Moisture Physics

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BEG
Building Engineering Group

Building Enclosure Performance

- Problems
  - many relate to moisture!
  - Cracking, heat loss etc are also important
- Common "Causes" - Design error
- Moisture Sources
  - Rain, ground, water vapor in air
- Solutions
  - case specific
  - But … fundamentals are general

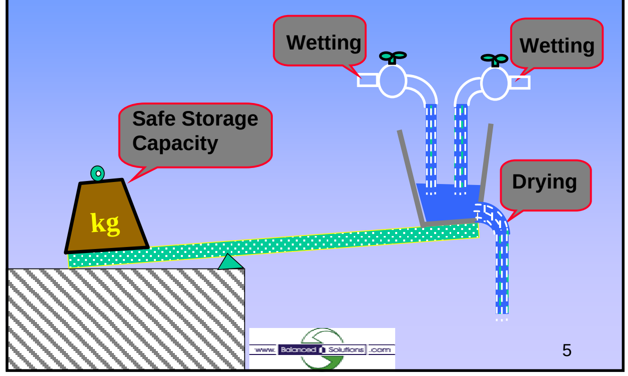
Moisture and Buildings

- Moisture is involved in almost all building enclosure performance problems
  - In-service .... Durability
- Examples:
  - rot,
  - corrosion,
  - mould (IAQ)
  - termites, (!),
  - staining
  - shrinkage/swelling
  - etc.

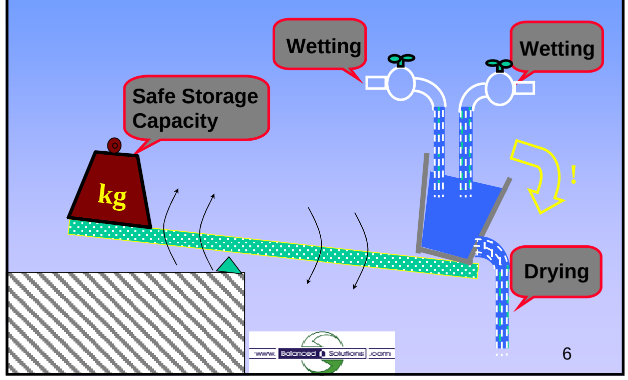
Moisture Control

- Moisture-related Problems
  1. *Moisture* must be available
  2. There must be a *route* or *path*
  3. There must be a *force* to cause movement
  4. The material must be *susceptible* to damage
- Theory: eliminate *any one* for complete control
- Practise: control *as many as possible*

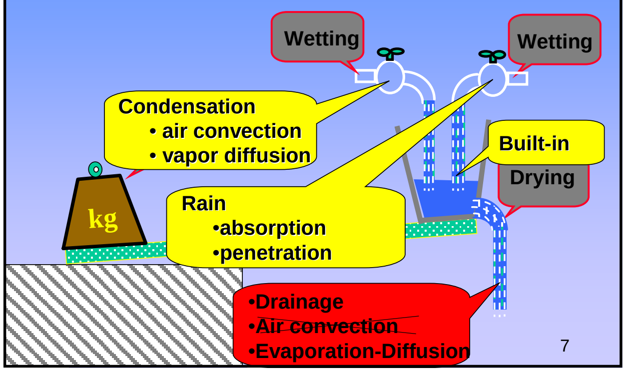
Moisture Balance



Moisture Balance

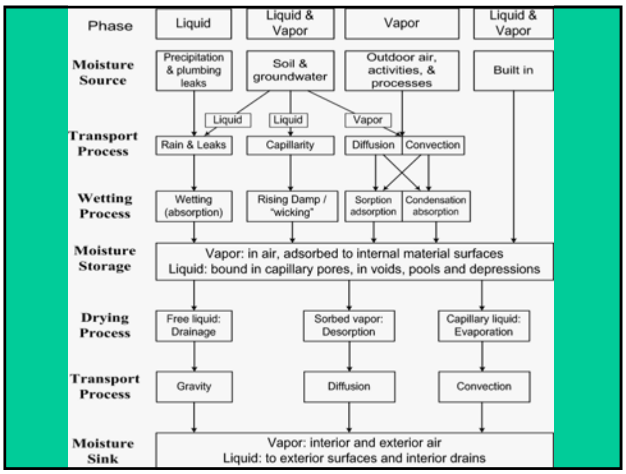


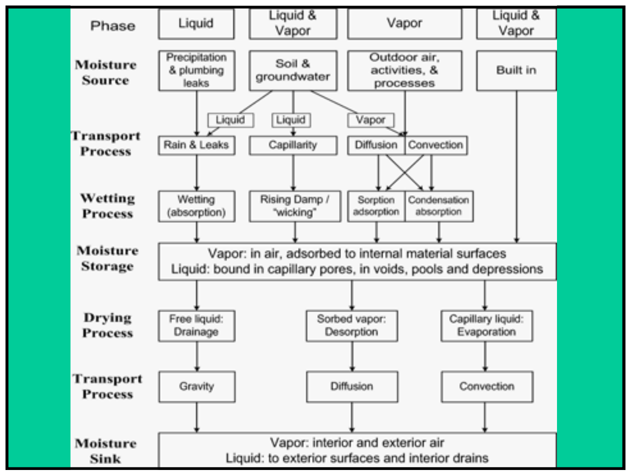
Moisture Balance



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



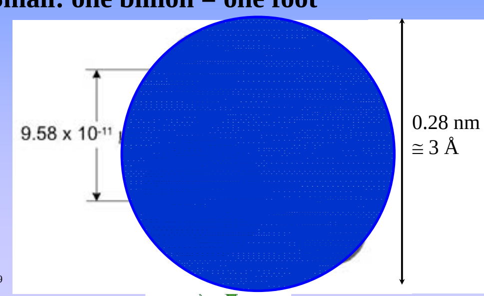


Overview

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

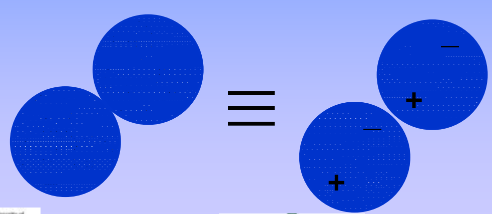
The Water Molecule

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



The Polar Molecule

- Hydrogen end is “more” positive
- Oxygen end is “more” negative

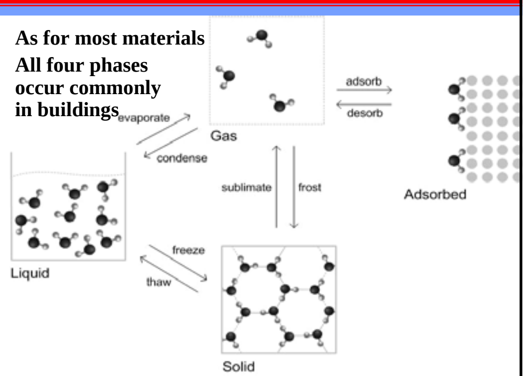


Polar Implications

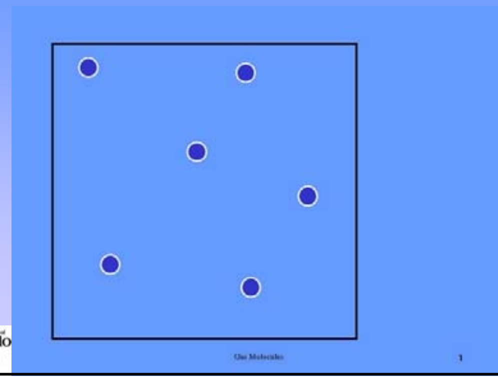
- Boiling point
  - higher than predicted
- Adsorption
  - water vapour sticks to surfaces
- Surface tension
  - liquid water sticks to itself and surfaces
- Surfactants
  - interact with water at surfaces

Moisture Phases

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



Moisture as a Gas (water vapor)

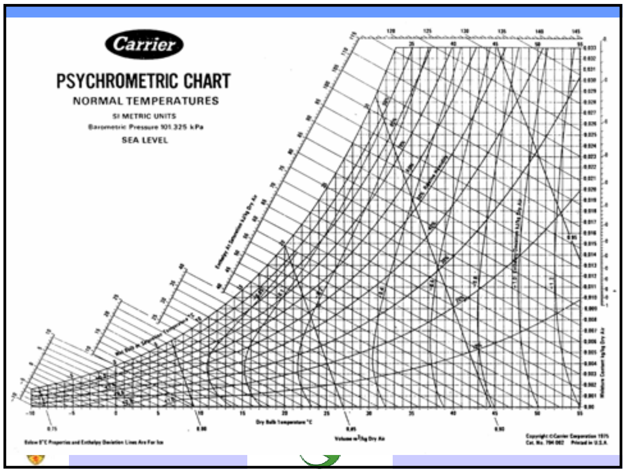


Vapour Pressure

- 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

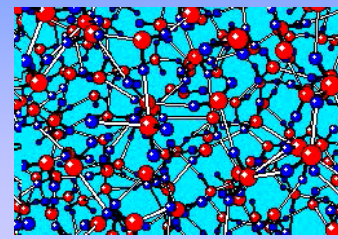
Water Vapour in Air

- 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

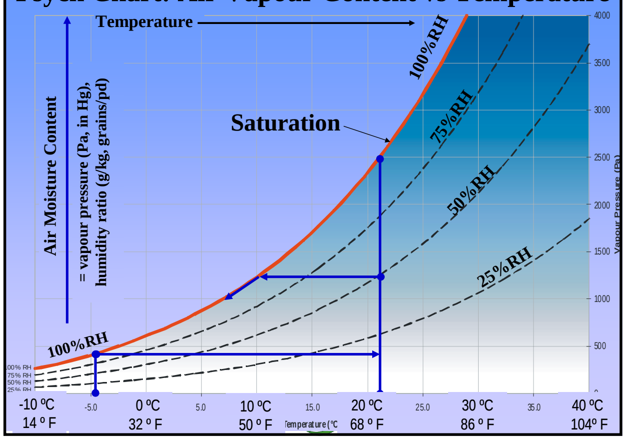


Vibrating Liquid Water

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



Psych Chart: Air Vapour Content vs Temperature

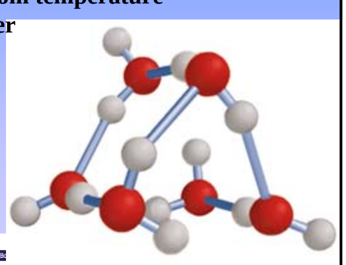


Moisture as Liquid

- 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

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

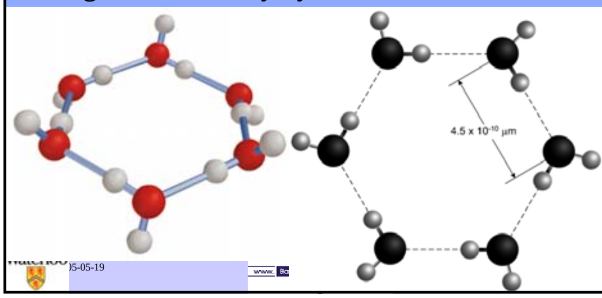


Moisture as a Solid

Canadian moisture jokes

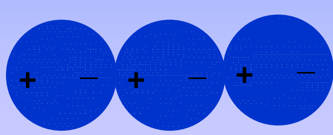
Ice : Moisture as Solid

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

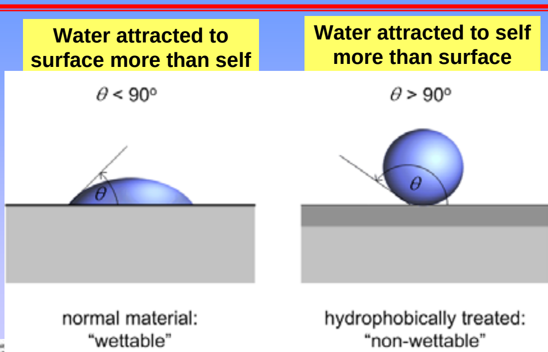


Surface Tension

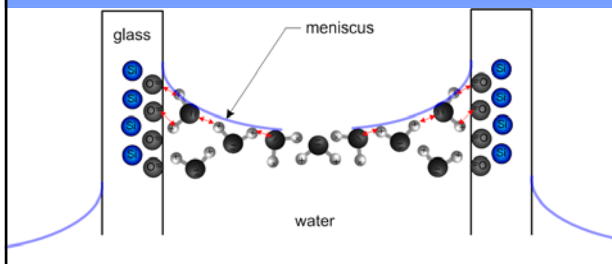
- Water is attracted to self
- Creates a “membrane” or “surface film”



Surface Tension: Wettable



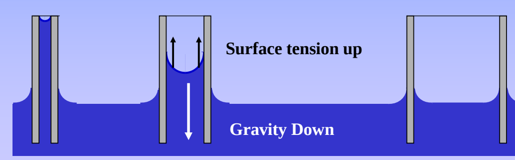
Capillary Suction Pressure



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

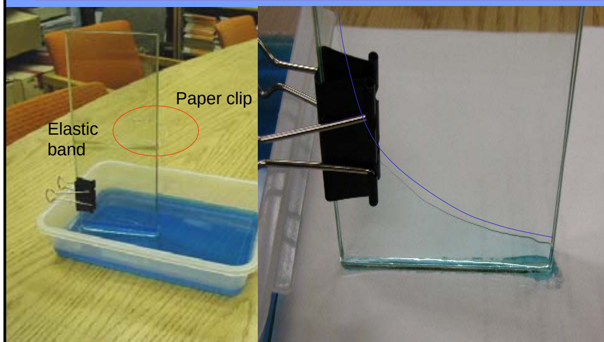
Capillary Pressures

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

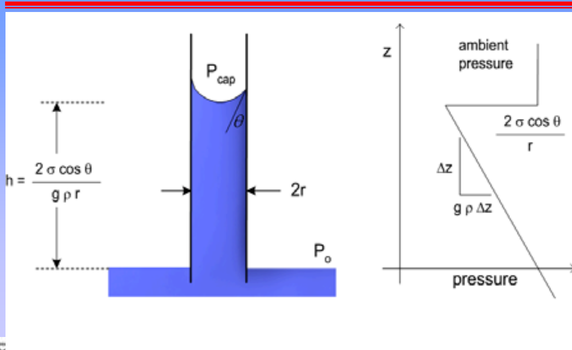


Surface Tension

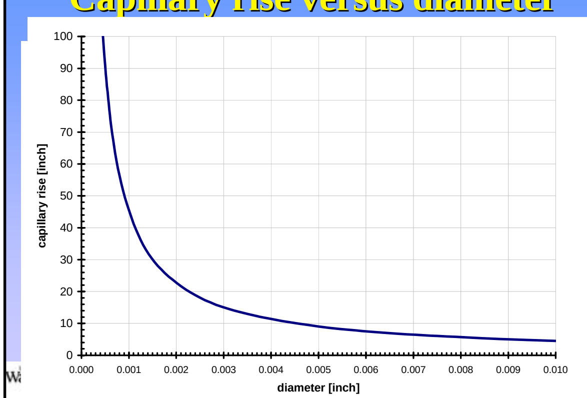
Capillary rise between plates



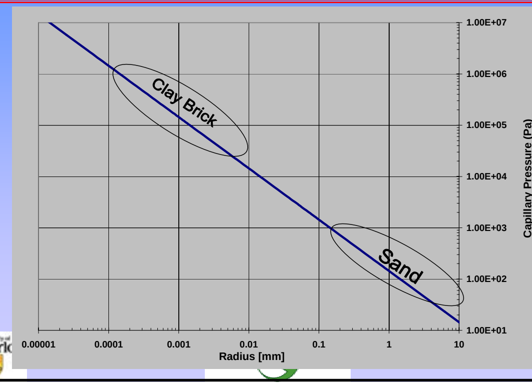
Calculating capillary rise



Capillary rise versus diameter



Particle Size vs Capillary Suction



Surfactants

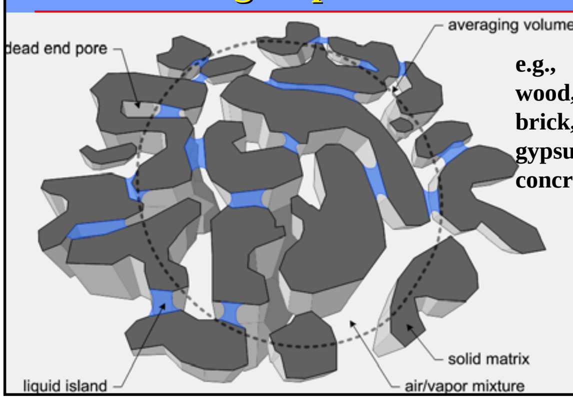
- Changes the way water molecules interact with surfaces
  - dramatically reduces surface tension
- Soap is a surfactant
  - connects water to grease
  - one end is polar
  - one end is non-polar (sticks to oil and grease)

Soap and Water

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

Slice through a porous material



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

Real Materials

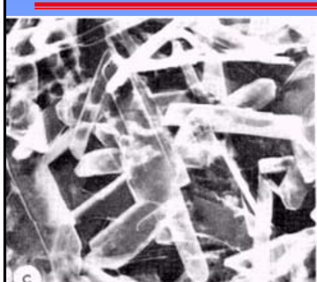


Figure 1c. Gypsum, hydrated from plaster of paris and water, porosity 30 per cent.

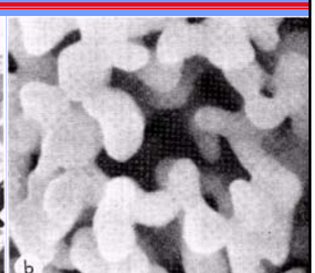
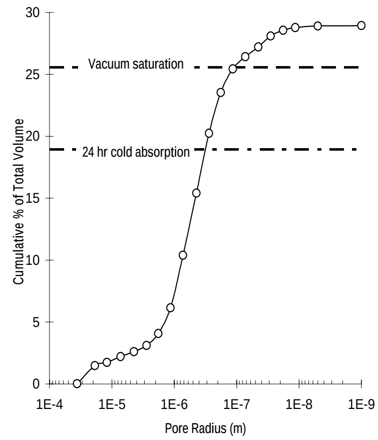


Figure 1b. Brick, sintered clay, porosity 40 per cent.

Clay Brick



Mercury porosimetry

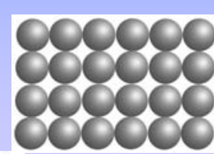
Pressure plate

Brick Sucks!

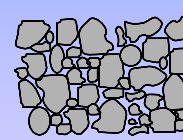
Simple Models

Simple → **Reality**

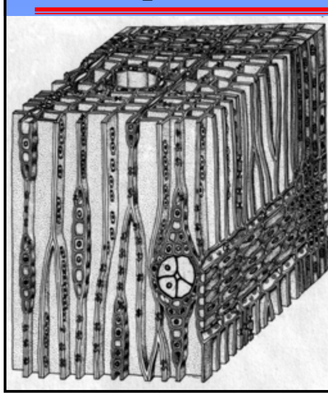
Cubic packing of spherical particles



Random particles size and packing



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

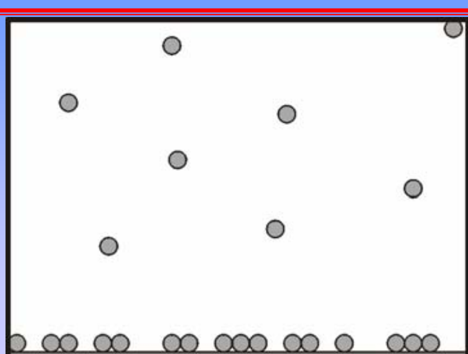
Storage Mechanisms

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

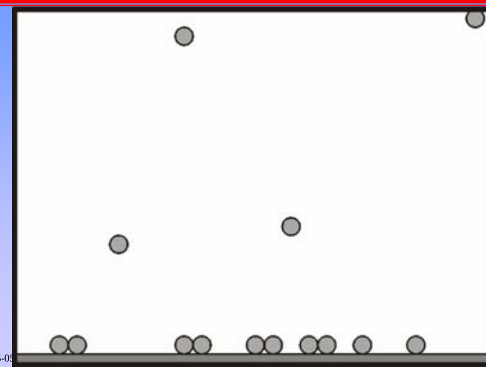
Adsorbed State of Moisture

- 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

Adsorbed Moisture

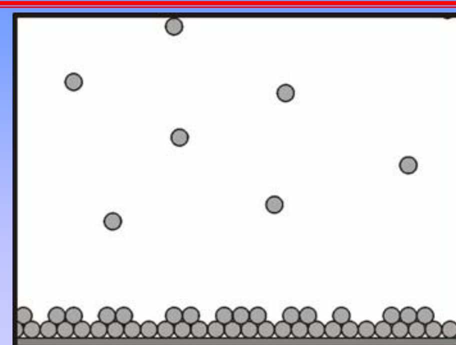


Adsorption Lower RH



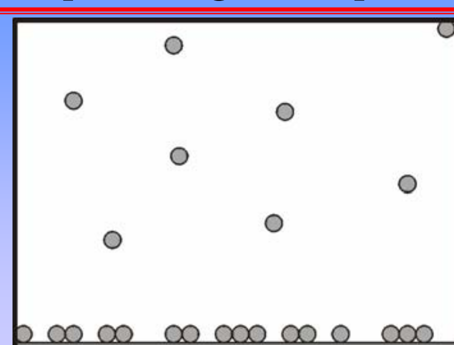
Adsorption higher RH

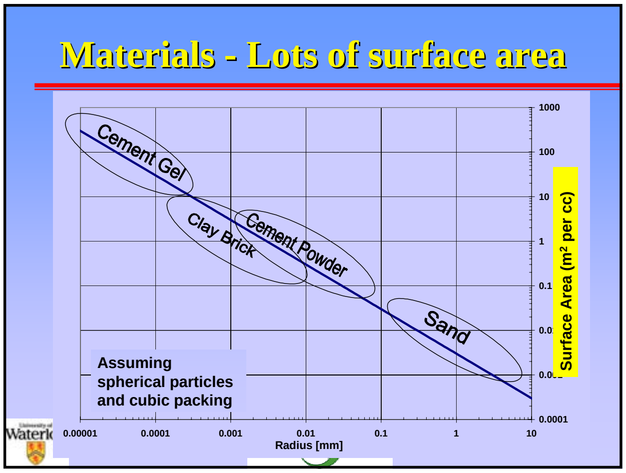
More H20 sticks

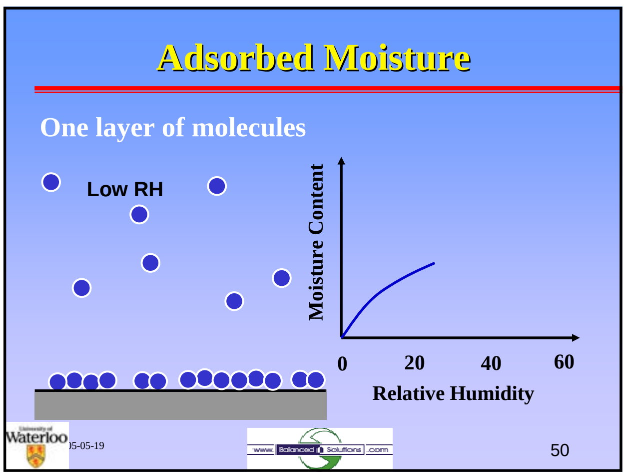


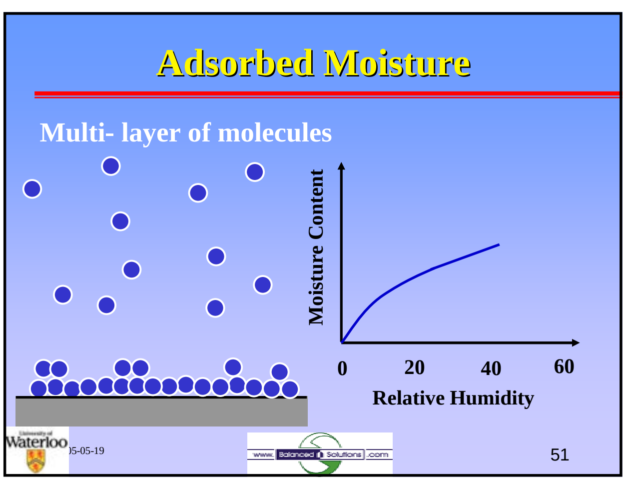
Adsorption - higher temperature

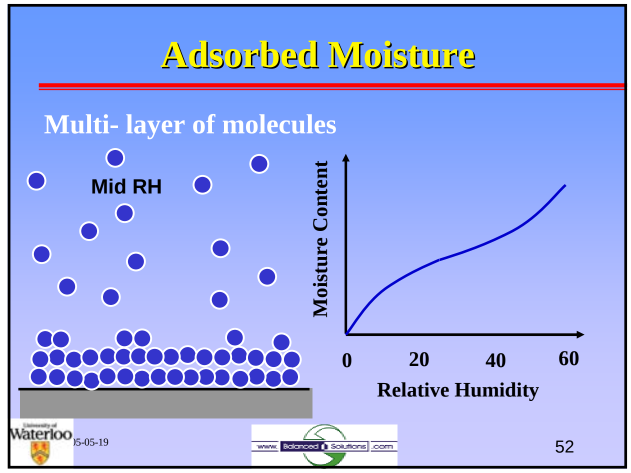
Higher Energy Less H20 sticks

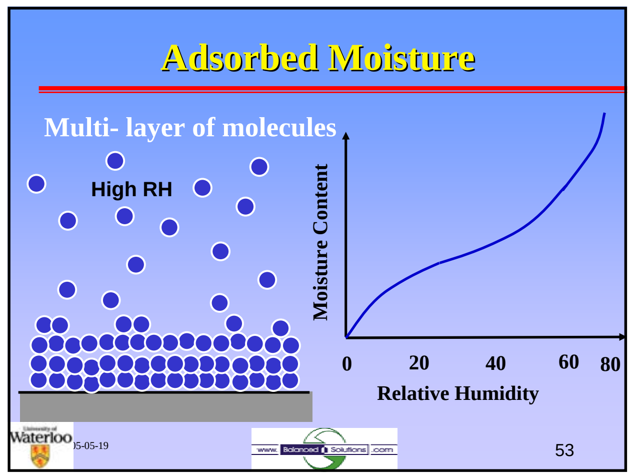


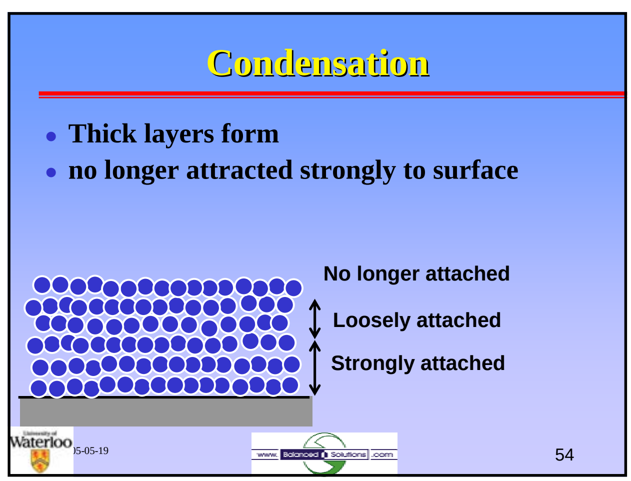

Materials - Lots of surface area
Cement Gel
Clay Brick
Cement Powder
Sand
Assuming spherical particles and cubic packing
Surface Area (m² per cc)
Radius [mm]
0.00001
0.0001
0.001
0.01
0.1
1
10
1000
100
10
1
0.1
0.0001

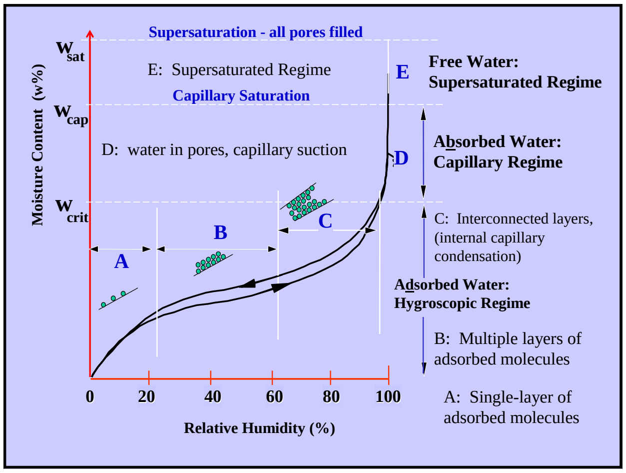

Adsorbed Moisture
One layer of molecules
Low RH
Moisture Content
0
20
40
60
Relative Humidity
50

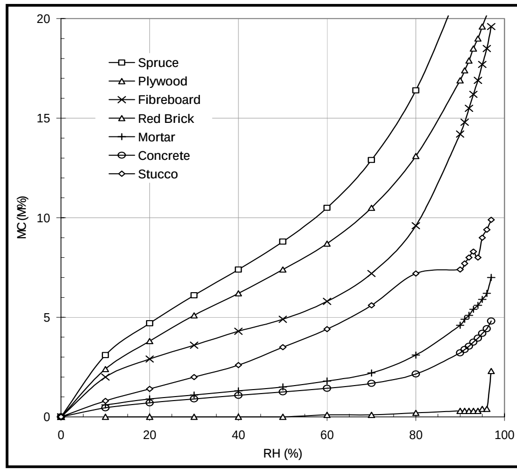

Adsorbed Moisture
Multi- layer of molecules
Moisture Content
0
20
40
60
Relative Humidity
51


Adsorbed Moisture
Multi- layer of molecules
Mid RH
Moisture Content
0
20
40
60
Relative Humidity
52


Adsorbed Moisture
Multi- layer of molecules
High RH
Moisture Content
0
20
40
60
80
Relative Humidity
53


Condensation
• Thick layers form
• no longer attracted strongly to surface
No longer attached
Loosely attached
Strongly attached
54





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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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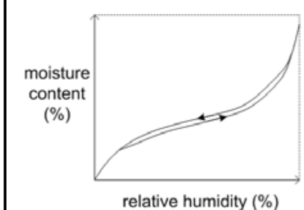
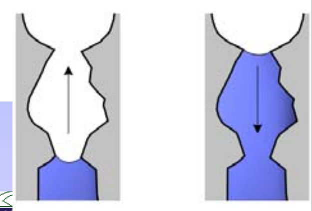
Hysteresis of Sorption

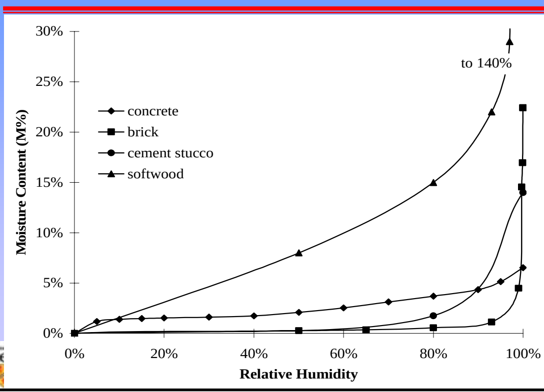


- Ink Bottle effect



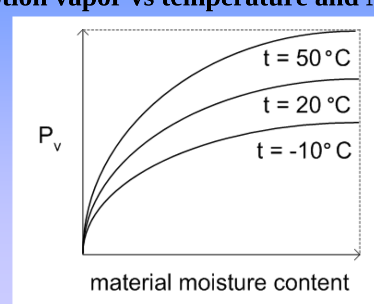
wetting drying

Sorption



Sorption vs Temperature

- Sorption vapor vs temperature and MC



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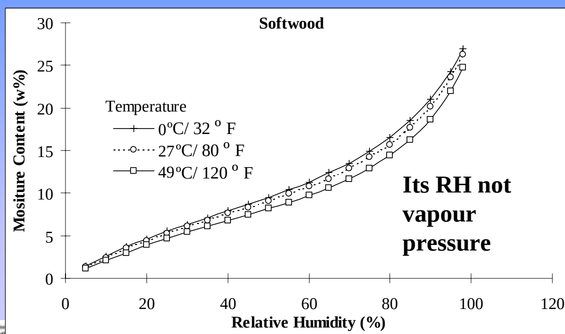
Temperature Effects



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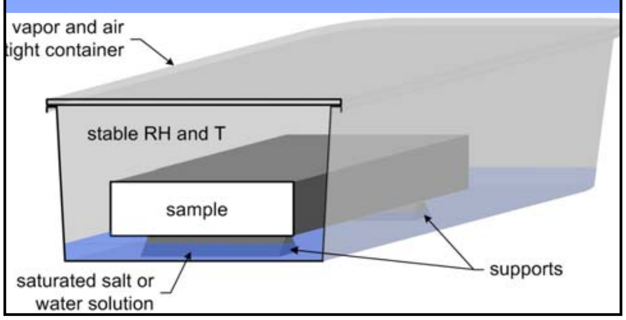
Sorption test

- 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

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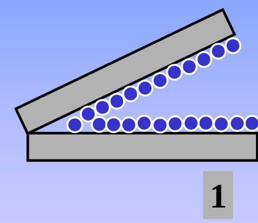
Swelling



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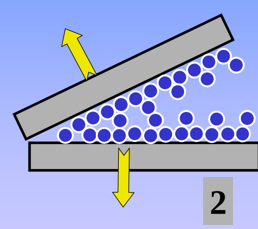
Swelling



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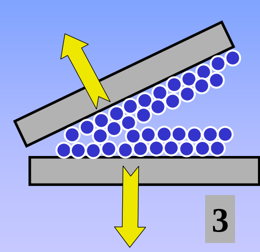
Swelling



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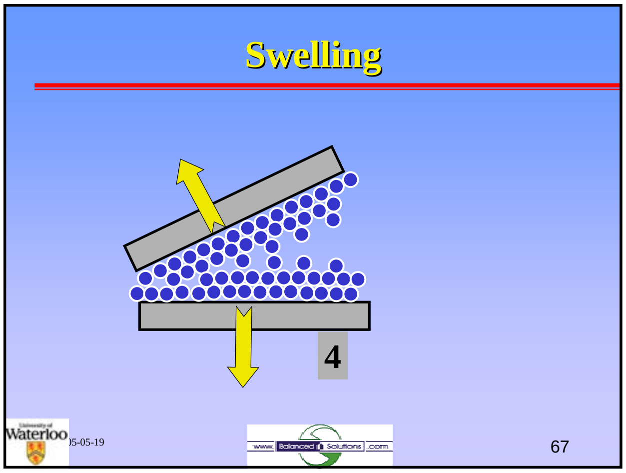
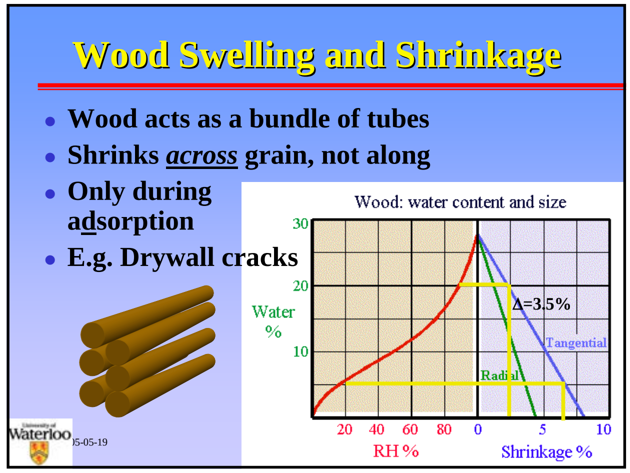
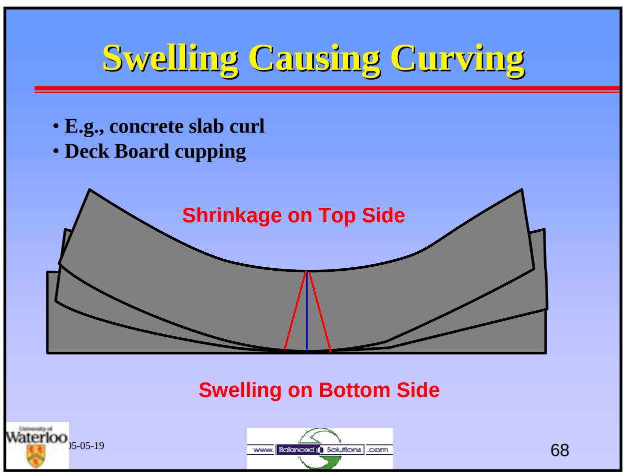
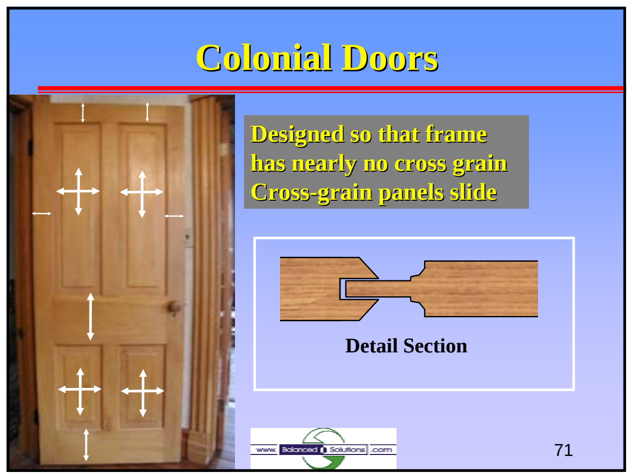

Swelling
4
Waterloo
05-05-19
www. Balanced Solutions .com
67


Wood Swelling and Shrinkage
• Wood acts as a bundle of tubes
• Shrinks *across* grain, not along
• Only during adsorption
• E.g. Drywall cracks
Wood: water content and size
Water %
30
20
10
Δ=3.5%
Tangential
Radial
20 40 60 80 0 5 10
RH %
Shrinkage %
Waterloo
05-05-19


Swelling Causing Curving
• E.g., concrete slab curl
• Deck Board cupping
Shrinkage on Top Side
Swelling on Bottom Side
Waterloo
05-05-19
www. Balanced Solutions .com
68


Colonial Doors
Designed so that frame has nearly no cross grain
Cross-grain panels slide
Detail Section
www. Balanced Solutions .com
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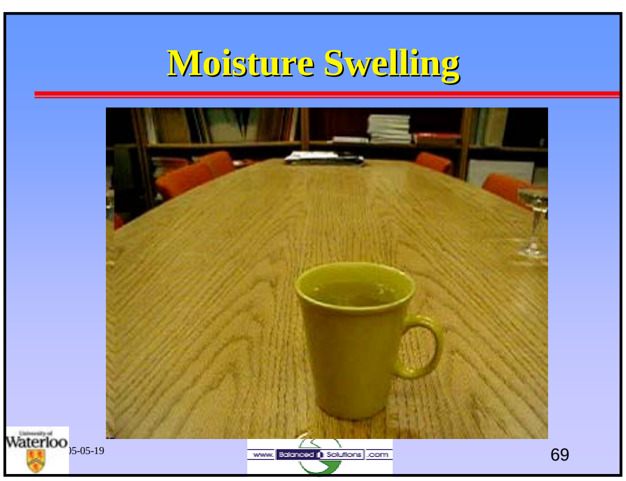
Moisture Swelling
Waterloo
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Wood expansion
Concrete Shrinkage
Frame Shrinkage
Stucco Shrinkage

73

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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Moisture Transport

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!) 2000 psi
- 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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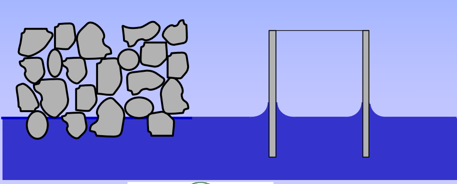
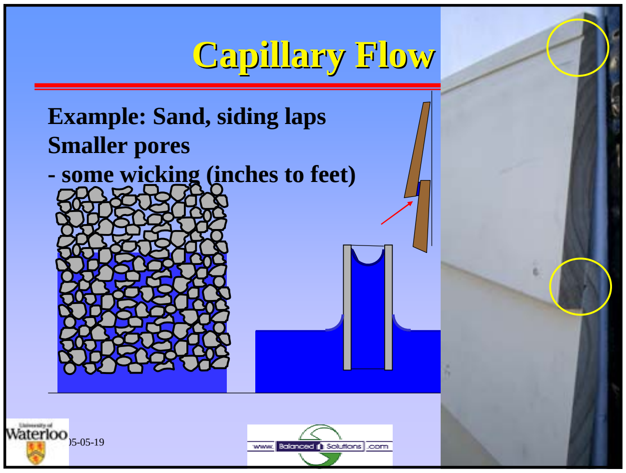
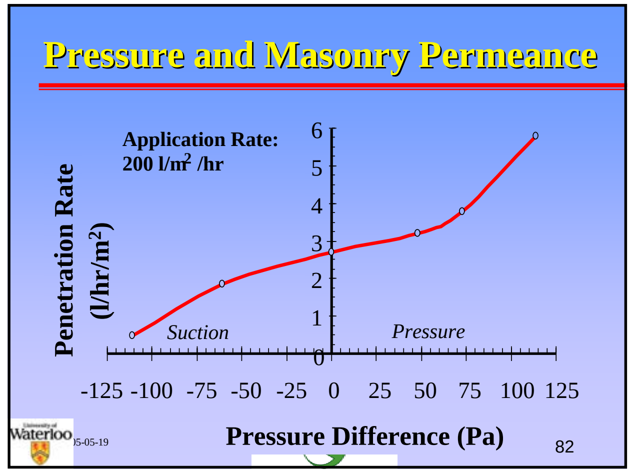
Capillary Flow

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

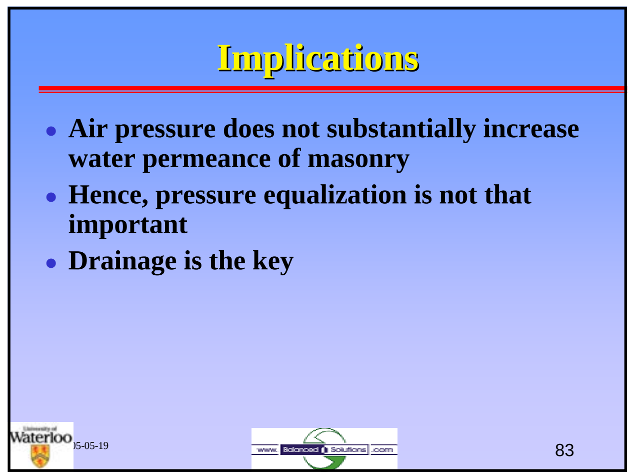


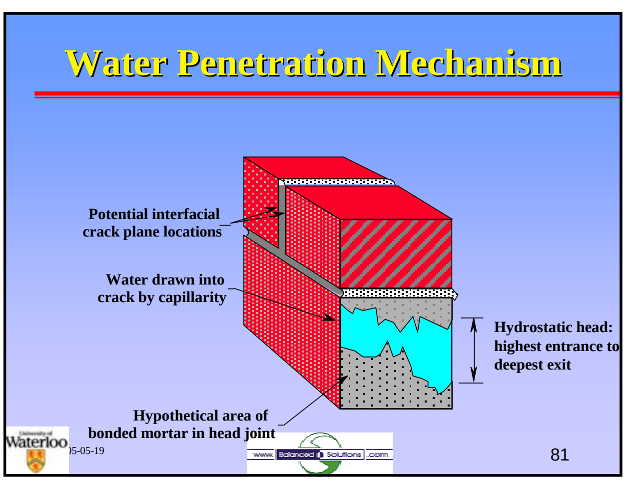
78

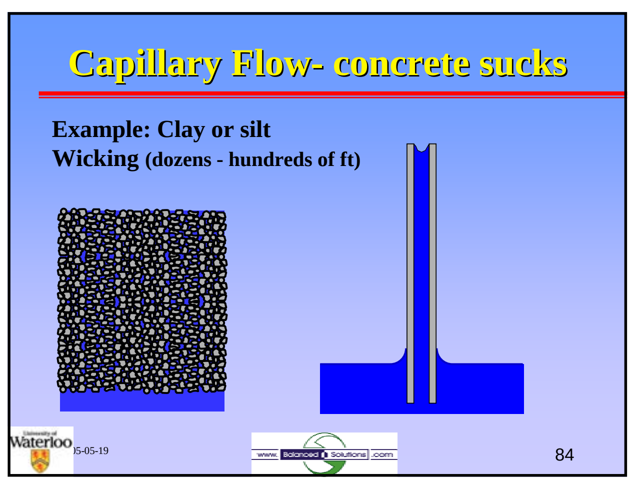

Capillary Flow
Example: Sand, siding laps
Smaller pores
- some wicking (inches to feet)

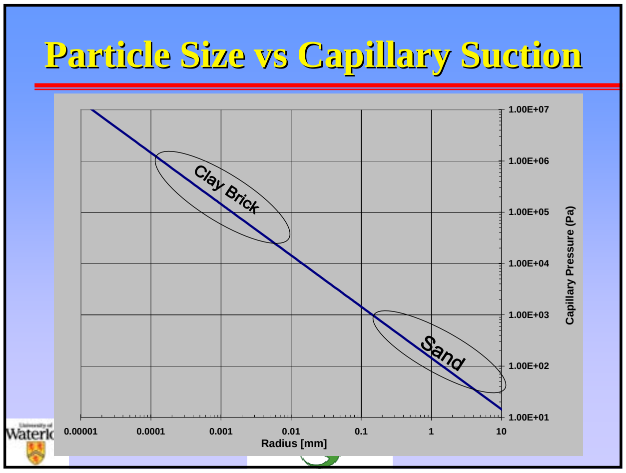

Pressure and Masonry Permeance
Application Rate:
200 l/m² /hr
Penetration Rate
(l/hr/m²)
Suction
Pressure
Pressure Difference (Pa)
82

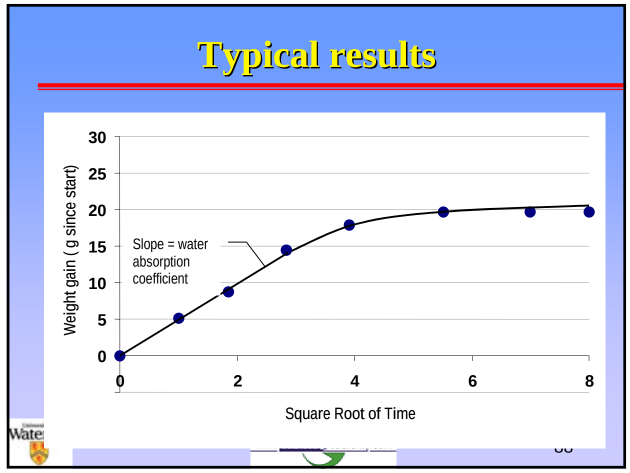

Head Joints – capillary crack

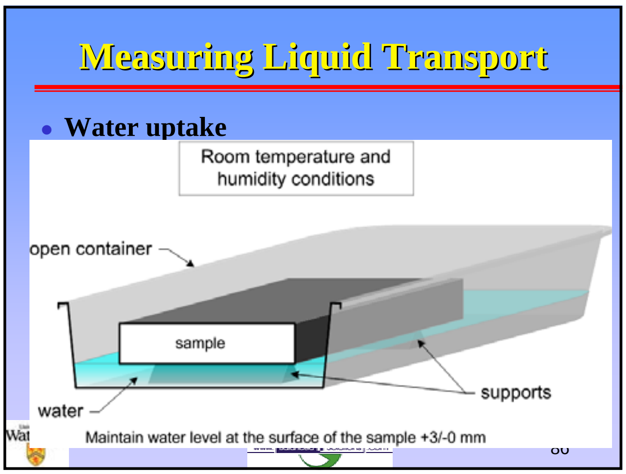

Implications
• Air pressure does not substantially increase water permeance of masonry
• Hence, pressure equalization is not that important
• Drainage is the key
83

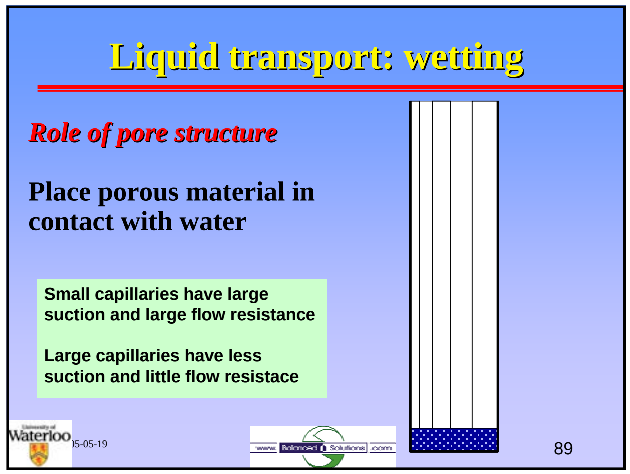

Water Penetration Mechanism
Potential interfacial crack plane locations
Water drawn into crack by capillarity
Hydrostatic head: highest entrance to deepest exit
Hypothetical area of bonded mortar in head joint
81

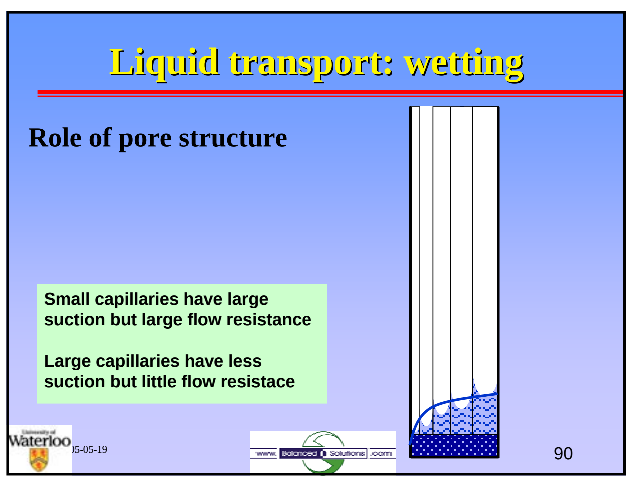

Capillary Flow- concrete sucks
Example: Clay or silt
Wicking (dozens - hundreds of ft)
84

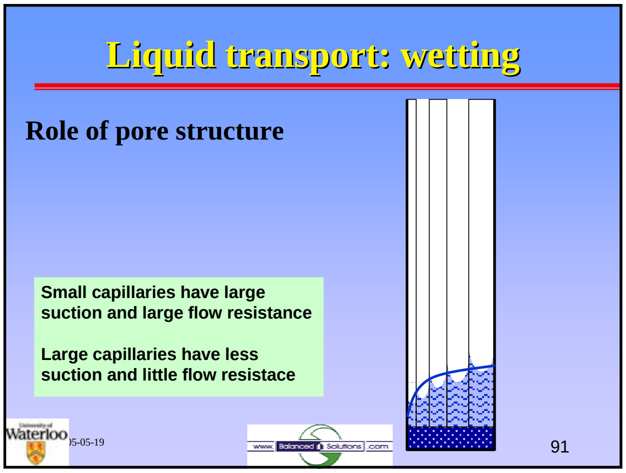

Particle Size vs Capillary Suction
Clay Brick
Sand
1.00E+07
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
Capillary Pressure (Pa)
0.00001
0.0001
0.001
0.01
0.1
1
10
Radius [mm]

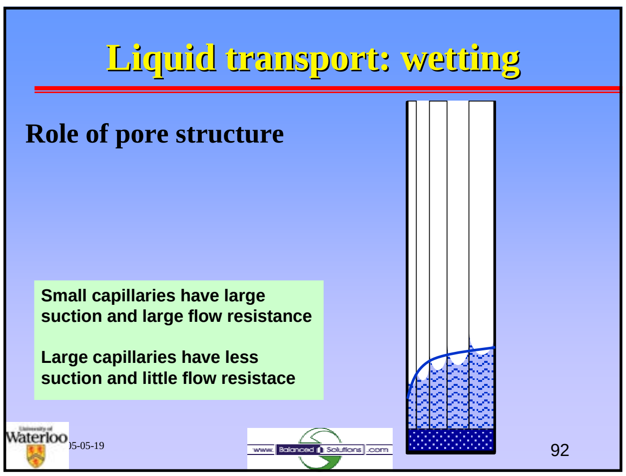

Typical results
Weight gain (g since start)
30
25
20
15
10
5
0
Slope = water absorption coefficient
0
2
4
6
8
Square Root of Time

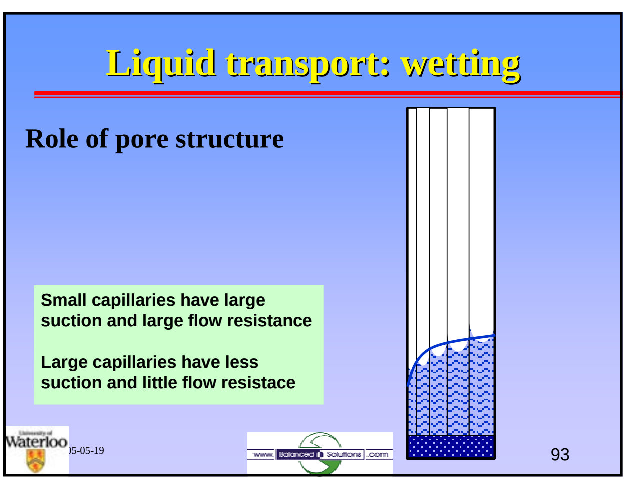

Measuring Liquid Transport
Water uptake
Room temperature and humidity conditions
open container
sample
supports
water
Maintain water level at the surface of the sample +3/-0 mm


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
89


Liquid transport: wetting
Role of pore structure
Small capillaries have large suction but large flow resistance
Large capillaries have less suction but little flow resistace
90


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
Waterloo
91


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
Waterloo
92


Liquid transport: wetting
Role of pore structure
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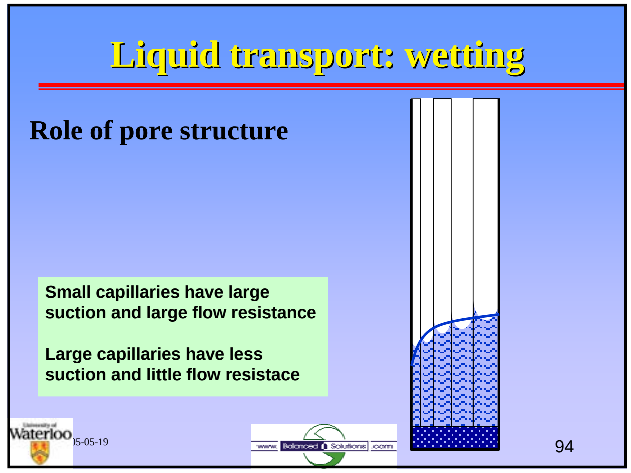
Large capillaries have less suction and little flow resistace
Waterloo
93


Liquid transport: wetting
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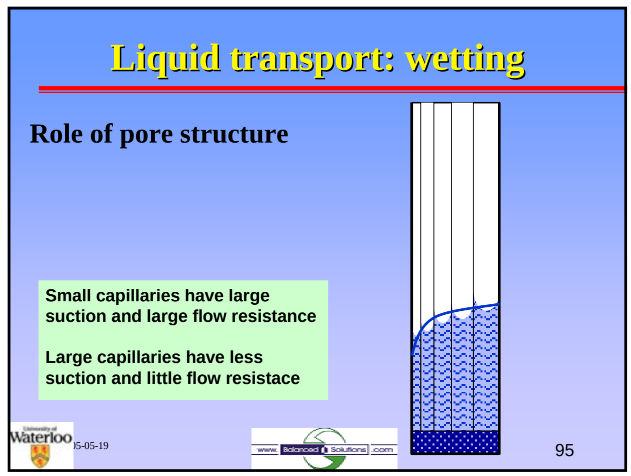
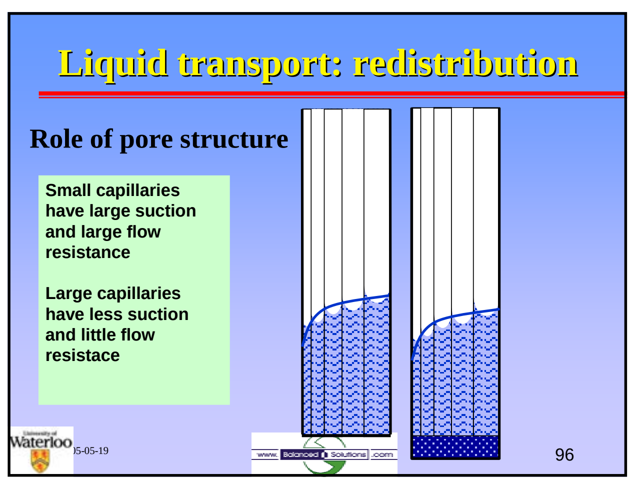
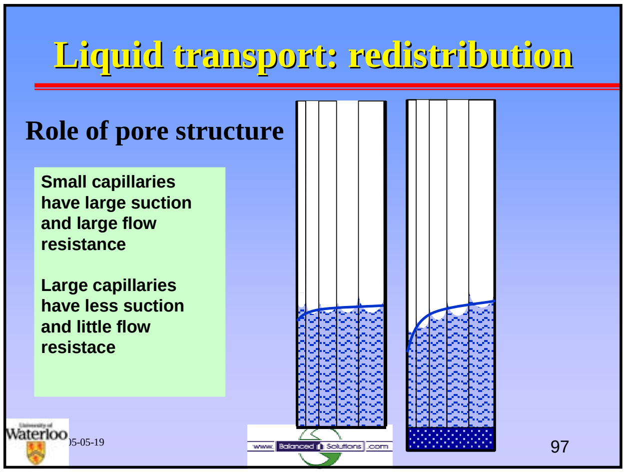
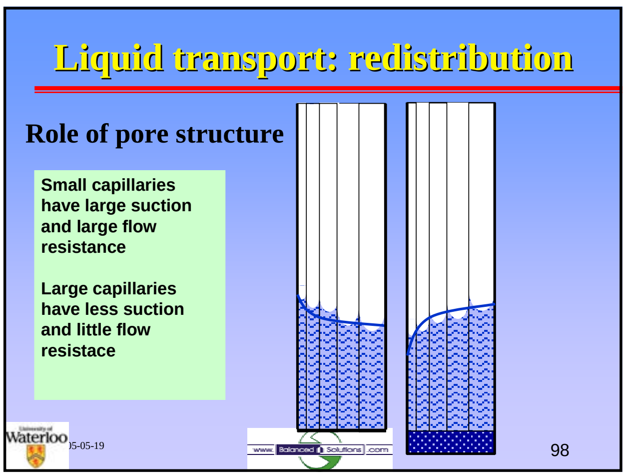
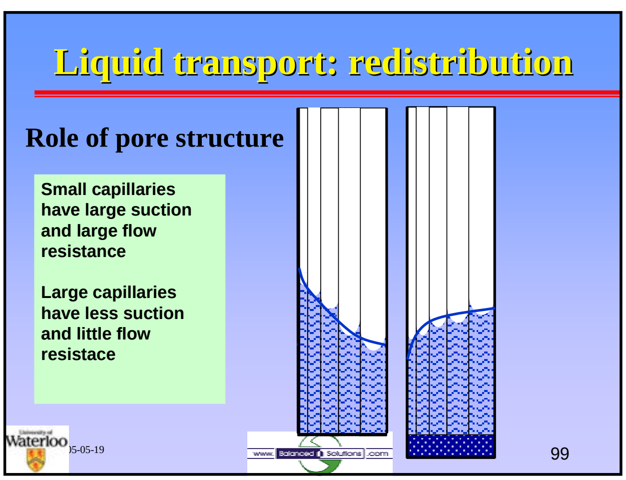
Waterloo
94


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
Waterloo
95


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
Waterloo
96


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
97


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
98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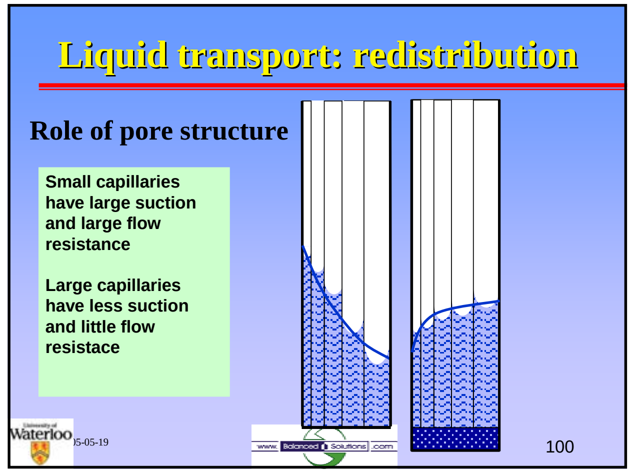
99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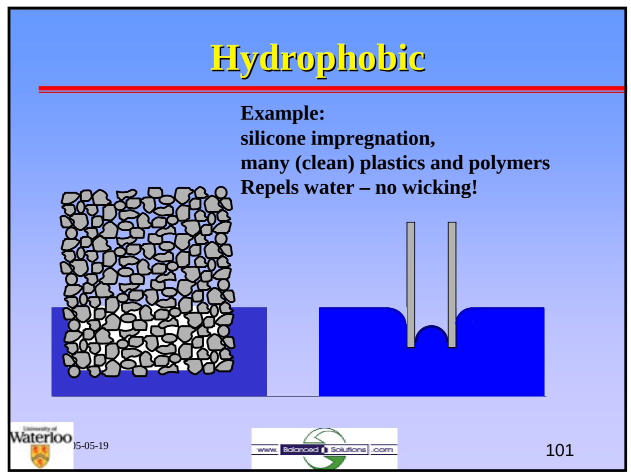
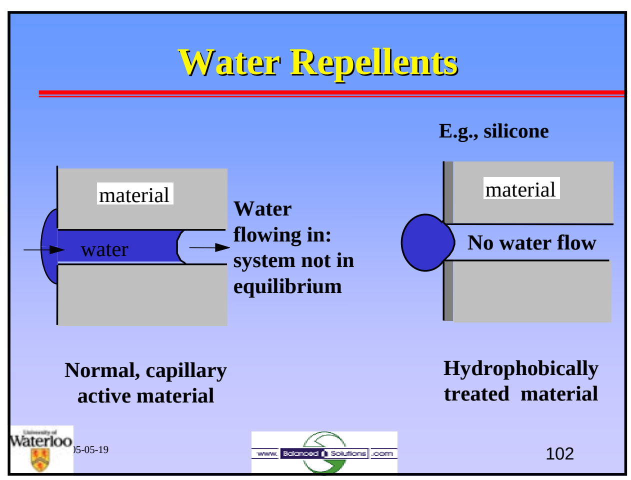

Hydrophobic
Example:
silicone impregnation,
many (clean) plastics and polymers
Repels water – no wicking!
101


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
102

Capillary break

- Either
  - no pores (glass, plastic, steel, etc.)
  - Large pores (say 1/16" , 3 mm)
  - Air gap (very small is enough)
  - hydrophobic

Water Vapour Transport

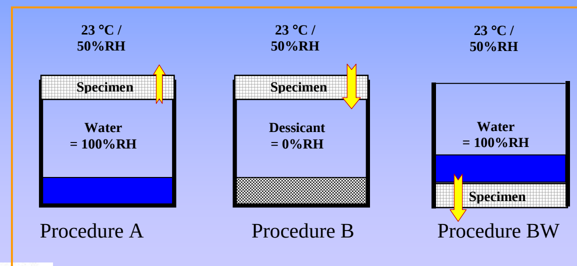
- **Vapour Diffusion** (like heat conduction)
  - more to less vapour
- **Air Convection** (like heat convection)
  - more to less air pressure
  - flow through cracks and holes
  - vapour is along for the ride

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

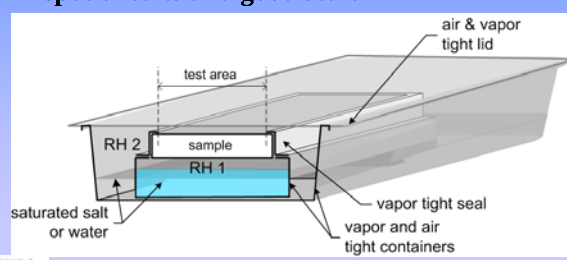
Vapour Permeability Measurement

- e.g. ASTM E96

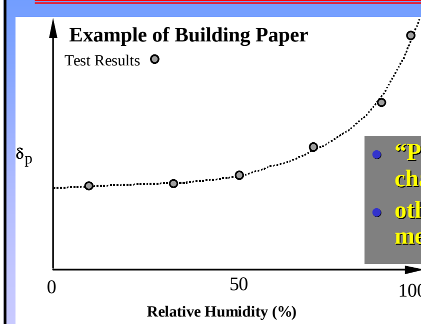


The Tupperware standard

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



Vapour Permeance vs RH

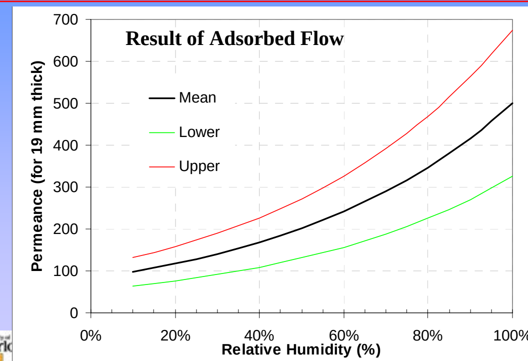


- "Permeance" changes with RH
- other transport mechanisms as work

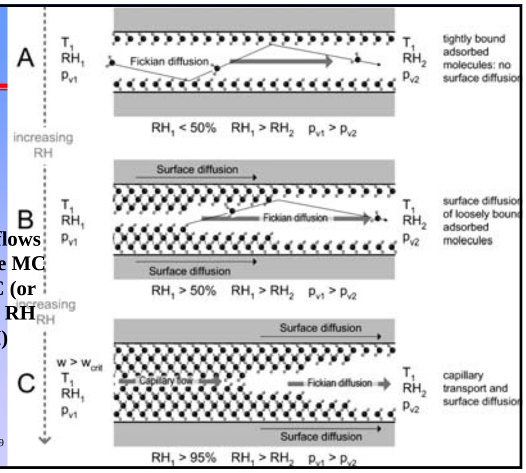
Adsorbed Flow

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

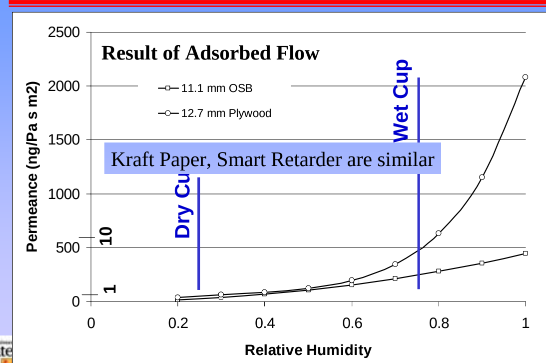
Vapour Permeance: Stucco



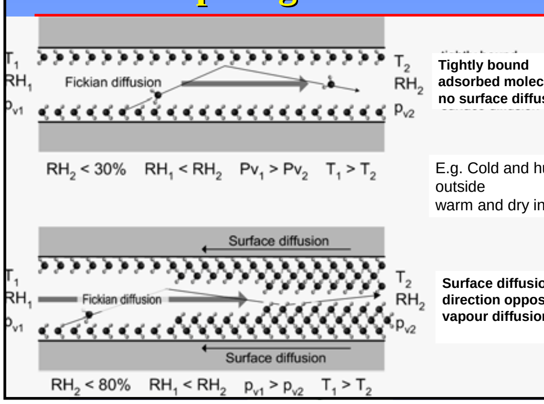
Adsorbed moisture flows from more MC to less MC (or from high RH to low RH)



Vapour Permeance: Sheathing



Competing Mechanisms



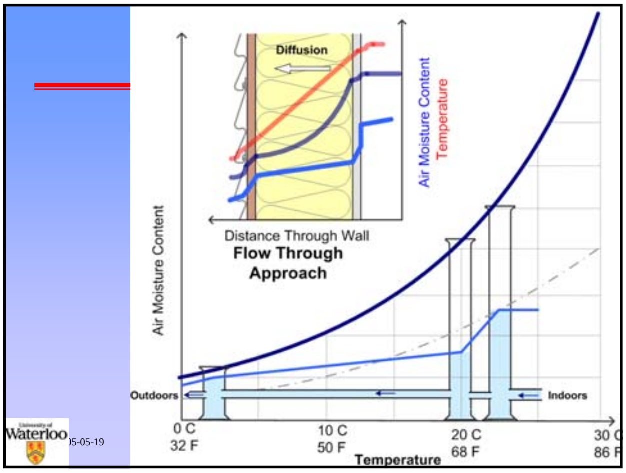
Tightly bound adsorbed molecules -- no surface diffusion

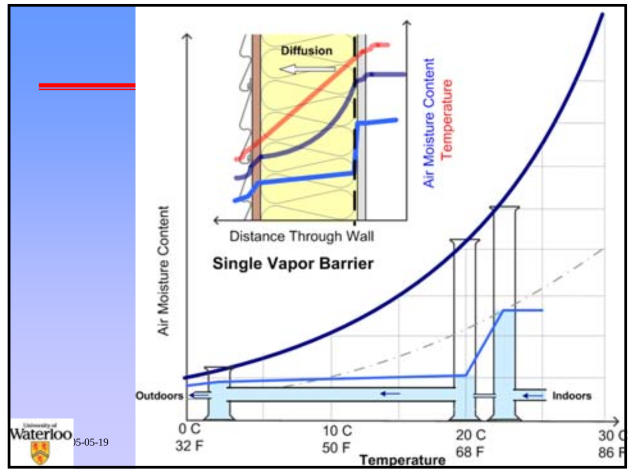
E.g. Cold and humid outside warm and dry inside

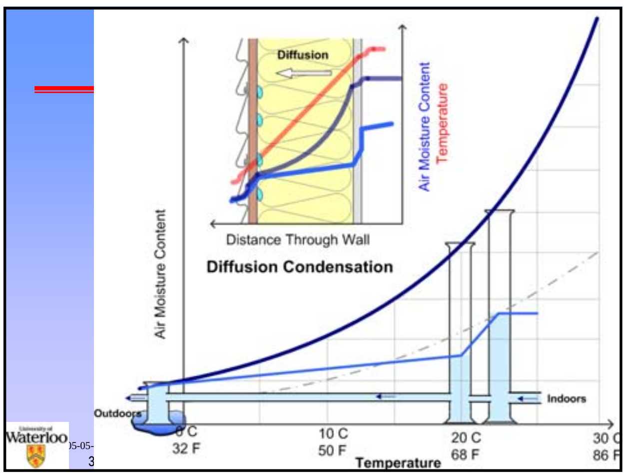
Surface diffusion flow direction opposes vapour diffusion !

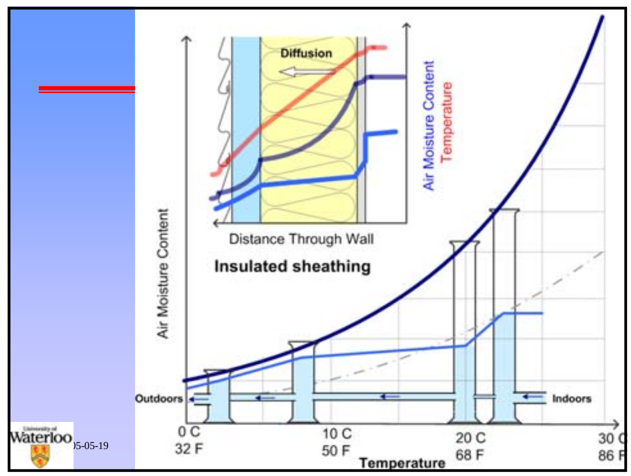
Vapour Barriers/Retarders

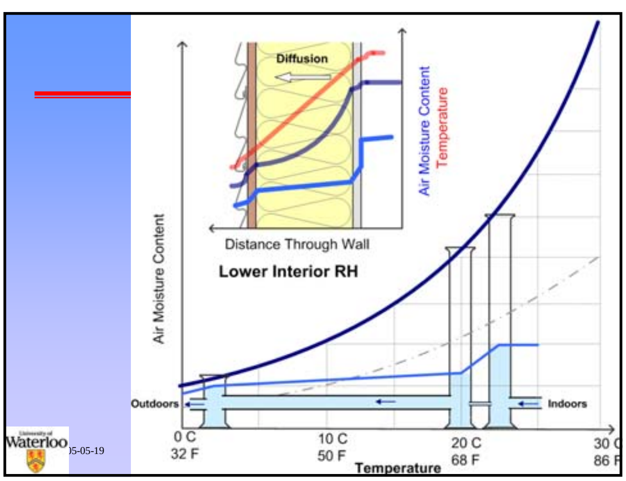
- Vapour retarders are needed to *control vapour diffusion*
- ***Don't*** need be continuous – small tears and openings OK
- Usually placed near the warm side of the wall or roof -- near the inside in cool climates
- Semi-permeable barriers allow more design flexibility (and more drying)

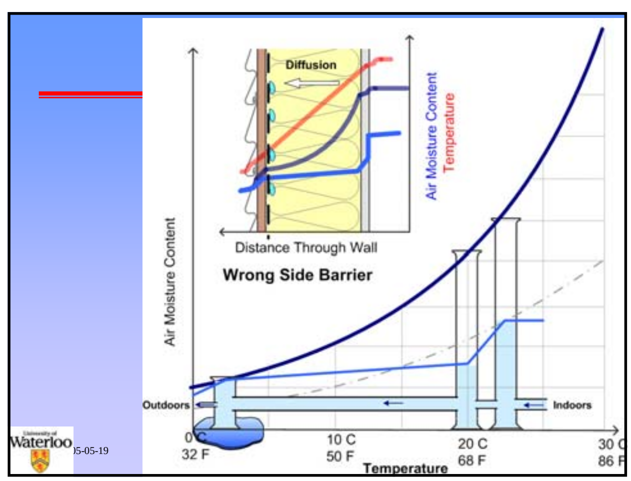

Diffusion
Air Moisture Content
Temperature
Distance Through Wall
Flow Through Approach
Air Moisture Content
Outdoors
Indoors
0 C
32 F
10 C
50 F
20 C
68 F
30 C
86 F
Temperature

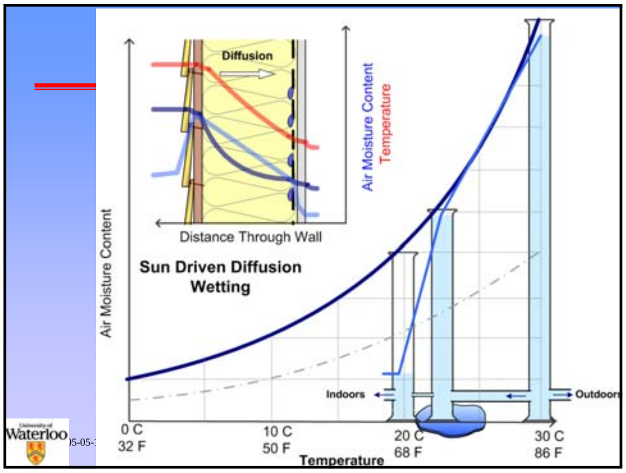

Diffusion
Air Moisture Content
Temperature
Distance Through Wall
Single Vapor Barrier
Air Moisture Content
Outdoors
Indoors
0 C
32 F
10 C
50 F
20 C
68 F
30 C
86 F
Temperature


Diffusion
Air Moisture Content
Temperature
Distance Through Wall
Diffusion Condensation
Air Moisture Content
Outdoors
Indoors
0 C
32 F
10 C
50 F
20 C
68 F
30 C
86 F
Temperature


Diffusion
Air Moisture Content
Temperature
Distance Through Wall
Insulated sheathing
Air Moisture Content
Outdoors
Indoors
0 C
32 F
10 C
50 F
20 C
68 F
30 C
86 F
Temperature

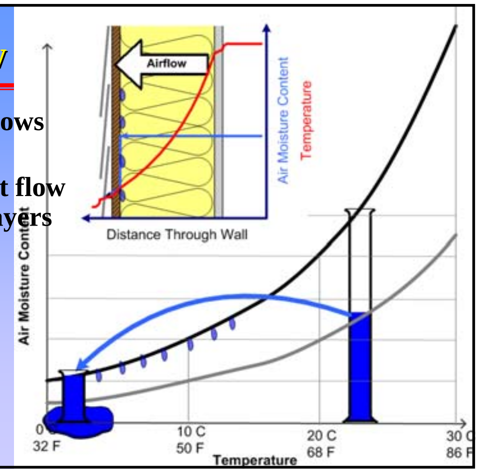

Diffusion
Air Moisture Content
Temperature
Distance Through Wall
Lower Interior RH
Air Moisture Content
Outdoors
Indoors
0 C
32 F
10 C
50 F
20 C
68 F
30 C
86 F
Temperature


Diffusion
Air Moisture Content
Temperature
Distance Through Wall
Wrong Side Barrier
Air Moisture Content
Outdoors
Indoors
32 F
10 C
50 F
20 C
68 F
30 C
86 F
Temperature



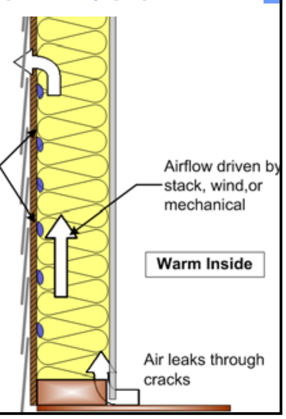
Airflow

- Vapor flows with air
- Constant flow across layers



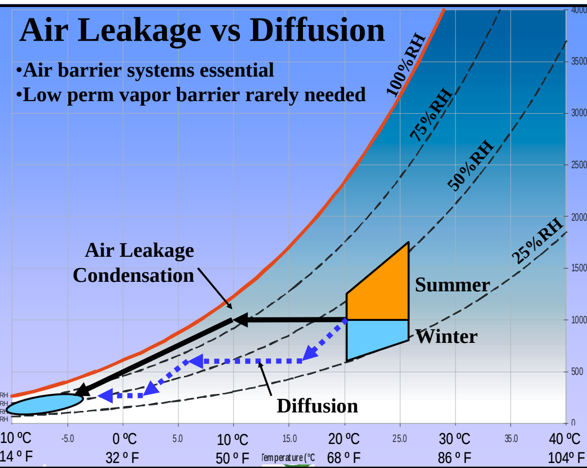
Air leakage vs Diffusion

- Air leakage is much more critical
- Walls sensitive to diffusion-related condensation will be more sensitive to air leakage



Air Leakage vs Diffusion

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



Airflow

- Vapor moves along with the air
- Air moves through large openings
  - Small pores don't move enough air!!!
    - Brick pores, foam plastic, etc
  - Cracks of 1 mm (1/32") and up could matter
  - Holes of 1" (25 mm) and up must be sealed

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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)

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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)

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

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)

Air Barriers

- Not code required in most places
- Material property is not that important
  - Air permeance, say <0.1 l/s/m2 @ 75 Pa
  - Joints, penetrations, interfaces leaks
- Requirements
  - Continuous
  - Strong
  - Stiff
  - Durable

Moisture Thresholds

Material Performance Thresholds

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

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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

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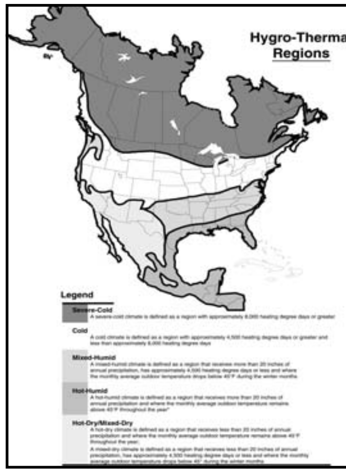

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Material Performance

- 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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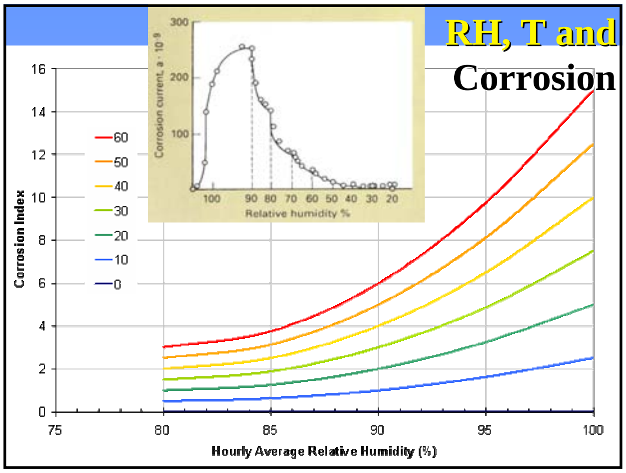
Steel Corrosion

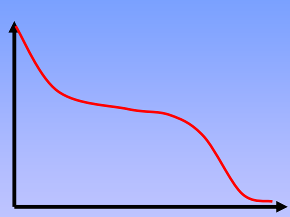
- Electrochemical Process - oxygen + electrolyte
- Can begin if RH>80%
- Coatings protect
- Zinc galvanizing is sacrificial
- Factors
  - Temperature (Arhenius Law)
  - Time of Wetness (TOW)
  - pH of environment
  - Salinity

RH, T and Corrosion



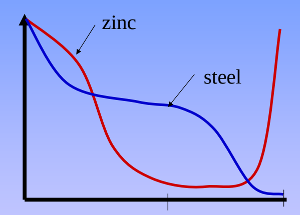
pH and Steel Corrosion

Corrosion Rate ($g/m^2/day$)



pH and Zinc Corrosion

Corrosion Rate ($g/m^2/day$)

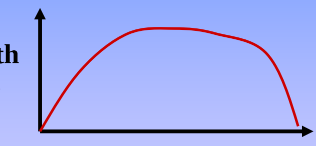


Fungal Growth

- 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

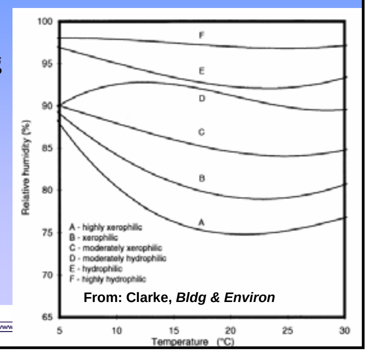
- ***Surface*** **Humidity > about 80%RH**
- **Temperature 5C/40F - 50C/120F**



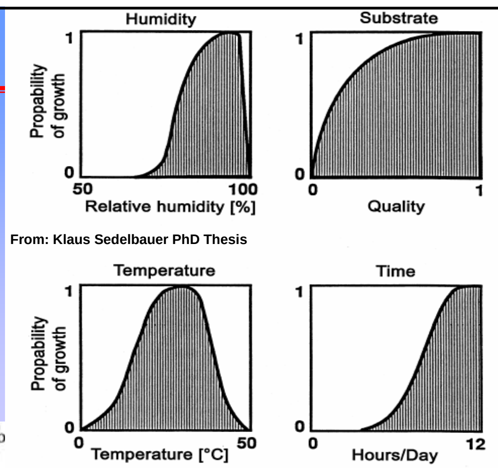
- **Food Source (cellulose, soap, wood, oil)**
- **pH - usually less than 8 - 10**

Minimum Levels

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



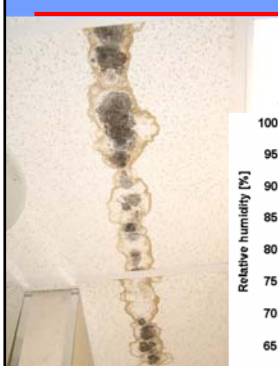
From: Clarke, *Bldg & Environ*



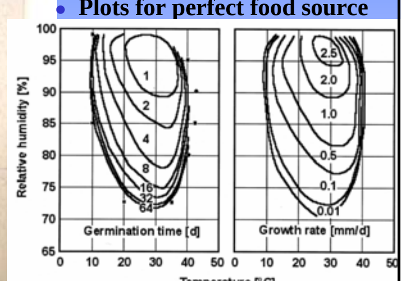
From: Klaus Sedelbauer PhD Thesis

Germination & Growth

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



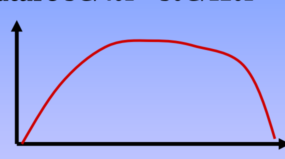
Brampton stripmall



From: Klaus Sedelbauer PhD Thesis

Wood Decay

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



- **Highly species, sample, exposure dependent**

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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Dissolution

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

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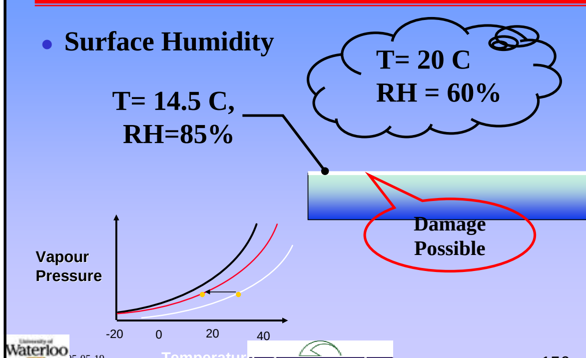
Subfluorescense

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

Microclimate

- Surface Humidity



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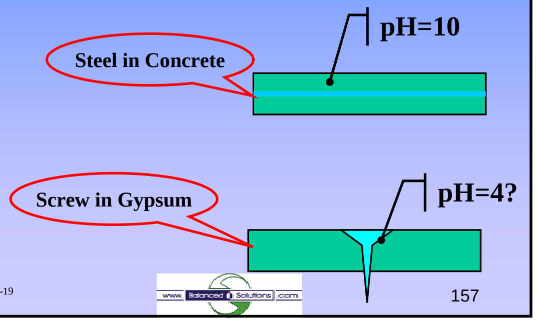
Microclimate

- 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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