Thermodynamics of water in concrete

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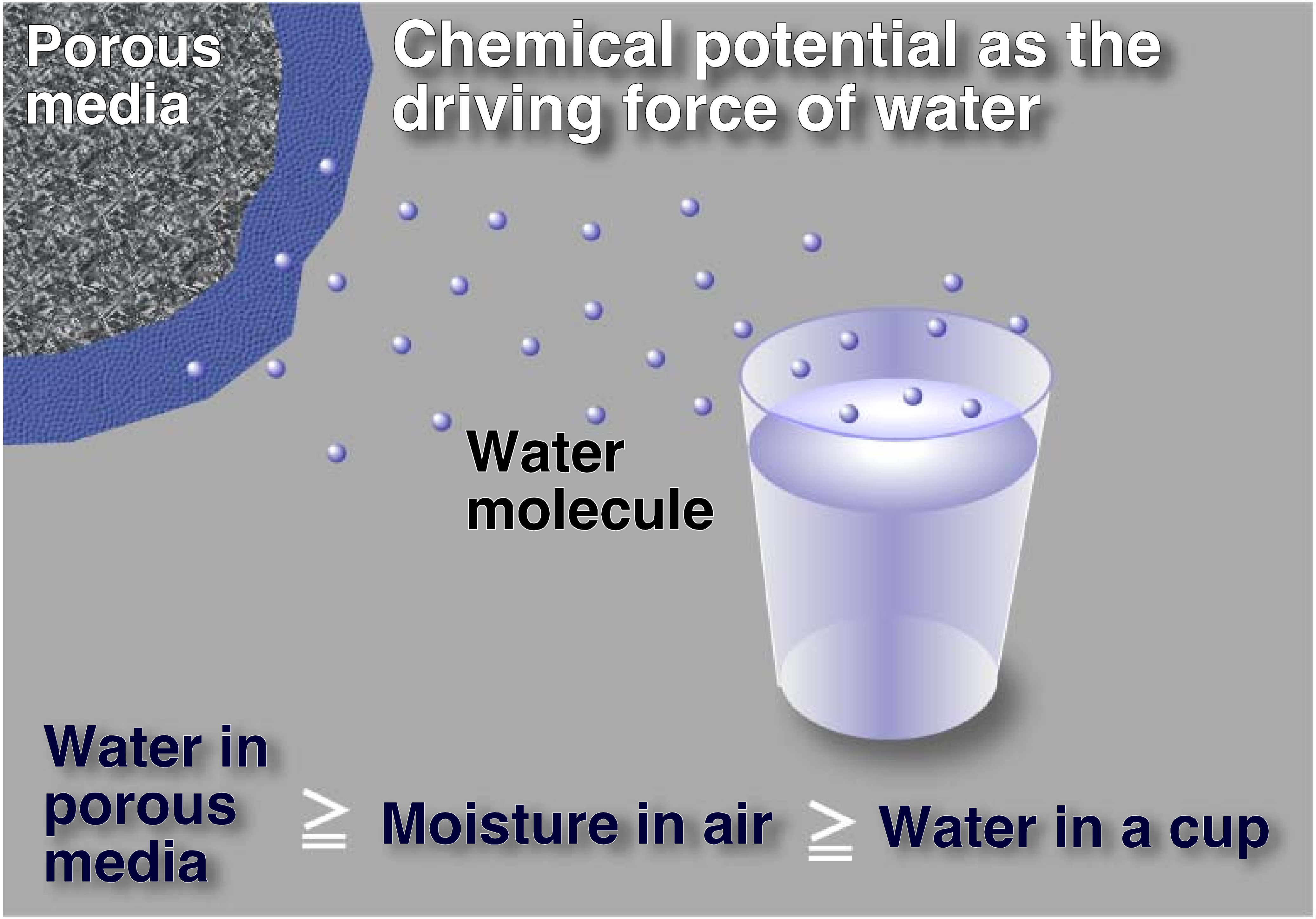
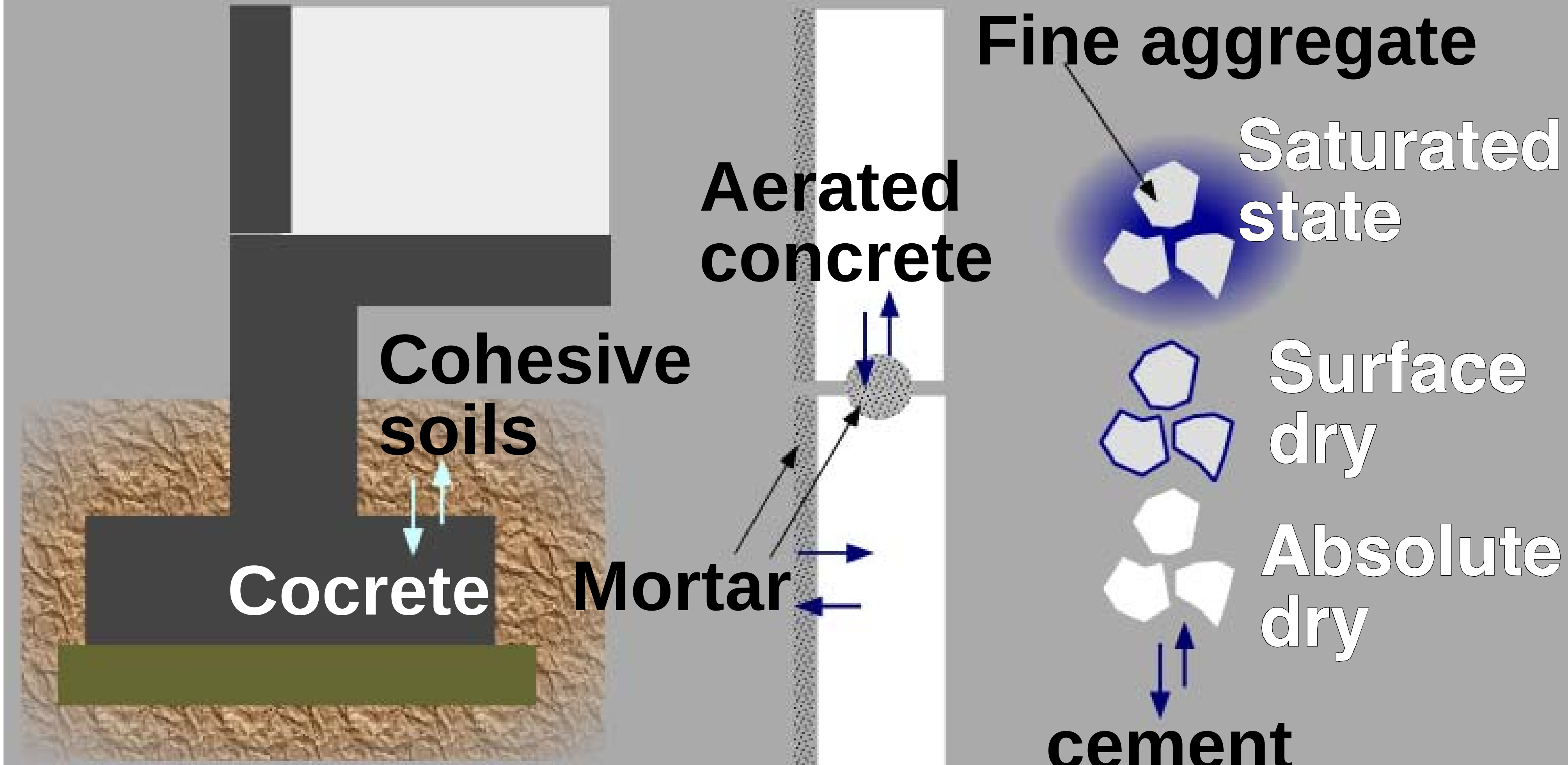
Outline

The role of chemical potential of water in porous system.

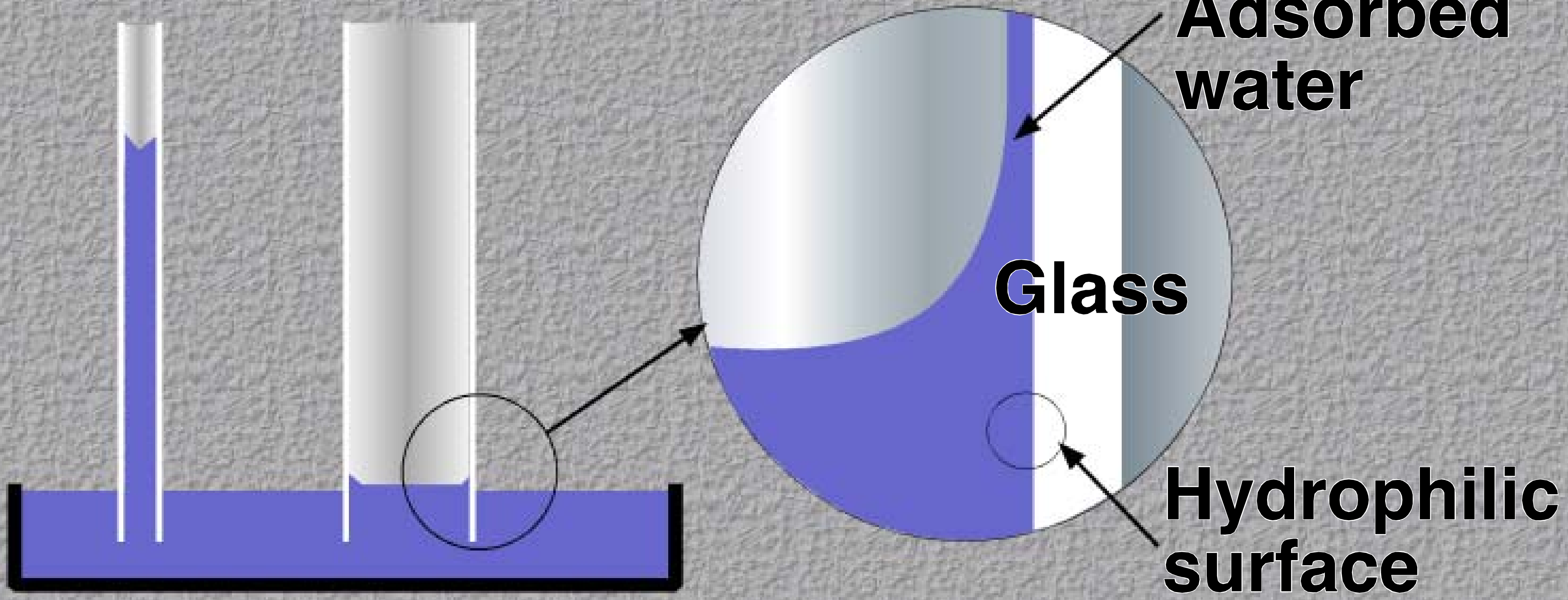
Transport of water in concrete and new method to determine transport properties.	Equilibrium of water in concrete and shrinkage, AAR expansion and frost damage.


Porous media
Chemical potential as the driving force of water
Water molecule
Water in porous media ≧ Moisture in air ≧ Water in a cup

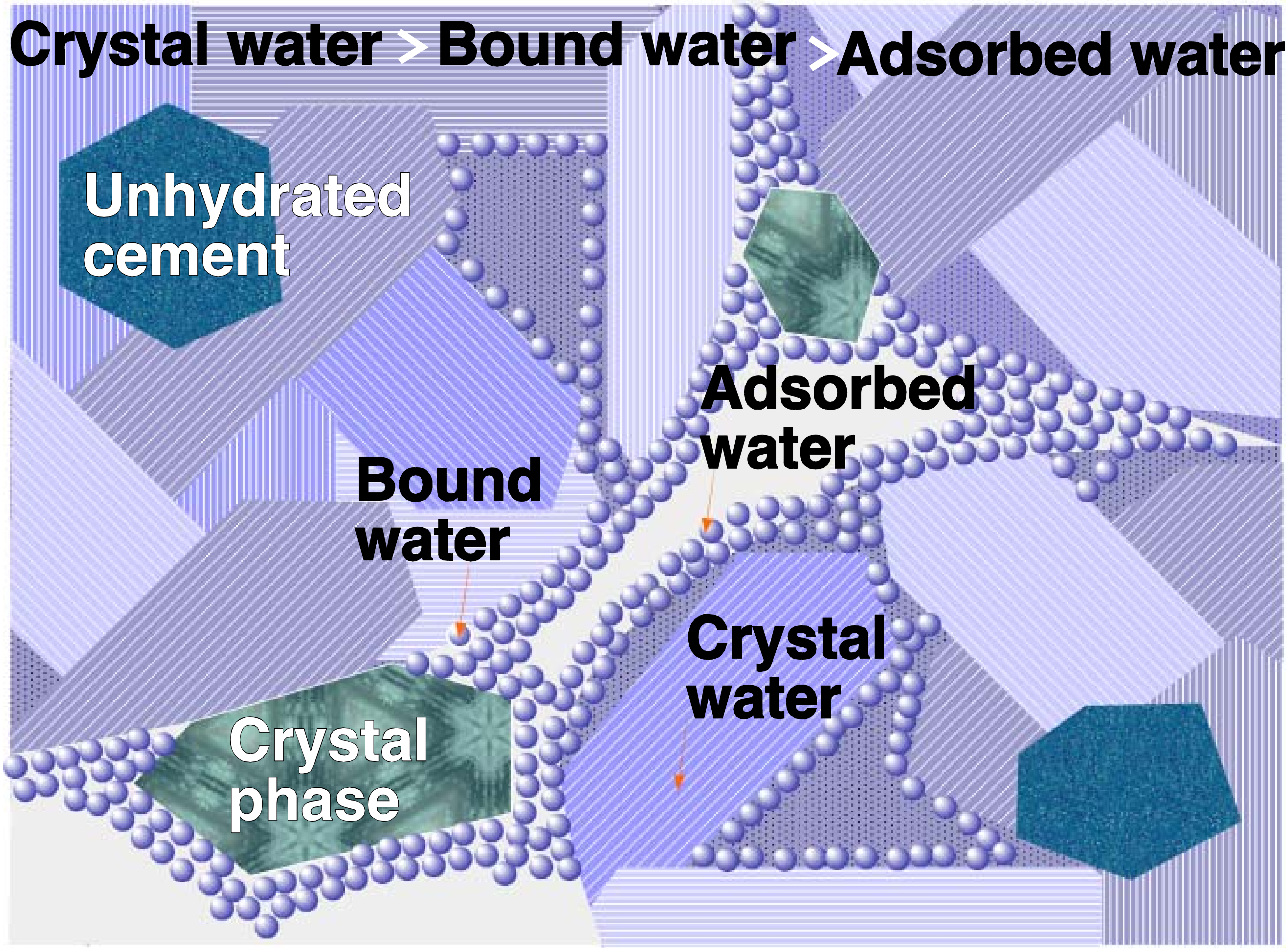
Moisture transport between different materials



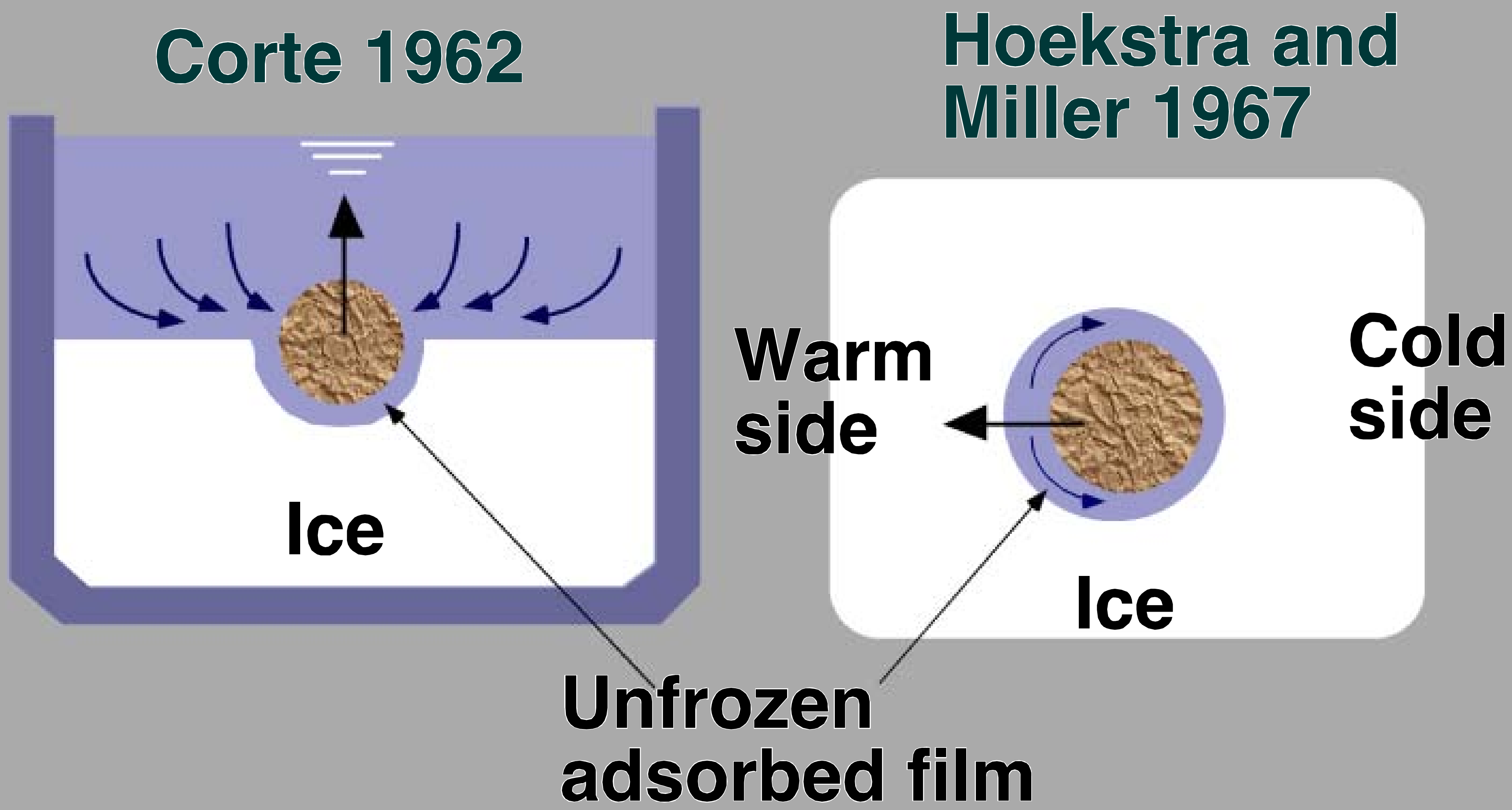
Origin of the capillary force



Capillary force = Free water rising induced by the adsorbed water


Crystal water > Bound water > Adsorbed water
Unhydrated cement
Adsorbed water
Bound water
Crystal water
Crystal phase

Adsorbed water transport



Chemical potential

$$W = -\int_{P}^{P_s} V\,dp = RT\int_{P_s}^{P} \frac{dp}{P} = RT\ln\left(P/P_s\right)$$

Work

Gas constant

Absolute temperature

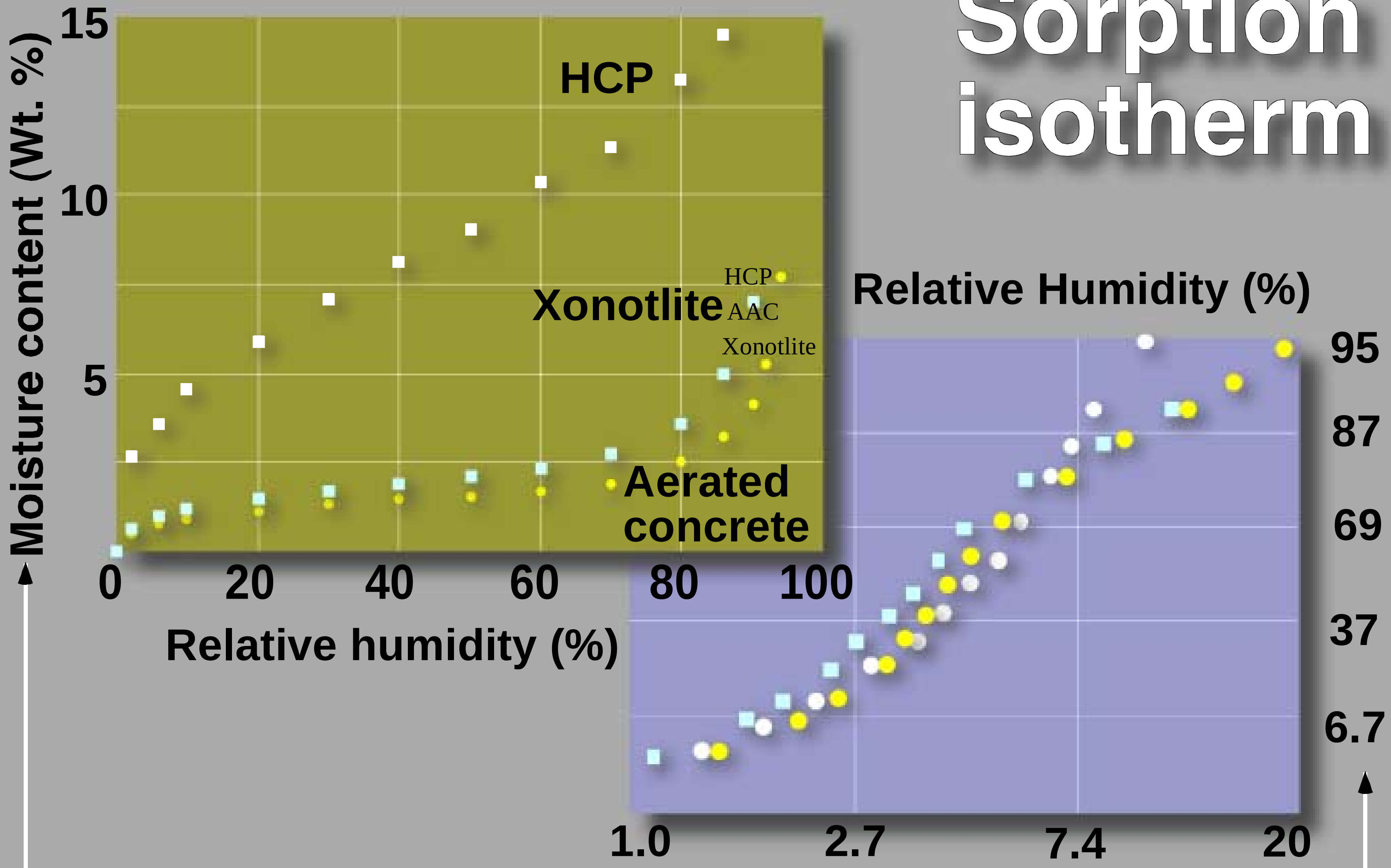
Water vapor pressure

Volume

Saturated water vapor pressure

- Fundamental driving force of mass.
- Equal regardless of phase in equilibrium.
- Comparable regardless of medium.

Sorption isotherm



$$\frac{\Phi}{\text{BET surface area}} = \text{Statistical thickness of adsorbed water (Å)}$$

Kelvin equation

Pressure due to the difference in chemical potential of water

Surface tension of water

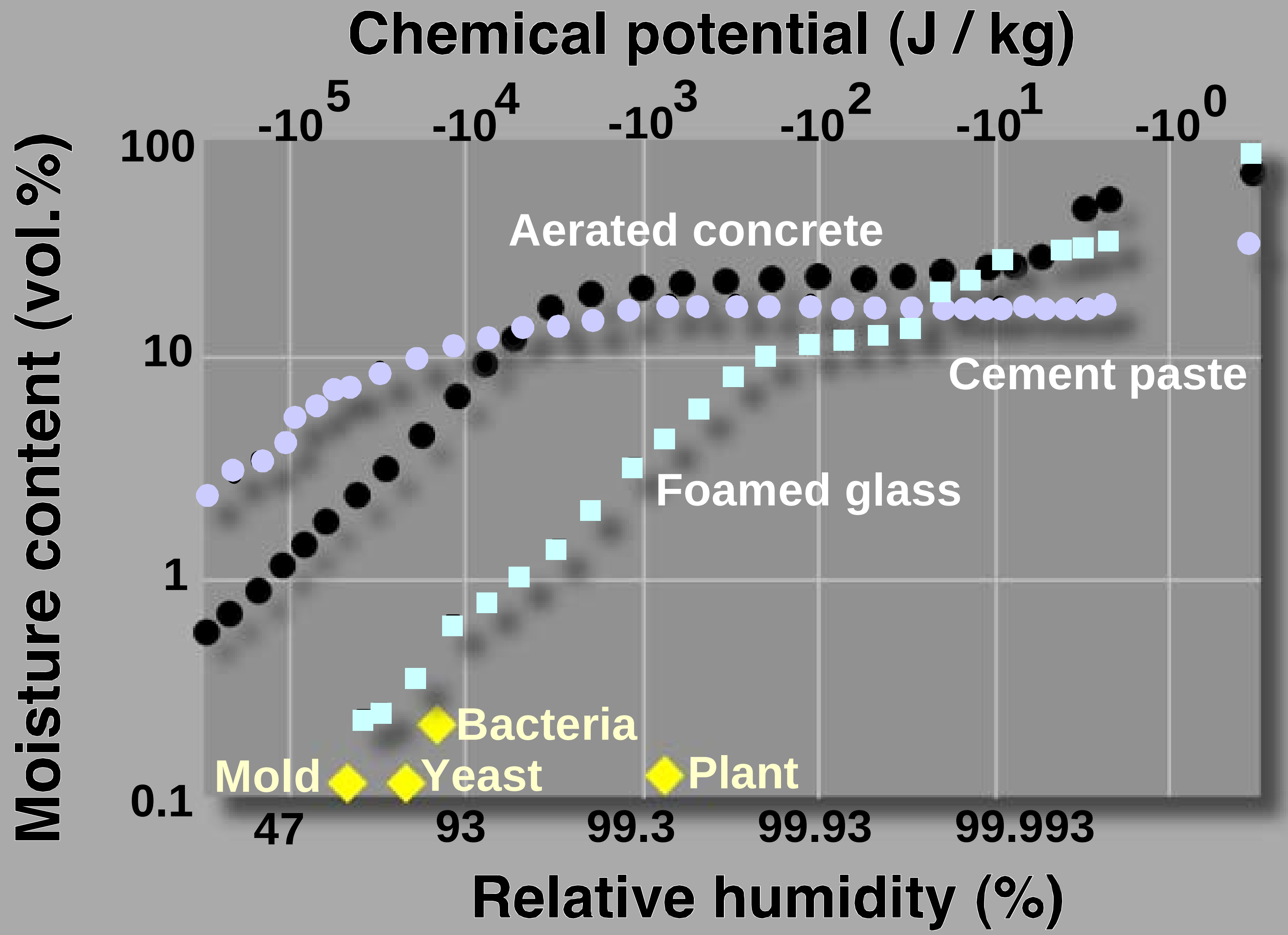
$$\frac{RT\ln(P/P_s)}{\bar{v}} = -\frac{2\Phi}{r}$$

Molar volume of water

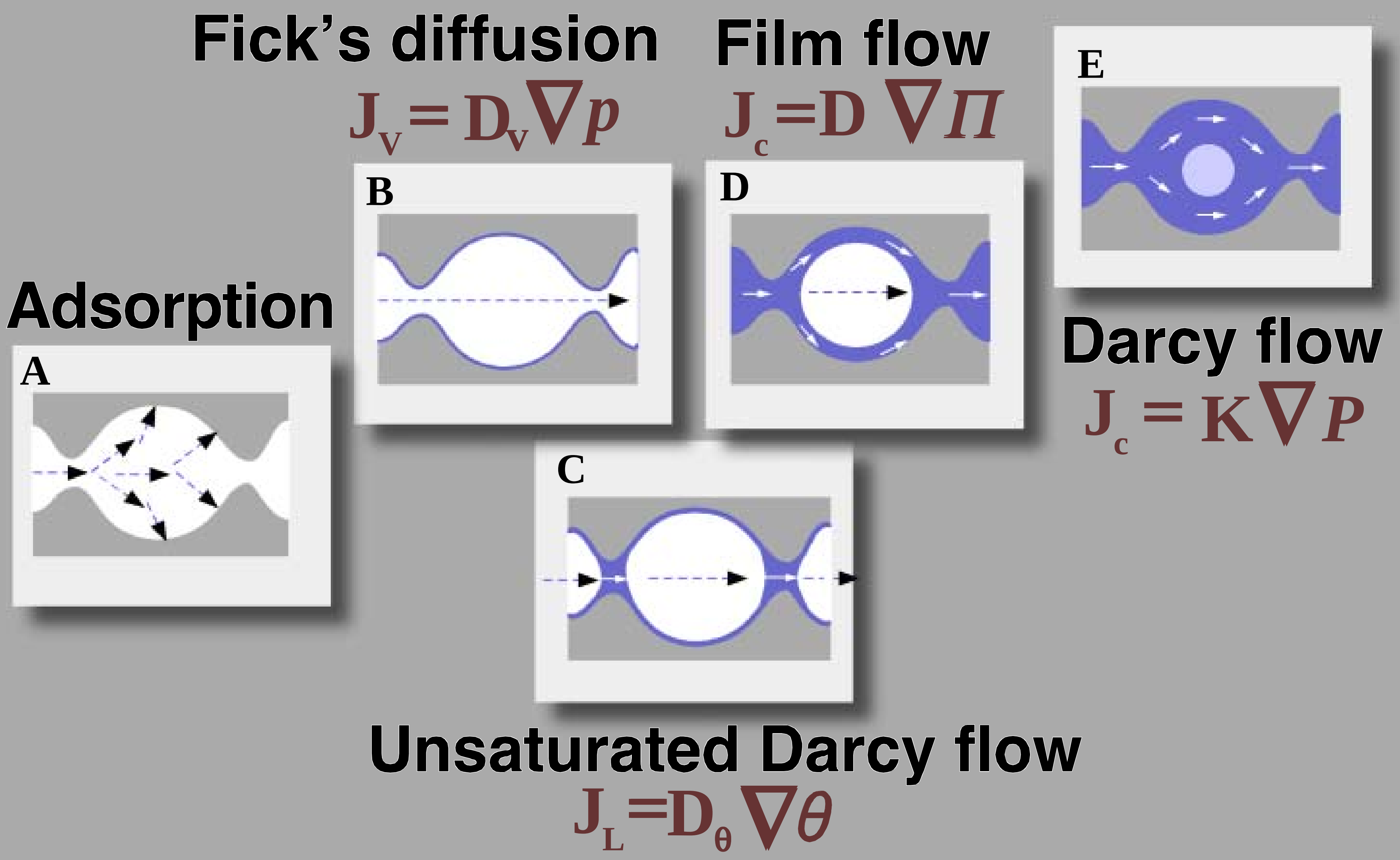
Radius of curvature at liquid-gas interface

- An equation of state at the interface
- Negative pressure due to difference in $\Delta\mu$
- Osmotic pressure

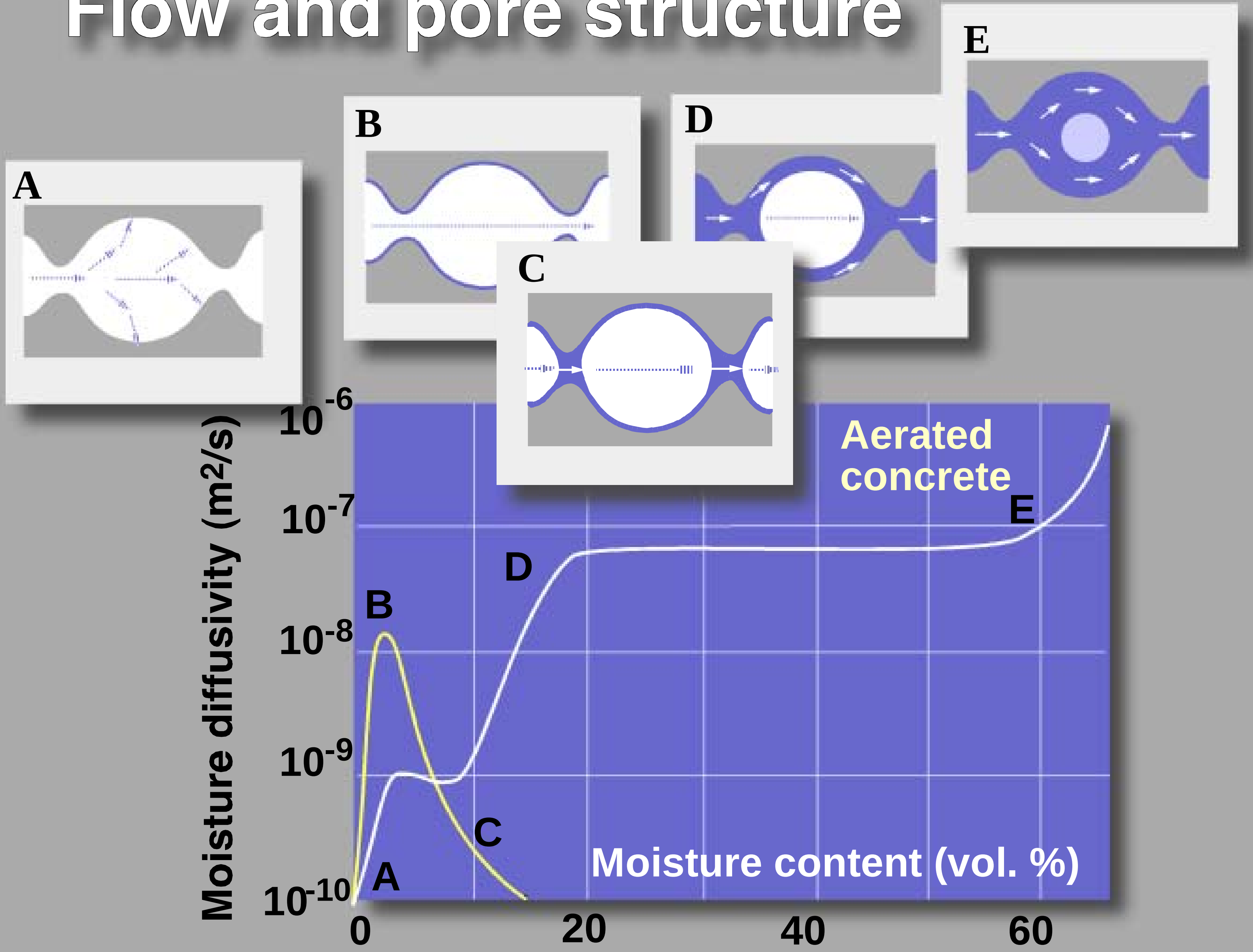
Moisture characteristic curve



Flow of water



Flow and pore structure



Water flux

Fick's diffusion flow

Water vapor pressure

$$J_V = -D_V \nabla p_V$$

$$J_V = -p_{VS} D_V \nabla h$$

Saturated water vapor pressure

Unsaturated Darcy flow

Capillary pressure

$$J_L = -\frac{K_L}{\mu} \nabla p_C$$

Unsaturated permeability

Gas constant

$$J_L = -\frac{K_L}{\mu} \frac{RT}{vh} \nabla h$$

Dynamic viscosity

Specific volume

Relative pressure

Moisture content gradient as an apparent driving force

Gradient of sorption isotherm

$$\nabla h = \boxed{\frac{\partial h}{\partial \theta}} \nabla \theta,$$

$$\mathbf{J}_{\mathrm{V}} = -\mathrm{D}_{\theta \mathrm{V}} \nabla \theta,$$

$$\mathrm{D}_{\theta \mathrm{V}} = \rho_{VS} \frac{\partial h}{\partial \theta} \mathrm{D}_{\mathrm{V}},$$

Gradient of moisture characteristic curve

$$\nabla p_C = \boxed{\frac{\partial p_C}{\partial \theta}} \nabla \theta$$

$$\mathbf{J}_{\mathrm{L}} = -\mathrm{D}_{\theta \mathrm{L}} \nabla \theta$$

$$\mathrm{D}_{\theta \mathrm{L}} = \frac{\mathrm{K}_{\mathrm{L}}}{\mu} \frac{\partial p_c}{\partial \theta}$$

Moisture balance equations

$$\frac{\partial \theta}{\partial t} = \nabla(D_\theta \nabla \theta)$$

$$D_\theta = D_{\theta V} + D_{\theta L}$$

When D is not a function of x, one dimensional flow driven by moisture content is

$$\frac{\partial \theta}{\partial t} = D_\theta \frac{\partial^2 \theta}{\partial x^2}$$

Experimental determination

Vapor conductivity

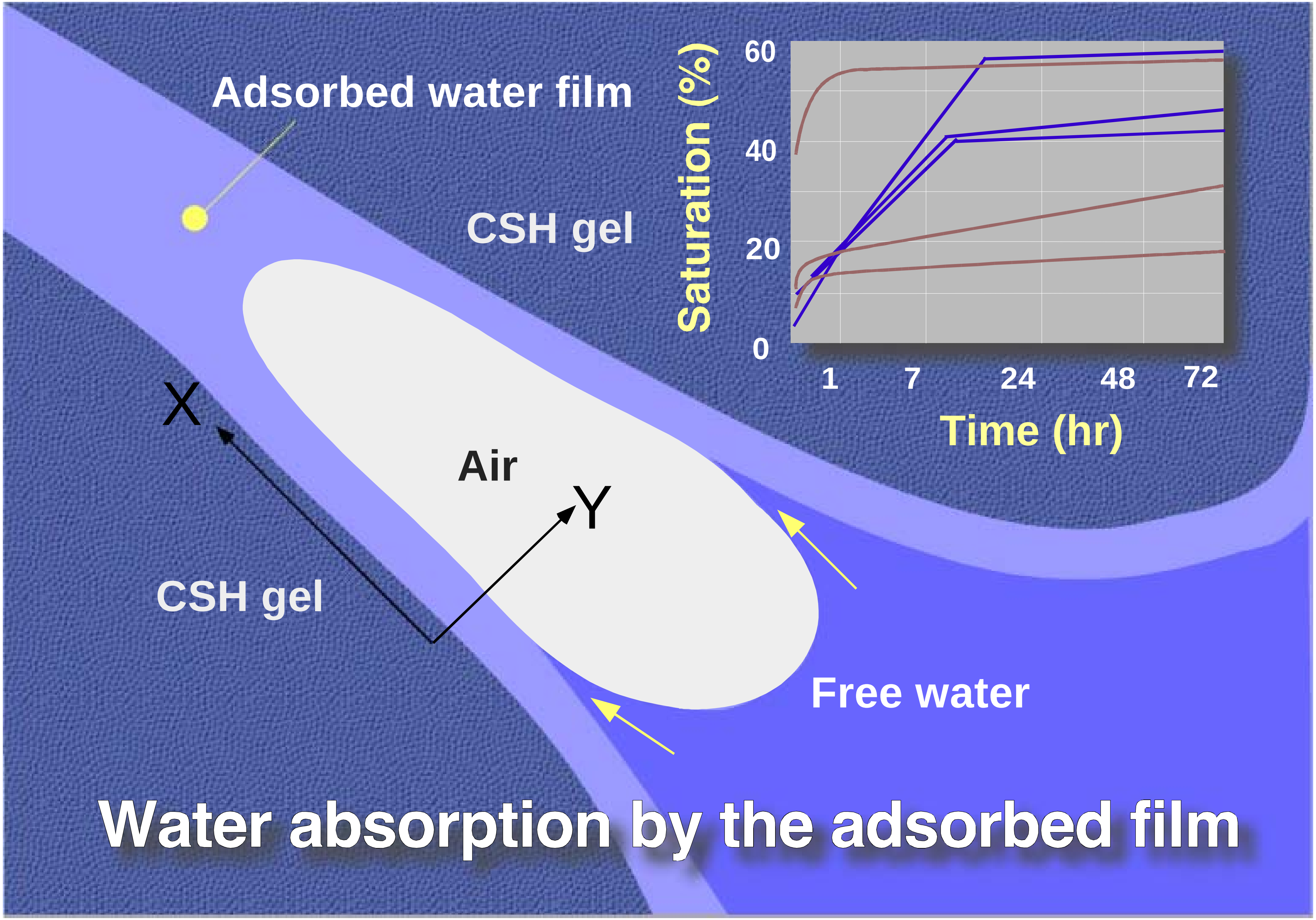
Sorption isotherm

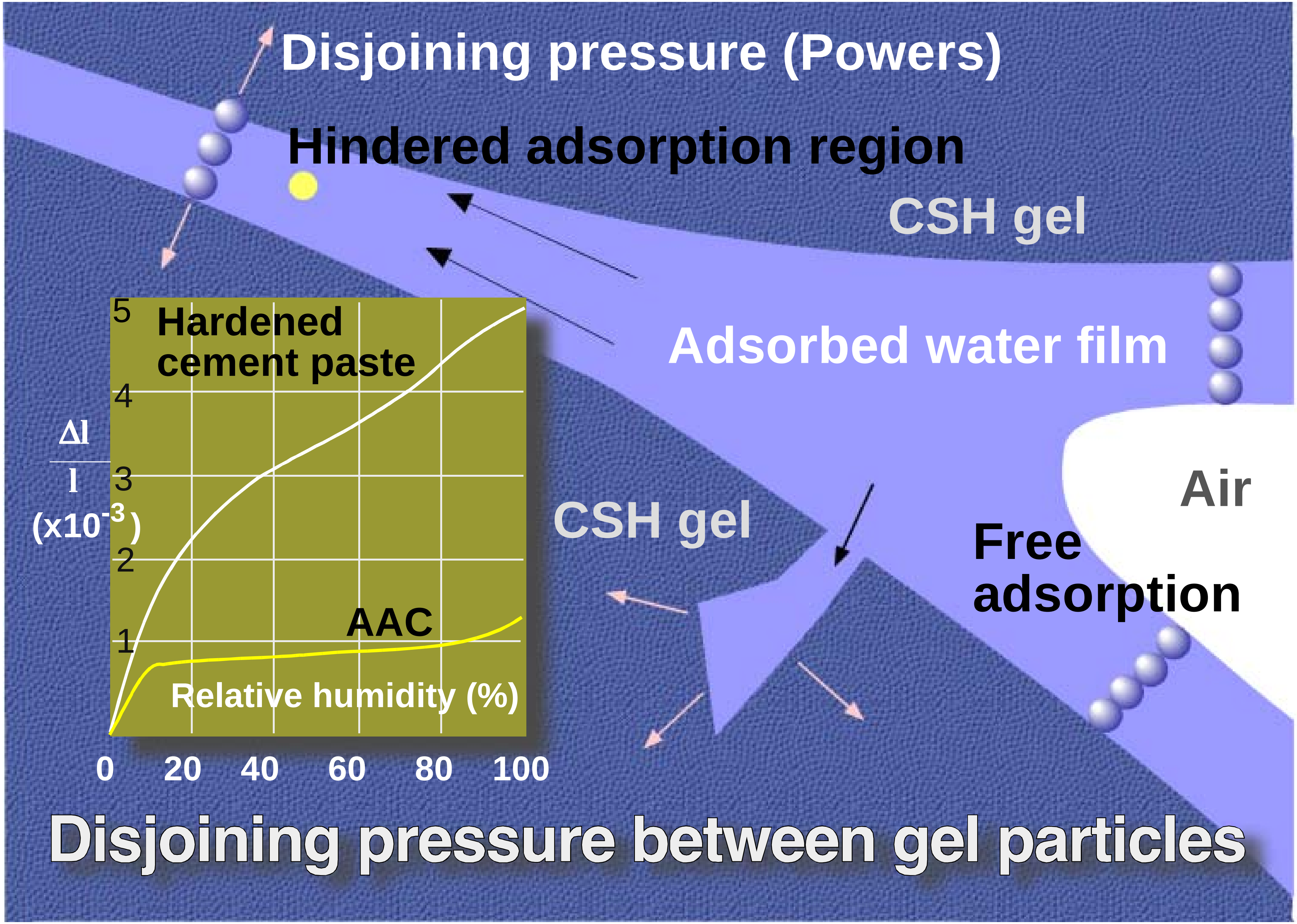
Moisture characteristics

$$\mathbf{J} = -\left(\rho_{VS}\frac{\partial h}{\partial \theta}D_V\right)\nabla\theta - \left(\frac{K_L}{\mu}\frac{\partial p_c}{\partial \theta}\right)\nabla\theta$$

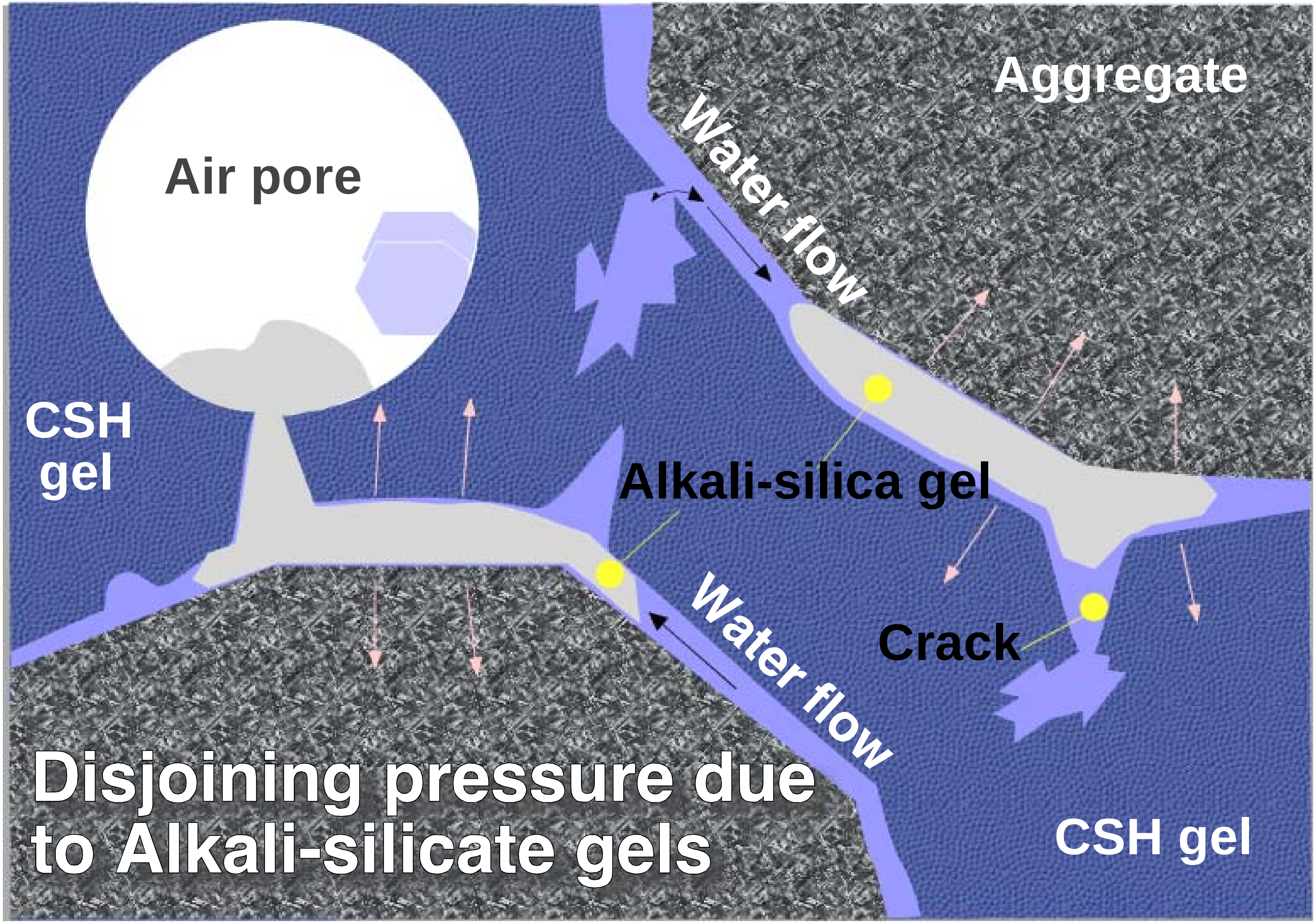
$D_{\theta V}$ $D_{\theta L}$

Vapor diffusivity **Water diffusivity**

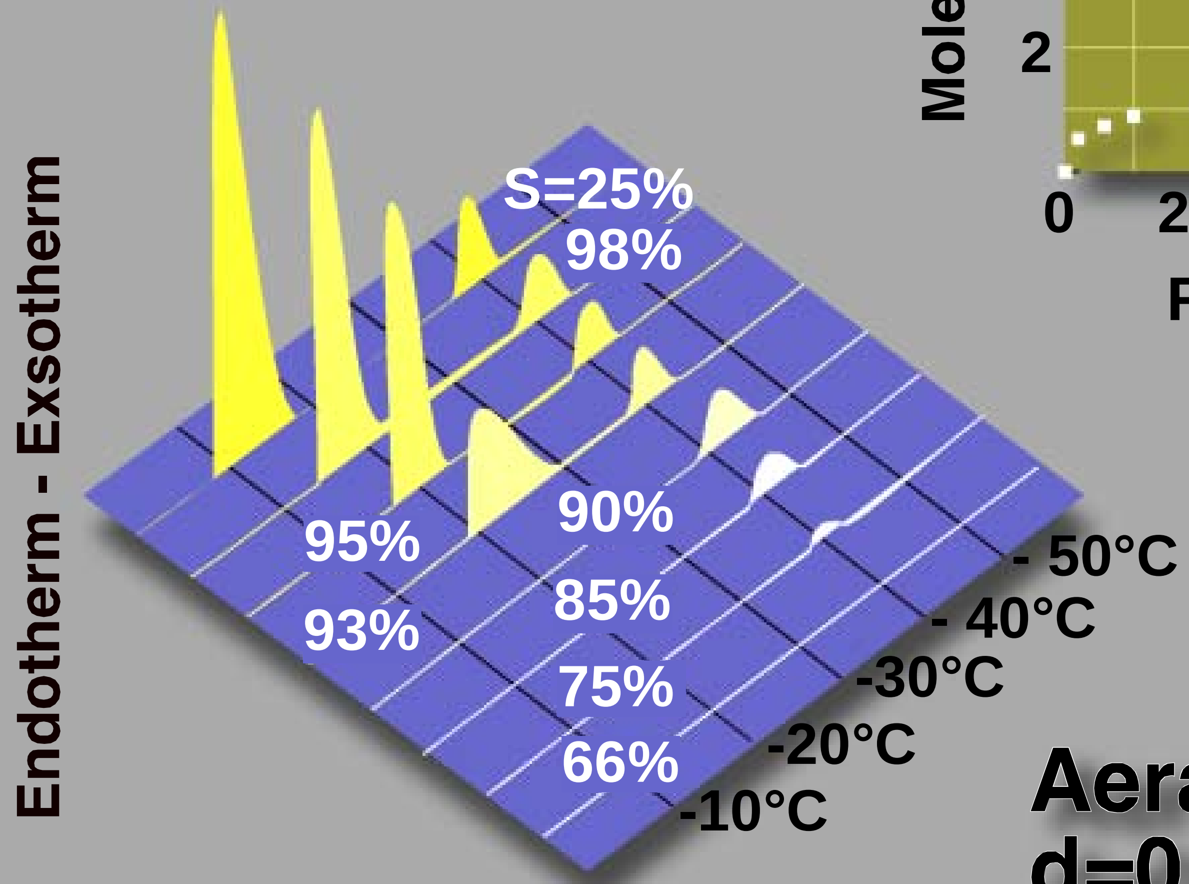

Adsorbed water film
CSH gel
Saturation (%)
60
40
20
0
1
7
24
48
72
Time (hr)
X
Air
Y
CSH gel
Free water
Water absorption by the adsorbed film

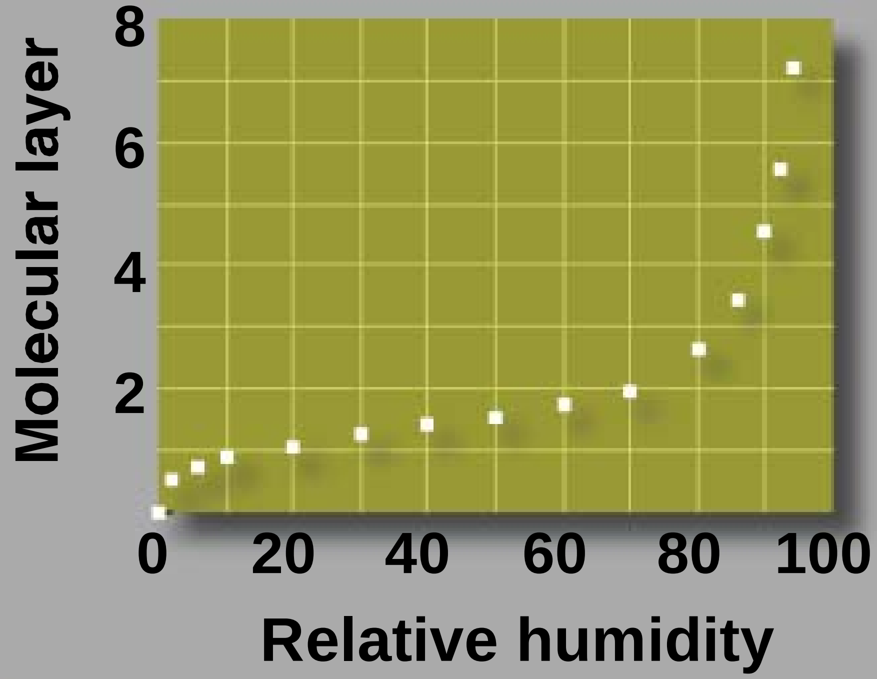


Disjoining pressure (Powers)
Hindered adsorption region
CSH gel
Adsorbed water film
Air
CSH gel
Free adsorption
Hardened cement paste
AAC
Relative humidity (%)
Δl / l (x10-3)
0 1 2 3 4 5
0 20 40 60 80 100
Disjoining pressure between gel particles


Aggregate
Air pore
Water flow
CSH gel
Alkali-silica gel
Water flow
Crack
Disjoining pressure due to Alkali-silicate gels
CSH gel

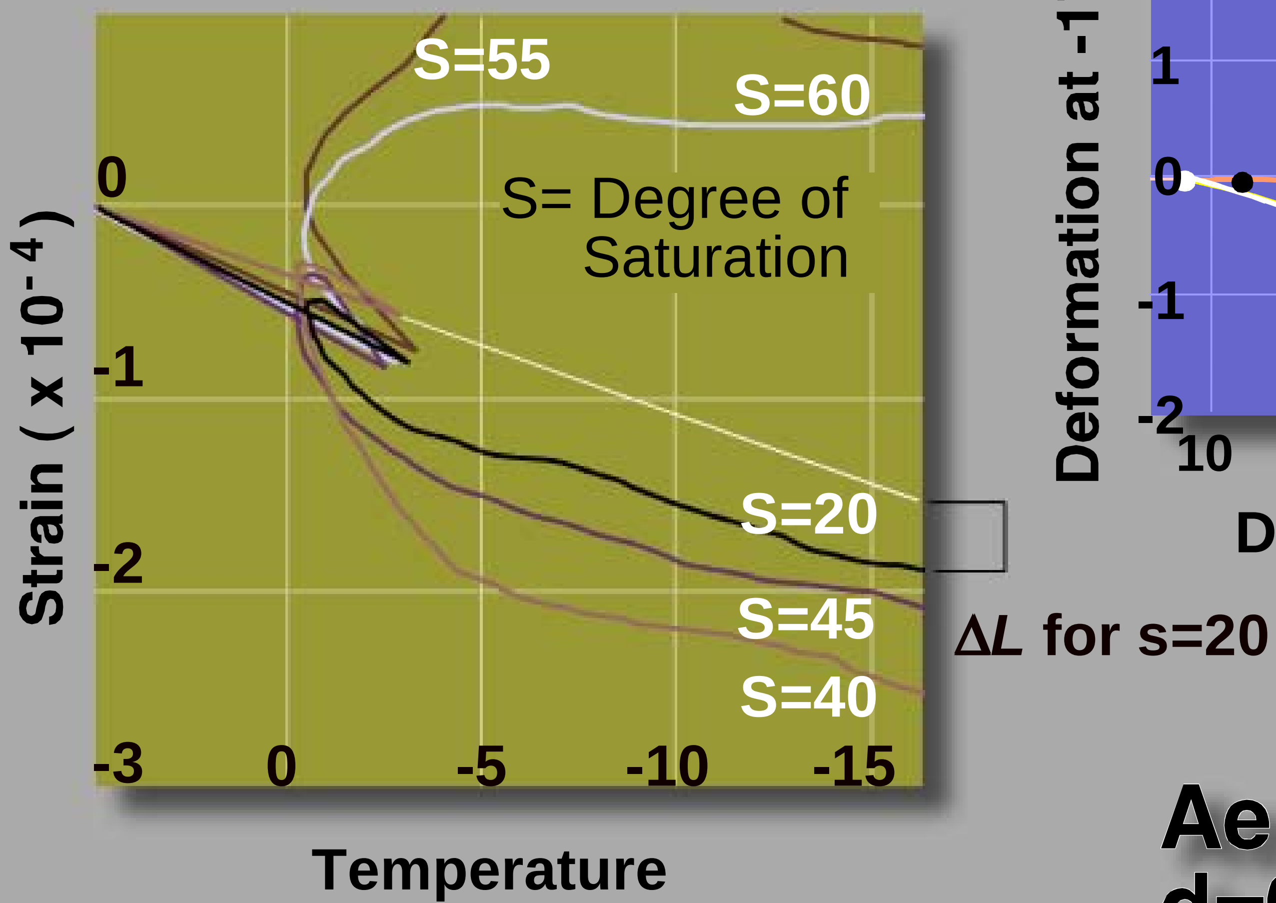
Unfrozen water film

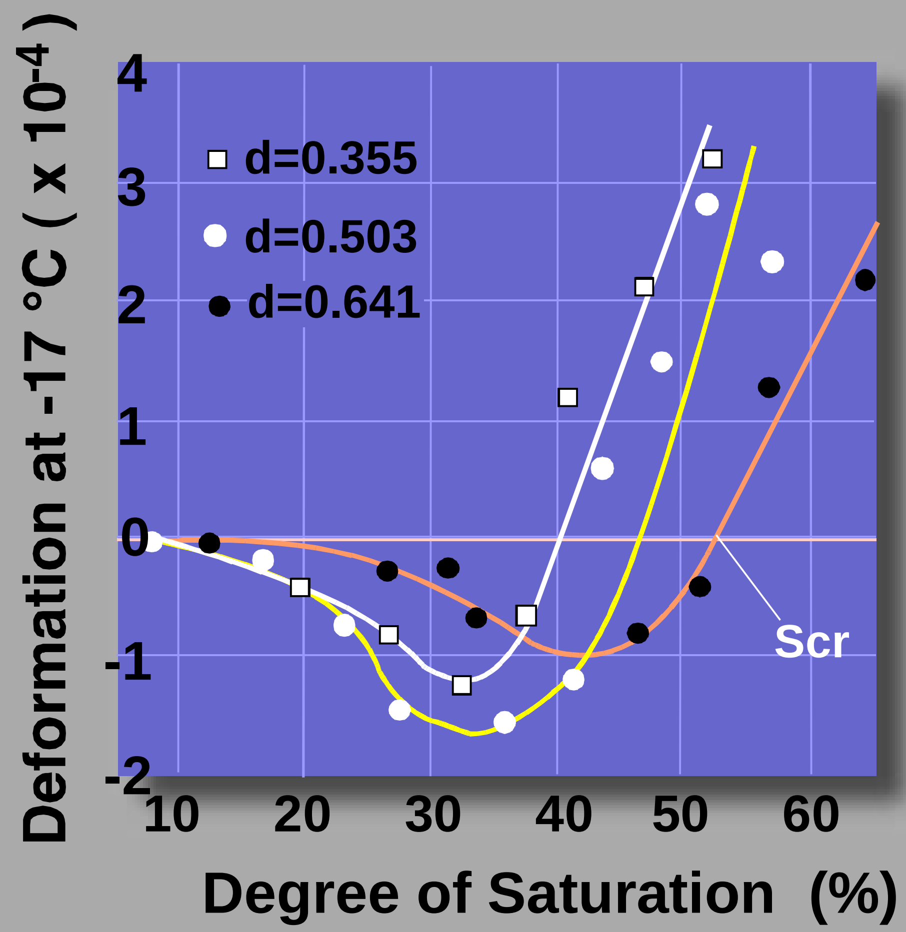




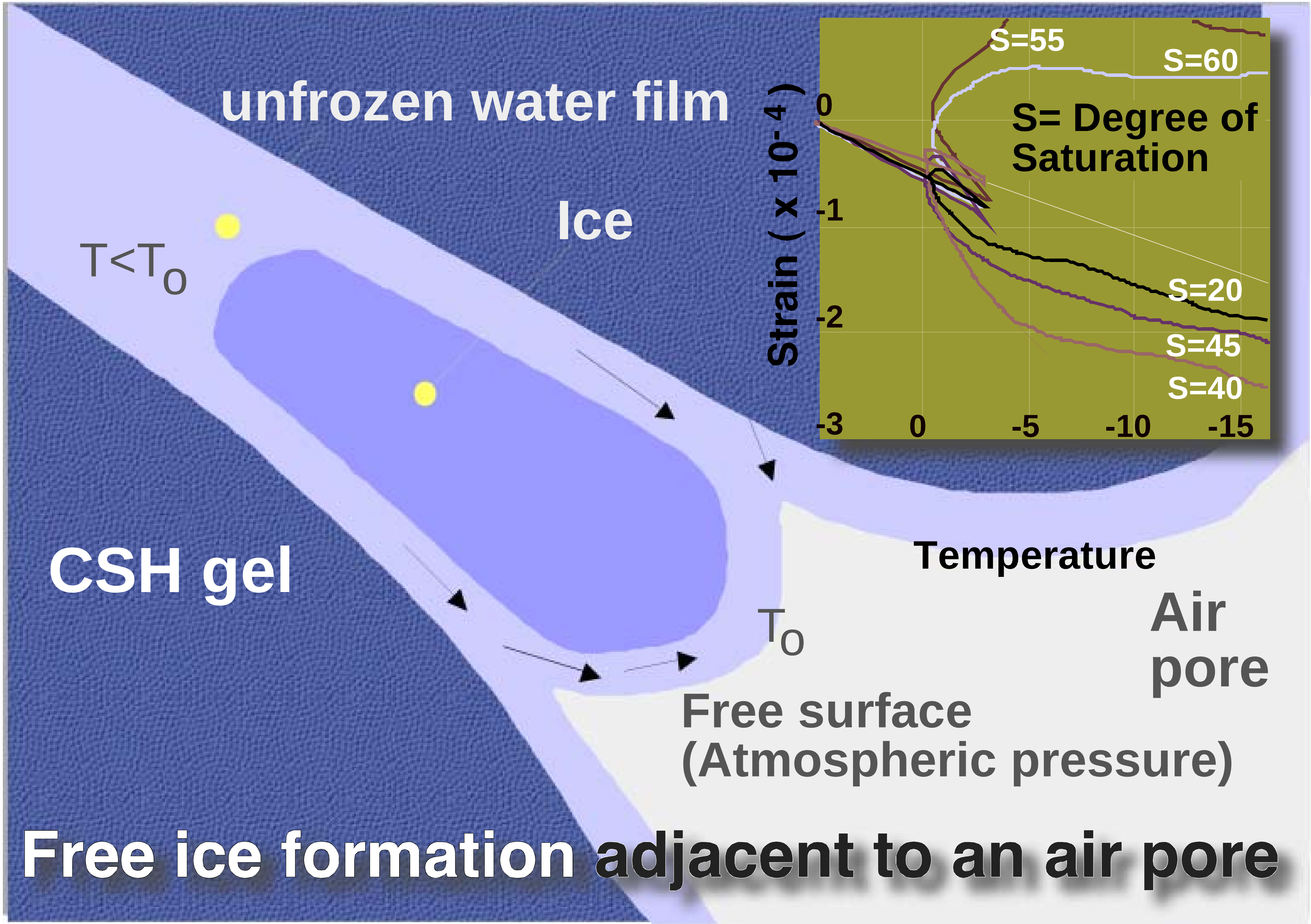
Aerated concrete d=0.503

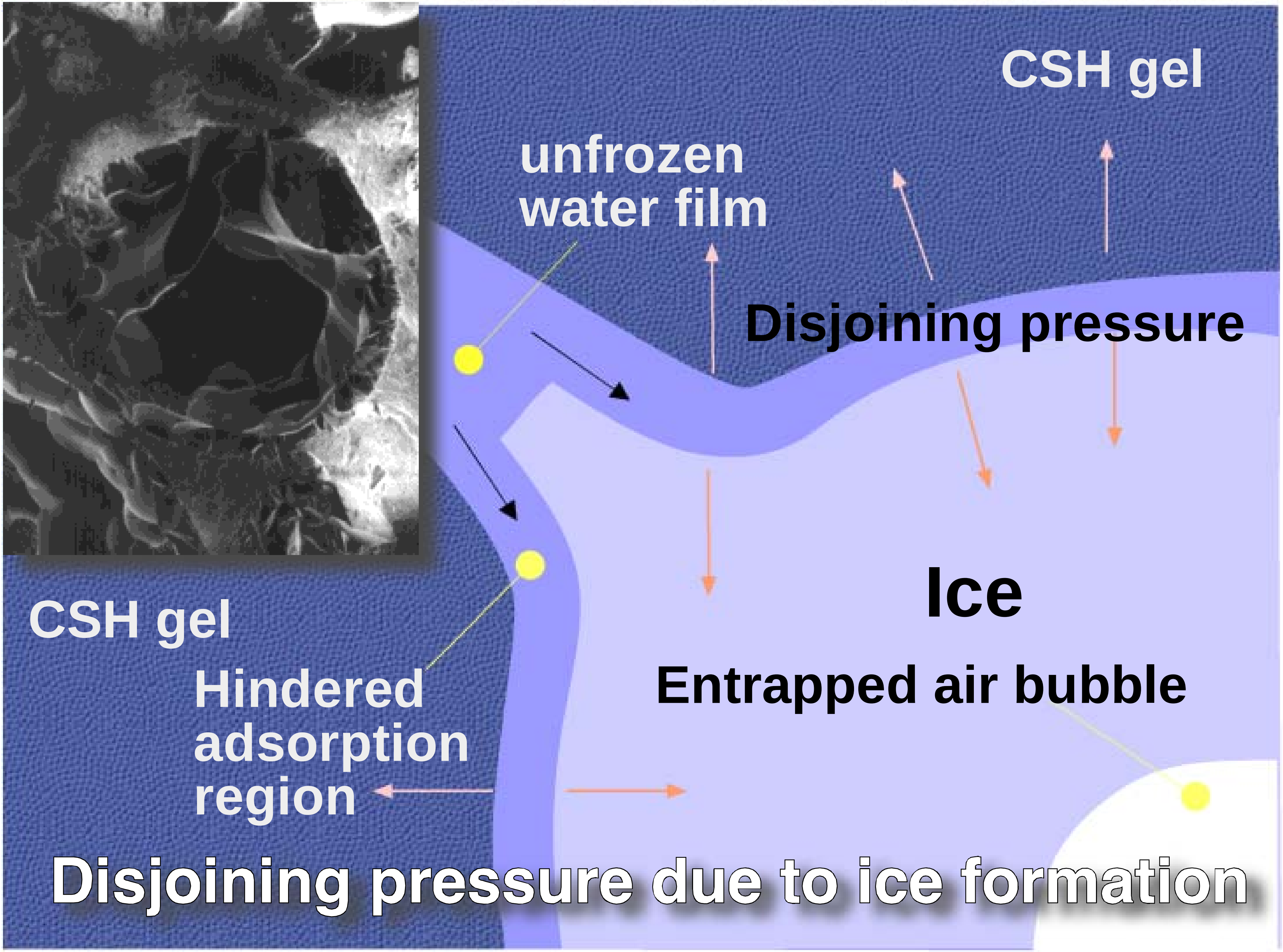
Critical saturation





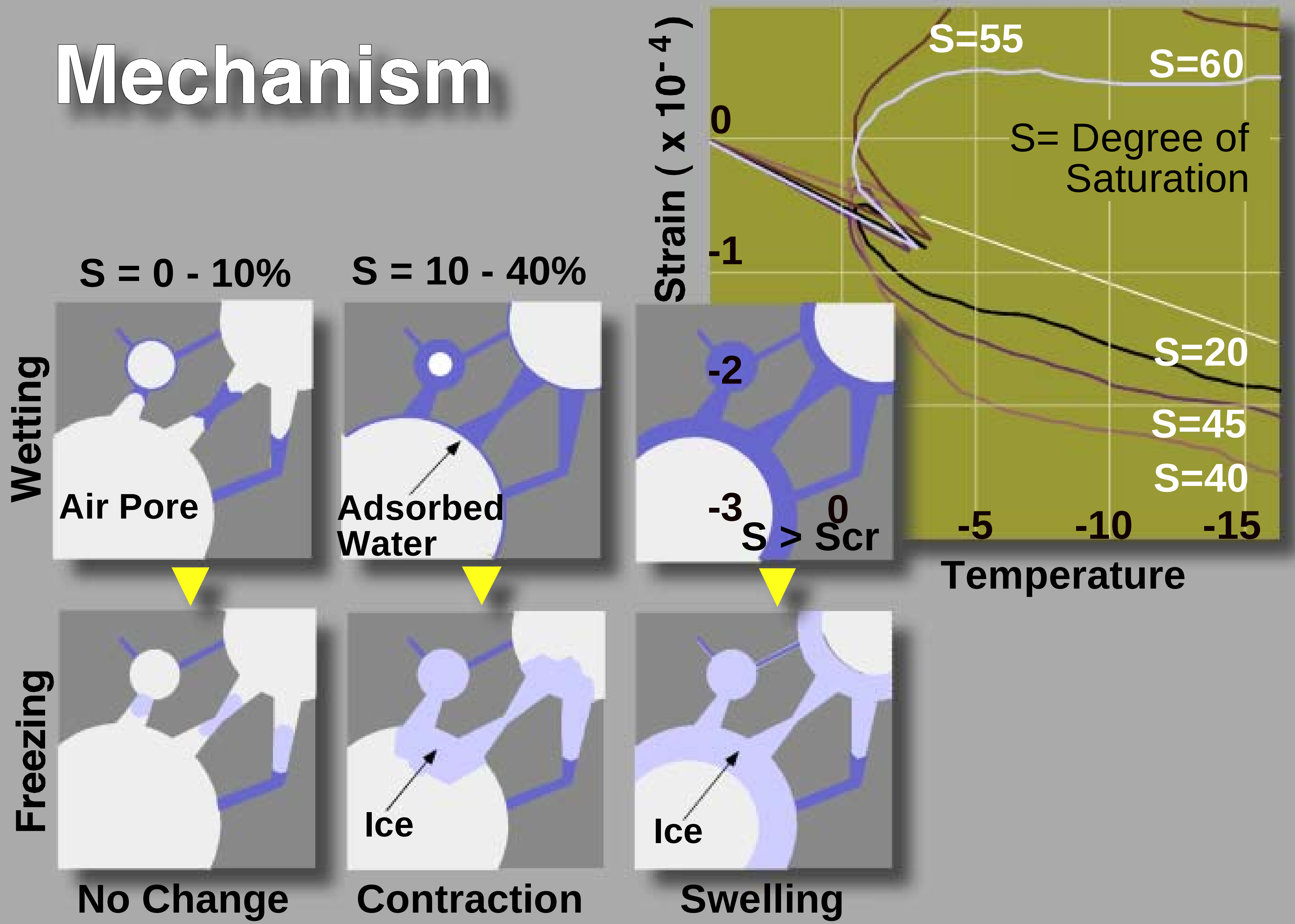
Aerated concrete d=0.503


unfrozen water film
Ice
T<To
CSH gel
To
Air pore
Free surface
(Atmospheric pressure)
Free ice formation adjacent to an air pore
Strain (x 10-4)
0
-1
-2
-3
0
-5
-10
-15
Temperature
S=55
S=60
S= Degree of Saturation
S=20
S=45
S=40



CSH gel
unfrozen
water film
Disjoining pressure
Ice
CSH gel
Hindered
adsorption
region
Entrapped air bubble
Disjoining pressure due to ice formation

Mechanism



S = 0 - 10%
S = 10 - 40%
S > Scr
Wetting
Freezing
Air Pore
Adsorbed
Water
Ice
Ice
No Change
Contraction
Swelling
Strain (x 10^-4)
0
-1
-2
-3
0
-5
-10
-15
Temperature
S=55
S=60
S= Degree of
Saturation
S=20
S=45
S=40

Thank you for your attentions