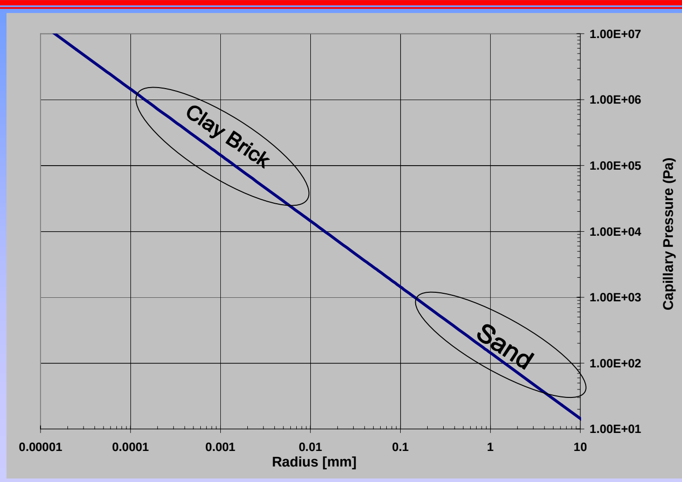
Particle Size vs Capillary Suction



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Surfactants

- **Changes the way water molecules interact with surfaces**
  - **dramatically reduces surface tension**
- **Soap is a surfactant**
  - **connects water to grease**
  - **one end is polar**
  - **one end is non-polar (sticks to oil and grease)**

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Soap and Water

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Nature of Porous Materials

- Many materials interact with moisture!
- Many building materials are porous
  - wood
  - concrete, brick, gypsum
- Nature of material is as important as nature of water

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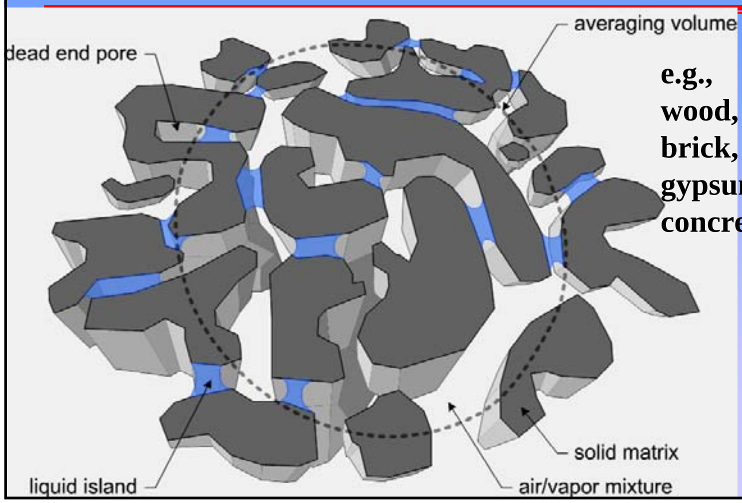
Slice through a porous material



e.g., wood, brick, gypsum, concrete

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Real Materials

Figure 1c. Gypsum, hydrated from plaster of paris and water, porosity 30 per cent.

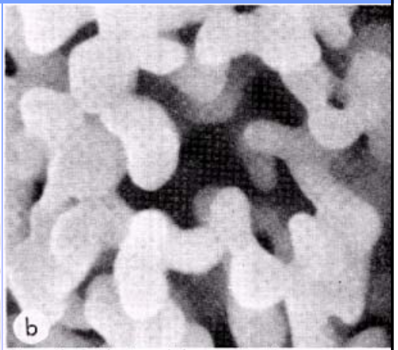

Figure 1b. Brick, sintered clay, porosity 40 per cent.

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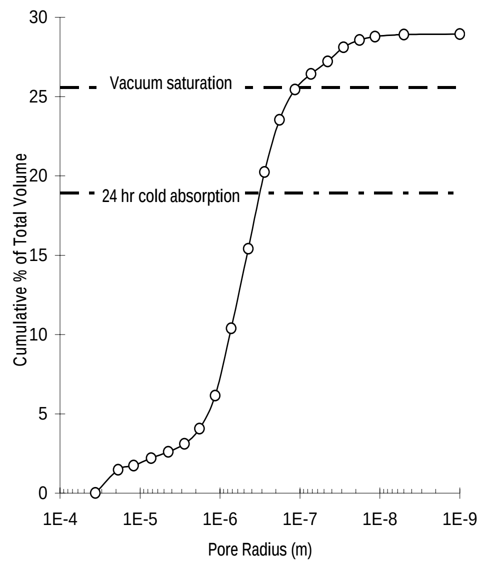


Clay Brick

Mercury porosimetry

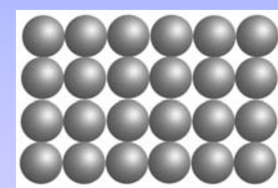
Pressure plate

Brick Sucks!

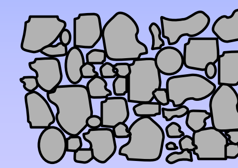
Simple Models

Simple → **Reality**

Cubic packing of spherical particles



Random particles size and packing



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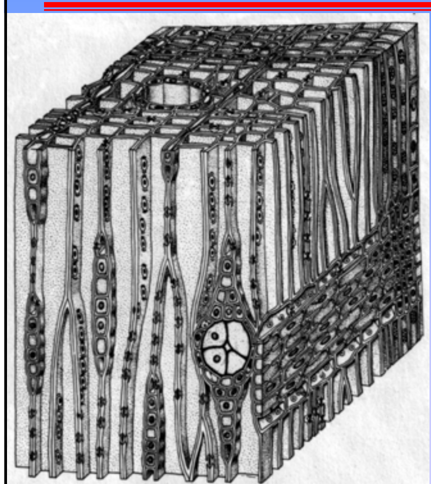
Isotropic matl's: Wood Structure



- Equivalent to a bundle of tubes
- flow along grain much faster

Surface tension in small tubes can feed water up 100m (300 ft) tall trees

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Storage Mechanisms

- Basic mechanisms
  - in materials
    - capillary pores (bound liquid, vapour, ice)
    - sorption (adsorbed)
  - in enclosures
    - pools and puddles (free liquid)

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Adsorbed State of Moisture

- Poorly understood by most
- Water vapour molecules stick to surfaces
  - like dust on glass table
  - dynamic balance
  - molecules stick and leave
  - depends on energy of water vapour
- Very important for porous materials with large surface areas

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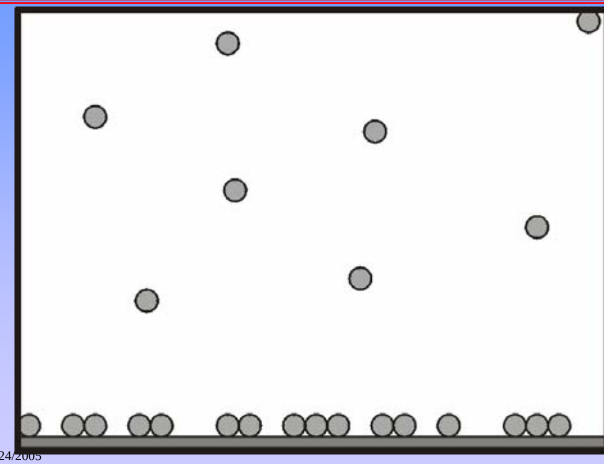
Adsorbed Moisture



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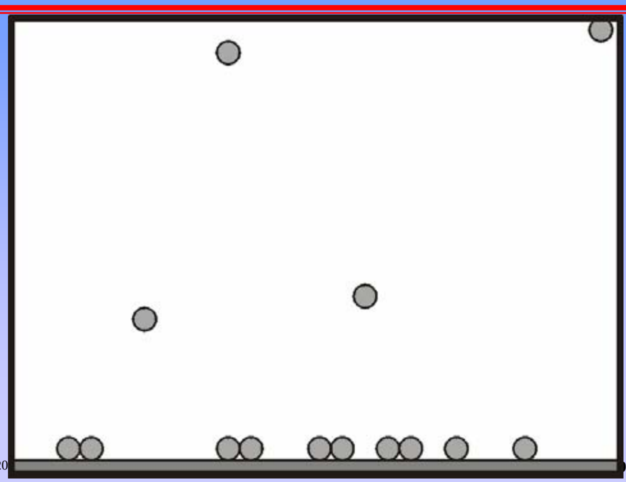
Adsorption Lower RH



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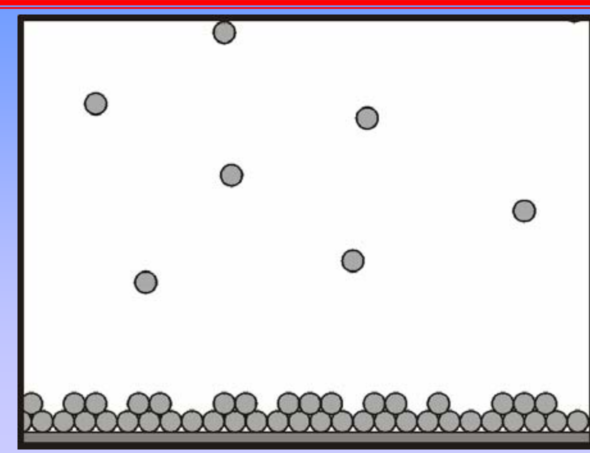
Adsorption higher RH



More
H20
sticks

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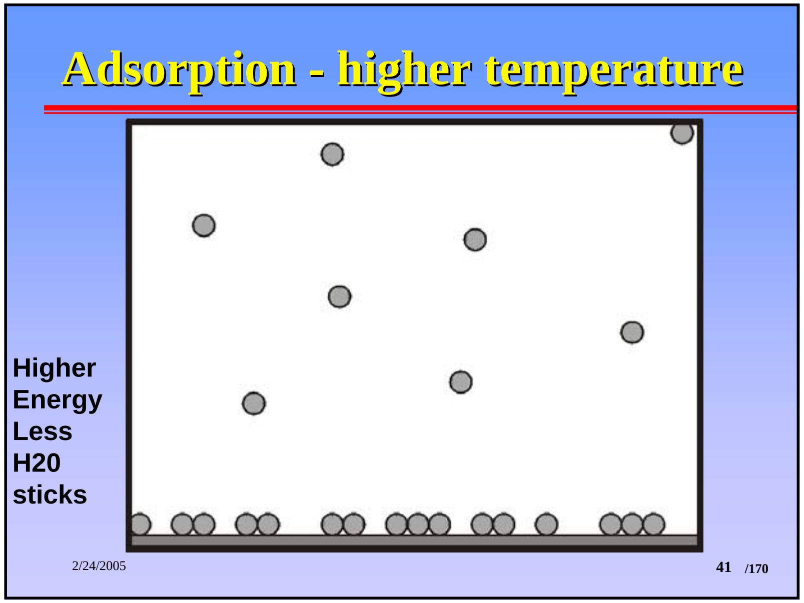
Adsorption - higher temperature
Higher
Energy
Less
H20
sticks
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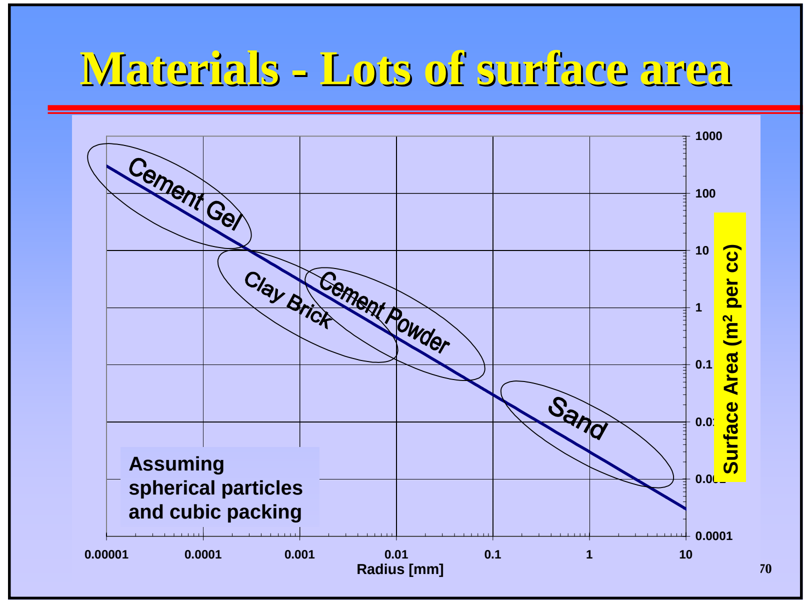
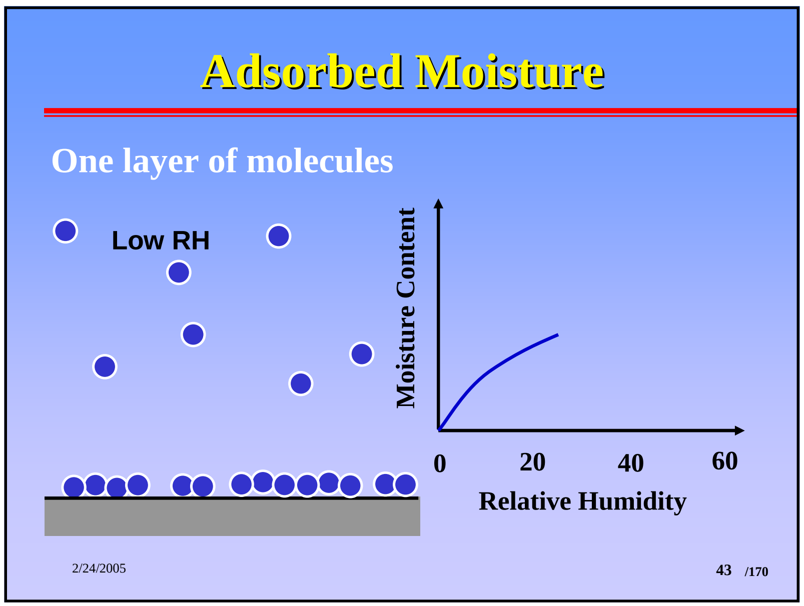

Materials - Lots of surface area
Cement Gel
Clay Brick
Cement Powder
Sand
Assuming
spherical particles
and cubic packing
1000
100
10
1
0.1
0.0001
Surface Area (m² per cc)
0.00001
0.0001
0.001
0.01
0.1
1
10
Radius [mm]
70


Adsorbed Moisture
One layer of molecules
Low RH
Moisture Content
0
20
40
60
Relative Humidity
2/24/2005
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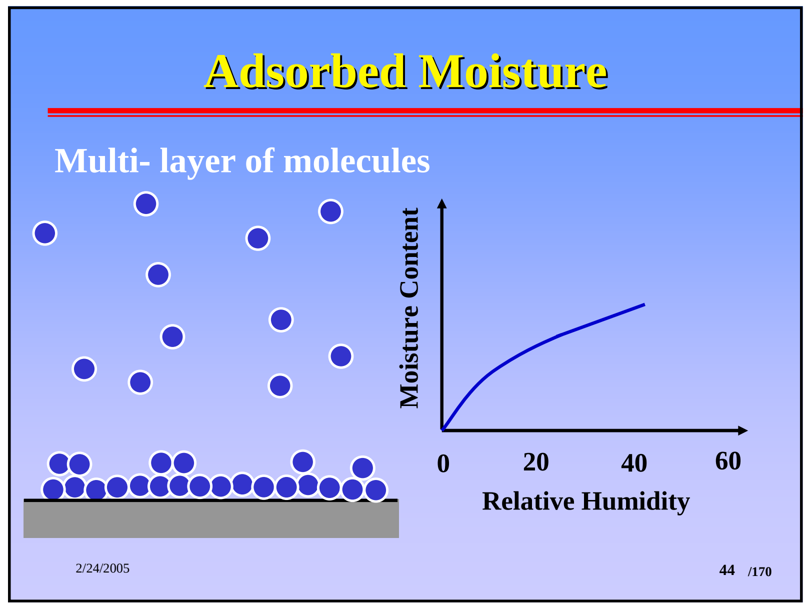
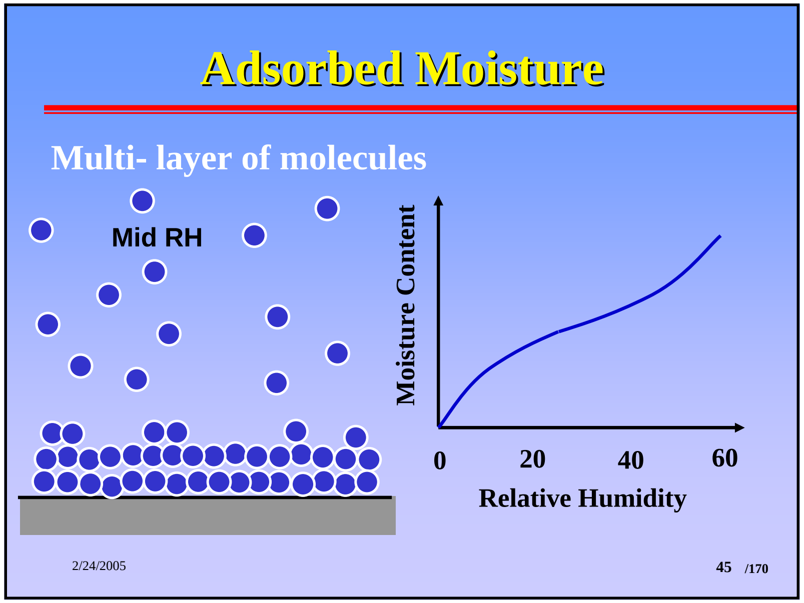
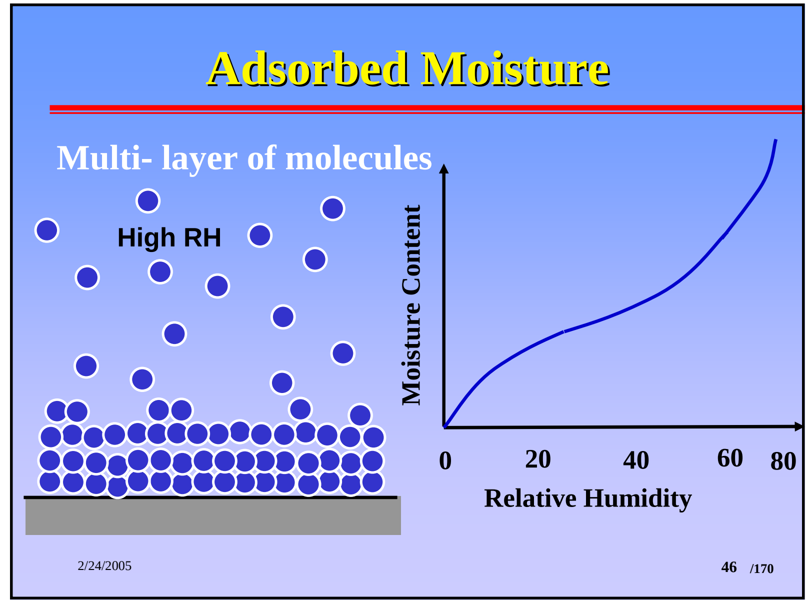

Adsorbed Moisture
Multi- layer of molecules
Moisture Content
0
20
40
60
Relative Humidity
2/24/2005
44 /170


Adsorbed Moisture
Multi- layer of molecules
Mid RH
Moisture Content
0
20
40
60
Relative Humidity
2/24/2005
45 /170


Adsorbed Moisture
Multi- layer of molecules
High RH
Moisture Content
0
20
40
60
80
Relative Humidity
2/24/2005
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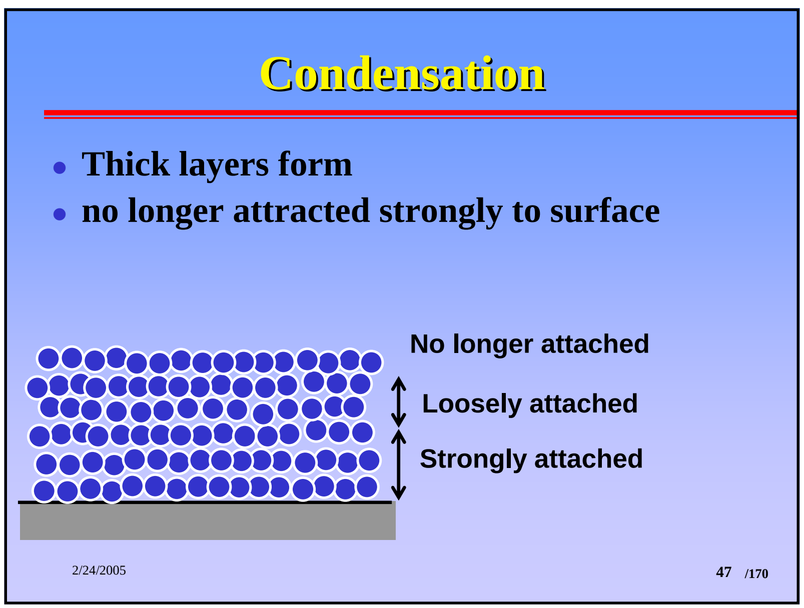
Condensation
Thick layers form
no longer attracted strongly to surface
No longer attached
Loosely attached
Strongly attached
2/24/2005
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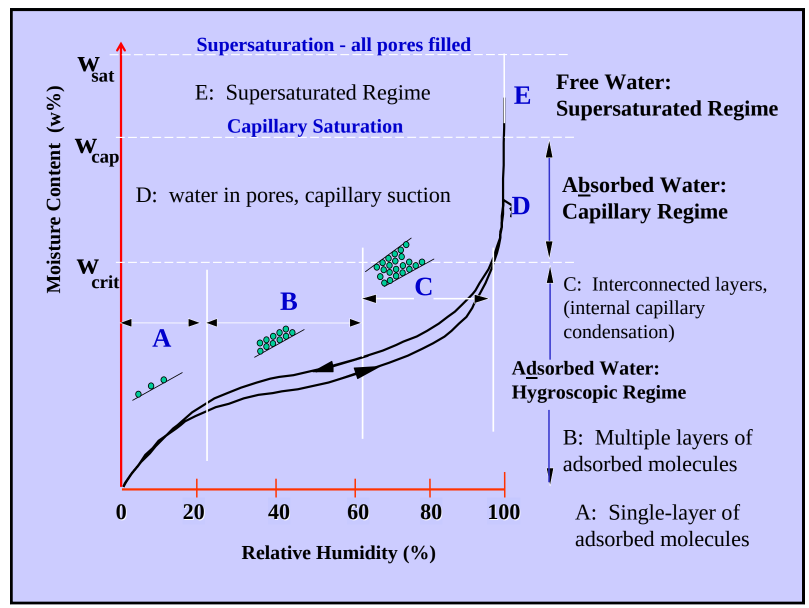

Supersaturation - all pores filled
W sat
E: Supersaturated Regime
Capillary Saturation
W cap
D: water in pores, capillary suction
W crit
Moisture Content (w%)
A
B
C
D
E
0
20
40
60
80
100
Relative Humidity (%)
Free Water:
Supersaturated Regime
Absorbed Water:
Capillary Regime
C: Interconnected layers,
(internal capillary
condensation)
Adsorbed Water:
Hygroscopic Regime
B: Multiple layers of
adsorbed molecules
A: Single-layer of
adsorbed molecules

Moisture Regions

- Hygroscopic
  - dry to the touch but still moisture
  - e.g., wood can store over 25% by weight
- Capillary range
  - wet to touch, but no draining (sponge)
  - e.g., brick 5 to 20% by weight
- Over-saturated range
  - water drains from material
  - e.g., crushed stone

Predicting Sorption

- BET with Rounsley enhancement

$$\frac{X}{X_1} = \frac{C\phi}{1+(C-1)\phi}\left[\frac{1-\phi^n}{1-\phi}\right]$$

where X is the equilibrium moisture content (M%),

X_1 is the moisture content in a mono-layer of adsorbate (M%),

ϕ is the relative humidity,

C is a constant, comprising the heat of adsorption, heat of condensation and the universal gas constant (typically 20 to 50),

n is the maximum number of layers that can be adsorbed (typically 4-6).

Vapor pressures

- Curved Surfaces
- Kelvin's Equation

$$\ln\left(\frac{P_{cap}}{P_w}\right) = \frac{-2\cdot\sigma\cdot\cos\theta}{r\cdot\rho\cdot R_{wv}\cdot T}$$

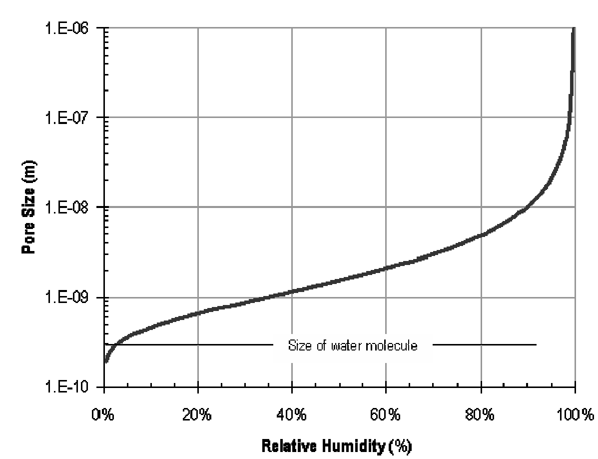
where, ρ is the density of water,

P_{cap} is vapor pressure over the curved surface of water in a capillary pore,

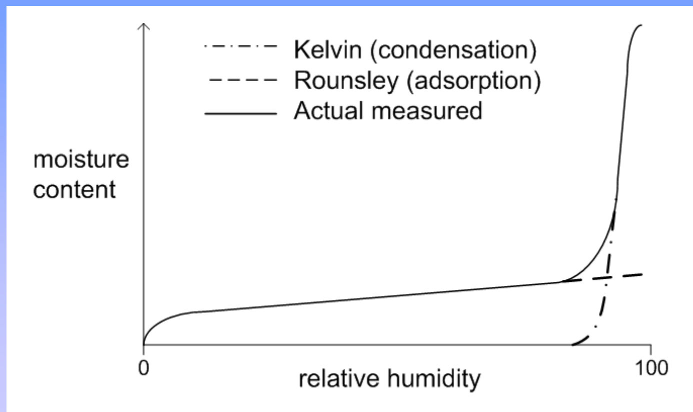
P_w is the water vapor pressure over a flat surface at the same temperature,

R_{wv} is the water vapor gas constant, and other terms are as before.

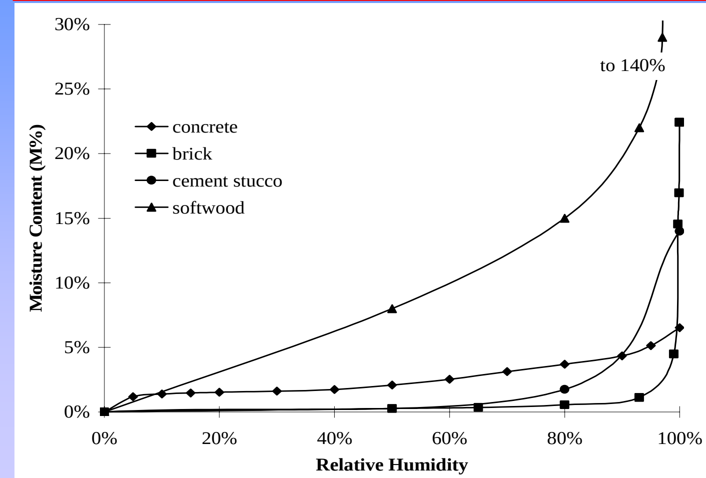
Kelvin: Capillary condensation

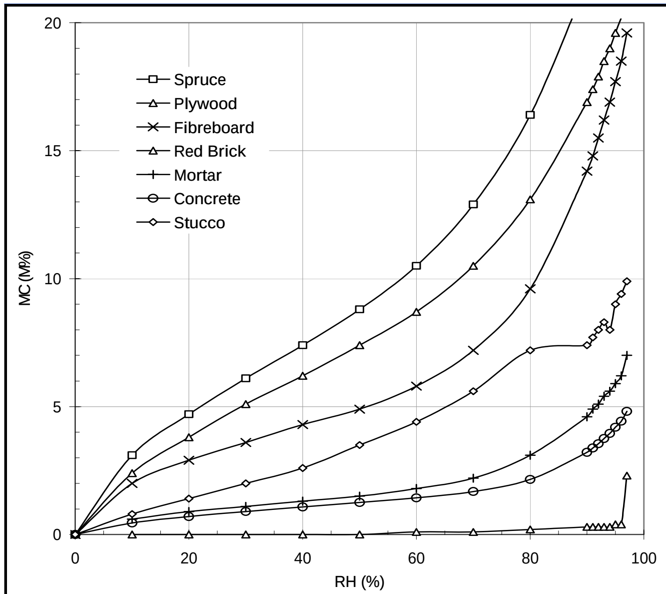


Sorption + Condensation

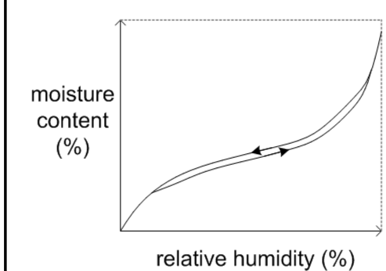


Sorption

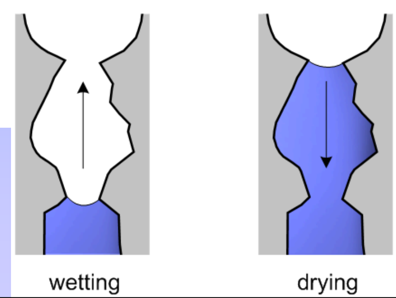




Hysteresis of Sorption

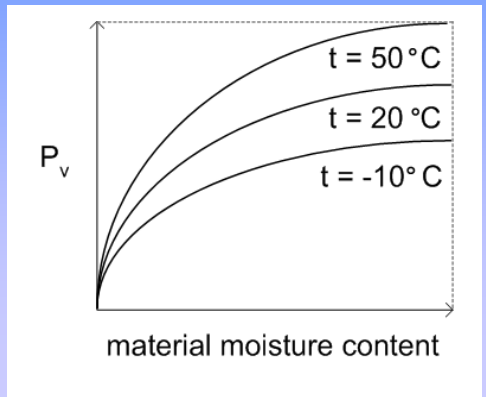


- **Ink Bottle effect**

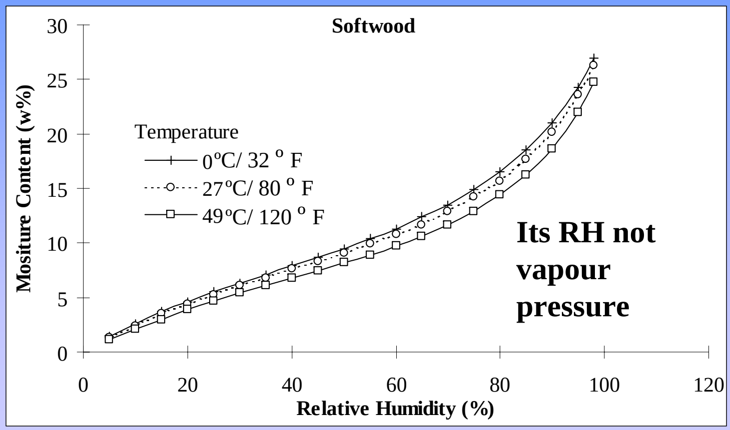


Sorption vs Temperature

- Sorption vapor vs temperature and MC

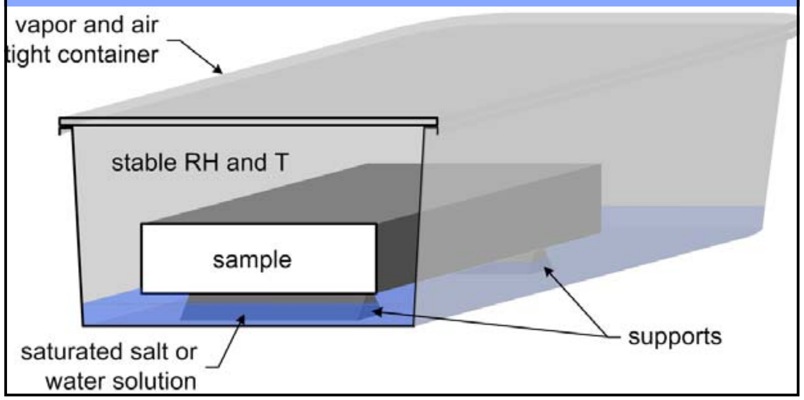


Temperature Effects



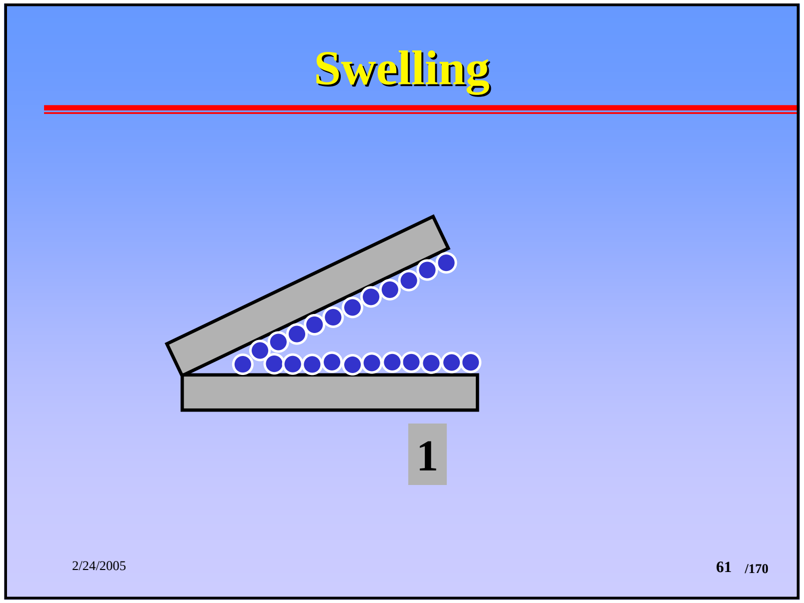
Sorption test

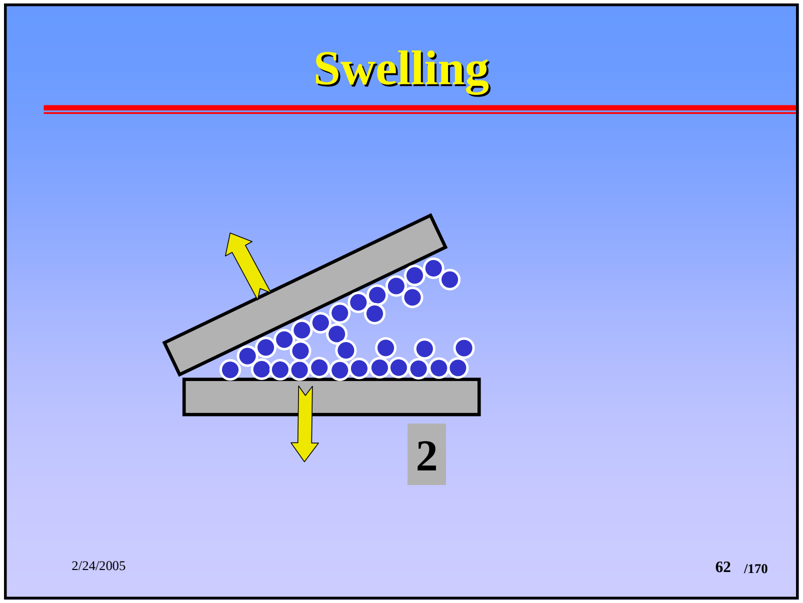
- Tupperware Standard- Balanced ASTM

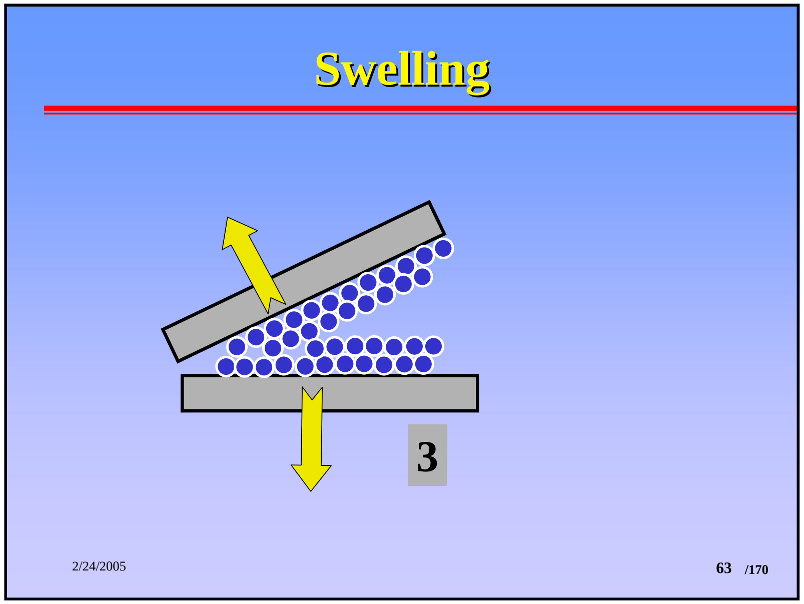


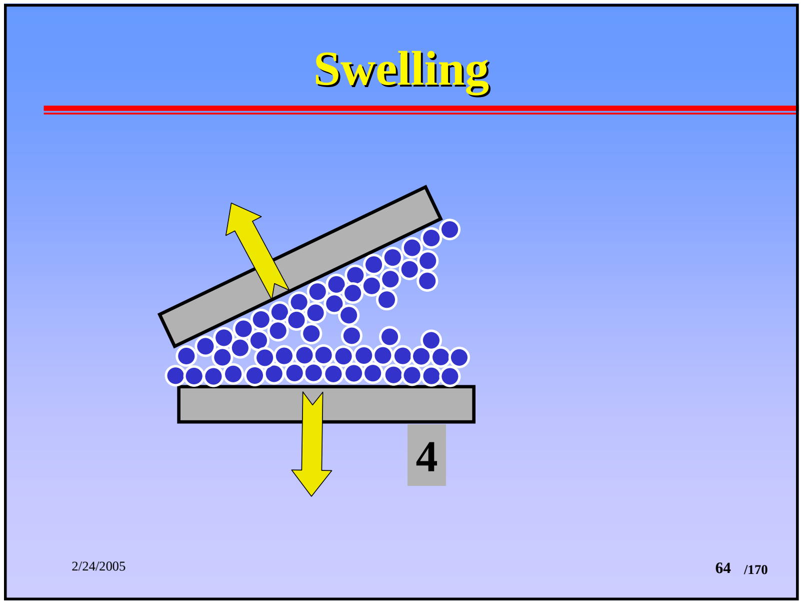
Significance Of Regions

- mould, corrosion
  - tend to begin around 80%
  - layer is thick enough that "free" H_20 is avail.
- Swelling
  - only occurs in hygroscopic range
- Freeze-thaw
  - capillary range


Swelling
1
2/24/2005
61 /170

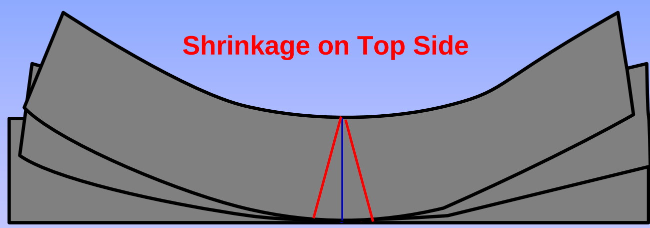

Swelling
2
2/24/2005
62 /170


Swelling
3
2/24/2005
63 /170


Swelling
4
2/24/2005
64 /170

Swelling Causing Curving

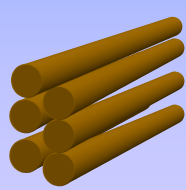
- E.g., concrete slab curl
- Deck Board cupping

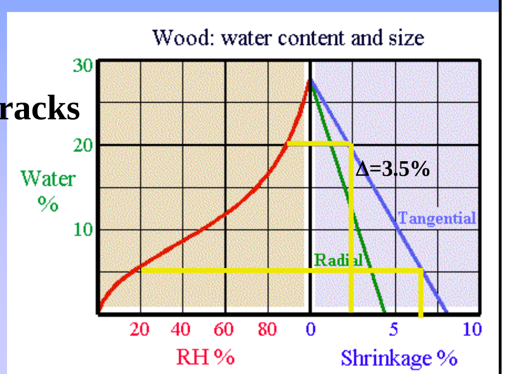


Moisture Swelling

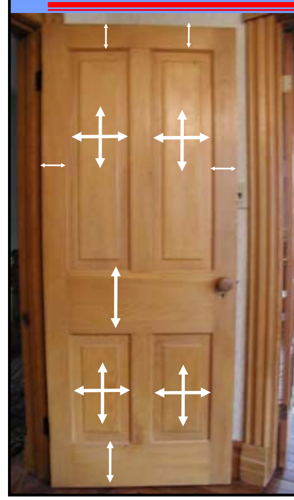
Wood Swelling and Shrinkage

- Wood acts as a bundle of tubes
- Shrinks *across* grain, not along
- Only during adsorption
- E.g. Drywall cracks

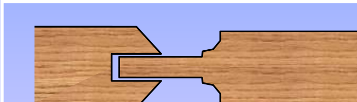




Colonial Doors



Designed so that frame has nearly no cross grain
Cross-grain panels slide



Detail Section

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Solutions

- Allow movement
- Cupping
  - Reduce gradient
  - Reduce thickness
  - Reduce stiffness & restrain
- Shrinkage swelling
  - Reduce range of RH
  - Reduce rate of change
  - Reduce cross grain!

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Measuring Moisture Storage

- Sorption, capillary saturation, pore volume

Material	Density (Dry) kg/m^3	Open Porosity (%)	MC @ ≅95%RH (M%)	w_{cap} (M%)
Concrete	2200	15-18	4-5	6-8
Brick	1600-2100	11-40	3-8	6-20
Cement Mortar	1800-1900	20-30	5-7	14-20
Softwood	400-600	50-80	20-30	100-200
Fibreboard	240-380	60-80	20-25	100-200
Wood chipboard	700	50-70	15-20	100-150
Expanded polystyrene	32	95	5	> 300
Gypsum (exterior)	1000	70	10	50-100

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Moisture Transport

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Moisture Transport

- Moves from high concentration to less
- This does not always mean more moisture content or more vapour pressure!
- Each phase should be considered separately
  - liquid
  - vapor (diffusion and air leakage)
  - adsorbed
  - ~~ice~~

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Liquid flow

- May be driven by:
  - gravity
  - pressure differences (air or water)
  - capillary pressures
- Capillary – 0 to 10 MPa (M!)
- Gravity always acts, downward
  - About 10 000 Pa/m (1.3 psi/yd =15 psi/33 ft)
- Air pressure varies
  - wind typically < 100 Pa (0.015 psi= 2 psf)
  - short 1000 Pa bursts (0.15 psi = 20 psf)

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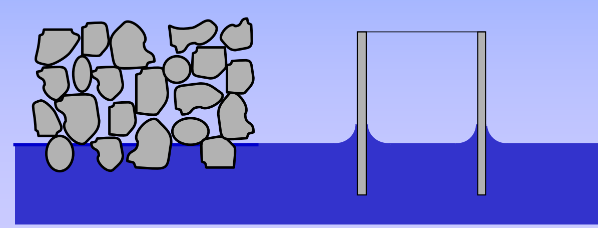
Capillary Flow

- Eg. : Crushed stone, air gaps
- large pores - no suction ("wicking")



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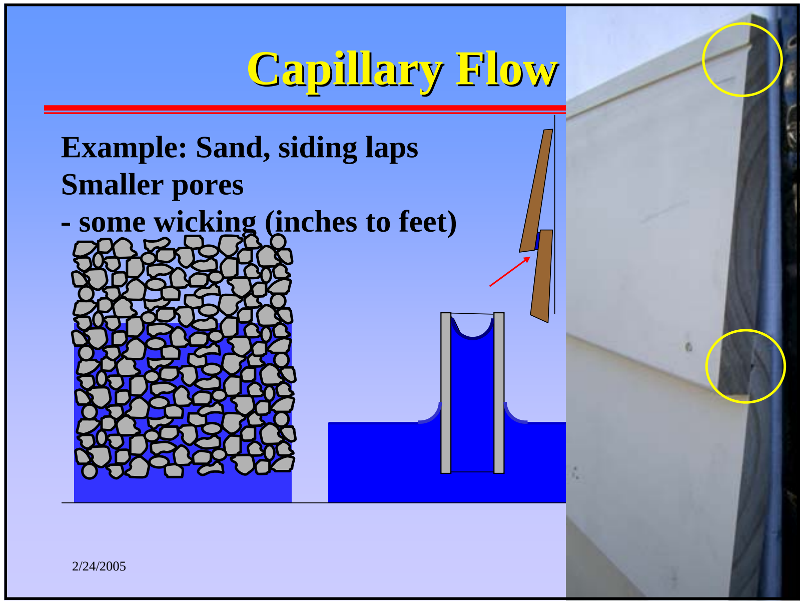
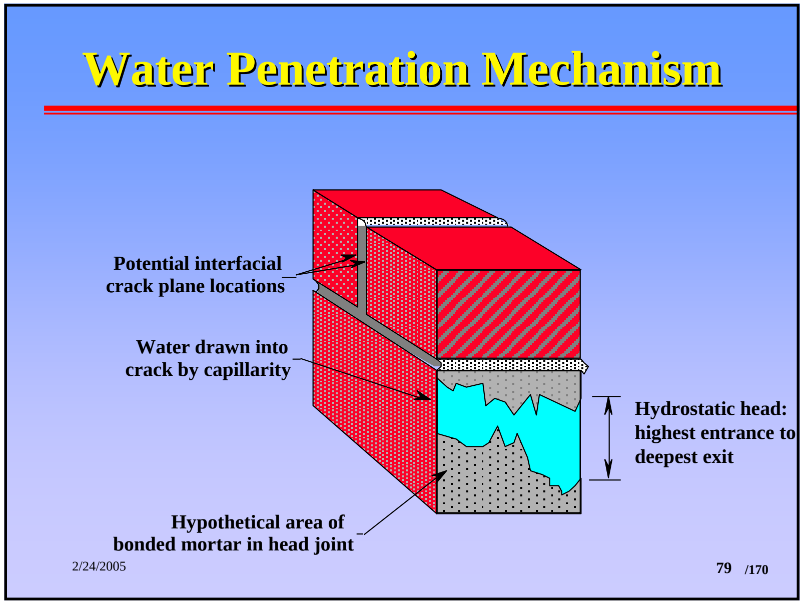

Capillary Flow
Example: Sand, siding laps
Smaller pores
- some wicking (inches to feet)
2/24/2005


Head Joints – capillary crack


Water Penetration Mechanism
Potential interfacial crack plane locations
Water drawn into crack by capillarity
Hydrostatic head: highest entrance to deepest exit
Hypothetical area of bonded mortar in head joint
2/24/2005
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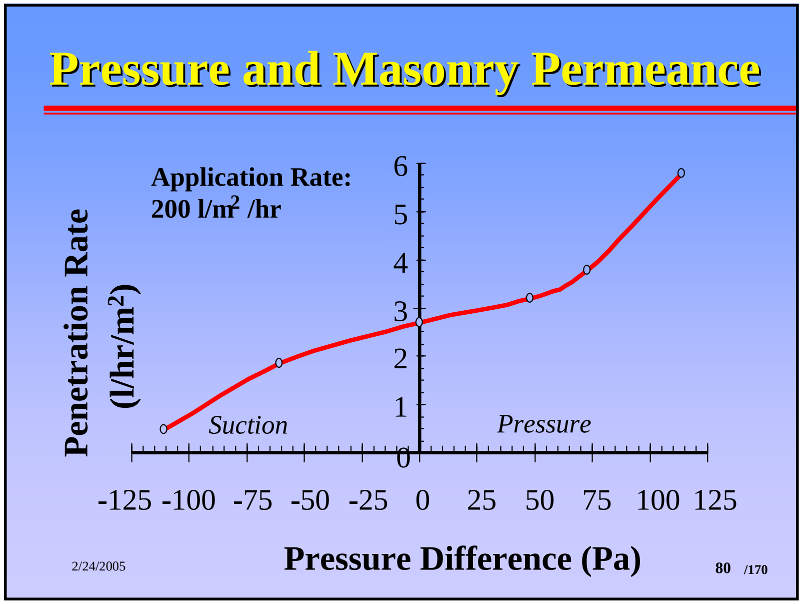
Pressure and Masonry Permeance
Application Rate: 200 l/m2 /hr
Penetration Rate (l/hr/m2)
Suction
Pressure
0
1
2
3
4
5
6
-125 -100 -75 -50 -25 0 25 50 75 100 125
Pressure Difference (Pa)
2/24/2005
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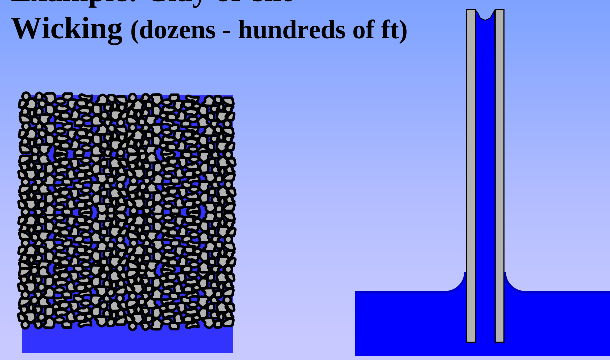
Implications

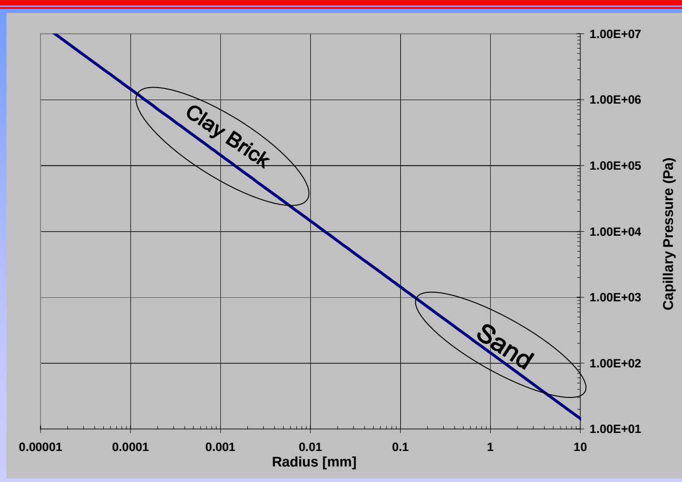
- Air pressure does not substantially increase water permeance of masonry
- Hence, pressure equalization is not that important
- Drainage is the key

Capillary Flow- concrete sucks

Example: Clay or silt
Wicking (dozens - hundreds of ft)

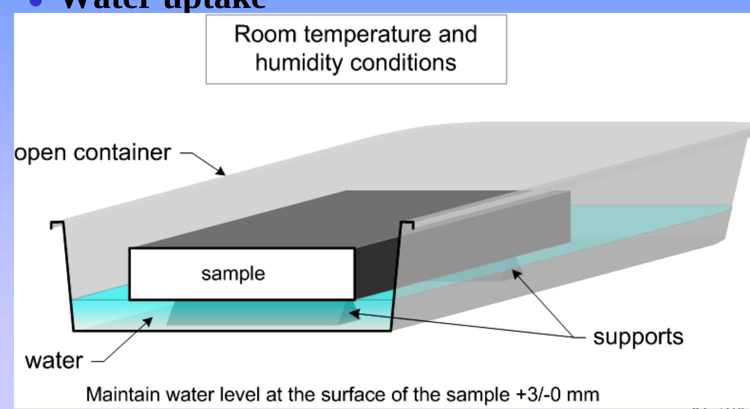


Particle Size vs Capillary Suction

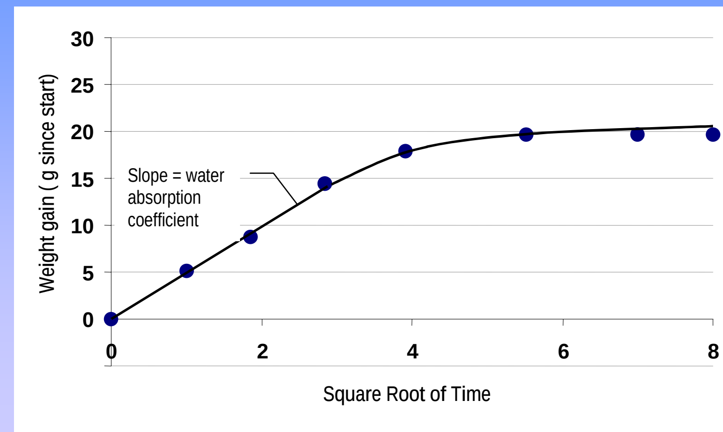


Measuring Liquid Transport

- Water uptake



Typical results



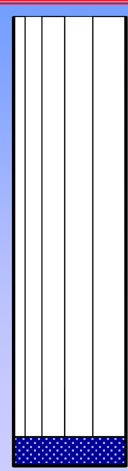
Liquid transport: wetting

Role of pore structure

Place porous material in contact with water

Small capillaries have large suction and large flow resistance

Large capillaries have less suction and little flow resistace



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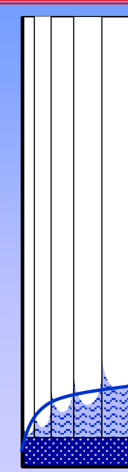
Liquid transport: wetting

Role of pore structure

Small capillaries have large suction and large flow resistance

Large capillaries have less suction and little flow resistace



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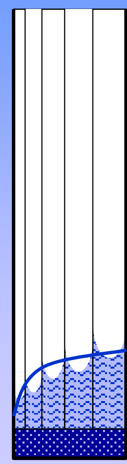
Liquid transport: wetting

Role of pore structure



Small capillaries have large suction and large flow resistance

Large capillaries have less suction and little flow resistace

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Liquid transport: wetting

Role of pore structure

Small capillaries have large suction and large flow resistance

Large capillaries have less suction and little flow resistace

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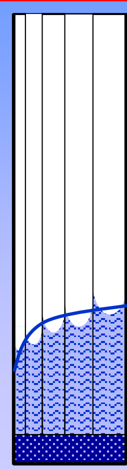
Liquid transport: wetting

Role of pore structure



Small capillaries have large suction and large flow resistance

Large capillaries have less suction and little flow resistace

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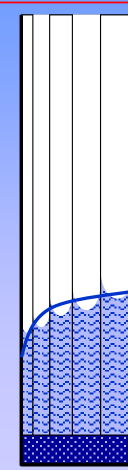
Liquid transport: wetting

Role of pore structure



Small capillaries have large suction and large flow resistance

Large capillaries have less suction and little flow resistace

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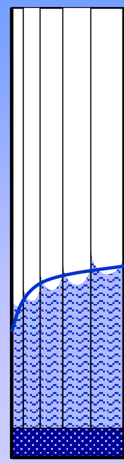
Liquid transport: wetting

Role of pore structure



Small capillaries have large suction and large flow resistance

Large capillaries have less suction and little flow resistace

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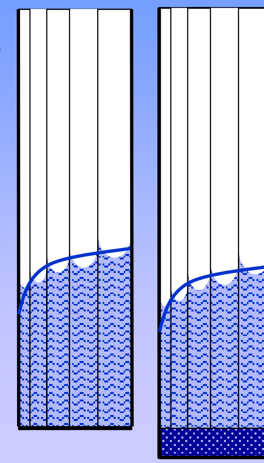
Liquid transport: redistribution

Role of pore structure

Small capillaries have large suction and large flow resistance

Large capillaries have less suction and little flow resistace



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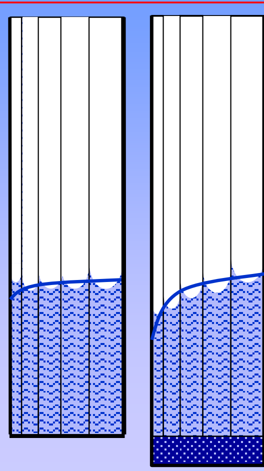
Liquid transport: redistribution

Role of pore structure

Small capillaries have large suction and large flow resistance

Large capillaries have less suction and little flow resistace



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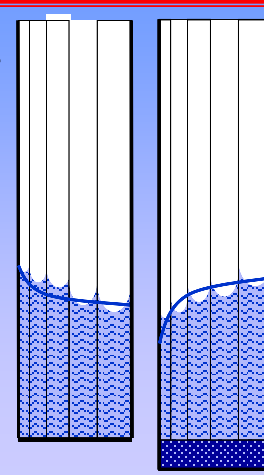
Liquid transport: redistribution

Role of pore structure

Small capillaries have large suction and large flow resistance

Large capillaries have less suction and little flow resistace



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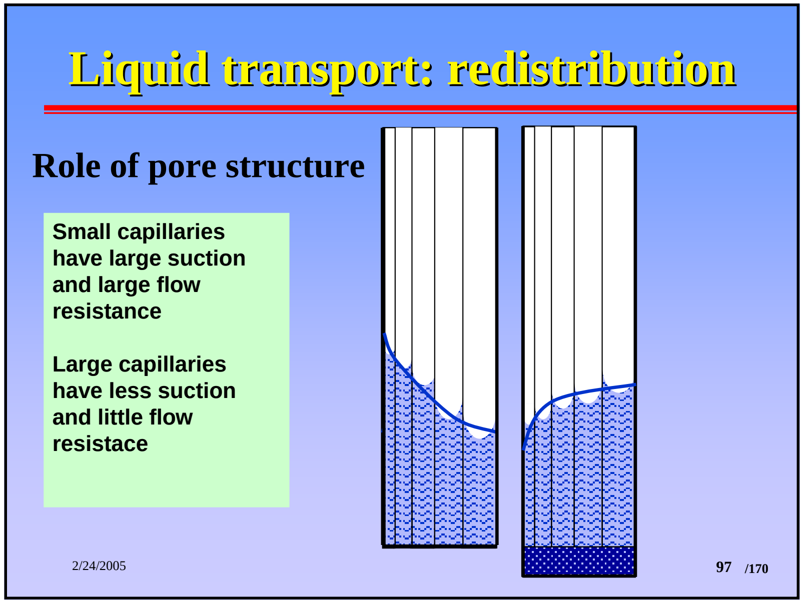
Liquid transport: redistribution
Role of pore structure
Small capillaries have large suction and large flow resistance
Large capillaries have less suction and little flow resistace
2/24/2005
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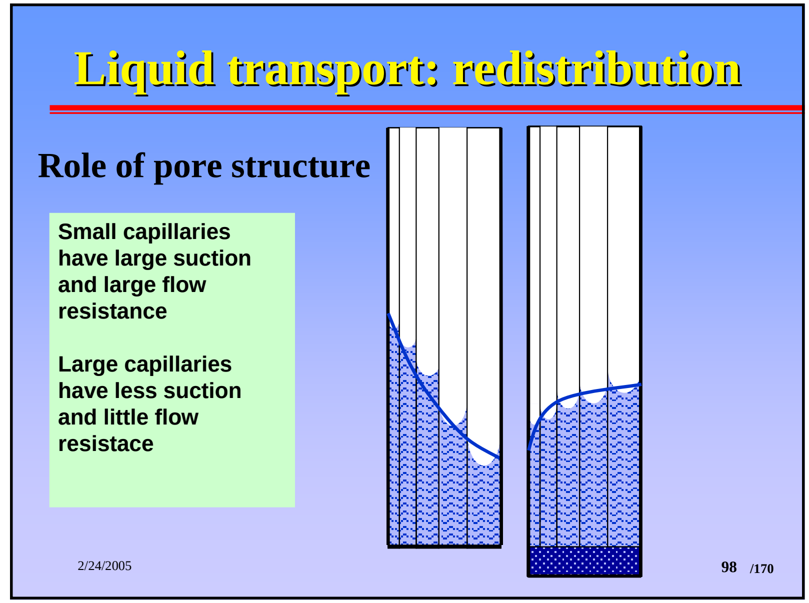
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2/24/2005
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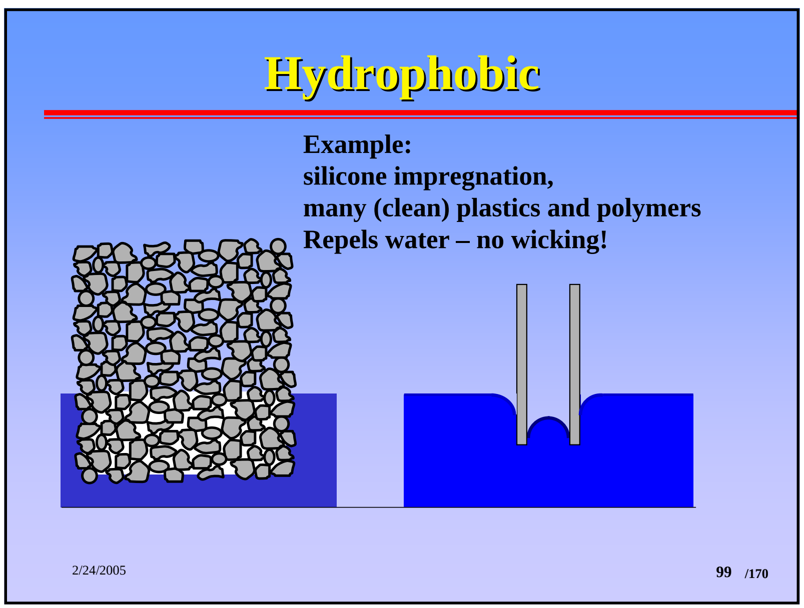
Hydrophobic
Example:
silicone impregnation,
many (clean) plastics and polymers
Repels water – no wicking!
2/24/2005
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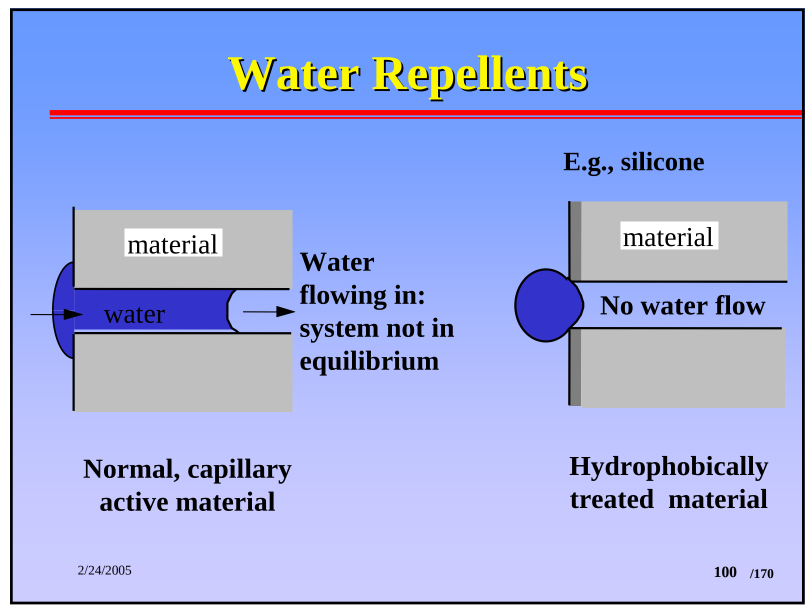
Water Repellents
E.g., silicone
material
water
Water flowing in: system not in equilibrium
material
No water flow
Normal, capillary active material
Hydrophobically treated material
2/24/2005
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Water Vapour Transport

- **Vapour Diffusion (like heat conduction)**
  - **more to less vapour**
- **Air Convection (like heat convection)**
  - **more to less air pressure**
  - **flow through cracks and holes**
  - **vapour is along for the ride**

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Vapour Diffusion

- **Slow process – <u>through *open* pores</u>**
- **Some materials allow easy diffusion**
  - **Very open pores**
  - **e.g. batt, gypsum, cellulose, etc**
- **Many materials resist diffusion**
  - **small pored materials**
  - **e.g., concrete, brick, stone**
- **Some stop, or practically stop it**
  - **crystals, or micropore**
  - **e.g., many plastics (poly), metals, glass**

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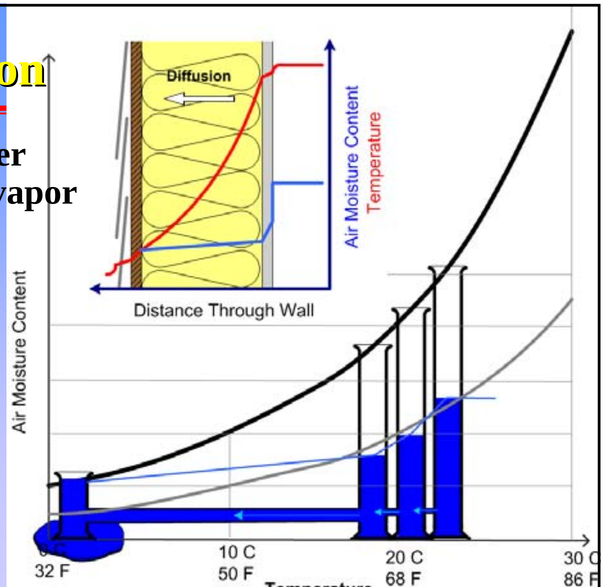
Diffusion

- **Each layer reduces vapor flow**



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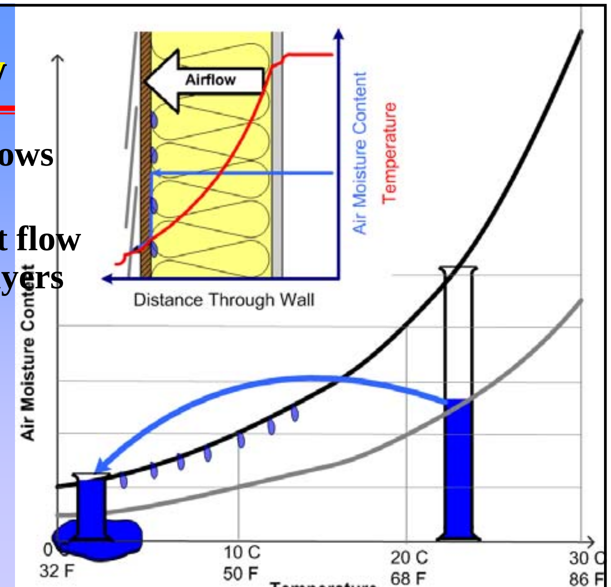
Airflow

- **Vapor flows with air**
- **Constant flow across layers**



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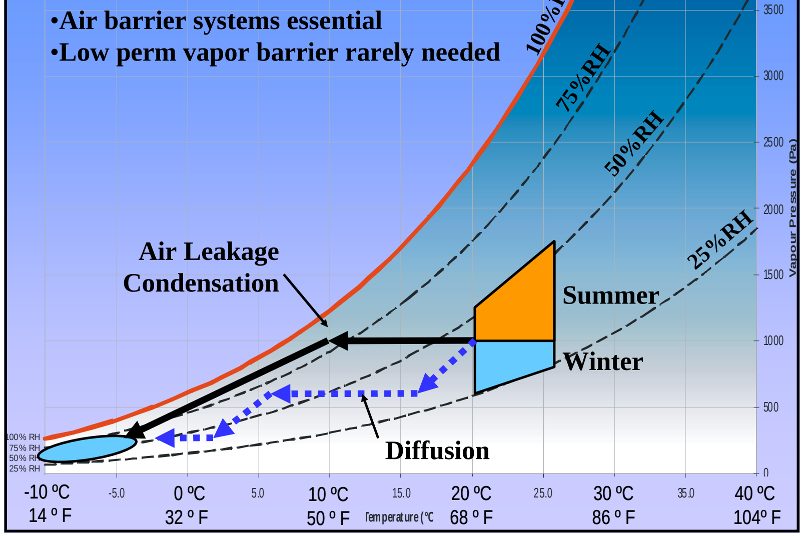
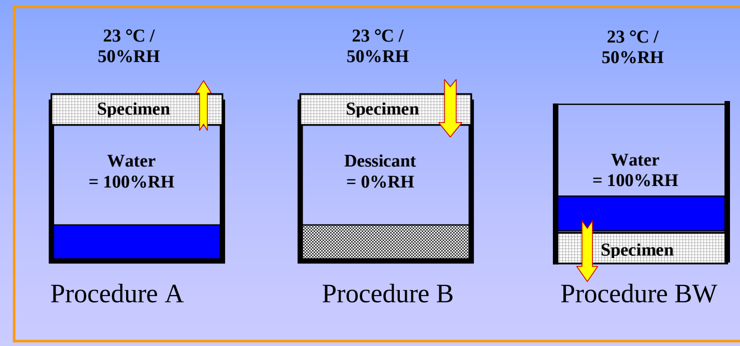
Air Leakage vs Diffusion

- Air barrier systems essential
- Low perm vapor barrier rarely needed



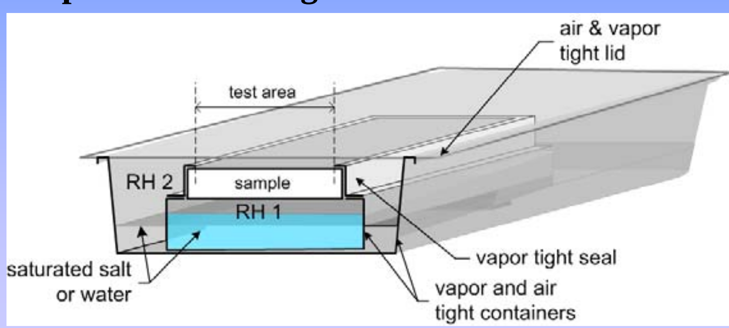
Vapour Permeability Measurement

- e.g. ASTM E96



The Tupperware standard

- Can conduct tests in your own kitchen with special salts and good scale

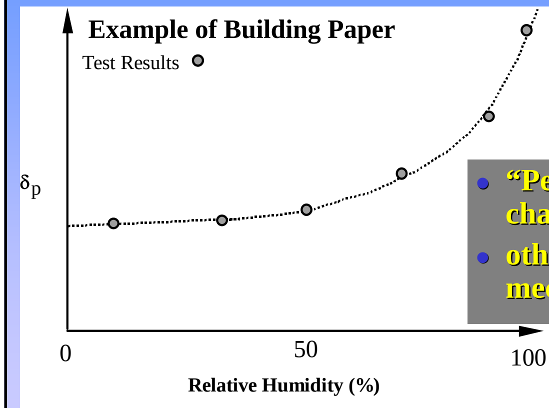


Typical salts

- Italics are temperature insensitive

Salt	RH%	Salt	RH
Lithium Chloride	*11.3*	*Sodium Chloride*	*75.3*
Potassium Acetate	22.5	Potassium Chloride	84.3
Magnesium Chloride	32.8	Barium Chloride	90
Potassium Carbonate	*43.2*	Potassium Nitrate	93.6
Magnesium Nitrate	52.9	Potassium Sulfate	97.3

Vapour Permeance vs RH



- "Permeance" changes with RH
- other transport mechanisms as work

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Adsorbed Flow

- Also called surface diffusion
- Driven by ***RH*** differences!
- Affects highly porous, especially fibrous natural materials

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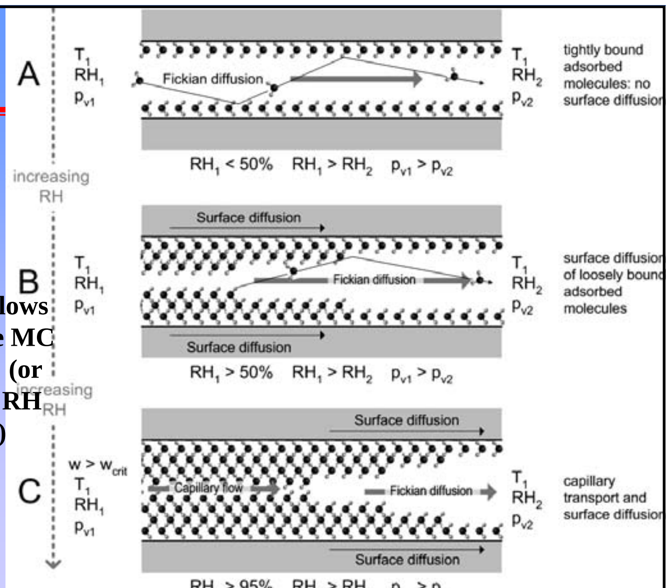
Adsorbed moisture flows from more MC to less MC (or from high RH to low RH)



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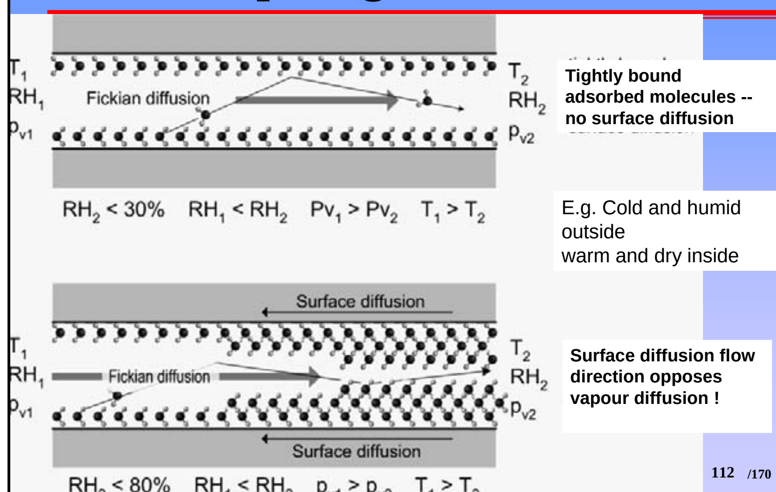
Competing Mechanisms



Tightly bound adsorbed molecules -- no surface diffusion

E.g. Cold and humid outside warm and dry inside

Surface diffusion flow direction opposes vapour diffusion !

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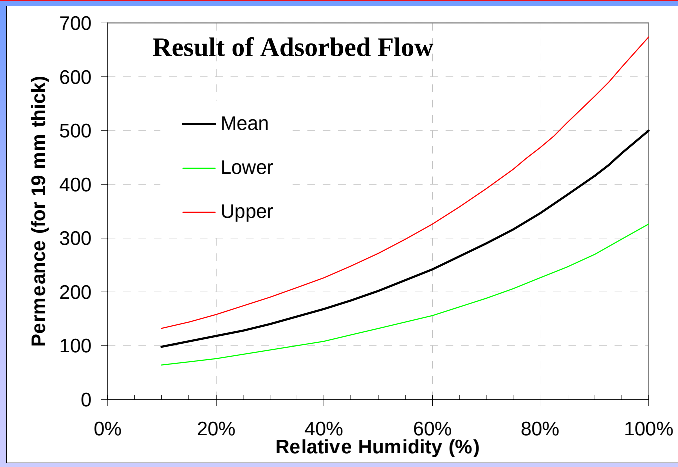
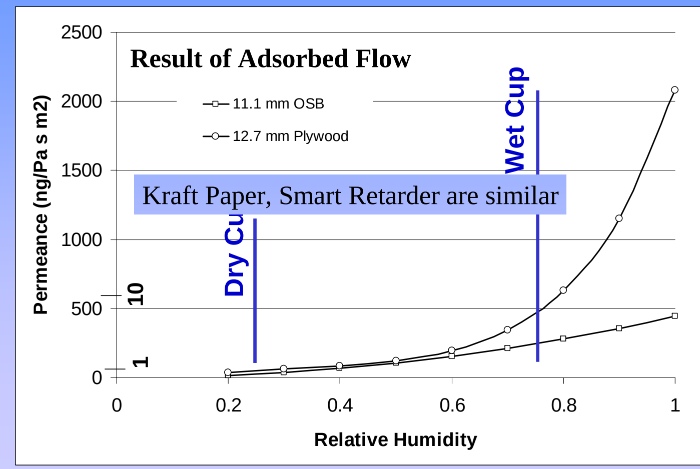
Vapour Permeance: Stucco



Vapour Permeance: Sheathing



Vapour Barriers

- Control vapour diffusion only
- Vapour barriers in Code: <1 US perm
  - based on Rowley 1937
  - no good science
- Vapour retarder approx 2-5 US perm
- Measurement Units
  - Metric perms ng /(s·m^2·Pa)
  - US perm grain/(hr·in Hg· ft^2)
  - WVT grams/(sq ft/24 hours)

Low-permeance Materials

- 6 mil Poly 3.5 metric (0.1 US perm)
- Vinyl wall paper 15 metric perm (0.3 US)
- Concrete 1/2 perm for 8" foundation wall
- Drywall with a VB paint 0.3 to 1 perm
- Brick veneer (1/2 - 2 US perms)
- Extruded foam 1/2 - 1 US perms for 1.5"
- Plywood 0.5 to 20 US perms (dry to wet)
- Kraft paper 0.3 to 2 US perms (dry and wet)

Semi-permeable Materials

- Plywood 0.5 to 20 US perms (dry to wet)
- Expanded foam 2.5 - 5 US perms for 1 inch
- Spray PUR about 2 US perms
- Drywall with latex paint (2-5 US perms)

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High-perm Materials

- Fibreboard over 20
- Plywood 0.5 to 20 (dry to wet)
- Icynene open cell spray foam 10 - 13
- Tyvek other housewraps 20 to 50 perms
- Building paper over 10 to 30

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Summary Moisture Transport

- Moisture in 3 phases moves with three mechanisms
  - Liquid capillary (suction)
  - Adsorbed flow (RH)
  - Vapour diffusion (vapor pressure)
- Moisture storage in all three phases, only two important for hygroscopic
  - Adsorbed (RH)
  - Liquid (capillary suction)

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Moisture Thresholds

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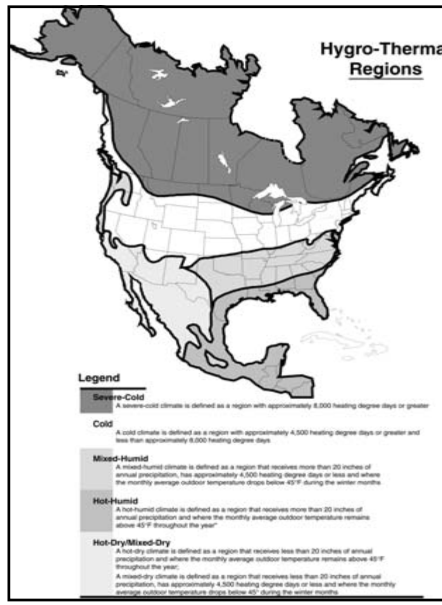
Material Performance Thresholds

- Depends on *What* Performance
  - Corrosion
  - Mould
  - Decay
  - Freeze-thaw
  - Dissolution/Dissassociation
- Also, mechanical properties, insulating, etc.

Performance of What?

- Materials - asphalt, paper
- Layers - building paper
- Sub-assembly - lapped, between airspace/sheathing
- Assembly - drained stucco over steel stud
- Enclosure - wall, joints, window
- Building - 12 storey apartment bldg
- Site - seashore or sheltered
- Climate -Miami or Minneapolis



Material Performance

- How to predict performance?
  1. We test materials or layers.
  2. Model assemblies in specific climates.
- Must know loads, microclimate
- **"No Wrong Material, Just Materials Used the Wrong Way"**

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Steel Corrosion

- Electrochemical Process - oxygen + electrolyte
- Can begin if RH>80%
- Coatings protect
- Zinc galvanizing is sacrificial
- Factors
  - Temperature (Arhenius Law)
  - Time of Wetness (TOW)
  - pH of environment
  - Salinity

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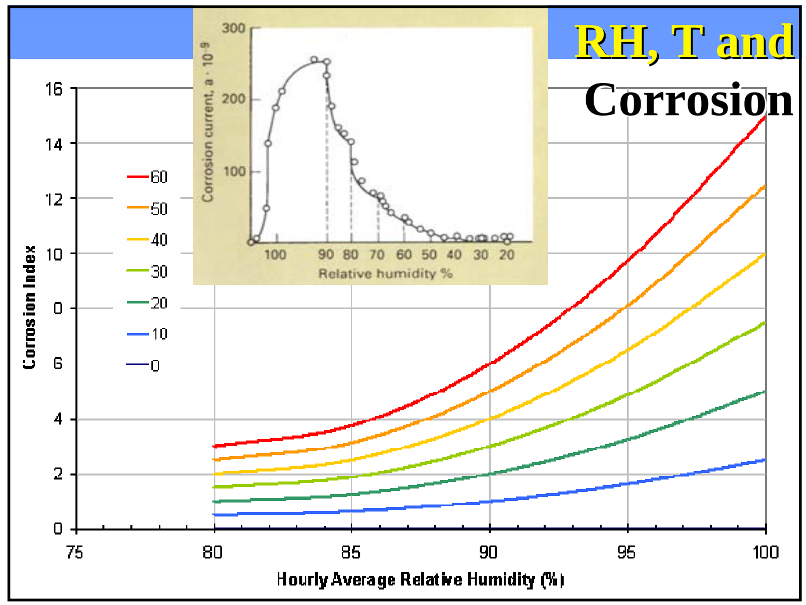

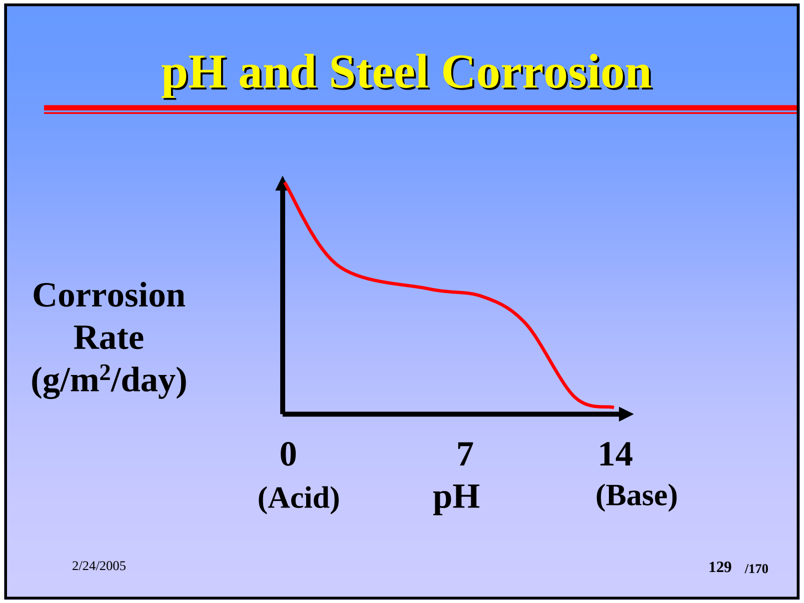
pH and Steel Corrosion
Corrosion Rate (g/m²/day)
0
(Acid)
7
pH
14
(Base)
2/24/2005
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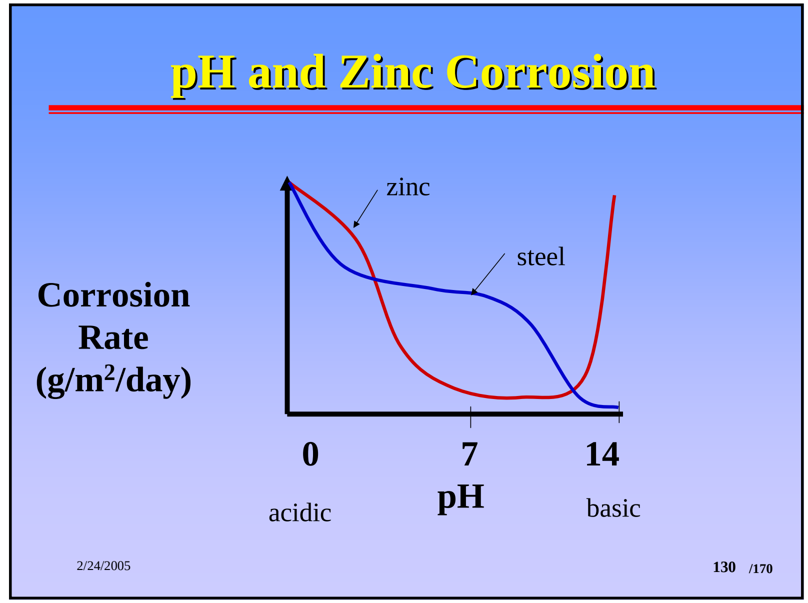
pH and Zinc Corrosion
zinc
steel
Corrosion Rate (g/m²/day)
0
7
14
acidic
pH
basic
2/24/2005
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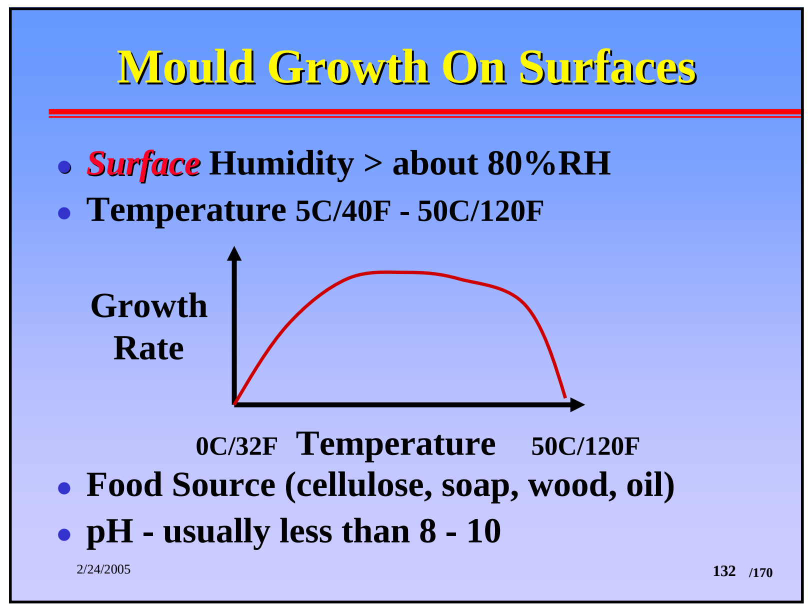
Fungal Growth
• Spores and toxins cause immuno-depression
• LBL estimates US health and productivity losses at $30 to 100 billion/yr
• "Sick Building Syndrome"


Mould Growth On Surfaces
• Surface Humidity > about 80%RH
• Temperature 5C/40F - 50C/120F
Growth Rate
0C/32F
Temperature
50C/120F
• Food Source (cellulose, soap, wood, oil)
• pH - usually less than 8 - 10
2/24/2005
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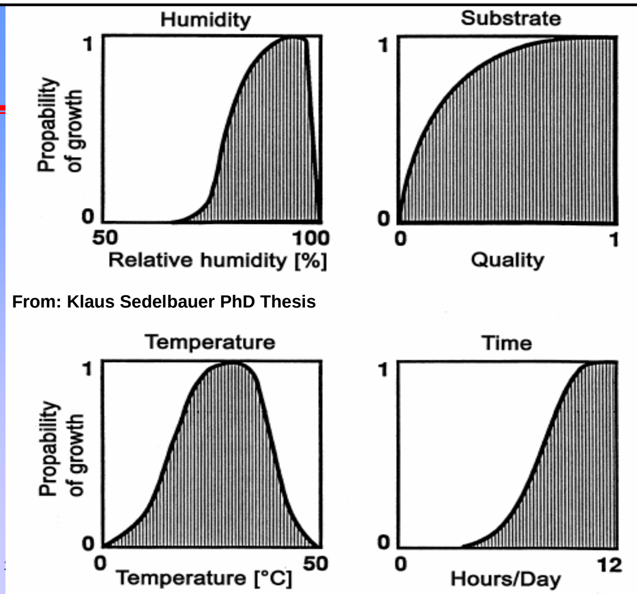

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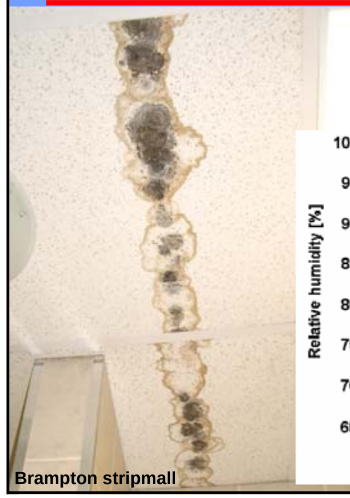
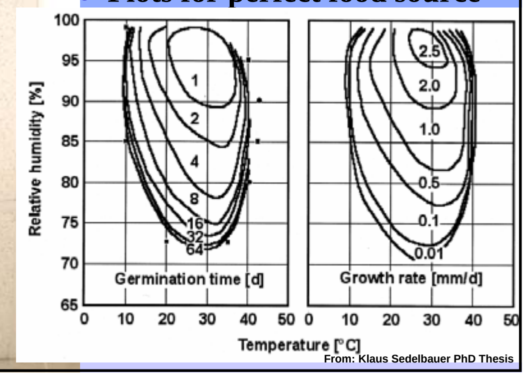
Germination & Growth

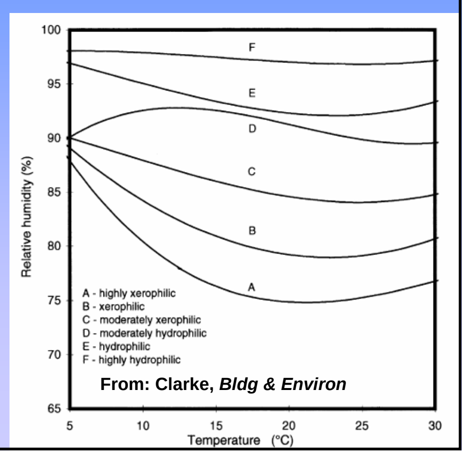
- Time for spore germination
- Rate of Growth
- Plots for perfect food source





Minimum Levels

- Different species = different conditions
- Dynamically varying mix as substrate and conditions change



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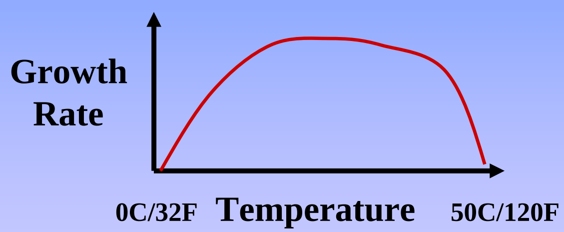
Wood Decay

- Surface Humidity > 95%RH, MC>30%
- Temperature 5C/40F - 50C/120F



- Highly species, sample, exposure dependent

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Freeze-thaw

- Must be nearly saturated while freezing
- Factors
  - degree of saturation
  - how cold
  - rate of freezing
  - pores size distribution
  - liquid diffusivity

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Subfluorescense

- Salts absorbed in porous mineral material while dissolved in liquid water
- Water evaporates salts recrystalize

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Dissolution

- Water is the universal solvent
- Avoid capillary saturation
- e.g.:
  - EIFS finish re-emulsification
  - Gypsum becomes goo
  - paper unglues

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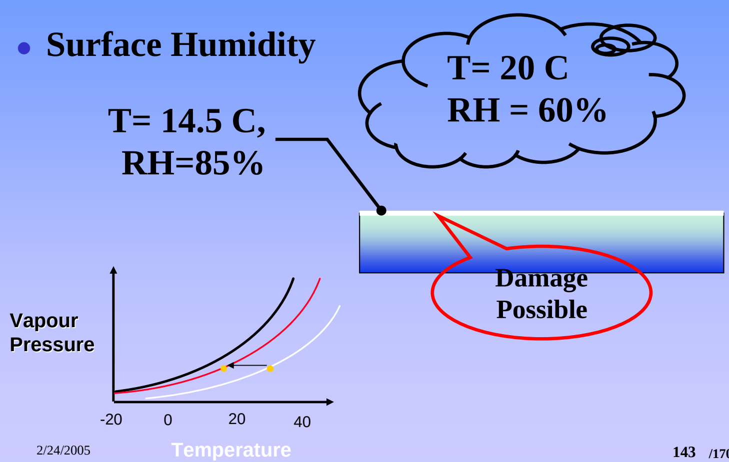
Microclimate

- Surface Humidity



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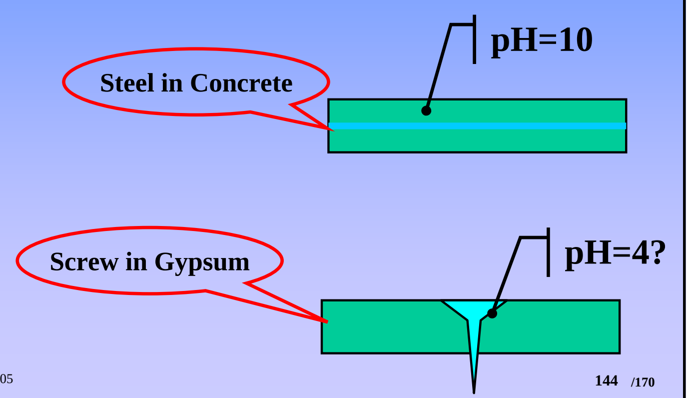
Microclimate

- pH Acid or Alkaline



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Conclusions

- **Moisture control is a balance of wetting and drying**
- **Water is a unique molecule**
  - **Adsorption – swelling/shrinking**
  - **Capillary / surface tension**
- **Separate the phases ….**
  - **Vapor, liquid, adsorbed, solid**
- **… and transport modes …**
  - **Diffusion, convection, capillary, adsorbed**
- **… when thinking about moisture**

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