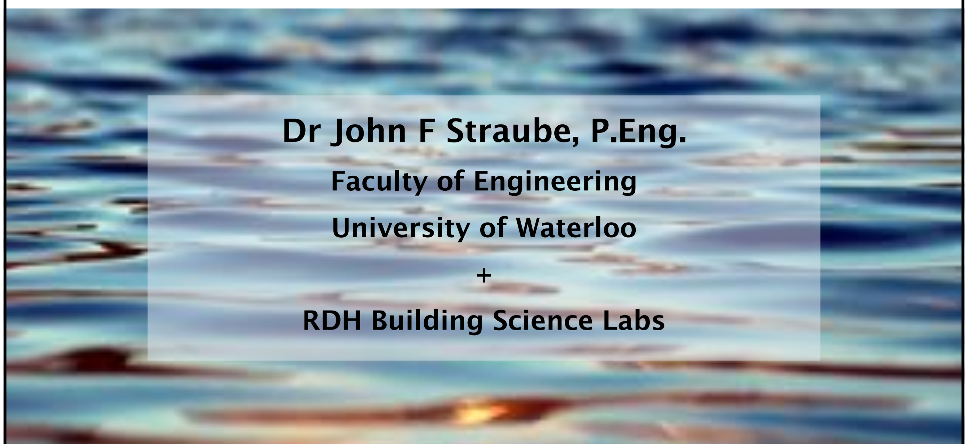
RDH Building Science

Moisture Physics



Dr John F Straube, P.Eng.
Faculty of Engineering
University of Waterloo
+
RDH Building Science Labs

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This presentation

- A Review of Moisture Fundamentals
- Focus on materials, not systems
- Details of water/moisture in all its forms
- Interaction of moisture with materials
- Porous materials
- Deeper dives.. Wood, concrete, etc

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Some definitions

- Water … usually liquid H_2O
- Moisture … liquid and vapor?
- Ice .. Unambiguous solid water

- Moisture barrier?
- Vapor barrier?
- Water Batter?

Why care about moisture?

- Moisture is involved in most building enclosure performance problems
  - Construction cycle and in-service durability
- Examples:
  - rot,
  - corrosion,
  - mould (IAQ)
  - buckling
  - termites, insects
  - staining
  - etc.

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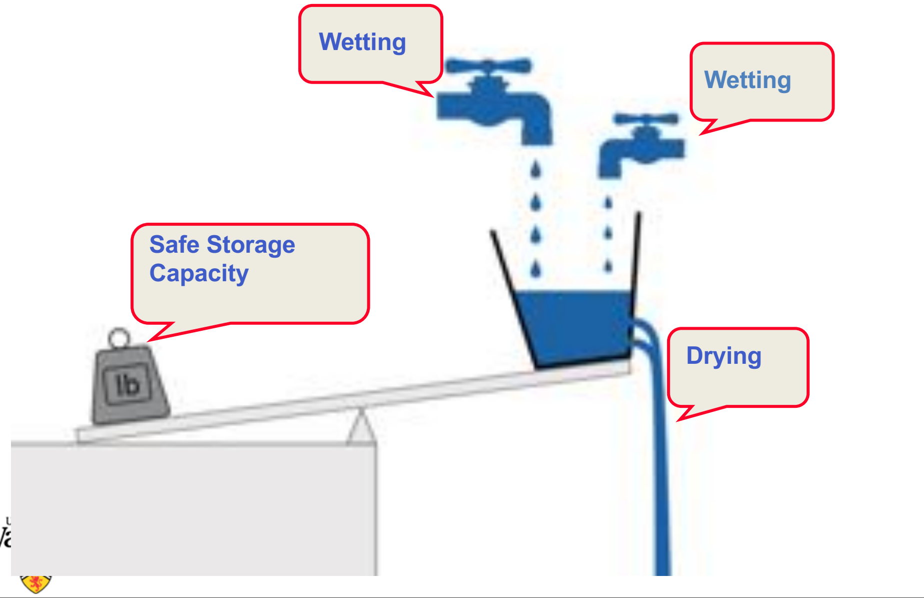
The Moisture Balance



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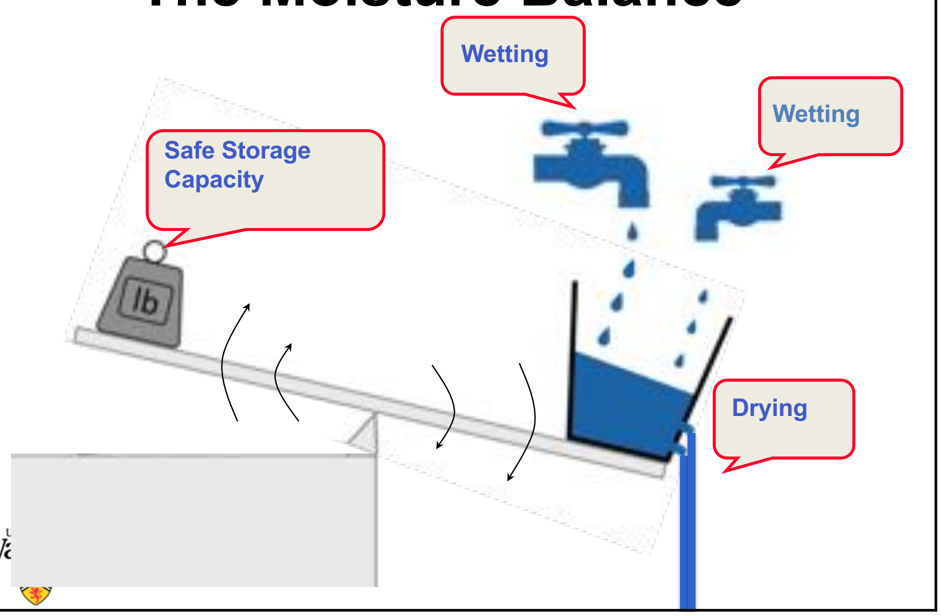
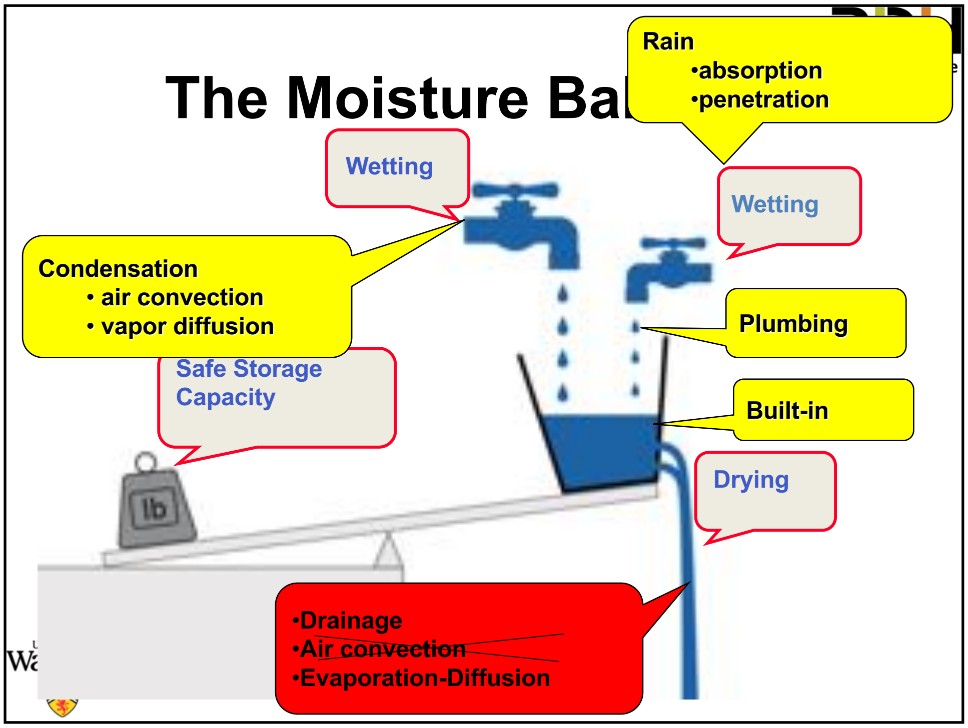
The Moisture Balance



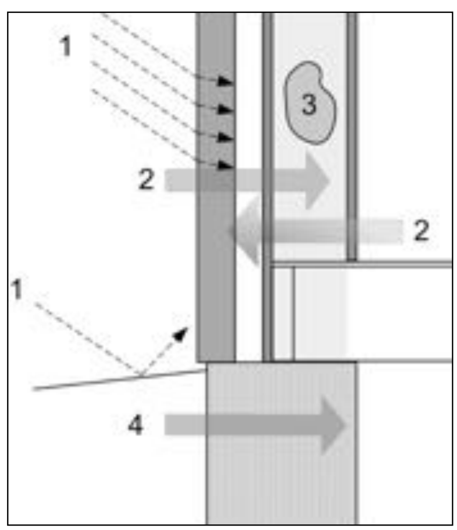


Enclosure Wetting

Sources & Mechanisms

1. **Rain**
   - absorption
   - gravity penetration
   - splash and drips
2. **Water Vapor in Air**
   - Diffusion
   - Convection (air leaks)
3. **Built in**
4. **Ground**
   - Capillary (wicking)
   - Gravity
   - Diffusion

Plumbing, floods, etc.



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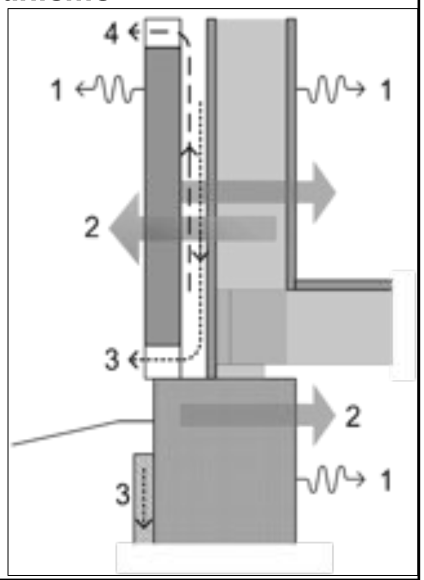
Enclosure Drying

Sinks and Mechanisms

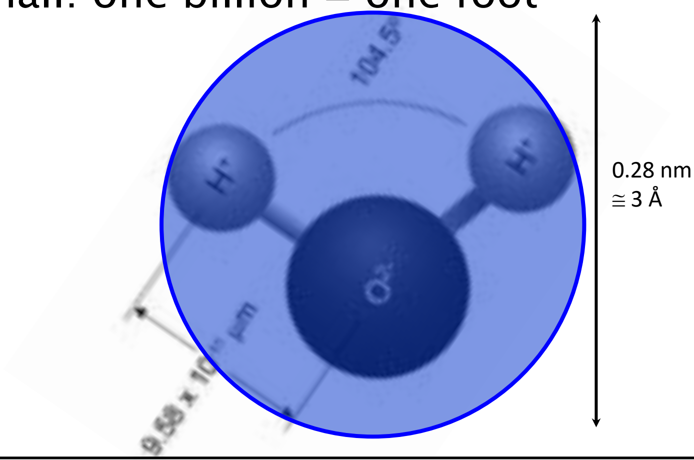
1. **Surface Evaporation**
   - Wicking to surface
2. **Indoor / outdoor air**
   - Diffusion
   - Convection (air leaks)
3. **Drainage**
   - liquid water
4. **Intentional Convection**
   - Ventilation Drying



Moisture, H_20

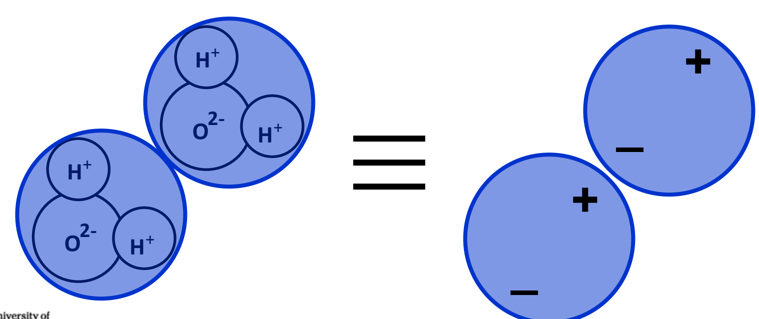
The Water Molecule

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



The Polar Molecule

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



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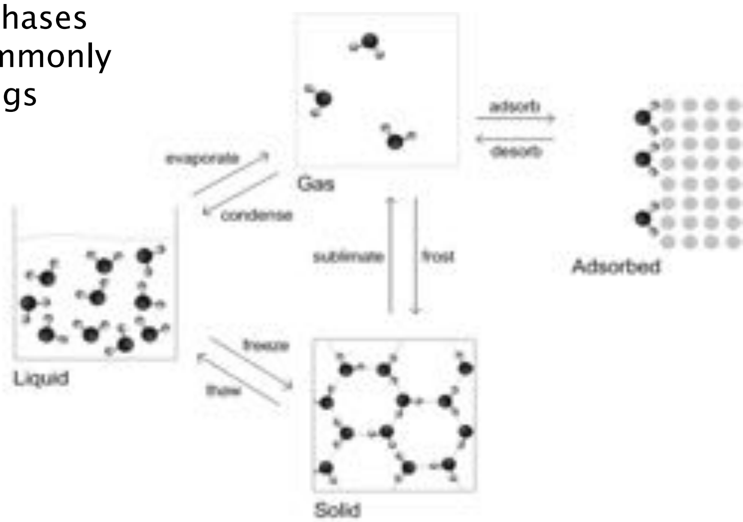
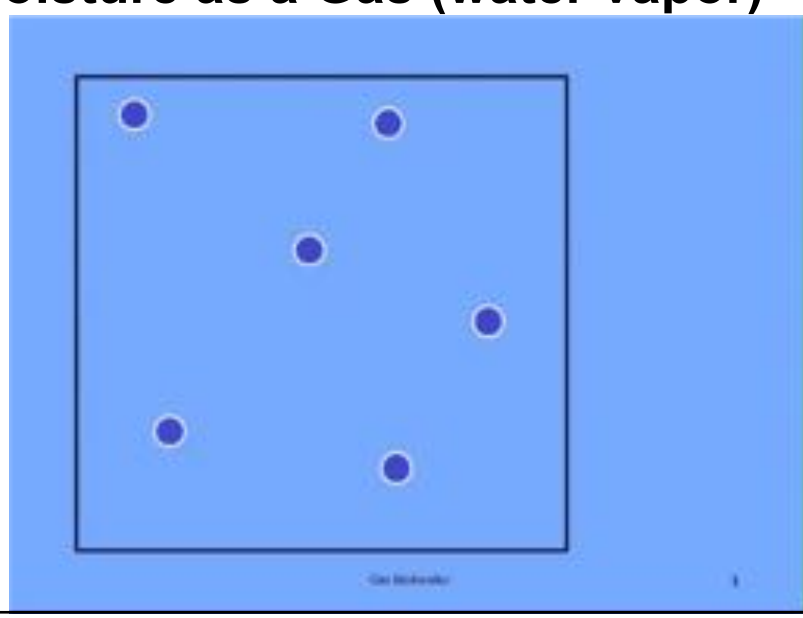
Moisture Phases

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



Moisture as a Gas (water vapor)



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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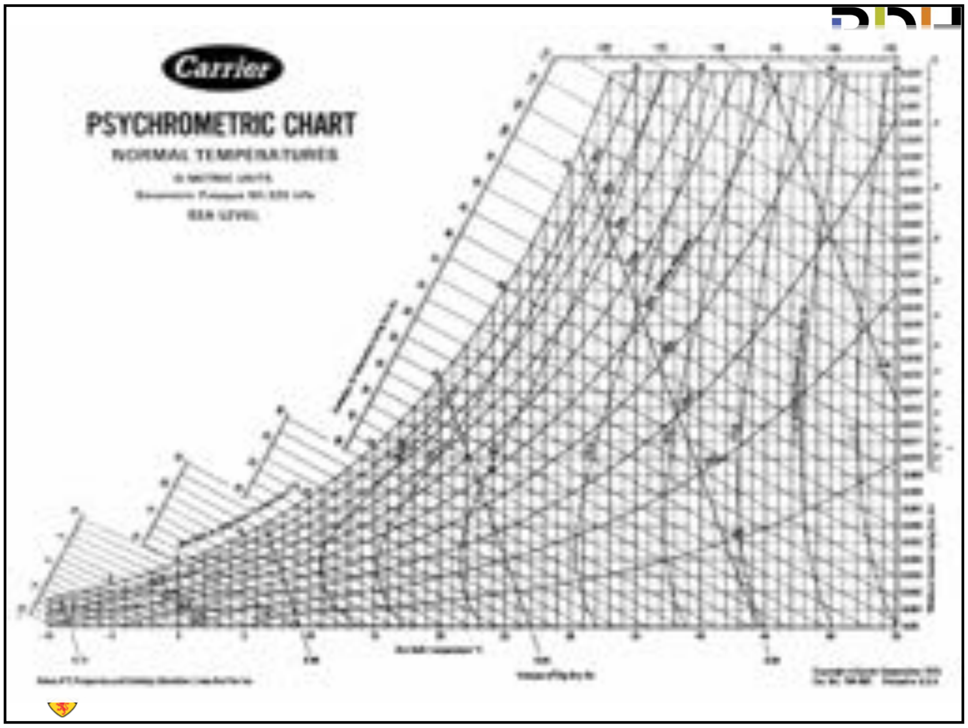
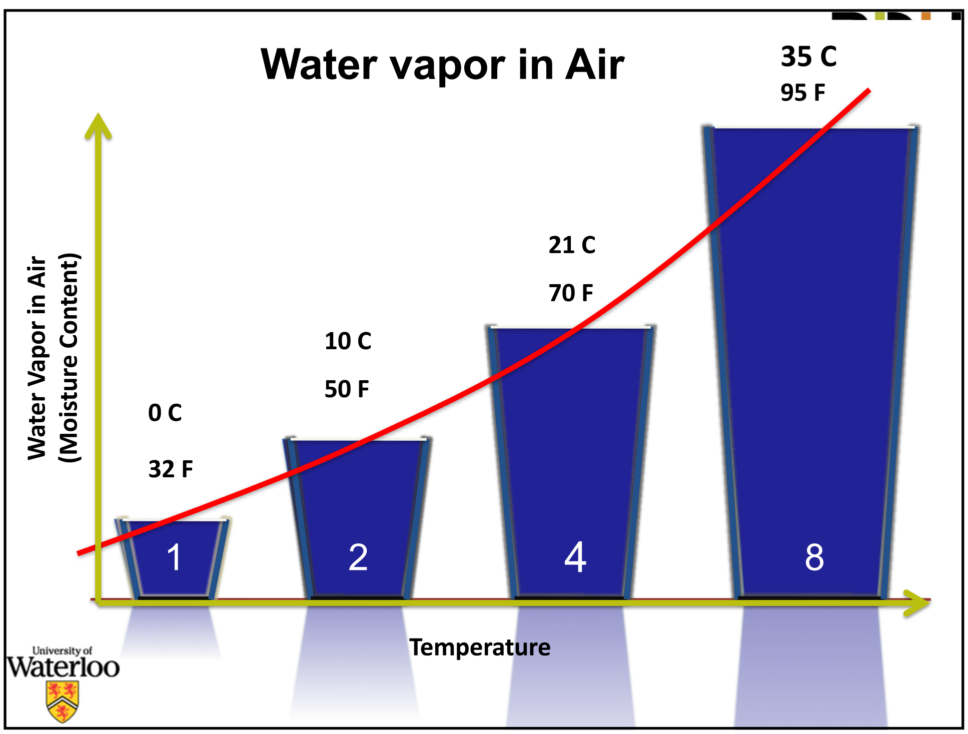

Carrier
PSYCHROMETRIC CHART
NORMAL TEMPERATURES


Water vapor in Air
35 C
95 F
21 C
70 F
10 C
50 F
0 C
32 F
1
2
4
8
Water Vapor in Air
(Moisture Content)
Temperature
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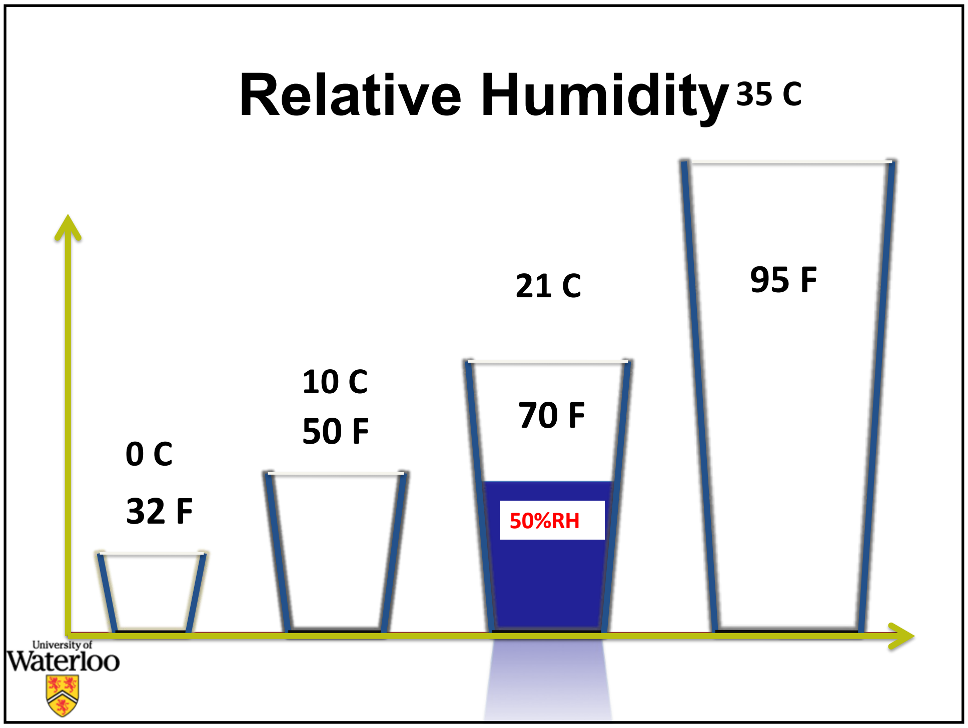
Waterloo


Relative Humidity
35 C
95 F
21 C
70 F
10 C
50 F
0 C
32 F
50%RH
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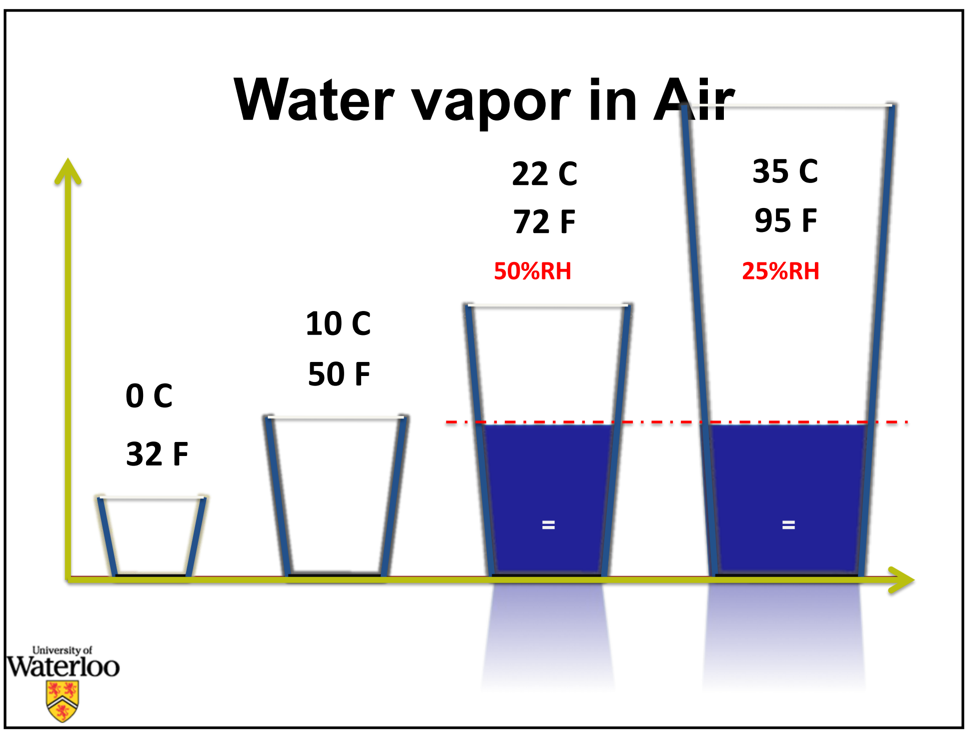
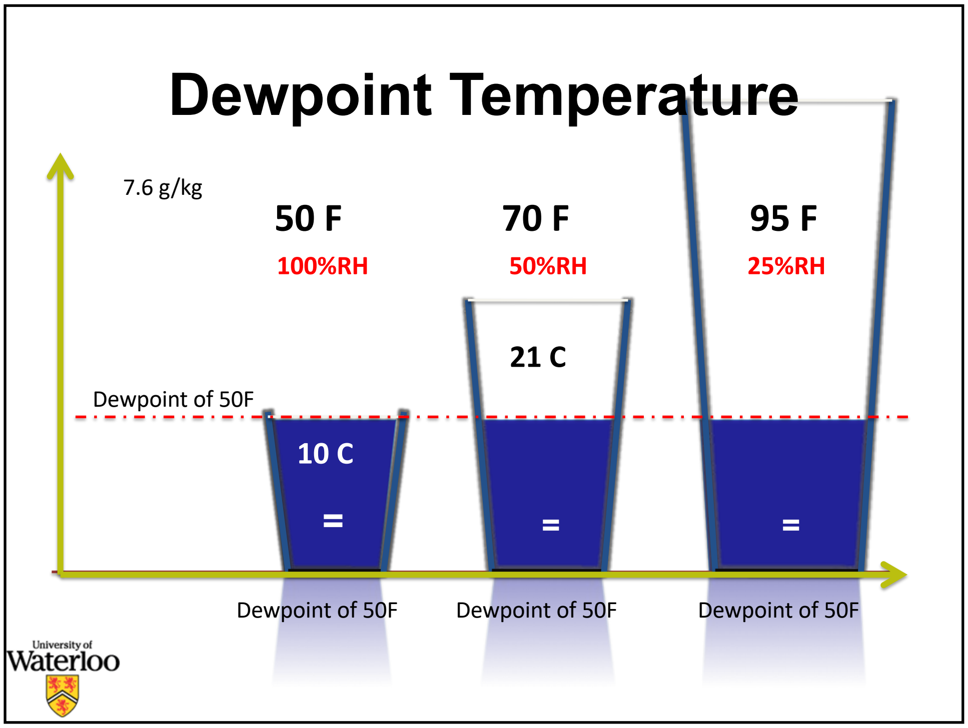
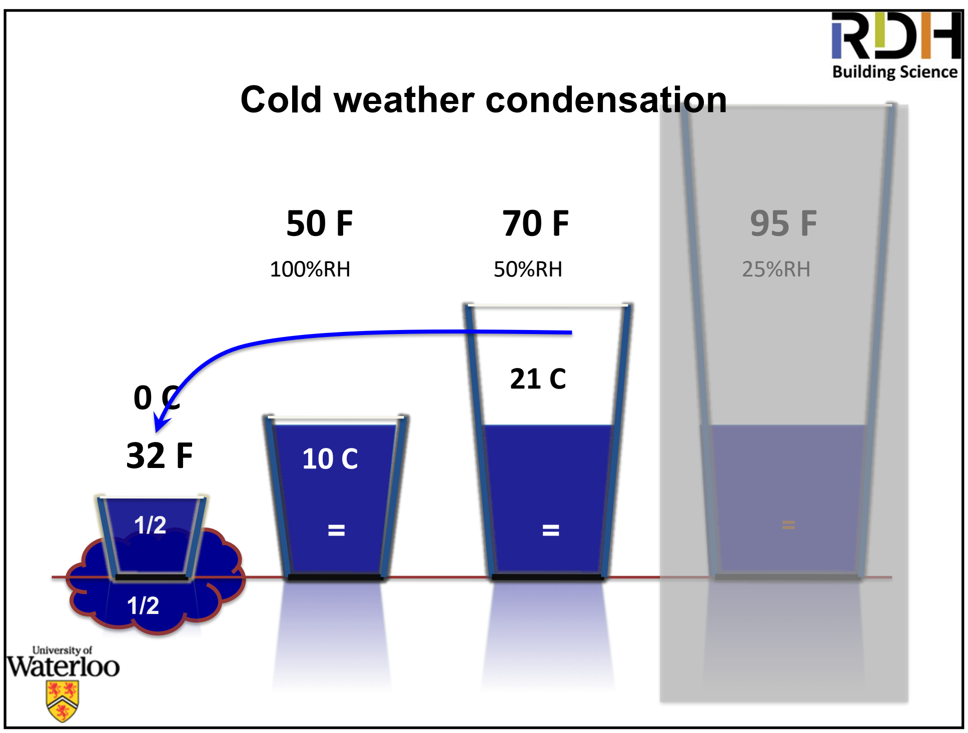

Water vapor in Air
22 C
72 F
50%RH
35 C
95 F
25%RH
10 C
50 F
0 C
32 F
=
=
University of Waterloo


Dewpoint Temperature
7.6 g/kg
50 F
100%RH
70 F
50%RH
95 F
25%RH
21 C
Dewpoint of 50F
10 C
=
=
=
Dewpoint of 50F
Dewpoint of 50F
Dewpoint of 50F
University of Waterloo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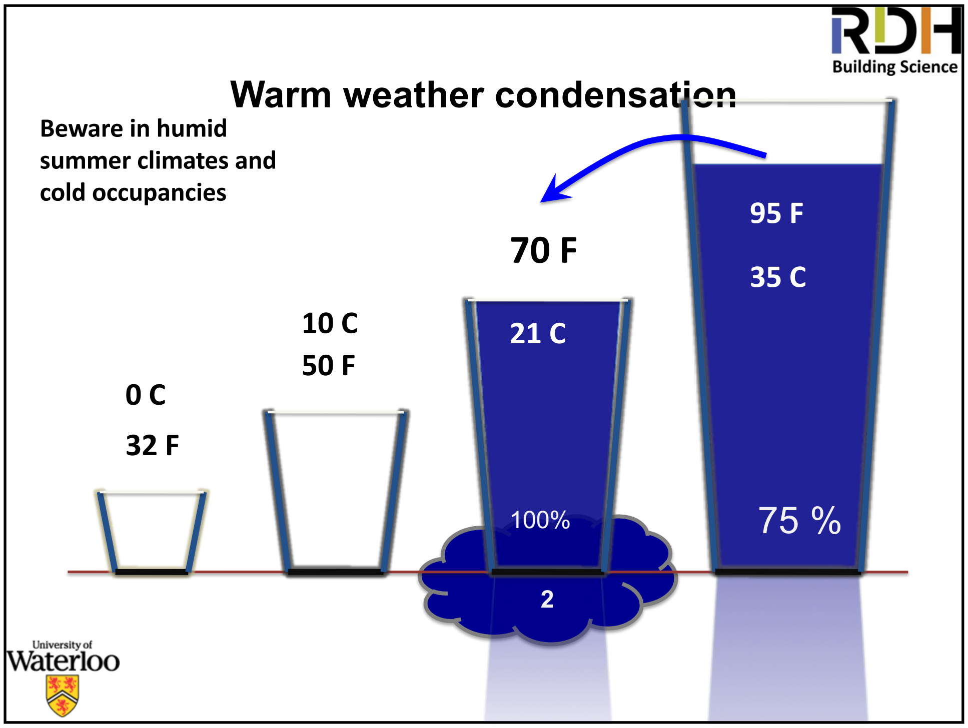
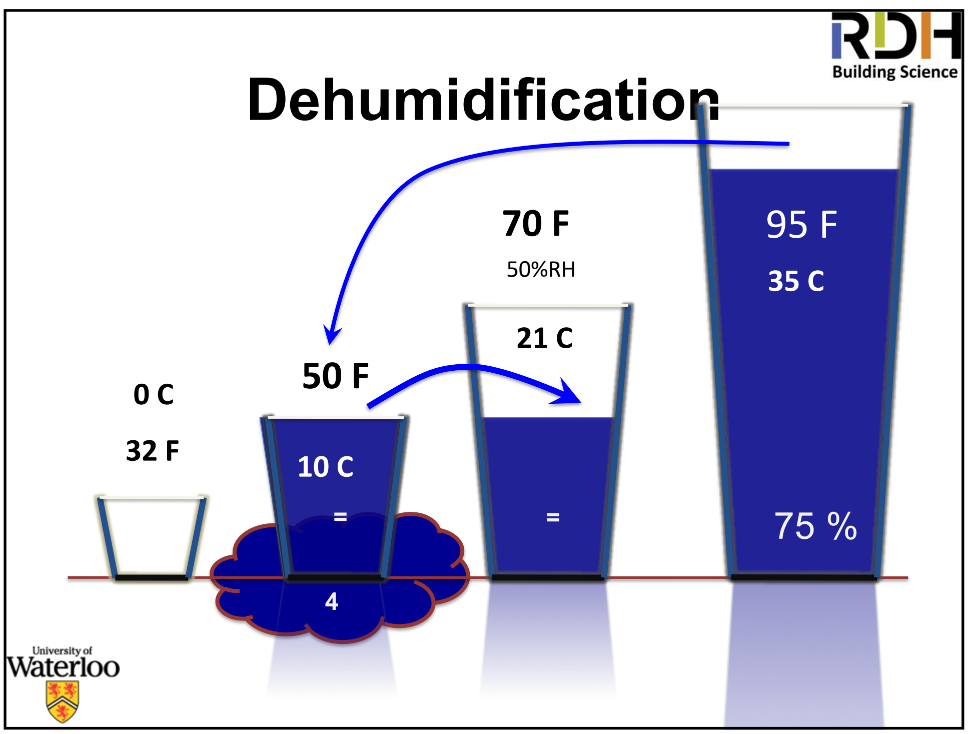
Cold weather condensation
50 F
100%RH
70 F
50%RH
95 F
25%RH
21 C
0 C
32 F
10 C
1/2
1/2
=
=
University of Waterloo


Building Science
Warm weather condensation
Beware in humid
summer climates and
cold occupancies
95 F
35 C
70 F
21 C
10 C
50 F
0 C
32 F
100%
75 %
2
University of
Waterloo


Building Science
Dehumidification
70 F
50%RH
95 F
35 C
21 C
50 F
0 C
32 F
10 C
=
=
75 %
4
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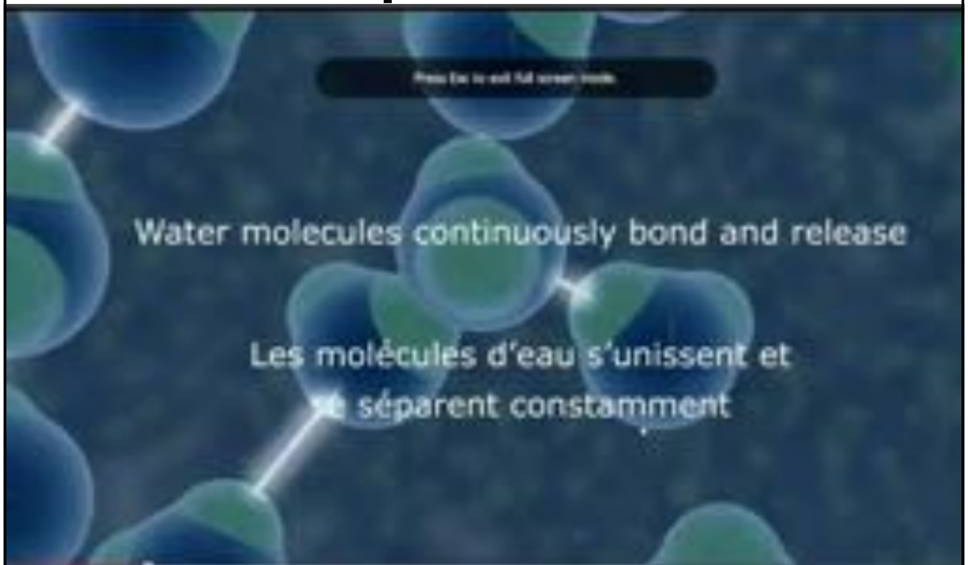
Waterloo

Liquid Water

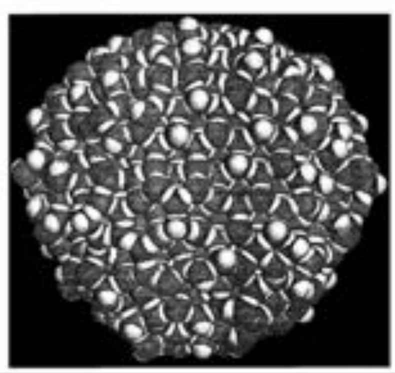


Source: Canadian Museum of Nature

Moisture as a Liquid

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

J. Phys. Chem. A, Vol. 104, No. 10, 2000 1975



Moisture as Liquid

- Single vapor molecule is small
- Liquid cluster is large
- Hence, Gore-Tex and Tyvek
  - Vapour molecules pass through small openings
  - Liquid molecules repelled by hydrophobic

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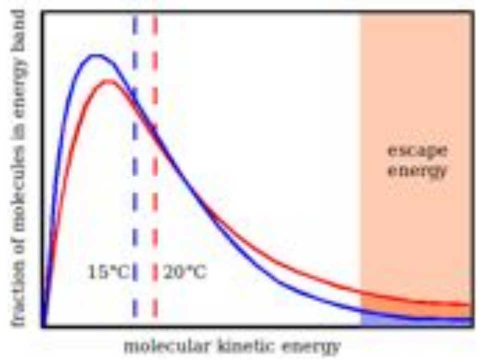
Phase change

- Liquid to gas: evaporation
- Boiling: vapor pressure of H_20 = atmospheric pressure
- Gas to liquid = condensation

Liquid to Gas

- Evaporation … some molecules have enough velocity/energy to escape



Moisture as a Solid

Canadian moisture jokes

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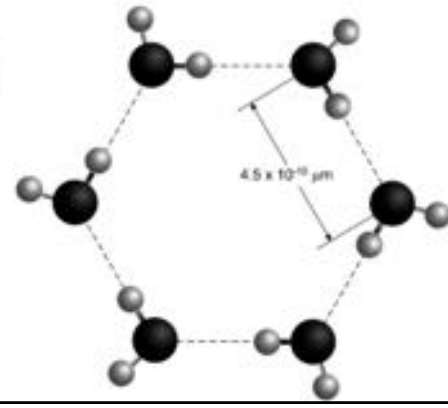
Ice : Moisture as Solid

- Ice forms a crystal and expands (9% by volume) as it freezes
- Water most dense at 3.98˚C



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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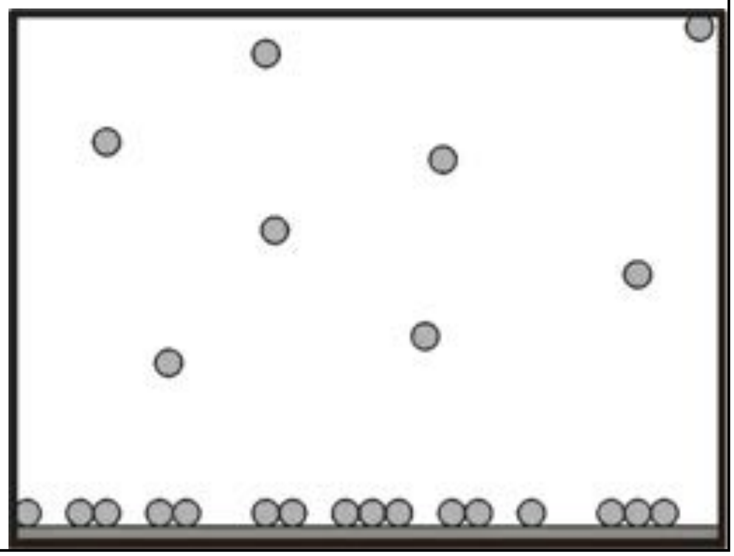
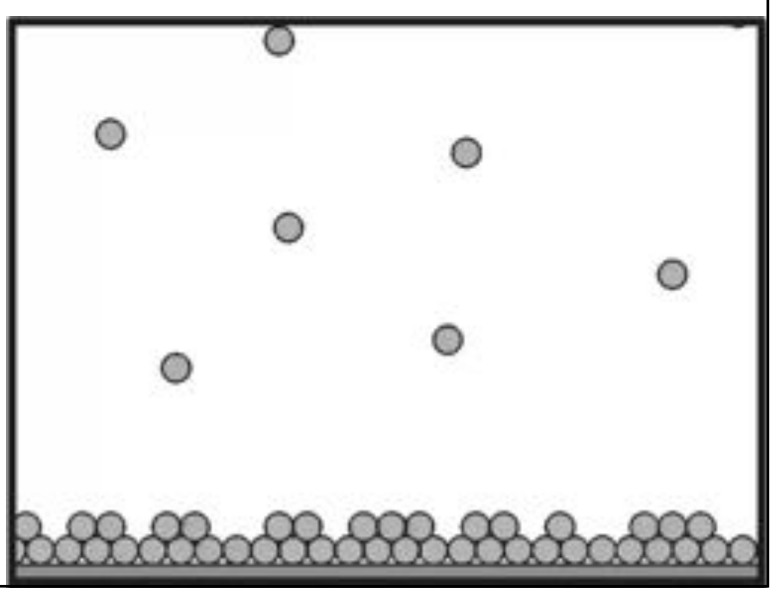
Adsorbed Moisture

Vapor molecules stick to surfaces



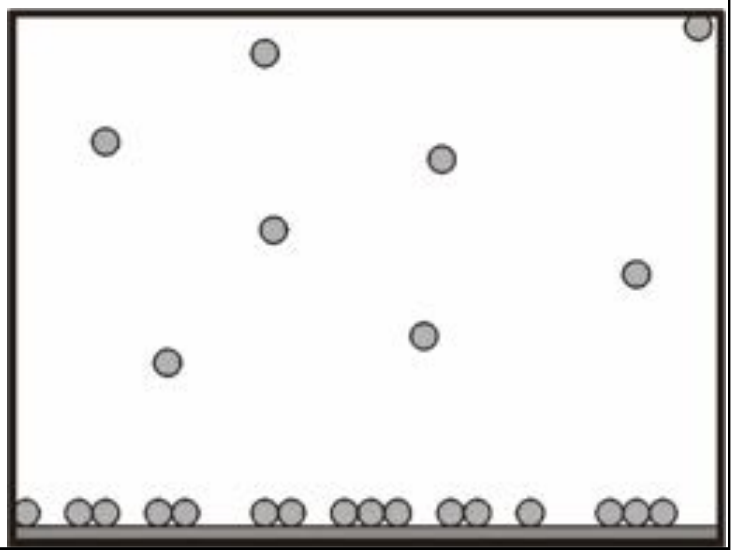
Adsorption higher RH

More vapor so more sticks



Adsorption - higher temperature

Higher temp = More energy so less vapor sticks



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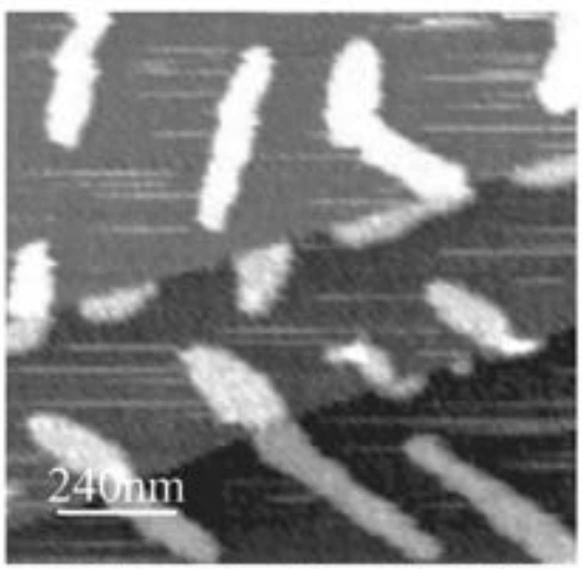
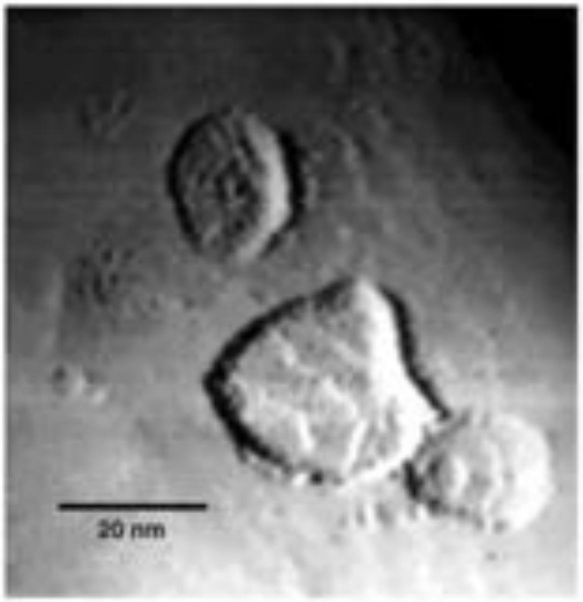


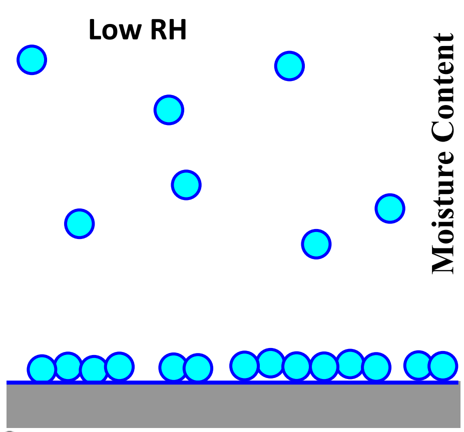
Figure 4. When the surface is left overnight at 90% RH, this higher terrace completely disappears and only islands of about 2 nm remain. These islands present a high surface diffusion barrier, and it can be clearly observed that, with the successive scans, the islands tend to align along the high-symmetry directions of the graphite crystal underneath.

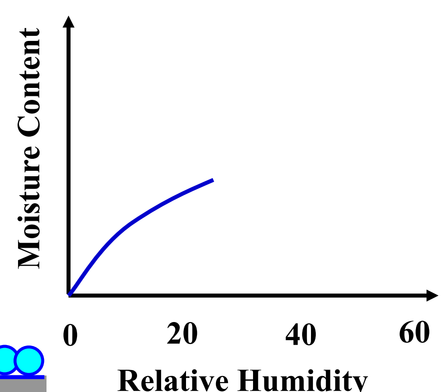
Langmuir **2000,** *16,* 5086-5092.



Microsc. Res. Tech. Vol. 44, pp. 327–338, 1999.

Adsorbed Moisture





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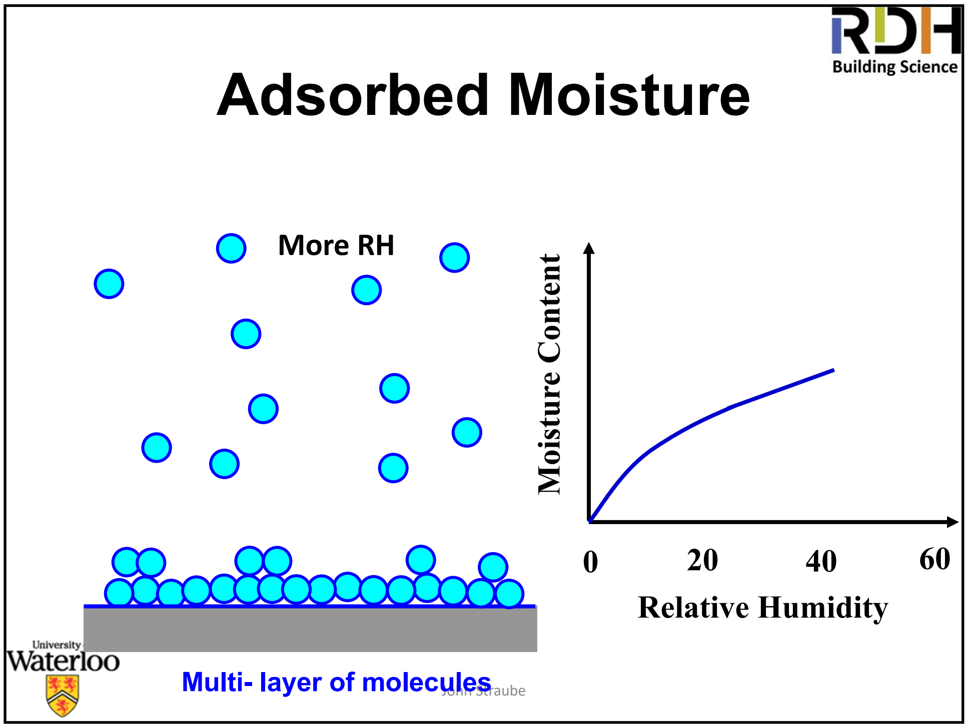
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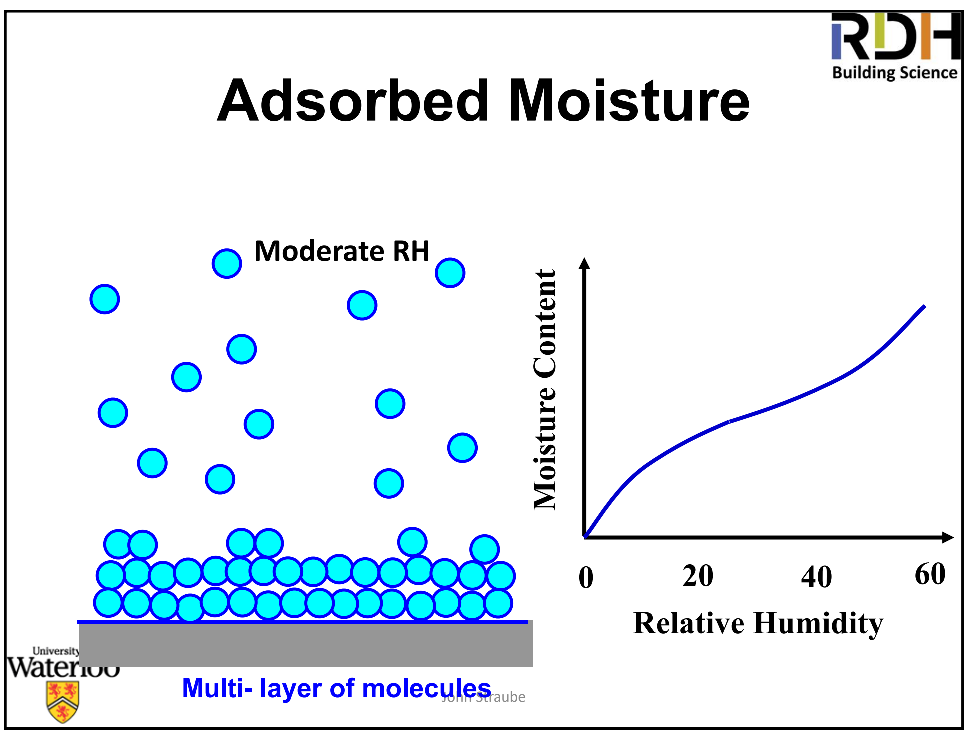
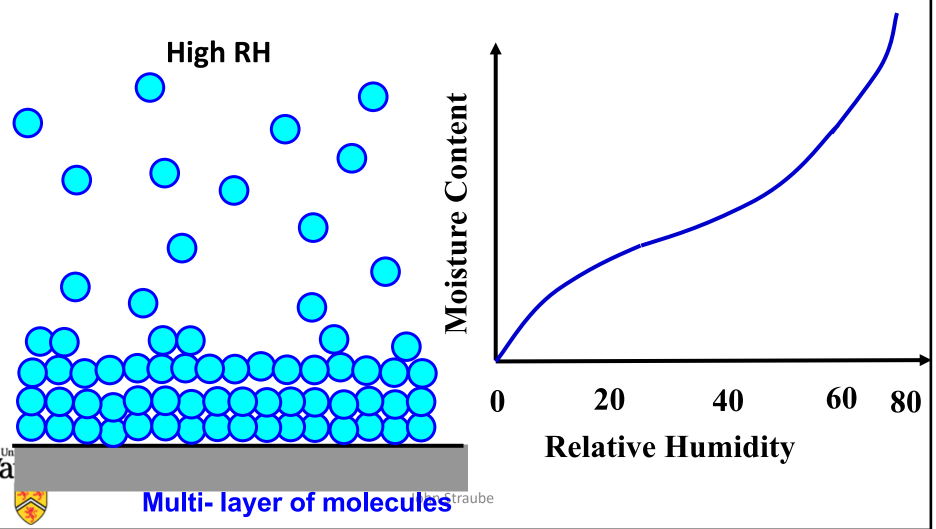
Adsorbed Moisture
More RH
Moisture Content
0
20
40
60
Relative Humidity
University of Waterloo
Multi- layer of molecules
John Straube

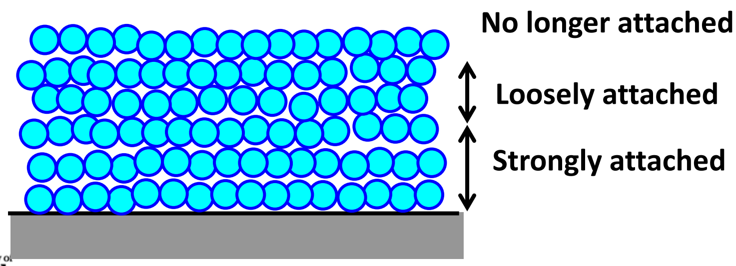

RDH Building Science
Adsorbed Moisture
Moderate RH
Moisture Content
0
20
40
60
Relative Humidity
University of Waterloo
Multi- layer of molecules
John Straube

Adsorbed Moisture



Condensation

- Thick layers form
- no longer attracted strongly to surface



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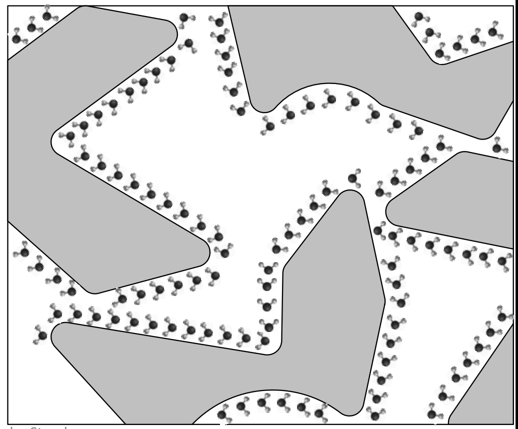
Water vapor stuck to porous material

- Porous materials have large interior surface area (more later)
- Adsorption of vapor is easily measurable & significant in practice



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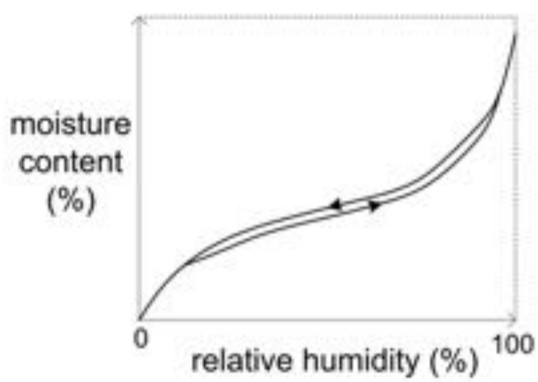
Adsorption Isotherm

- Numerous shapes… this is common



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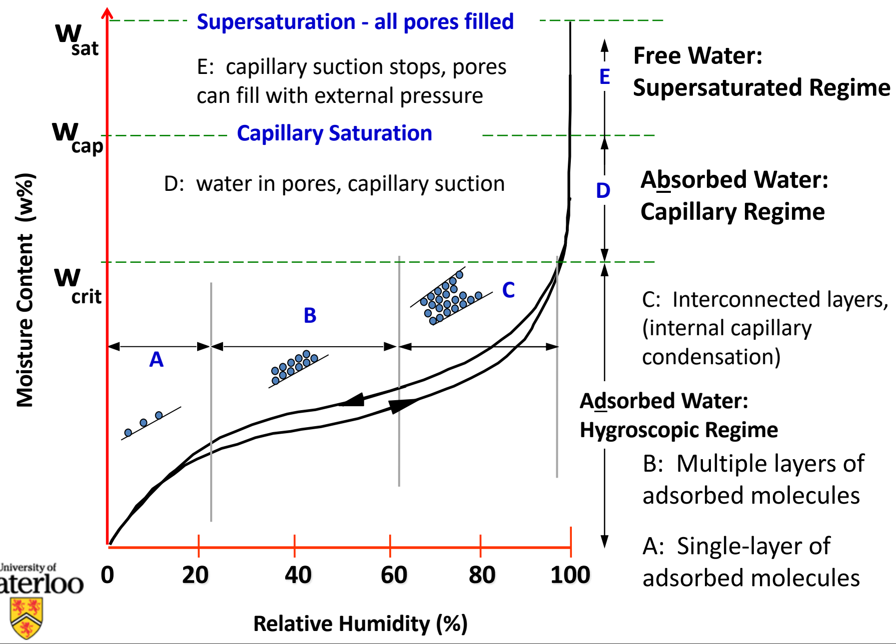
Moisture Storage Function (vapor + liquid)



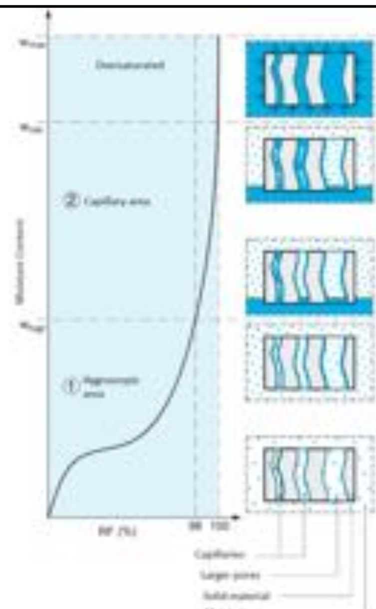
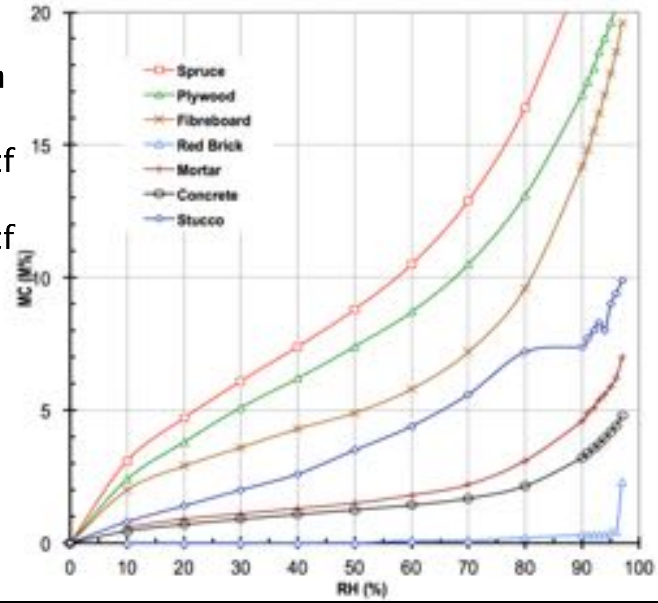


Figure 8 Moisture transport in porous materials. Pore model and sorption curve. Hygroscopic area with vapour and surface diffusion and capillary area with capillary conduction. Figure adapted from Geving, 2005.

When is a material wet?

- MC based on weight%
- 5% in 140 pcf concrete = 17% in 40 pcf wood



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

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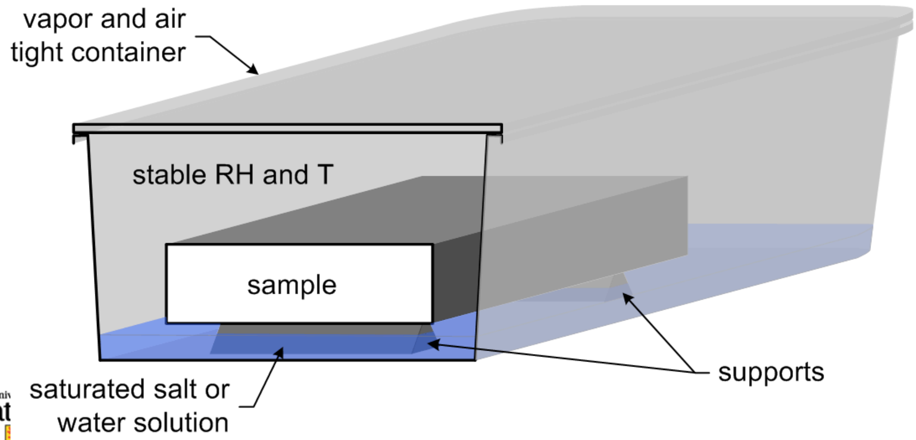
Sorption test

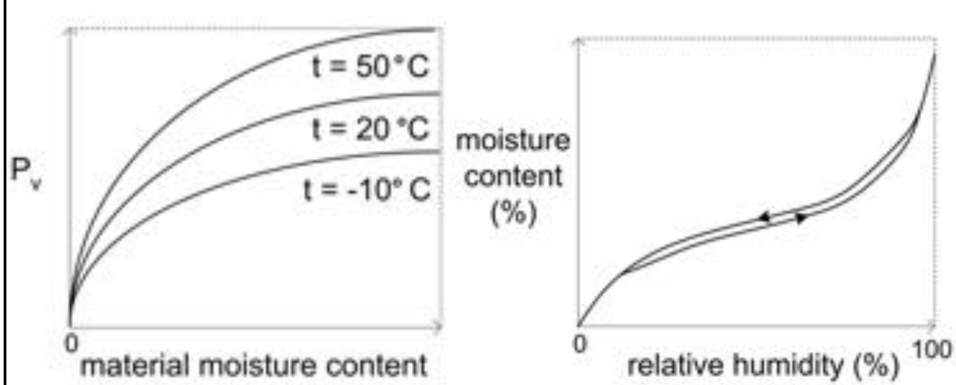
- Simple… Expose sample to controlled RH



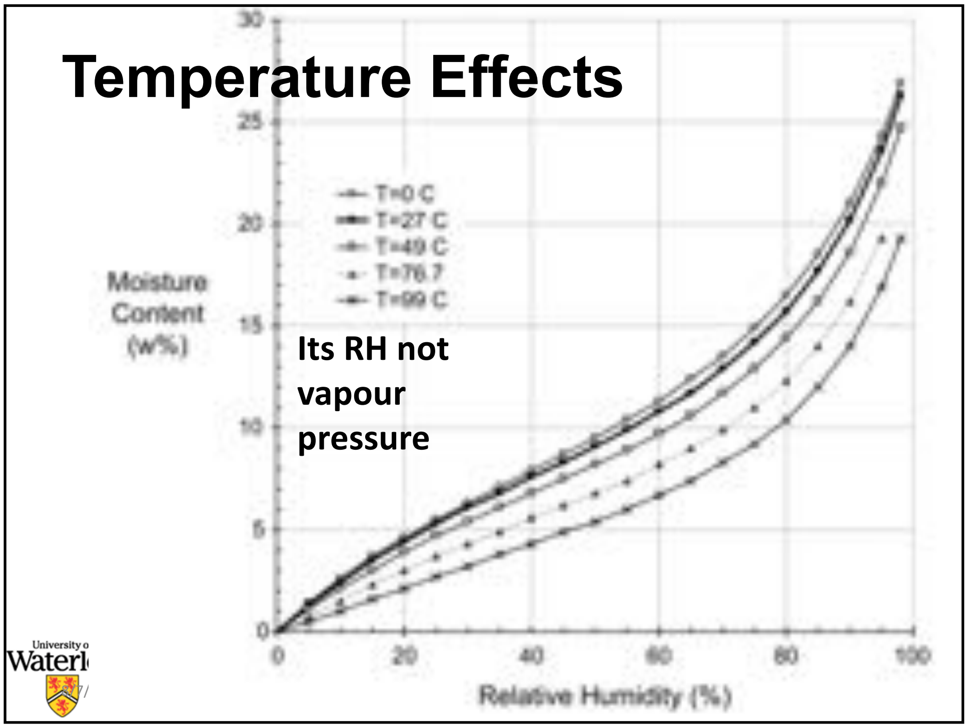
RDH 25C/50%RH Room

Sorption and Temperature

- Vapor pressure varies with temp
- RH varies with moisture content



Temperature Effects

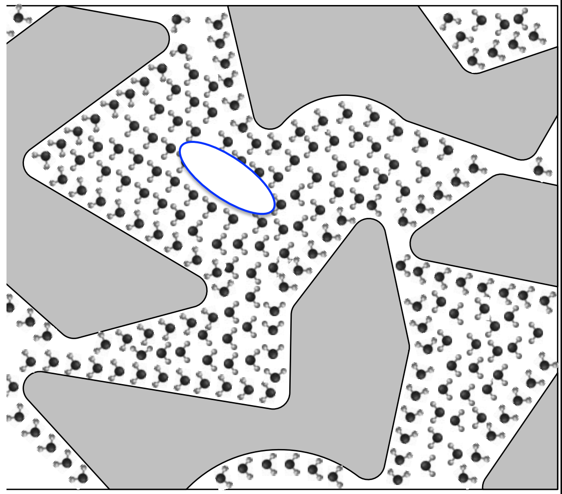


Its RH not vapour pressure

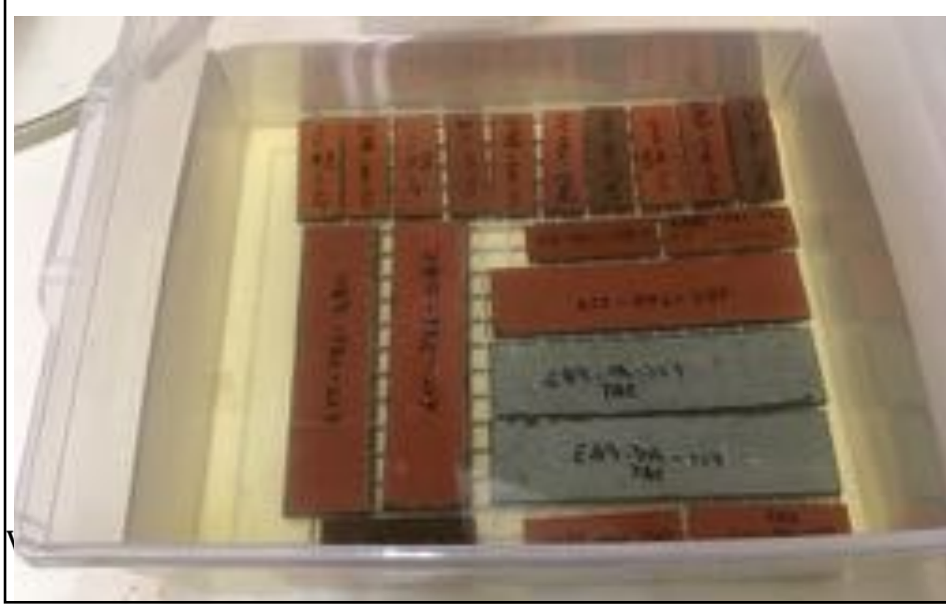
Capillary Saturation

"Wet" with liquid water

- Larger voids are not filled with capillary suction
- Dead end pores have trapped air



Saturated: underwater



Vacuum Saturated

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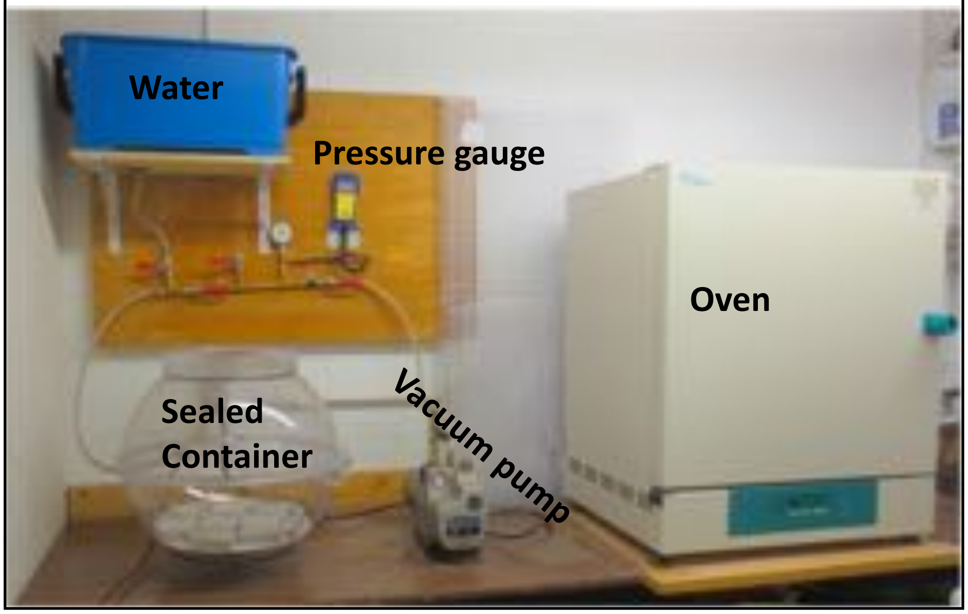

Vacuum Saturation

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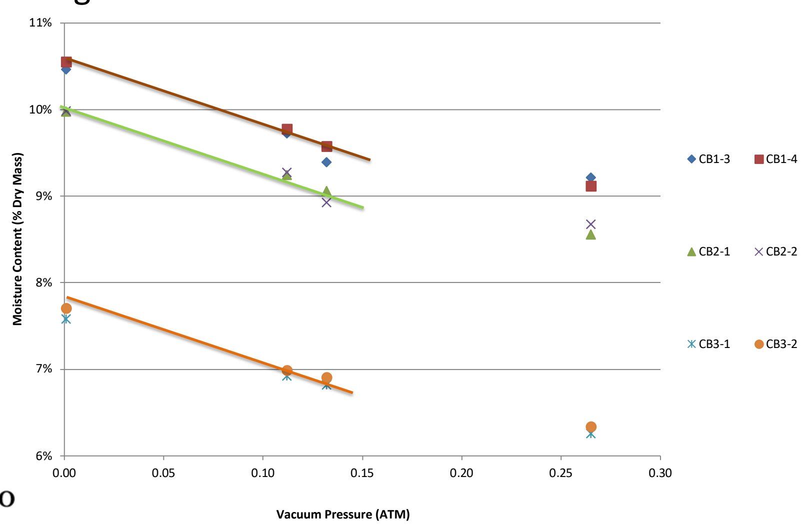
- Degree of Vacuum matters



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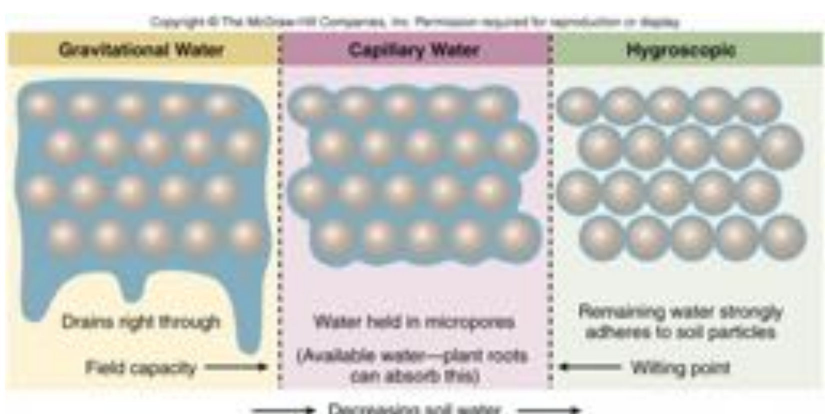
Source: P. Mensinga, MASc Thesis, University of Waterloo

Boiling vs Vacuum Saturation

Vacuum method gives higher saturation moisture content than boiling method.

Sample ID	Moisture Content (% Dry Mass) Boil	Vacuum	Vacuum:Boil
CB1	8.68%	10.29%	1.19
CB2	8.20%	9.87%	1.20
CB3	6.51%	7.72%	1.19
UC6	14.92%	15.56%	1.04
UC8	17.80%	18.89%	1.06
BR1	14.01%	14.01%	1.00
BR2	15.25%	15.25%	1.00

Example Storage Function: Soil



Significance Of Regions

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

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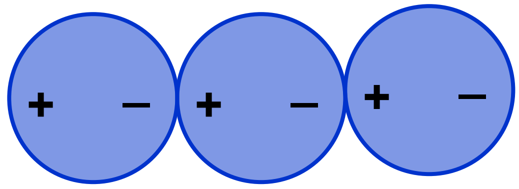
Surface Tension

- Water is attracted to self
- Creates a "membrane" or "surface film"



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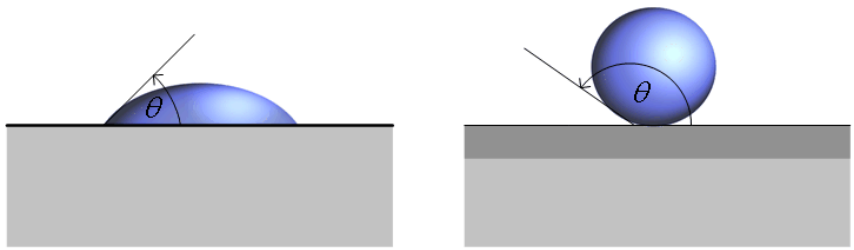
Surface Tension: Wettable

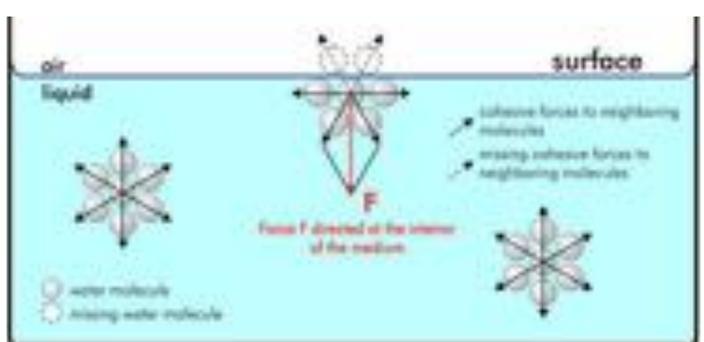
Water attracted to surface more than self	Water attracted to self more than surface
$\theta < 90^o$	$\theta > 90^o$



normal material: "wettable"	hydrophobically treated: "non-wettable"

Surface Tension

- A result of unbalanced attractive forces at the surface



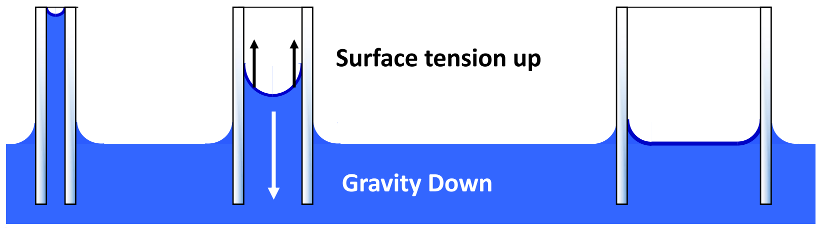
Water striding bugs

From: thenatureniche.com

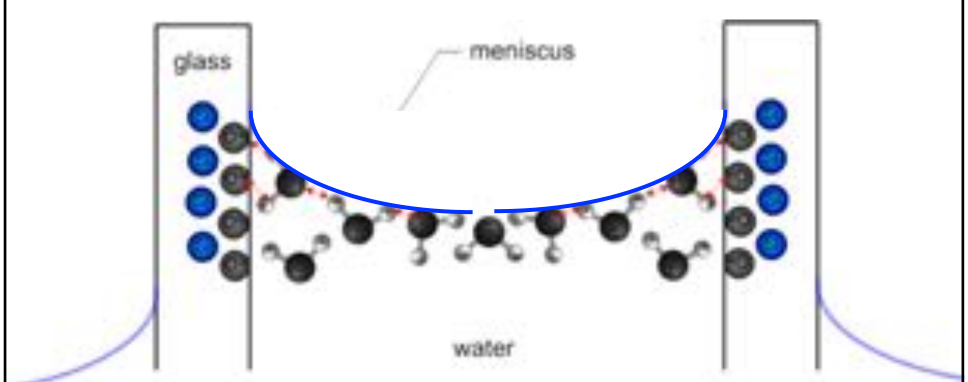
Surface Tension & Materials

Capillary Suction

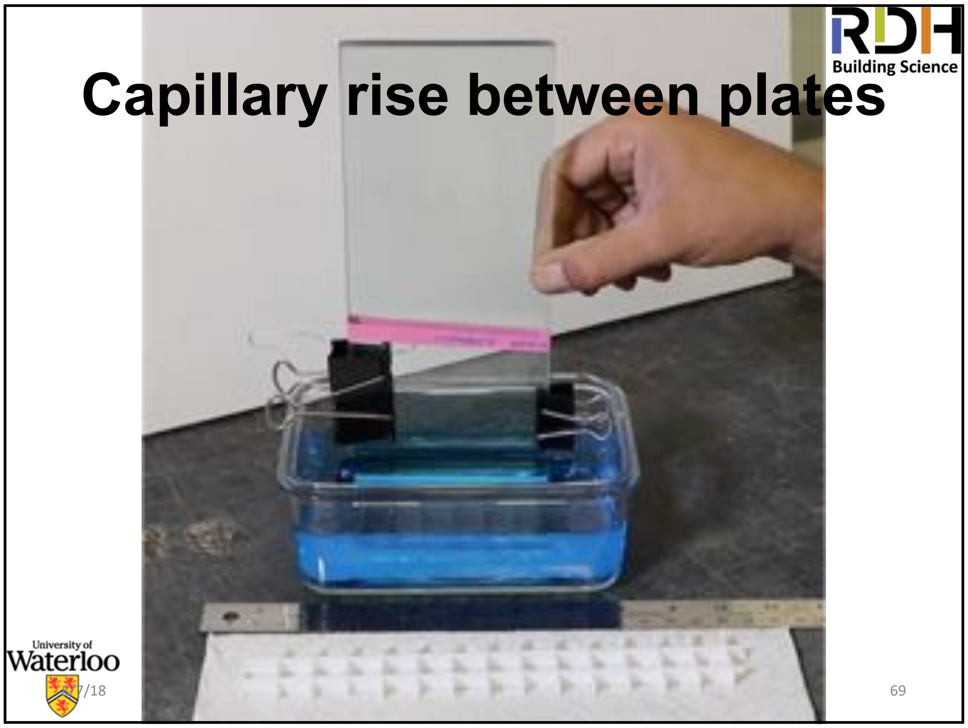
- Result of surface tension = attraction to surfaces
  - pressure varies with pore size
  - e.g., height rise in a glass tube



Capillary Suction Pressure



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


Capillary rise between plates
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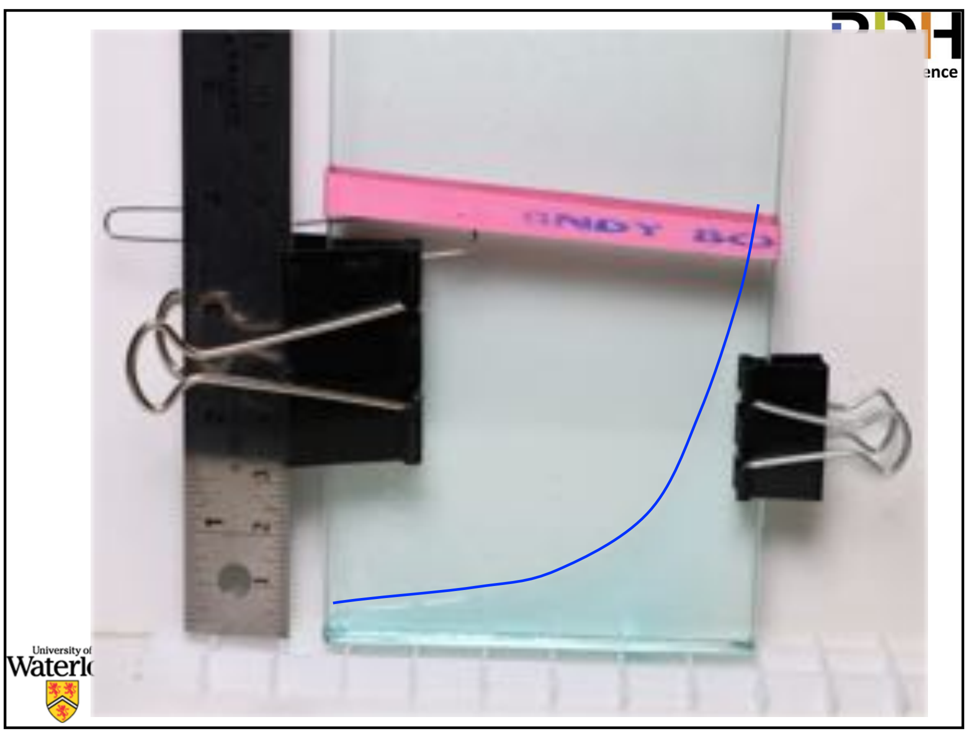
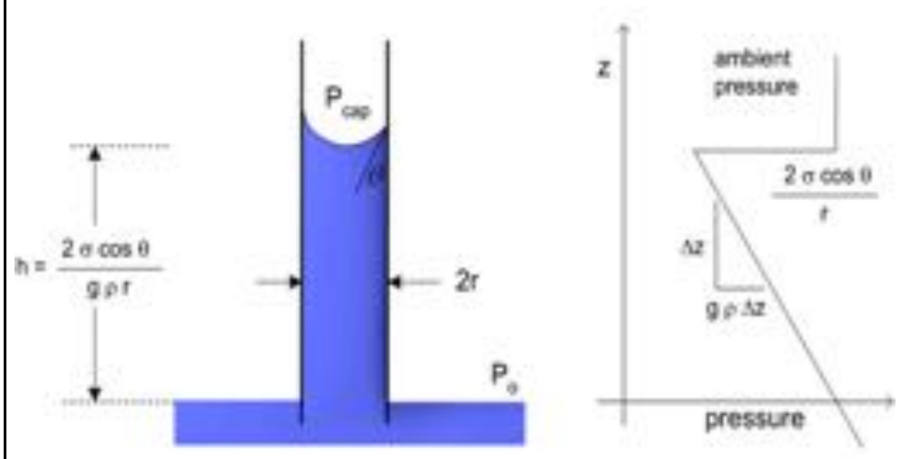


Calculating capillary rise



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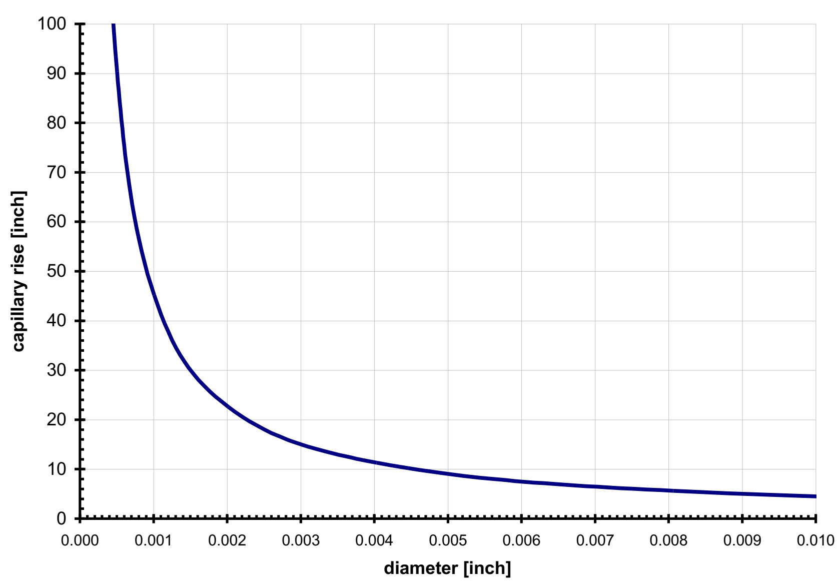
Capillary rise versus diameter

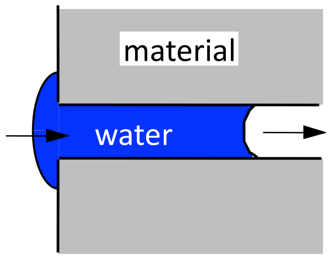


Surfactants

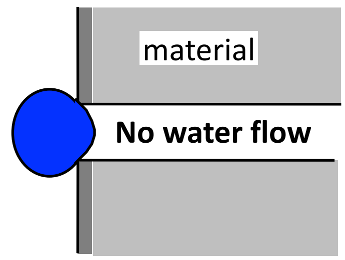
- Surfactants
  - Modify surface energy and reduce surface tension
  - Eg soap
- Water Repellents
  - Make surfaces hydrophobic

Water Repellents

E.g., silicone



Water flowing in: system not in equilibrium



Normal, capillary active material

Hydrophobically treated material

Requires pressure to force water into small cracks and holes

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Duck Hunting

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Porous Materials

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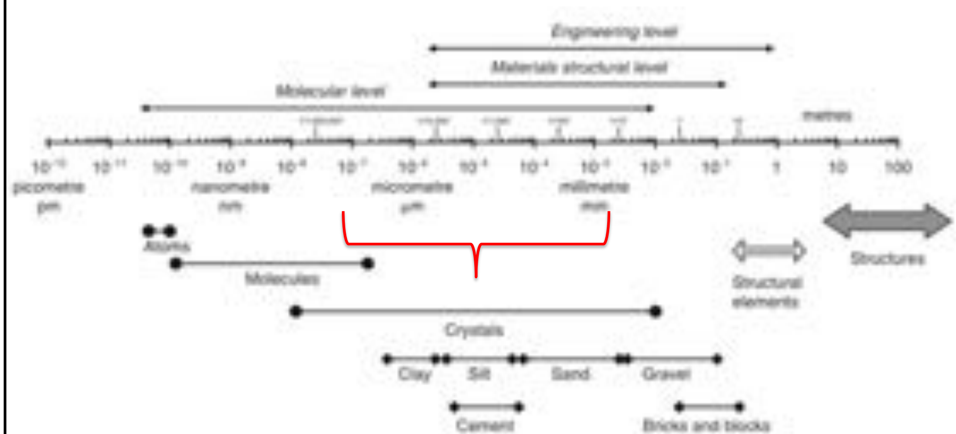
Material Scale

•



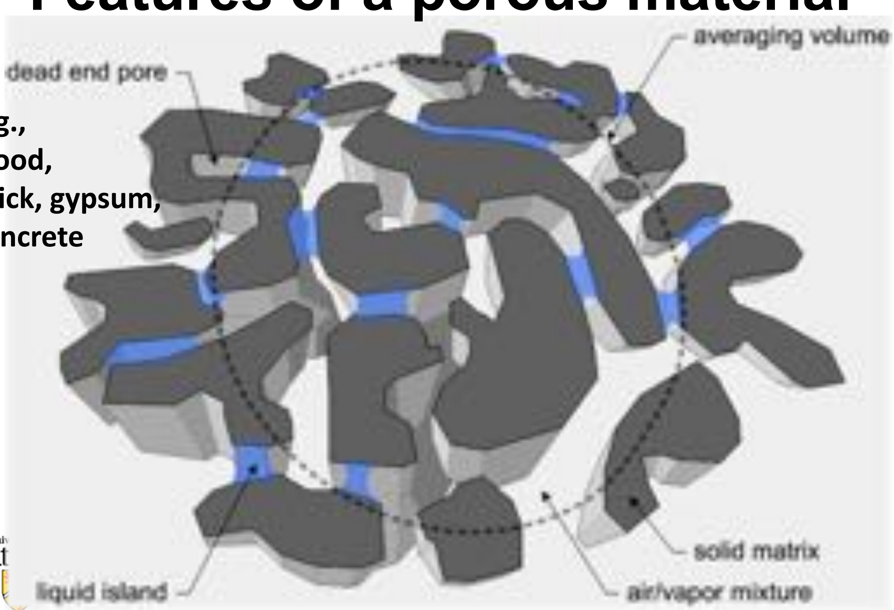
Source: Illston and Demone, *Construction Materials*, 2010.

Nature of Porous Materials

- Many building materials are porous
  - wood, gypsum
  - concrete, brick
- Metals are non-porous (mostly)
- Plastics are usually not very, but…
- Porous structure allows for lots of moisture interactions
- Nature of material is as important as nature of water

Features of a porous material

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



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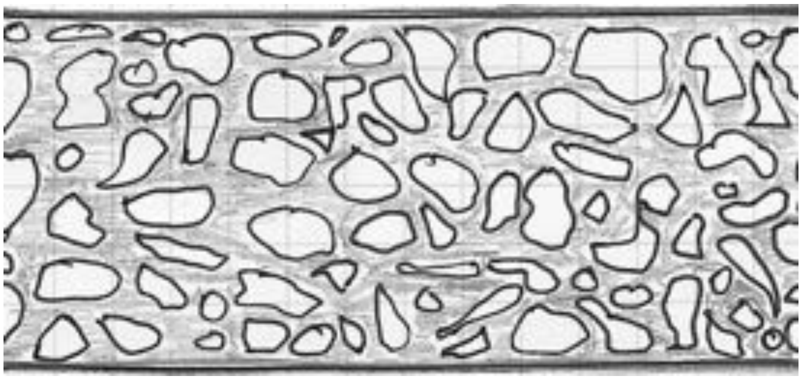
Porous Material

- Maybe 50% porosity, but not *permeable*



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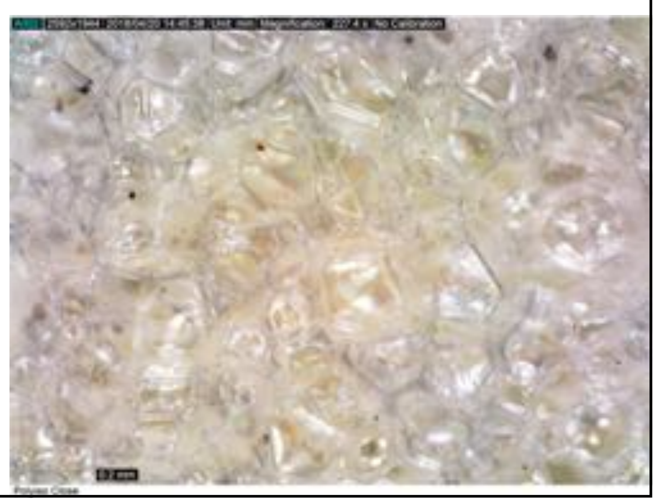
Closed Cell Foam

- Generally >90% of pores should be closed



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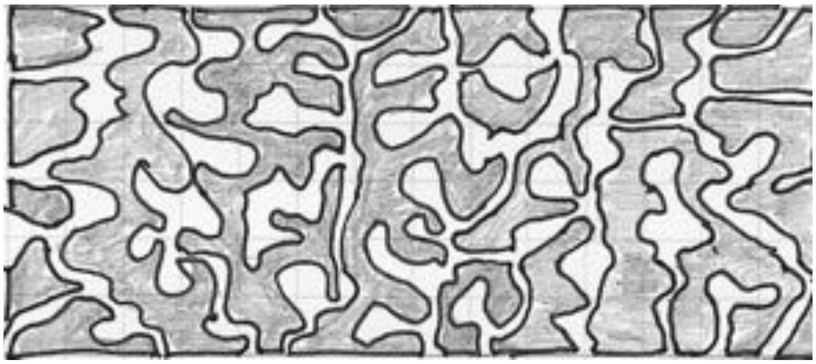
Porous Material

- Permeable



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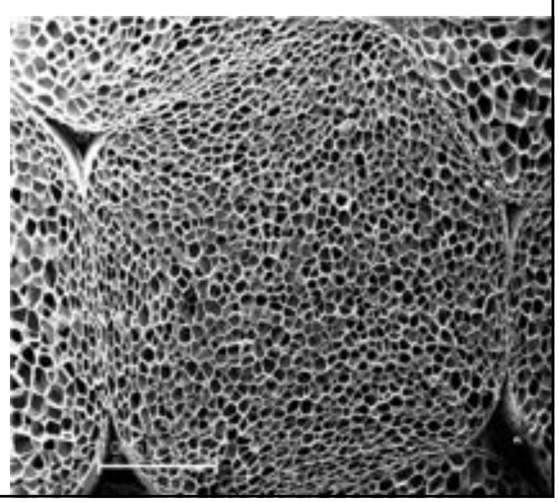
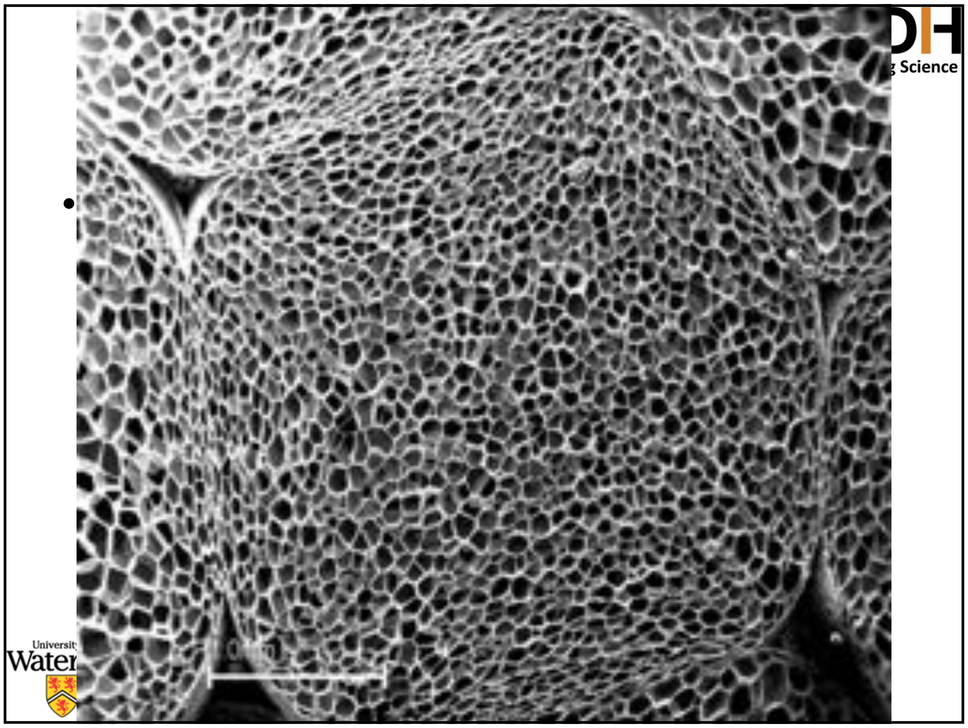
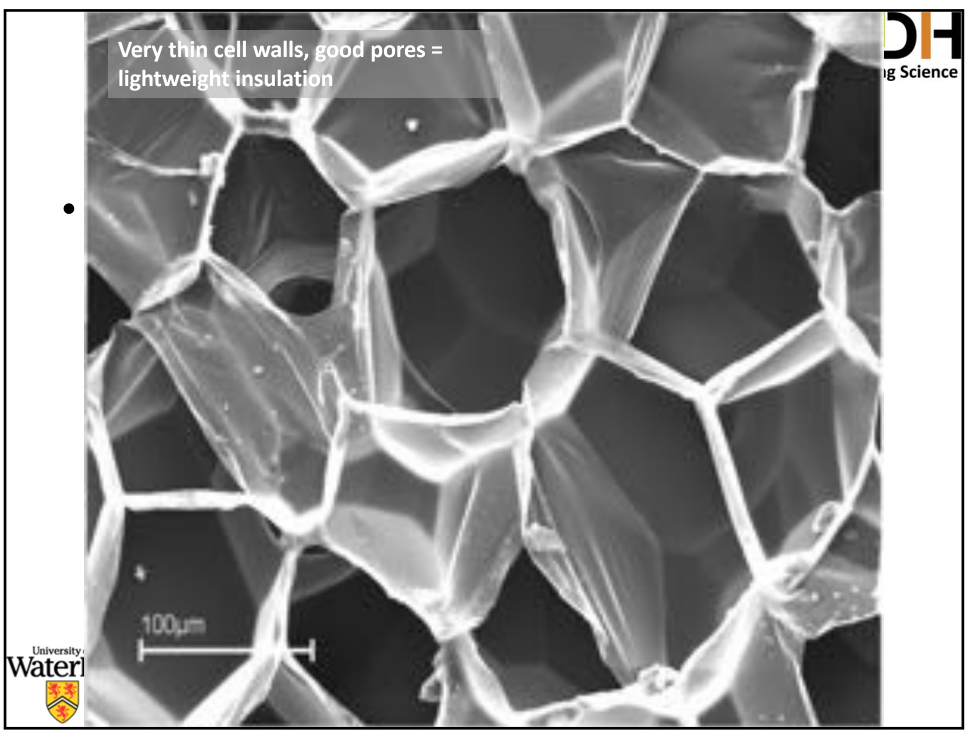
Expanded Polystyrene

- Open Pores

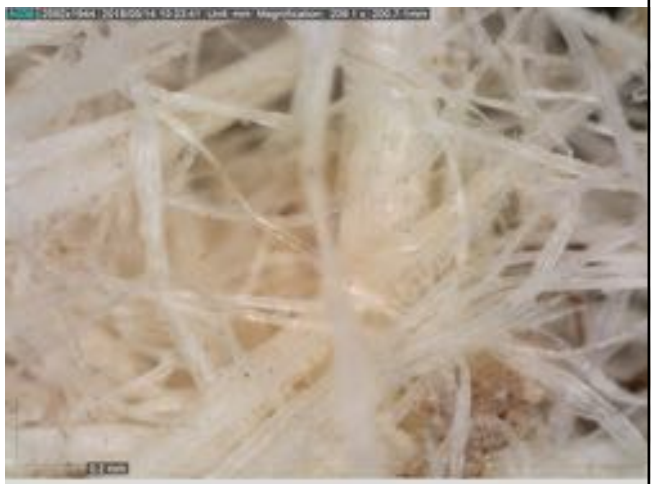





Very thin cell walls, good pores =
lightweight insulation
100µm

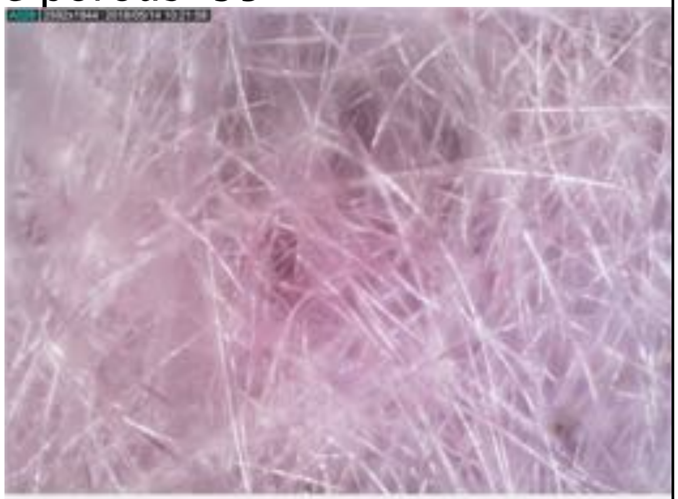
Wood Fiber Insulation

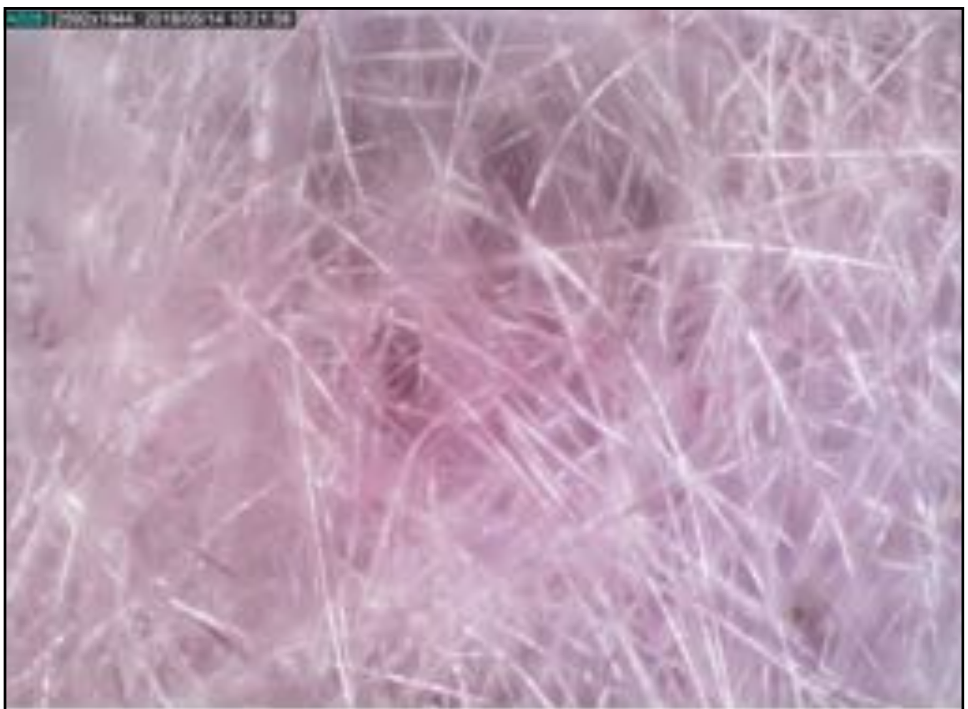
- Highly porous.. >90% voids



Glass Fiber Insulation

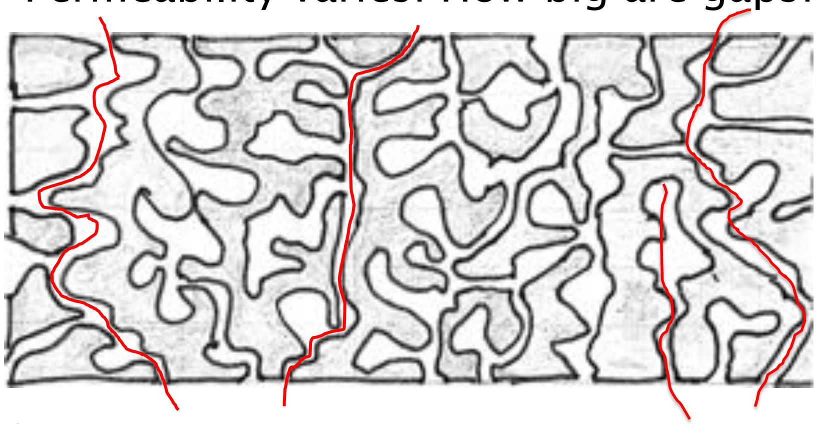
- Even more porous>95





Permeability

- Permeability varies! How big are gaps?



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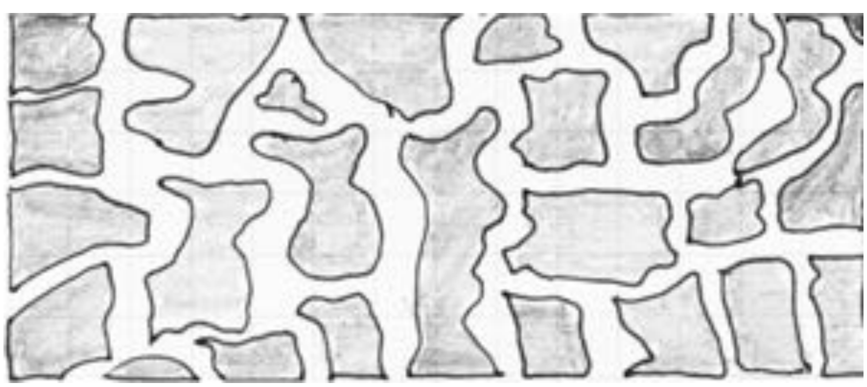
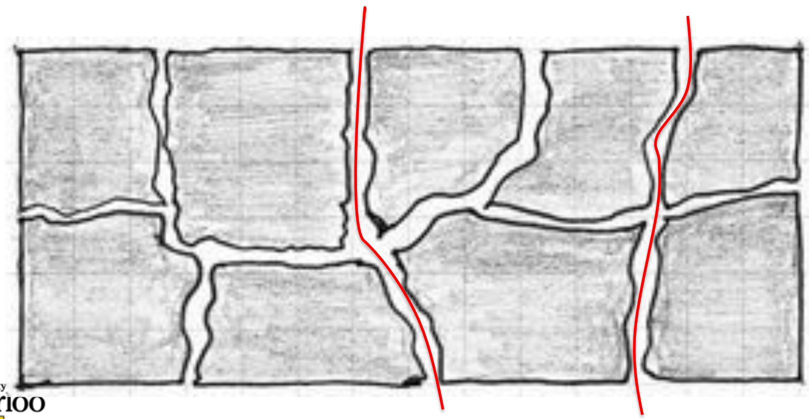
- More permeable, and more porous



Porous Material

- highly permeable, but low*ish* porosity



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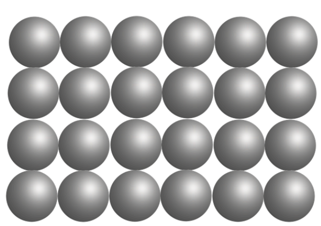
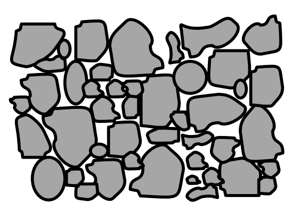
Simple Models

Simple → **Reality**

Cubic packing of spherical particles

Random particles size and packing





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Real Materials

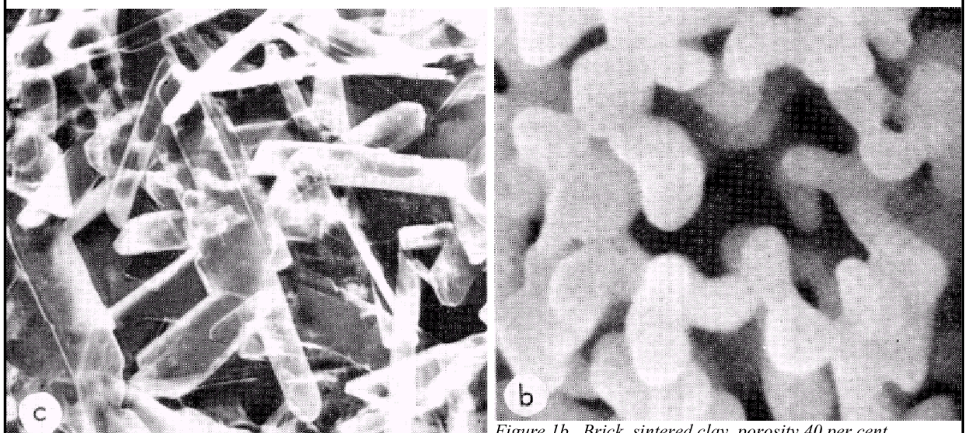

Figure 1c. Gypsum, hydrated from plaster of paris and water, porosity 30 per cent.

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

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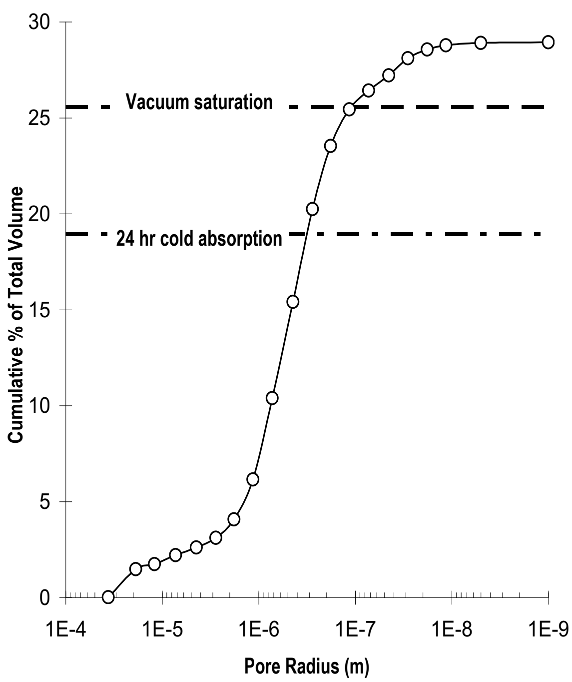
Clay Brick



Mercury porosimetry

Pressure plate

Brick Sucks!

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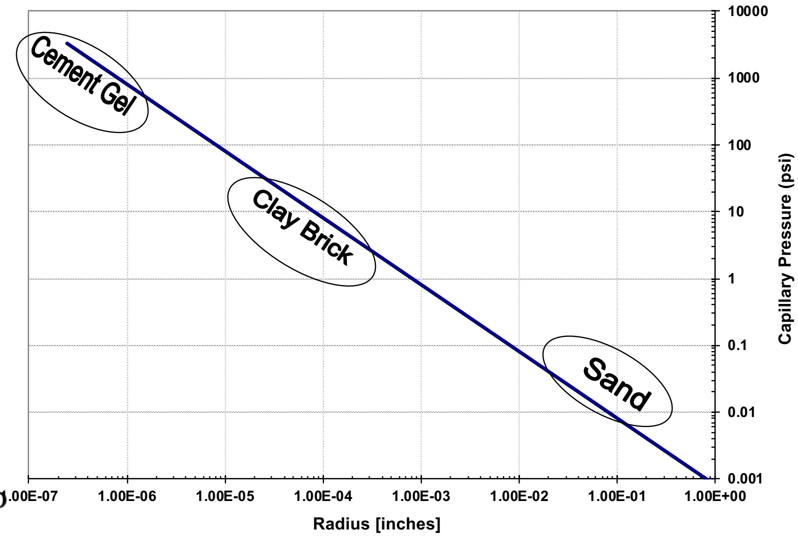
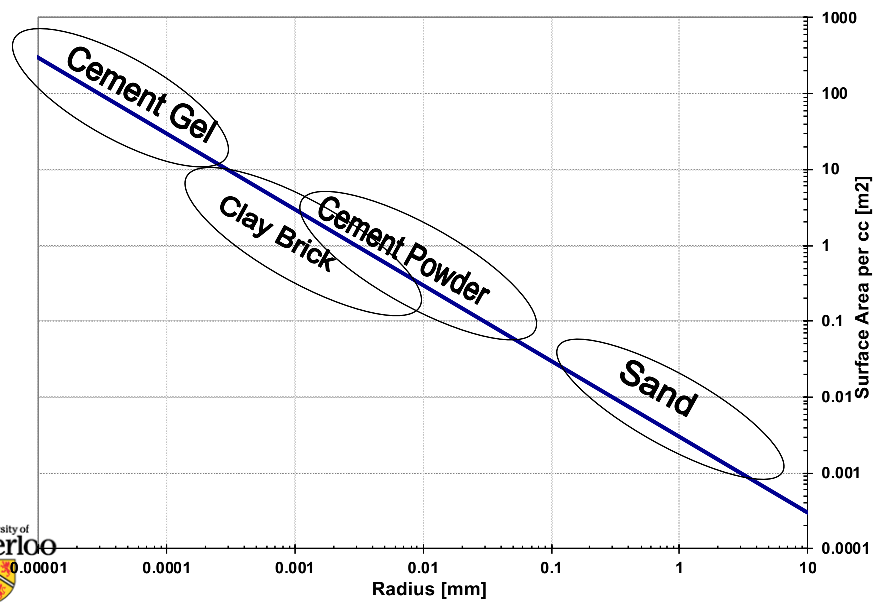
Small pores=high pressures



Interior Surface Area



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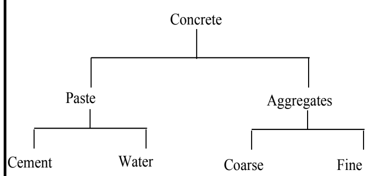
Concrete

- Complex mixture
- Calcium silicate hydrates are primary cure cement paste



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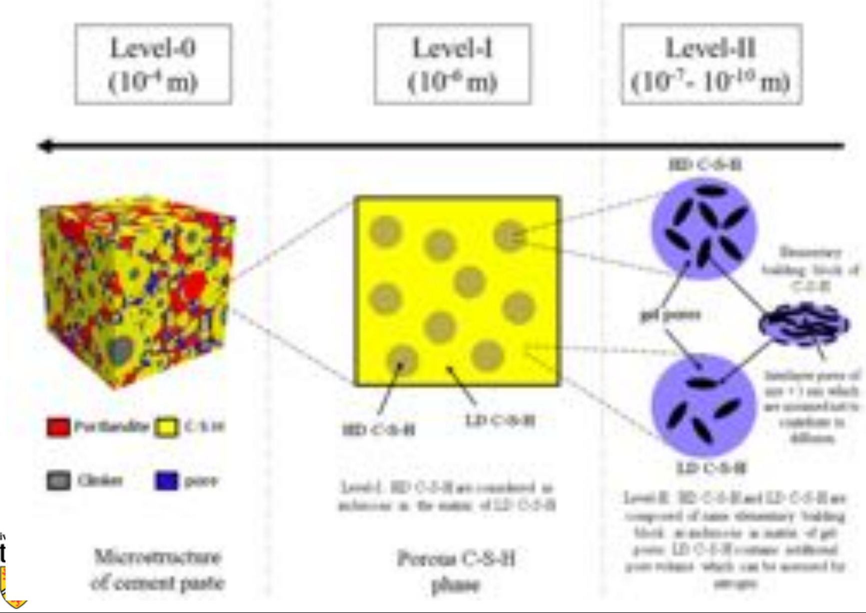
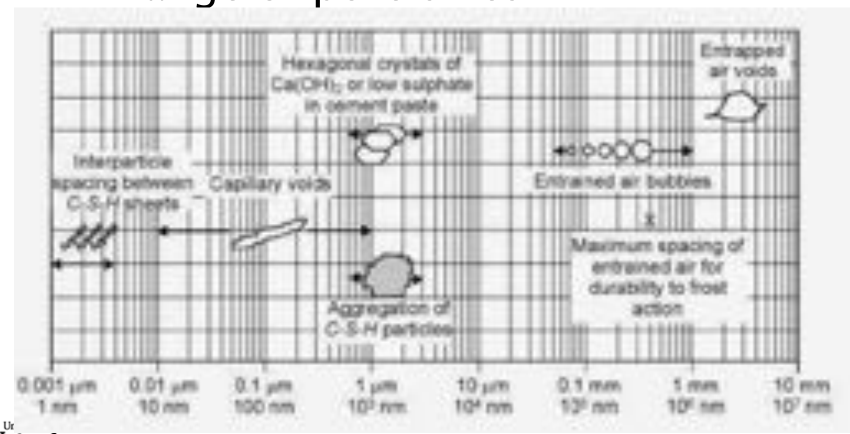


Concrete

- A range of pore sizes



Concrete Pore sizes

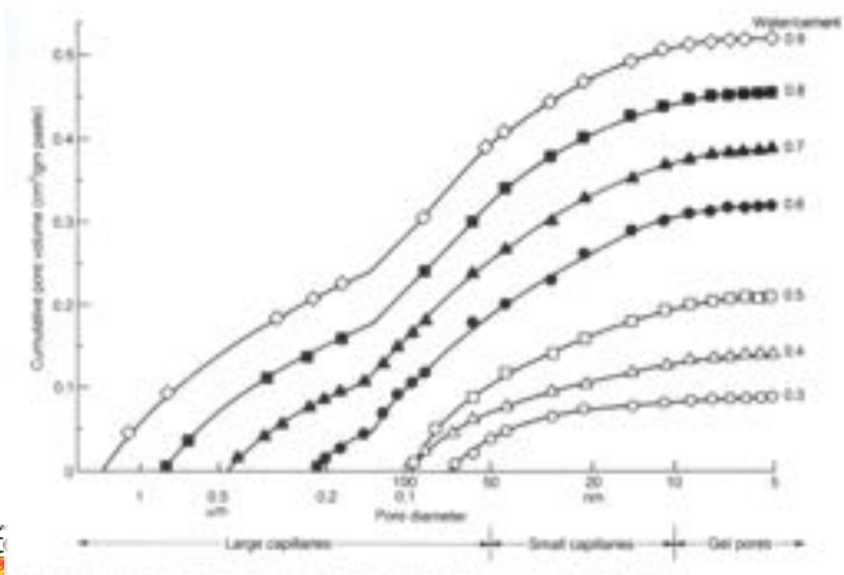


FIGURE 11.8 Pore size distribution in 28-day-old hydrated cement paste (Mehta, 1986).

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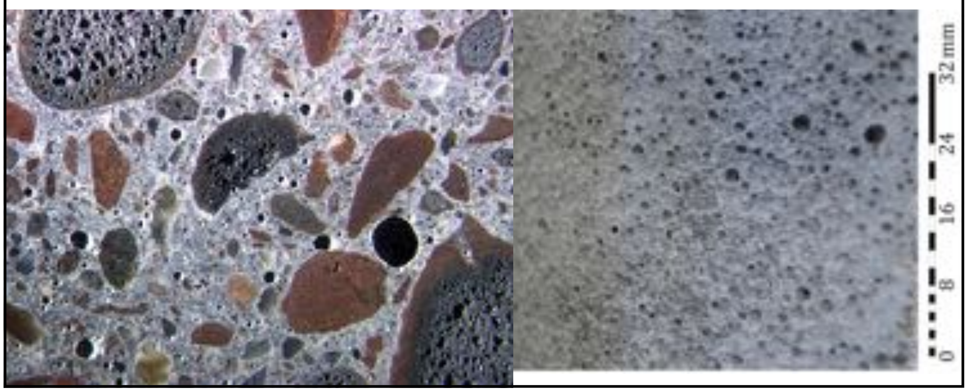
Lightweight & Foam Concrete

- Pores and voids added to decrease weight = places for water storage



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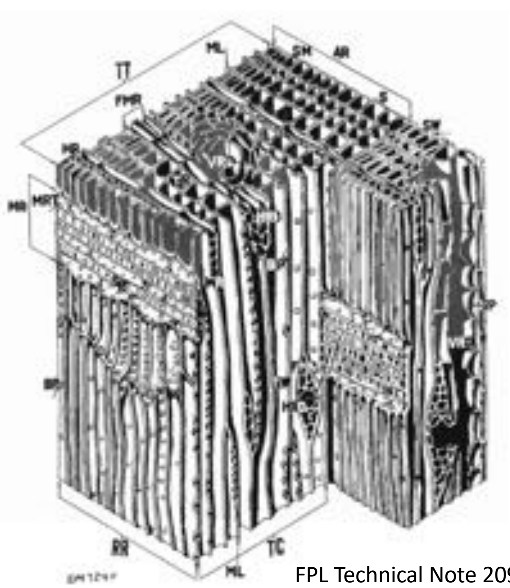
Isotropic matl's: Wood Structure



- Equivalent to a bundle of tubes
- flow along grain much faster
- Suction feeds tree leaves hundreds of feet

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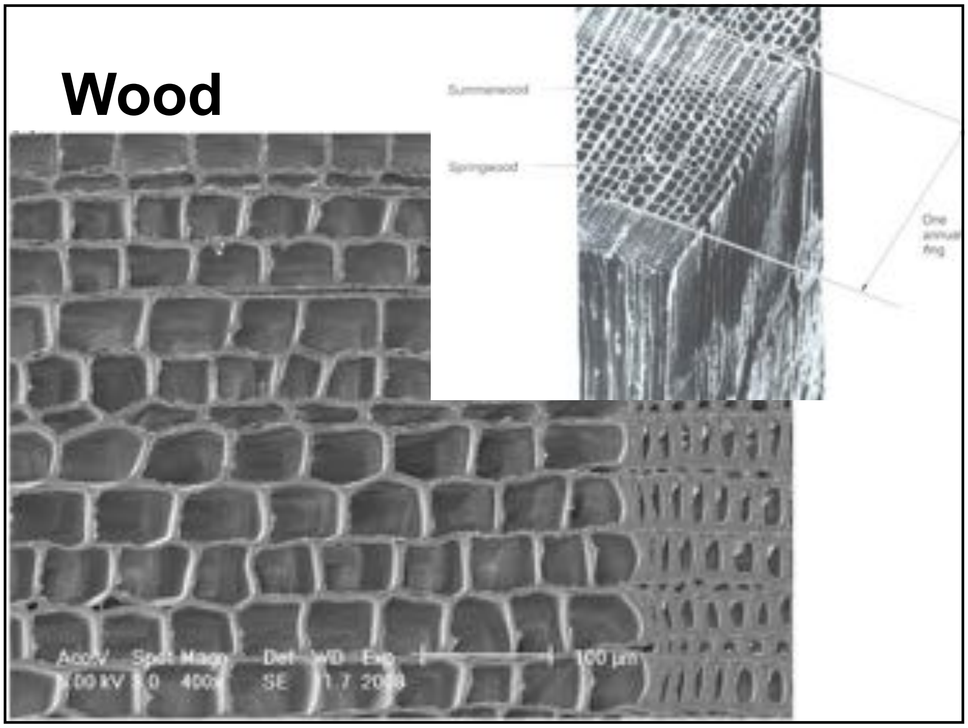
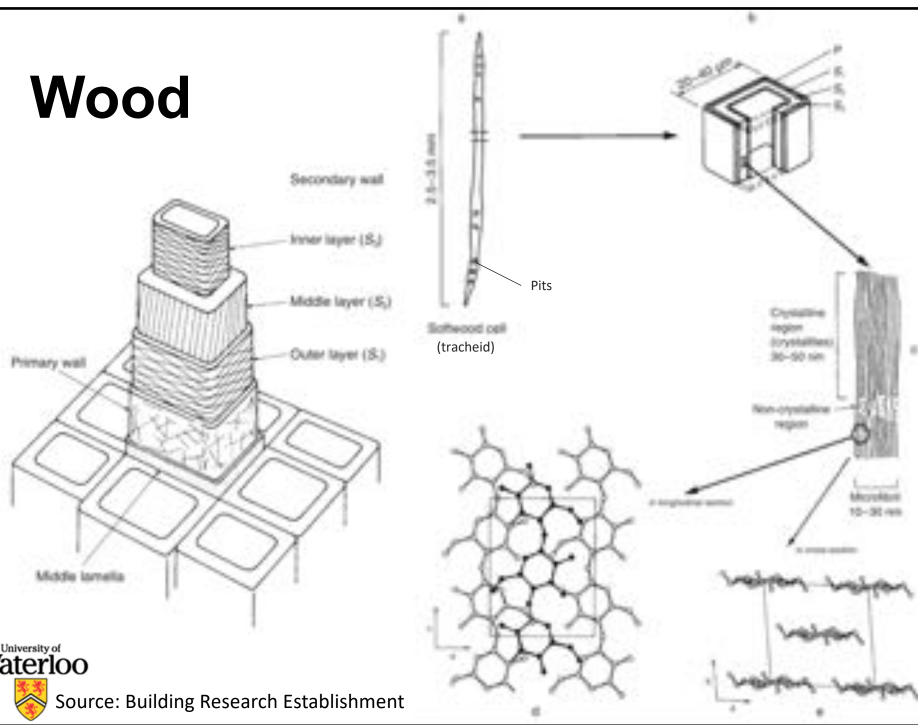
Wood



Wood



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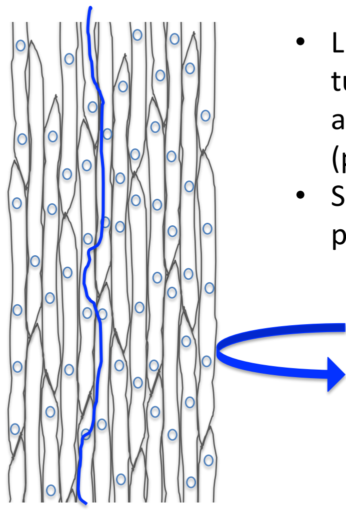
Source: Building Research Establishment

Softwood Cells / Tracheids



- Liquid water moves along tubular wood cells, and across holes between cells (pits)
- Slow moisture movement perpendicular to the grain

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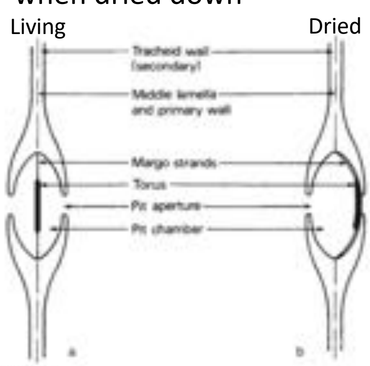
Bordered Pits

- The "bordered pits" open and close when tree is living
- Permanently torn & closed when dried down



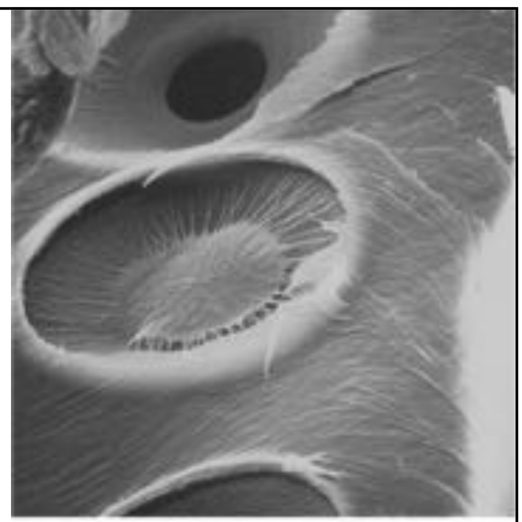


Fig. 52.10 Scanning electron micrograph of softwood bordered pits on the radial wall of a spruce tracheid. The arched upper dome of the pits has been removed in specimen preparation, and in the central pit the torus and supporting margo strands are revealed; these have been torn out of the lower and upper pits during the preparation process (magnification × 3000) (© Building Research Establishment).

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Some wood wicks *slowly*


Some wood wicks *slowly*
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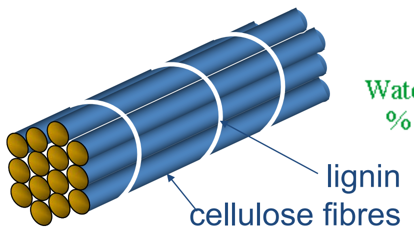
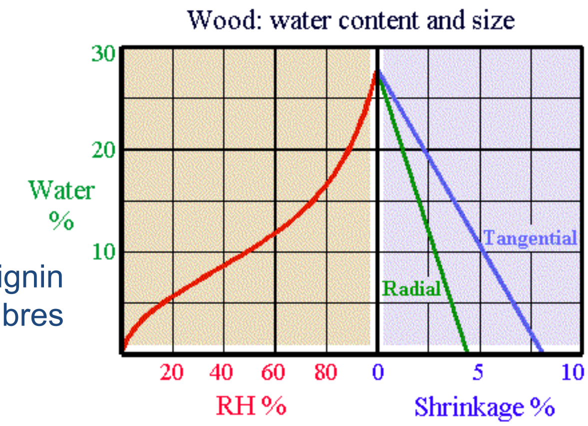
© thetroublewitholdboats.blogspot.com

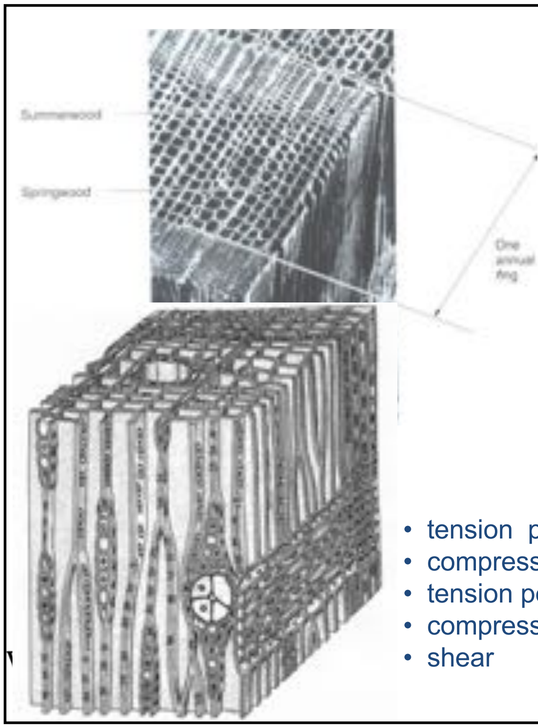
Wood Swelling and Shrinkage

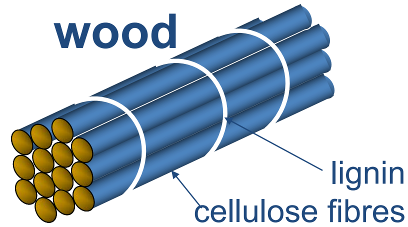
- Wood acts as a bundle of tubes
- Shrinks *across* grain, not along
- Only during adsorption





Material properties of wood



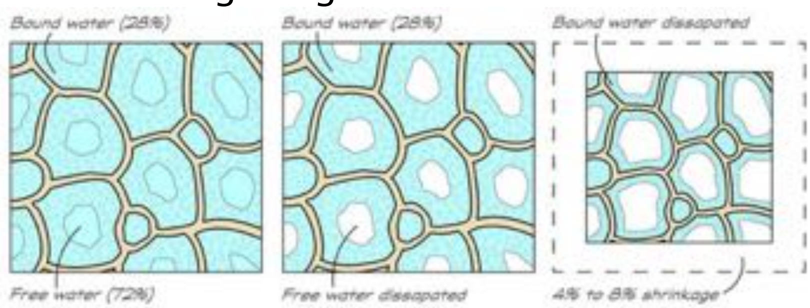


… imagine a bundle of straws held together with elastic bands

- tension parallel to grain
- compression parallel to grain
- tension perpendicular to grain
- compression perpendicular to grain
- shear

Shrinkage

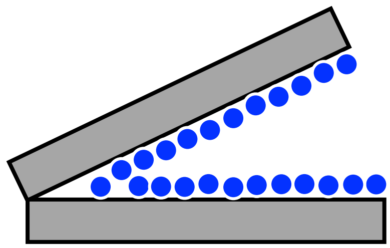
- Capillary saturated and higher, no moisture movement.
- When MC drops below about 28%=100%RH, the shrinkage begins



Swelling

Consider two microfibrils in a wood cell wall where come close to touching

Adsorption of water molecules to surfaces will occur



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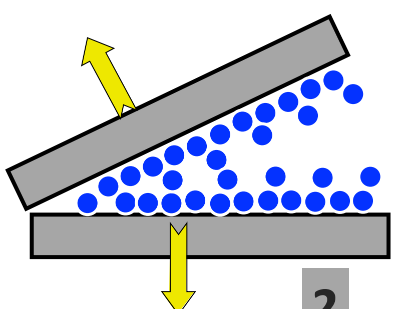
Swelling



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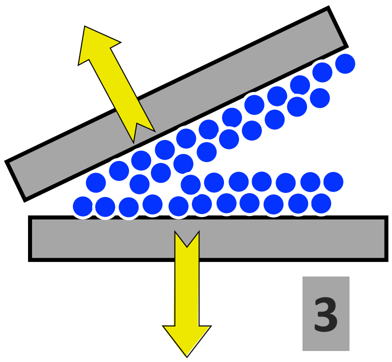
Swelling



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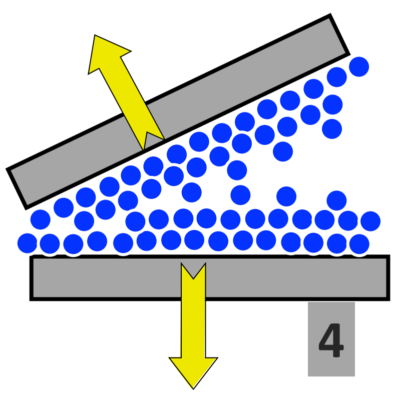
Swelling



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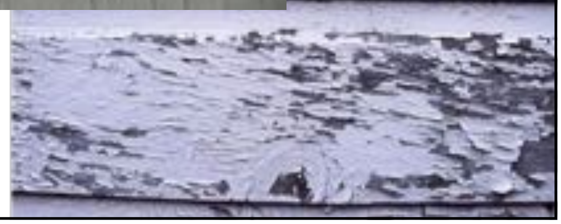
Moving wood causes cracking of brittle paint



Swelling

Wood Fiber insulation before & after 60 days, <100% RH

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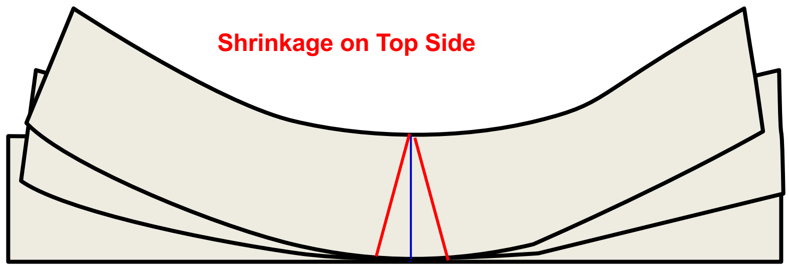
MC Gradient Causing Curving

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



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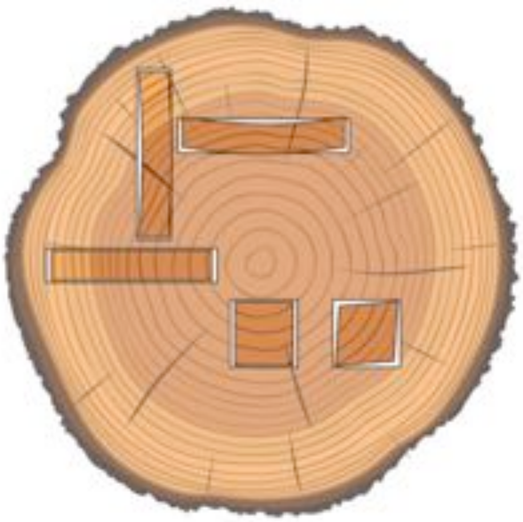
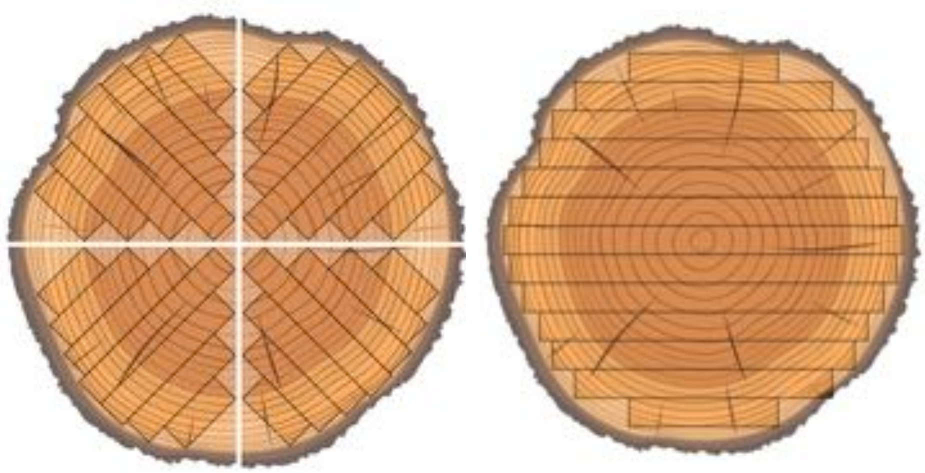
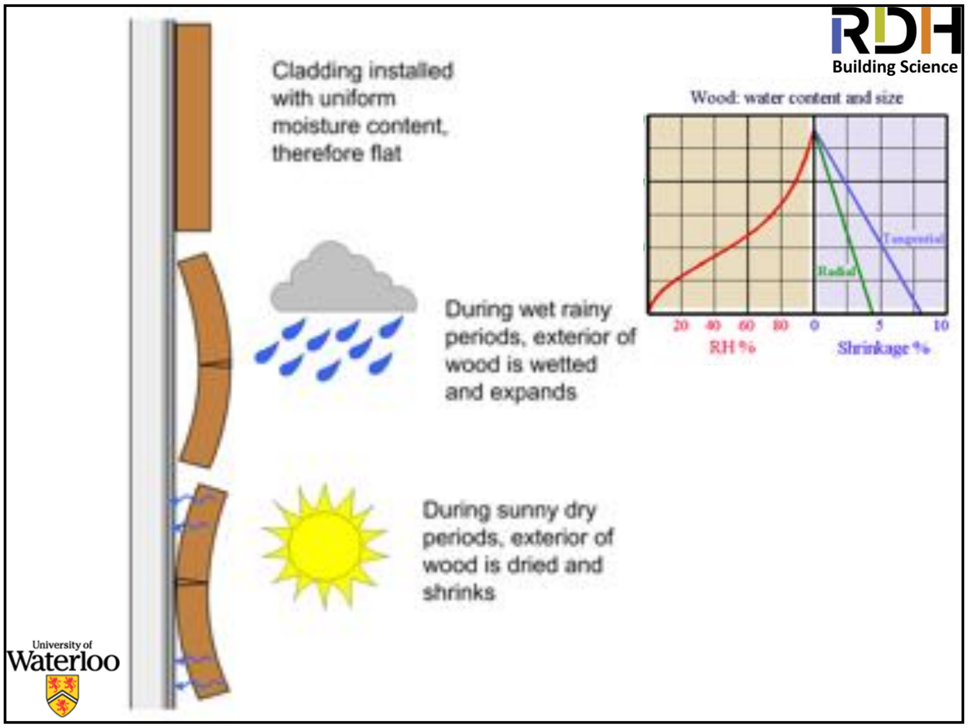
Differential Grain can also result in warping





Quarter Sawn Plane Sawn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Cladding installed with uniform moisture content, therefore flat
During wet rainy periods, exterior of wood is wetted and expands
During sunny dry periods, exterior of wood is dried and shrinks
Wood: water content and size
20 40 60 80 0 5 10
RH %
Shrinkage %
Radial
Tangential
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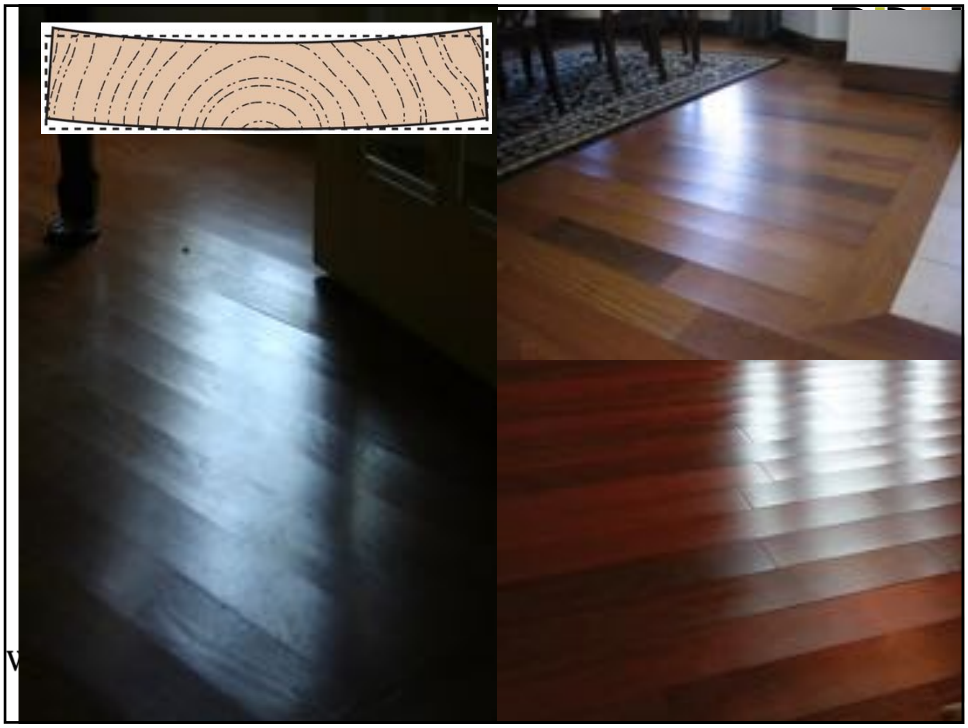
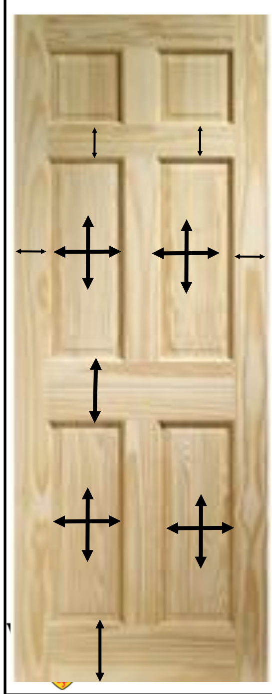
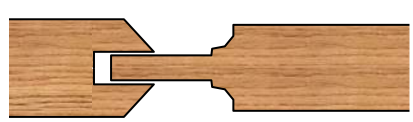




Colonial Doors

- Design is more than a style… it allows wood to move without changing the size of the door, much
- Not needed for steel or fiberglass doors of course



Detail Section

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Wood expansion
Concrete Shrinkage
Frame Shrinkage
Stucco Shrinkage


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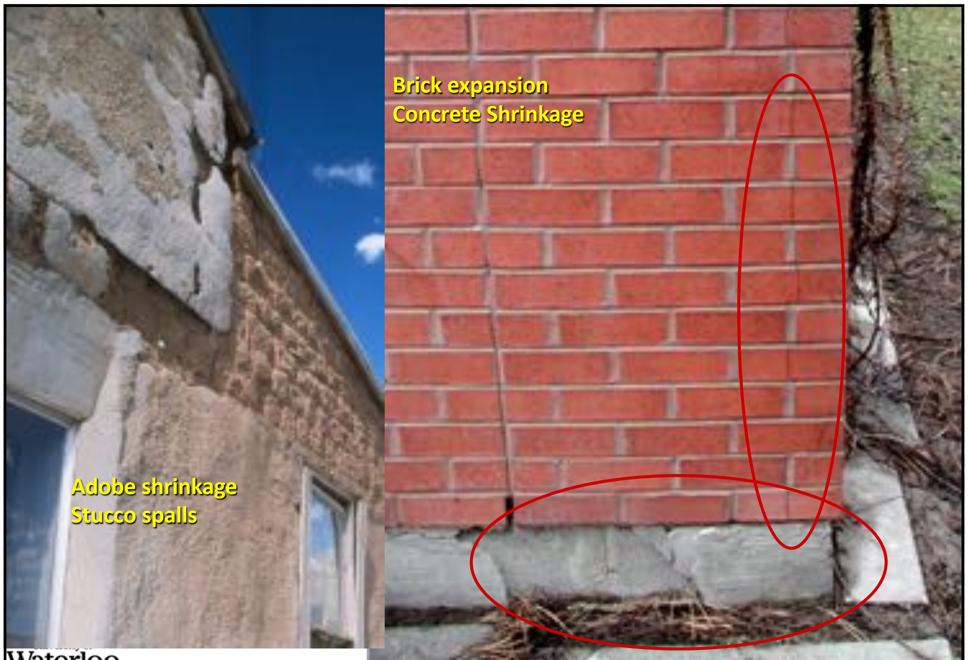

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Managing Movement

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- 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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Moisture transport

Moisture Transport

- Each Phase is separate
- Liquid
  - Gravity and air pressure
  - Capillary Suction
  - Osmosis
- Vapor
  - Diffusion
- Adsorbed
  - Surface flow

Liquid flow

- Air and gravity pressures
- Air pressure sometimes acts, small
  - wind typically < 100 Pa (0.015 psi= 2 psf)
  - short 1 000 Pa bursts (0.15 psi = 20 psf)
- Gravity always acts, and acts downward
  - About 10 000 Pa/m (1.3 psi/yd) height
- Capillary always acts on small pores (<1 mm) of hydrophilic materials

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Relative pressures

Force	Pascals (psi)
Air Pressure	10-1000 (0.0015 to 0.015)
Gravity Pressure	10 000/m (0.45 psi/ft)
Capillary Pressure	0–10 000 000 (0-1500 psi)
Osmotic Pressures	5-500

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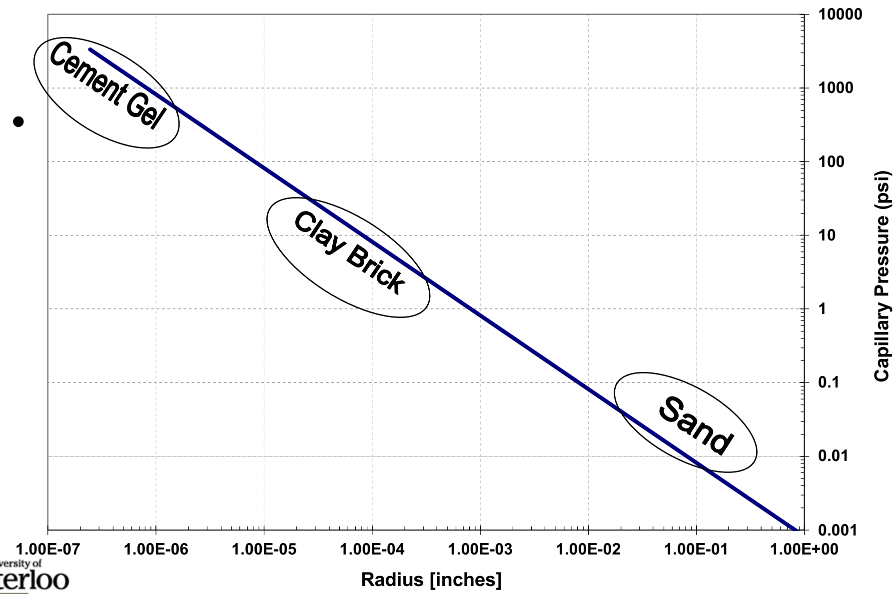

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Solutions to Capillary Wicking

- Back primed = plug the holes
- Plug the micro-holes
  - Need to coat and fill all micropores
  - Layer of non-porous materials
    - Metal, plastic
- Hydrophobic:
  Make surface repellent
  - Water beads up
    - Tyvek
  - Permeable paint back-prime sid
    - Resist water allow vapor

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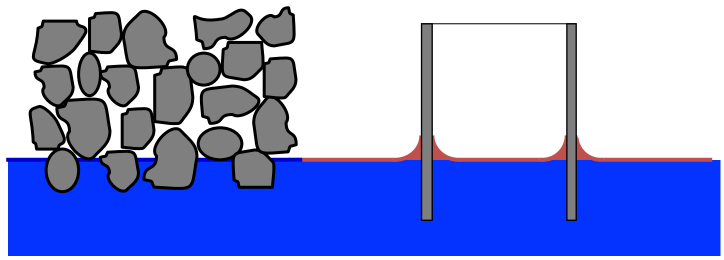
Capillary Flow

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



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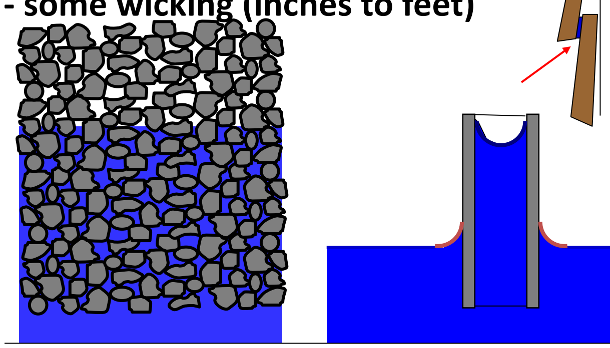
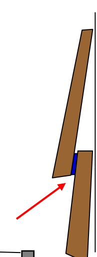
Capillary Flow

Example: Sand, siding laps
Smaller pores
- some wicking (inches to feet)





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Head Joints – capillary crack

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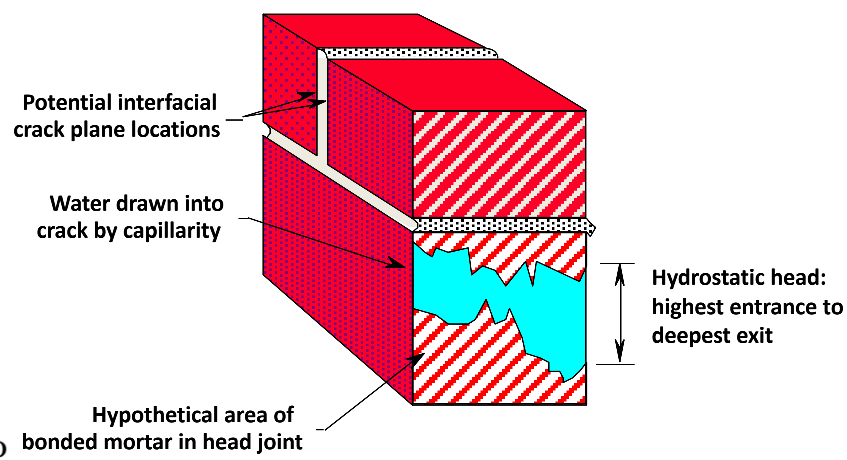
Water Penetration Mechanism



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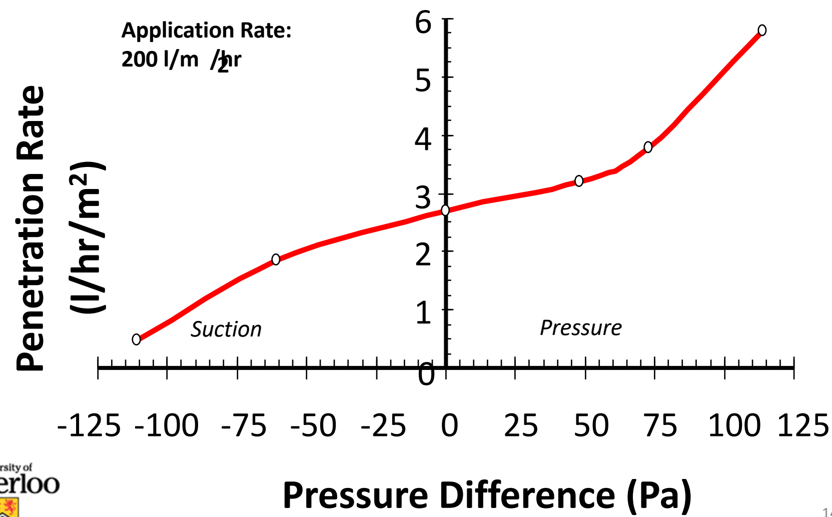
Pressure and Masonry Permeance



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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

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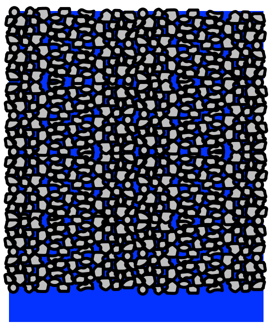
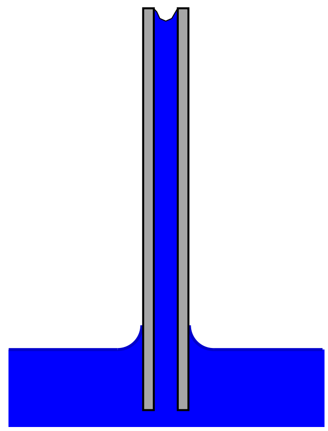
Capillary Flow- concrete sucks

Example: Clay or silt

Wicking (dozens - hundreds of ft)





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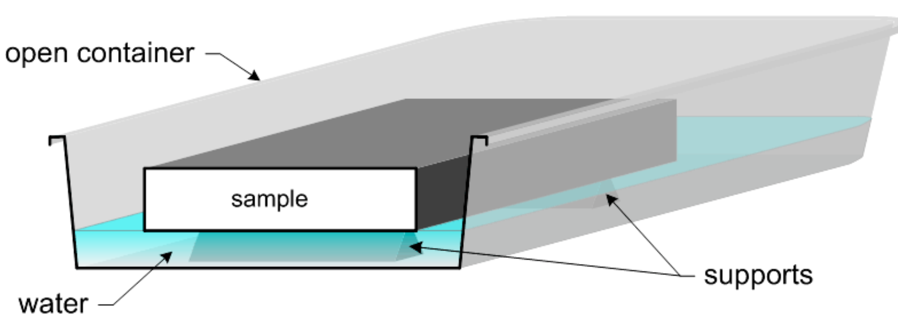
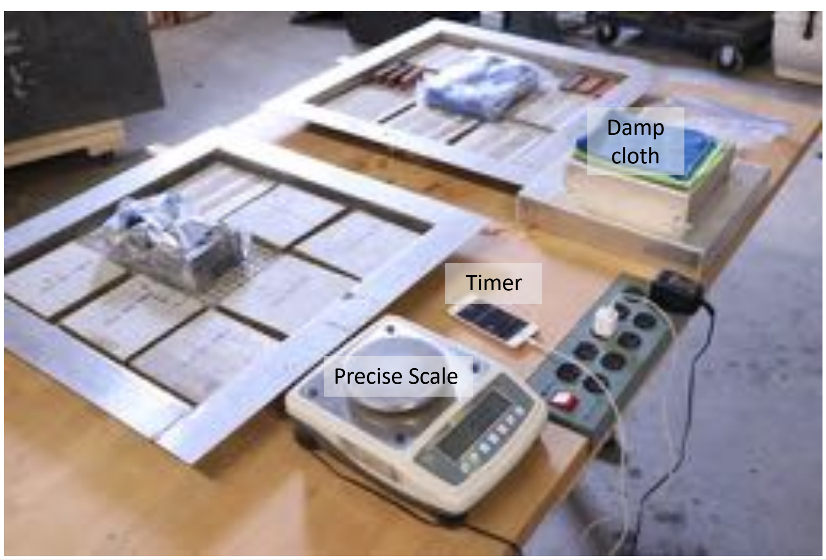
Liquid Transport Coefficients

- Measure water absorption coefficient (A-value) by water uptake test

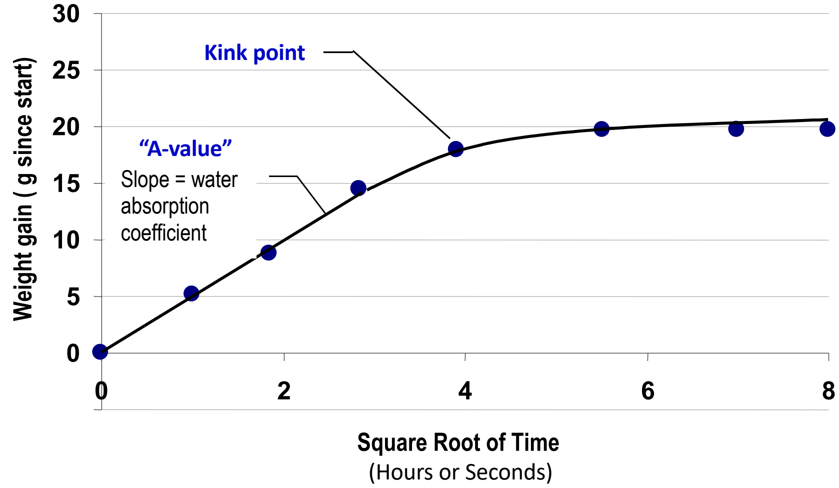


Maintain water level at the surface of the sample +3/-0 mm

Laboratory Test

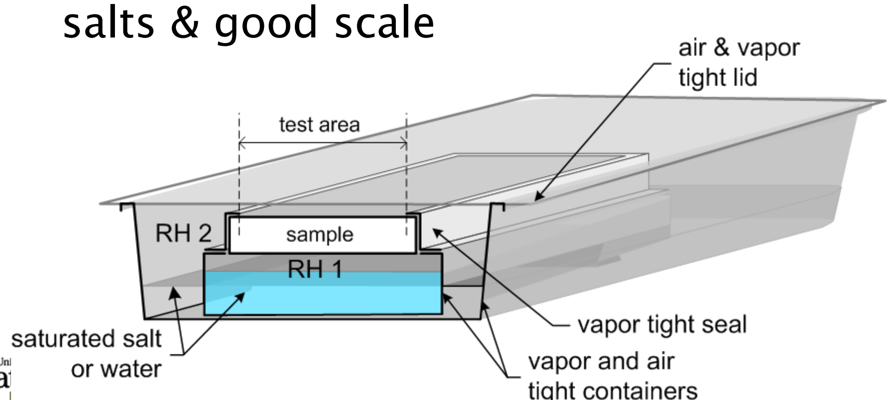


Analyzing results



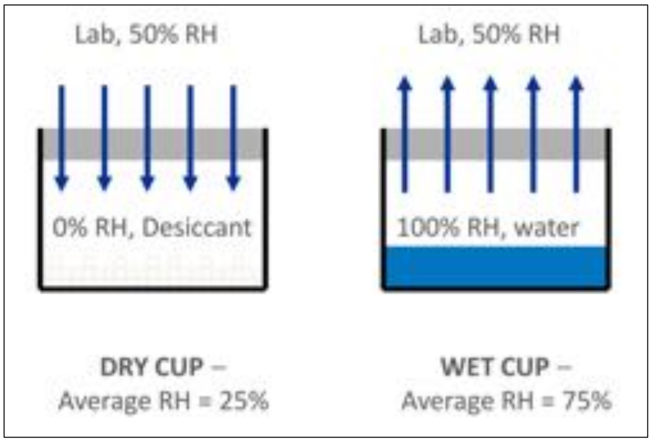
Vapor Permeability

- Using high-stability Humidity Chambers or cup method with special salts & good scale



Vapor permeance ASTM Testing

- ASTM E96: Wet cup, dry cup

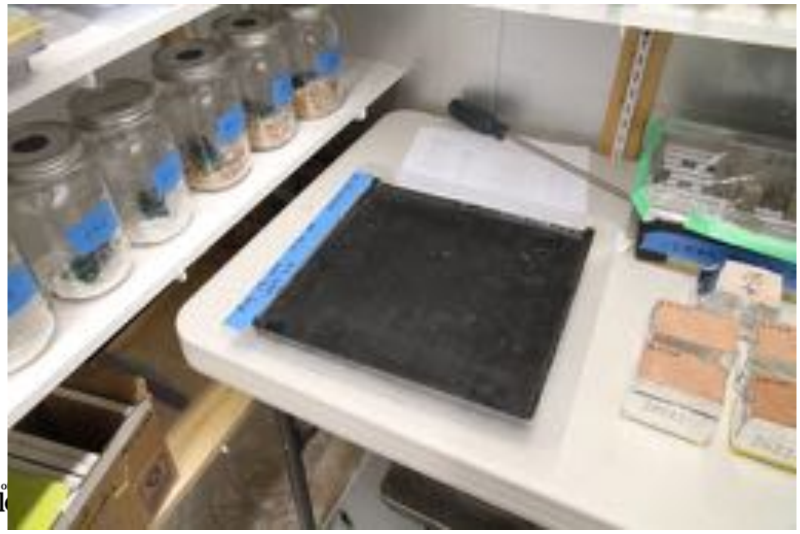


Vapour Permeance

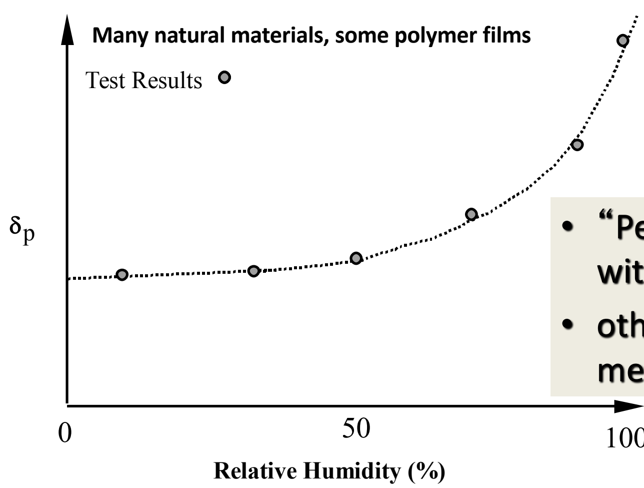
Dry Cup **Wet Cup**

Room filled with permeance samples @50%RH

Quality Control

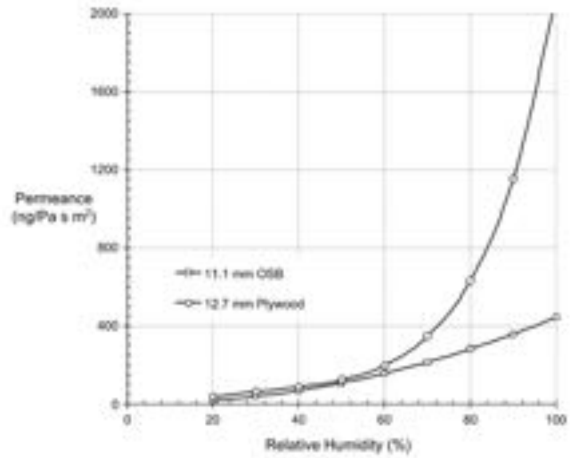


Vapour Permeance vs RH



- “Permeance” changes with RH
- other transport mechanisms as work

Wood products



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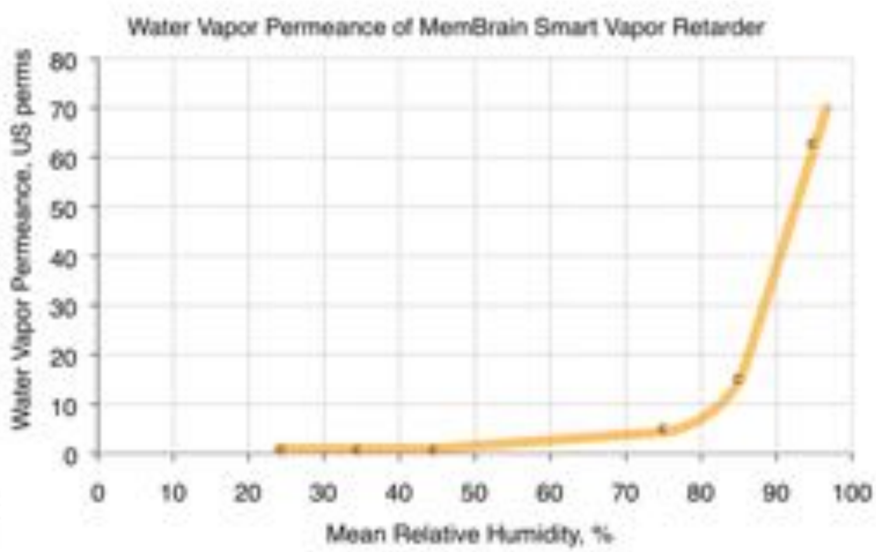
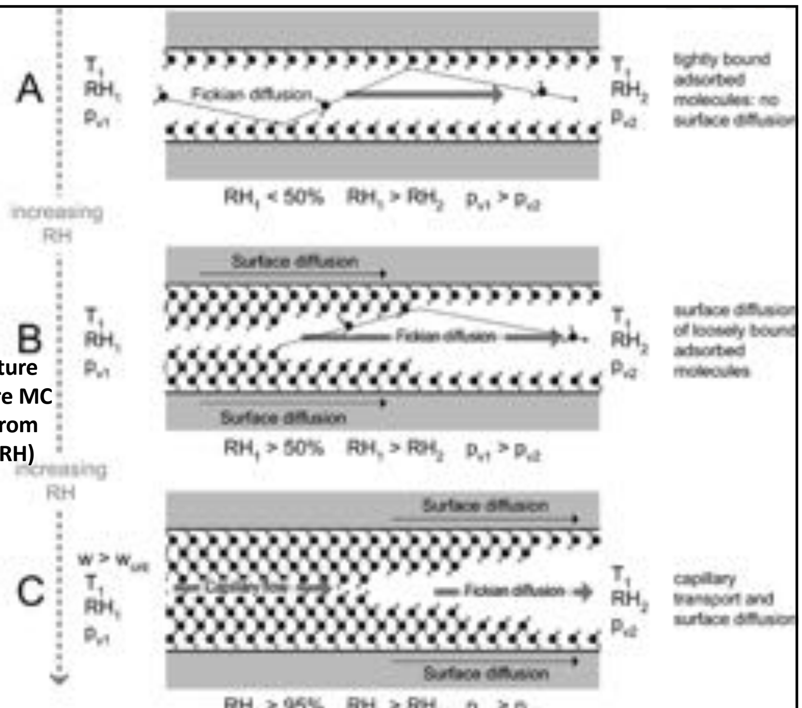
Smart Membranes



Adsorbed Flow

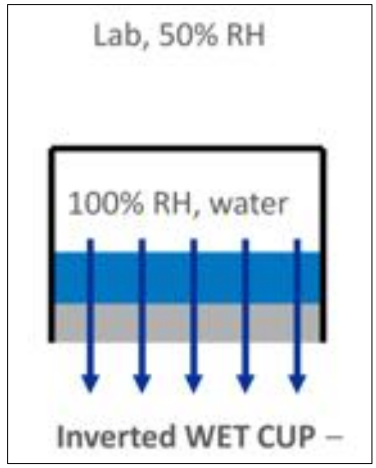
- Also called surface diffusion
- Driven by *RH* differences!
- Affects highly porous, especially fibrous natural materials



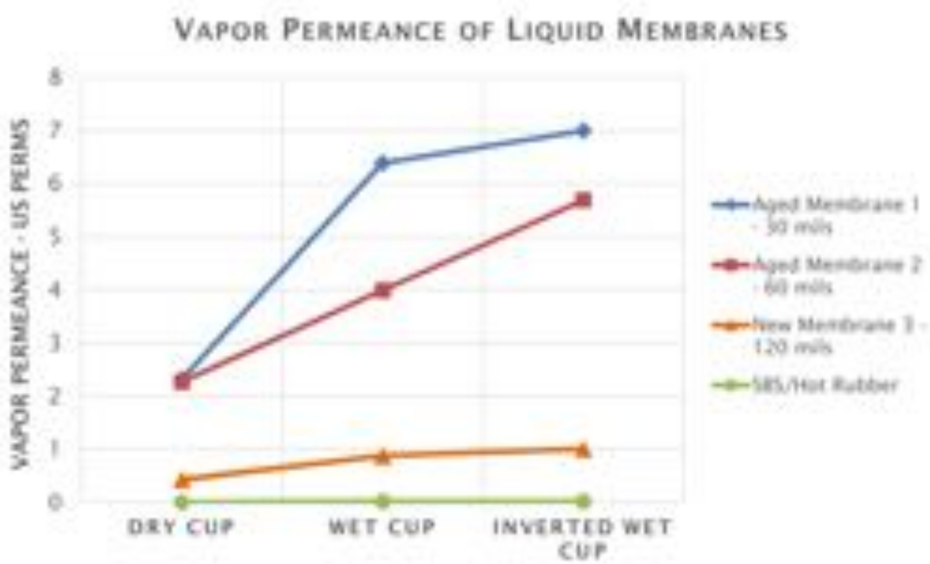
Adsorbed moisture flows from more MC to less MC (or from high RH to low RH)

Combined Flow ASTM Testing

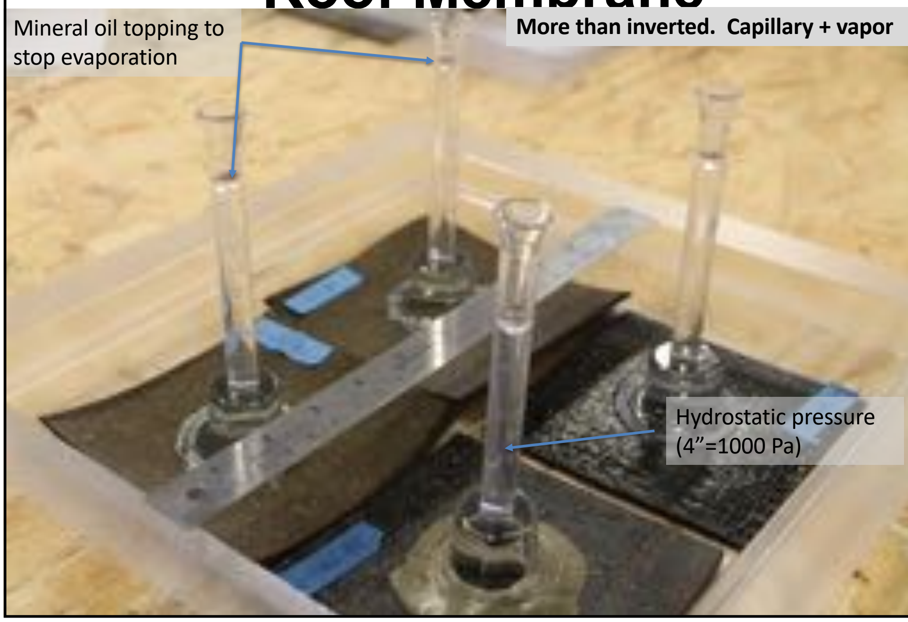
- Extends Vapor permeance test
- ASTM E96
  Inverted wet cup



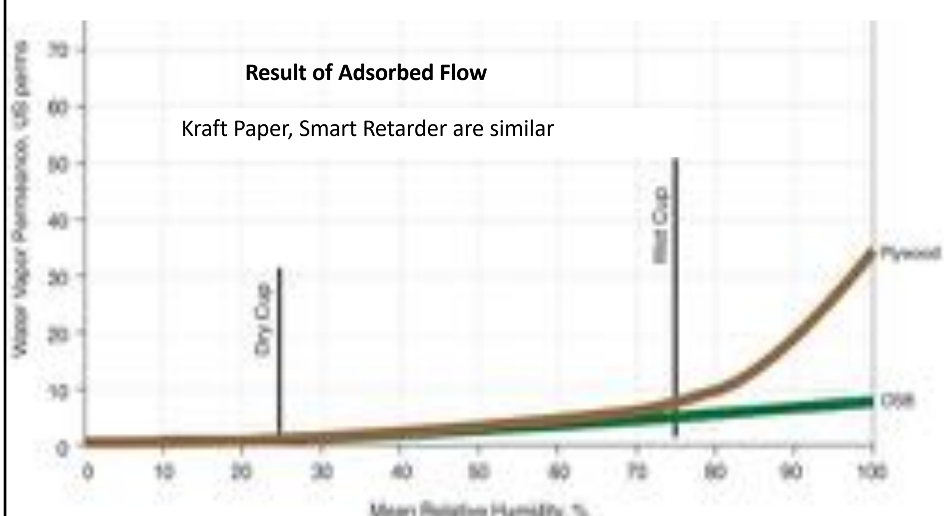
Measured waterproofing membranes



Roof Membrane



Adsorbed flow along RH gradient



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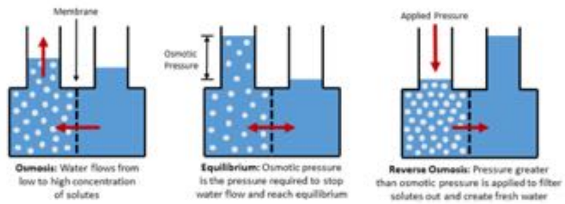
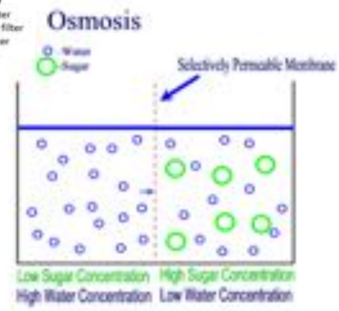
Osmosis

- Not *that* common an issue



Shown to be a problem with some waterproofing membranes.
See Finch at RDH



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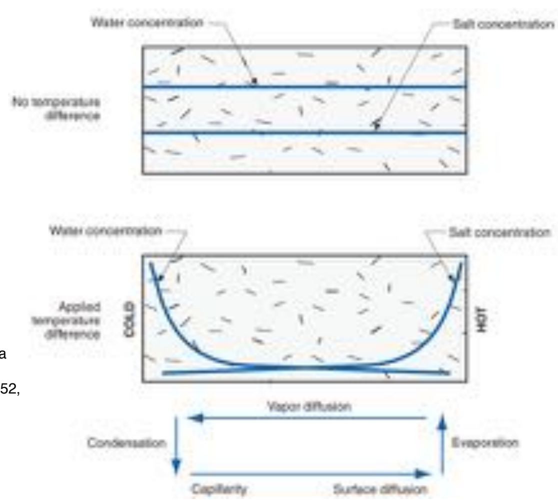
Combined Competing Flow

- Paxton & Hutcheon DBR/NRCC



J. A. Paxton and N. B. Hutcheon, ,,Moisture Migration in a Closed Guarded Hot Plate," *Transactions*, American Society of Heating and Ventilating Engineers, Vol. 58, 1952, pp. 301-320.

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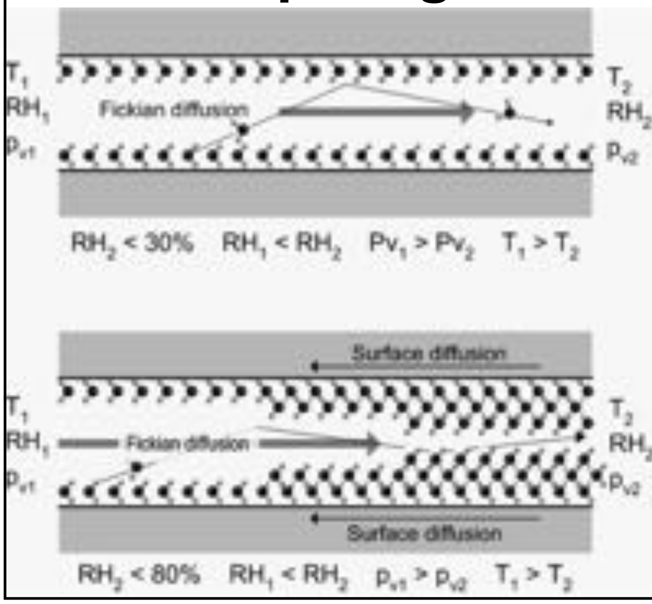
Competing Mechanisms



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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Conclusions

- Moisture is worth understanding
  - Small, sticky
- Porous materials are common… and much more porous than you think