Advanced Concrete Engineering

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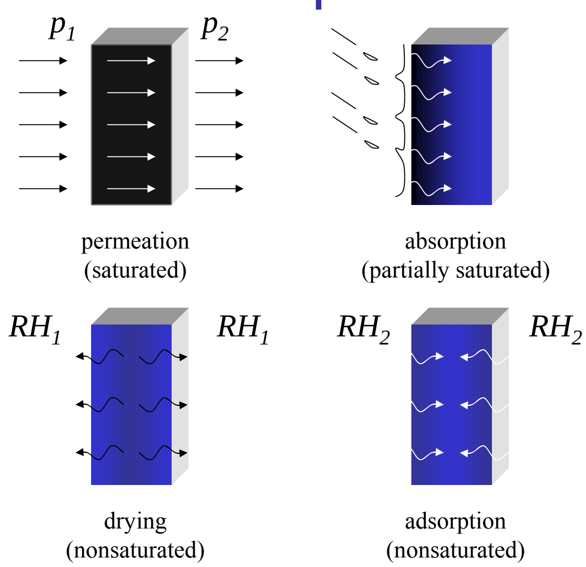
Topics in this course

- Simulation of behavior of concrete and concrete structures
  - microscopic mechanism
  - mathematical modeling
- Durability
  - transport phenomena in concrete
  - chemical reaction
  - volumetric change
- Structural
  - constitutive model for RC
  - nonlinear FE analysis of RC

Durability related topics

- Initial defect
  - creep
  - shrinkage
  - crack
- Transport phenomena
  - moisture transport in concrete
  - chloride diffusion in concrete
  - transport phenomena of wind-blown chloride
- Deterioration process
  - corrosion of reinforcement
  - corrosion crack
  - structural behavior after corrosion

Moisture transport in concrete

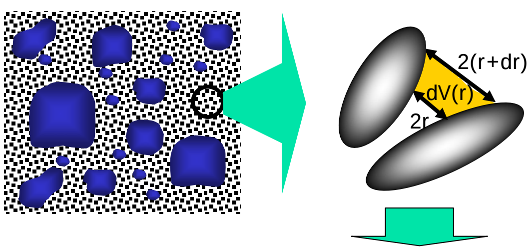


Moisture transport in nonsaturated concrete

- micropore structure of concrete
- thermodynamic behavior of water in pores
  - thermodynamic equilibrium
  - transport of vapor and liquid water in concrete
- numerical sumulation

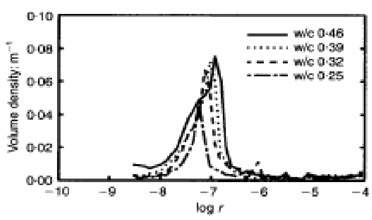
Micropore structure of concrete

concrete

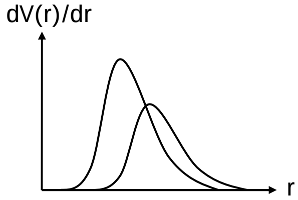


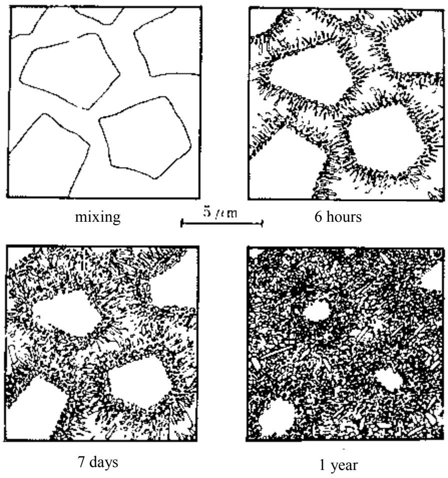
$V(r)=V_o\{1-\exp(-Br^c)\}$

pore size distribution measured by mercury injection method



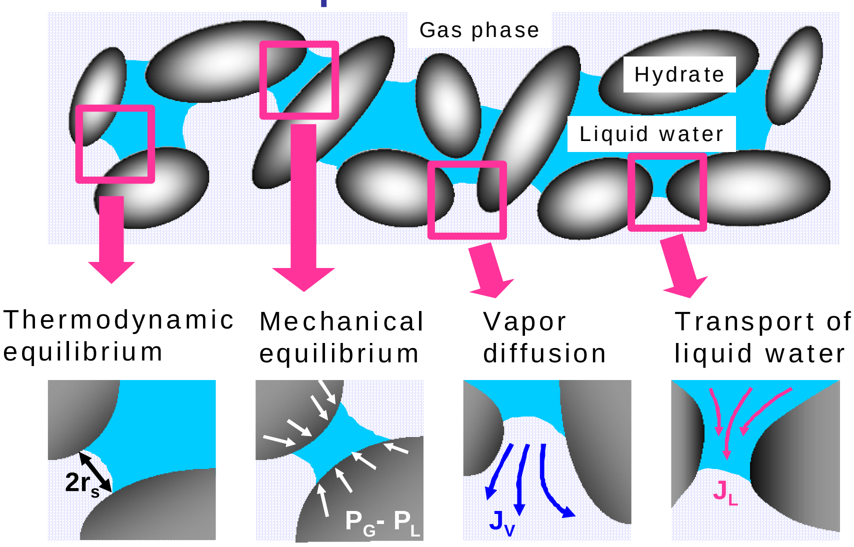
Pore size distribution function





Microstructural development of cement paste

Thermodynamic behavior of water in pores



Phases of materials in pores

- gas phase
  - ideal gas mixture of vapor and dry air
- liquid phase
  - pure liquid water with surface tension
- solid phase
  - not considered

$V_o = V_g + V_l$

V_o: total porosity in unit concrete volume (material constant)
V_g: volume of gas phase in unit concrete volume (variable)
V_l: volume of liquid phase in unit concrete volume (variable)

Properties of gas phase

- Mass: $w_g = w_v + w_a$
- molecule: $n_g = n_v + n_a$ $\quad n_g = \frac{w_g}{M_g} \quad n_v = \frac{w_v}{M_v} \quad n_a = \frac{w_a}{M_a}$
- density: $\rho_g = \frac{w_g}{V_g} \quad \rho_v = \frac{w_v}{V_g} \quad \rho_a = \frac{w_a}{V_g}$
- state equation for ideal gas:

$$p_g V_g = n_g RT \qquad p_v V_g = n_v RT \qquad p_a V_g = n_a RT$$

or

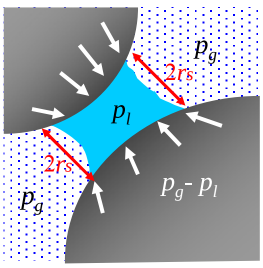
$$p_g = \rho_g \frac{RT}{M_g} \qquad p_v = \rho_v \frac{RT}{M_v} \qquad p_a = \rho_a \frac{RT}{M_a}$$

- pressure: $p_g = p_v + p_a$

Properties of liquid phase

- incompressive fluid: ρ_l=const.
- density: $\rho_l = \dfrac{w_l}{V_l}$

Mechanical equilibrium of liquid and gas in small pores



Thermodynamic pressure gap

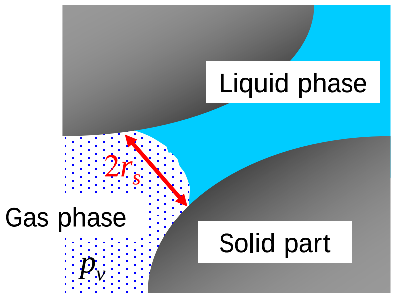
Laplace equation

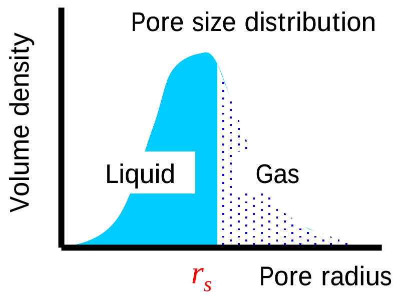
$$p_g - p_l = \frac{2\gamma}{r_S}$$

γ : surface tension of water (physical constant)

r_S: pore radius in which the interface between liquid and gas is developed (variable)

Thermodynamic equilibrium of liquid and gas in pores



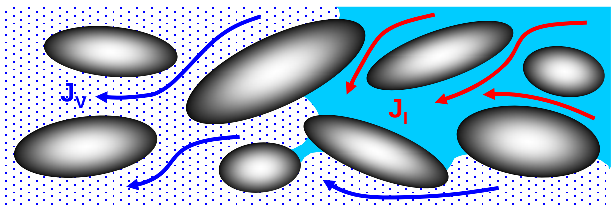


Kelvin equation
(capillary condensation theory)

$$\ln \frac{p_v}{p_{vo}} = -\frac{2\gamma M_w}{RT\rho_l}\frac{1}{r_s}$$

reversible

Transport of vapor and liquid water in pore structure



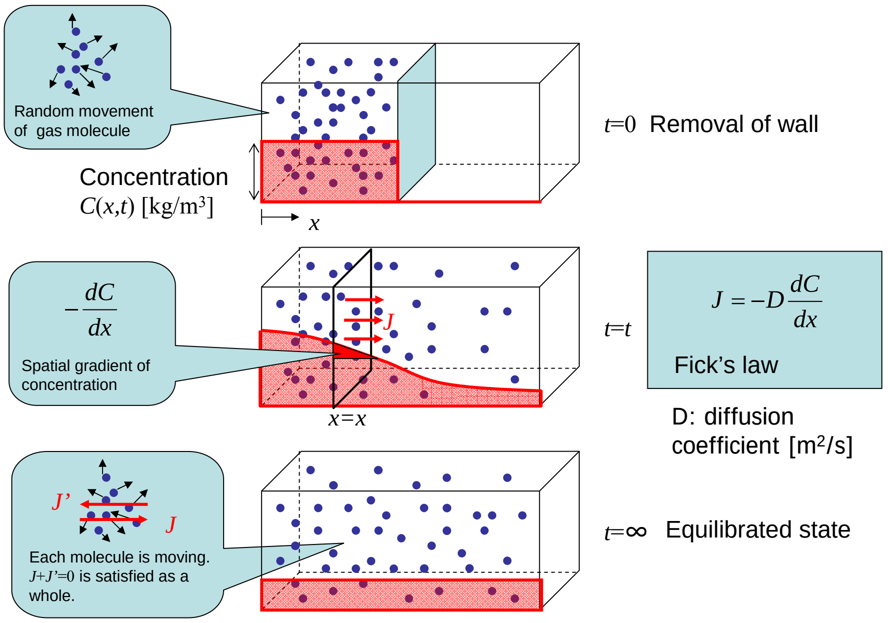
vapor $$J_v = -k_v V_g D_{vo} grad\rho_v$$

Reciprocal molecular diffusion in porous media

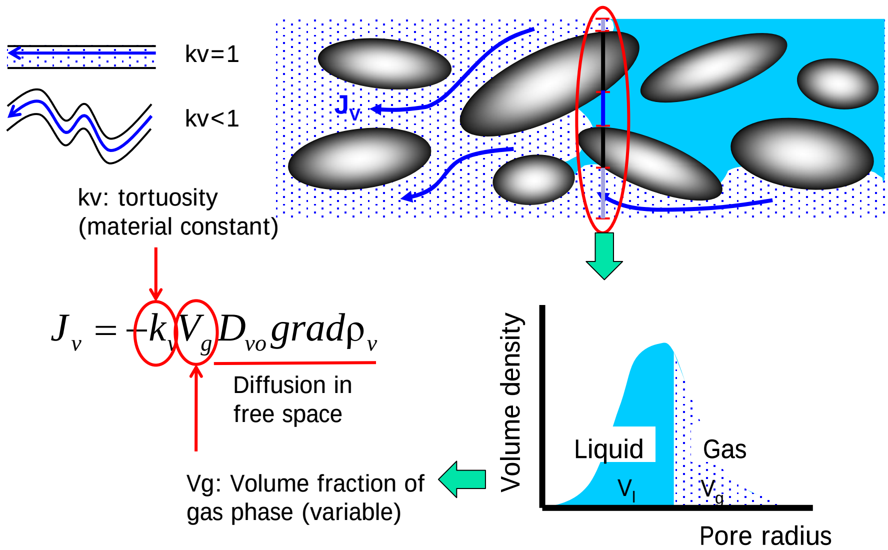
liquid water $$J_l = \int_0^{r_s}\left[\rho_l \frac{dV_{(r)}}{dr}\left\{-k_l \frac{r^2}{8\mu} grad\left(-\frac{2\gamma}{r_s}\right)\right\}\right]dr$$

Laminar flow in cylindrical pore driven by spatial gradient of pressure drop

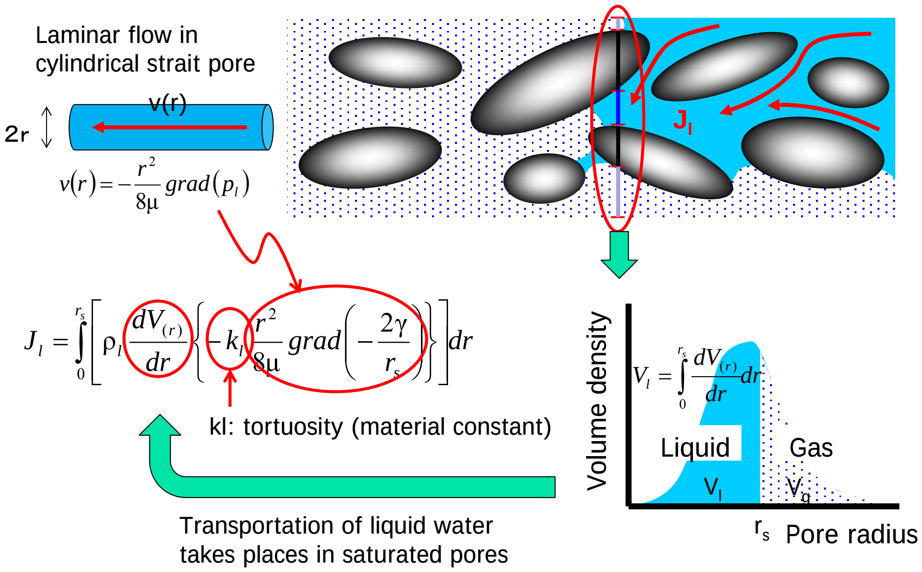
Diffusion of gas molecule in free space



Transport of vapor in pore structure



Transport of liquid water in (non-saturated) pore structure

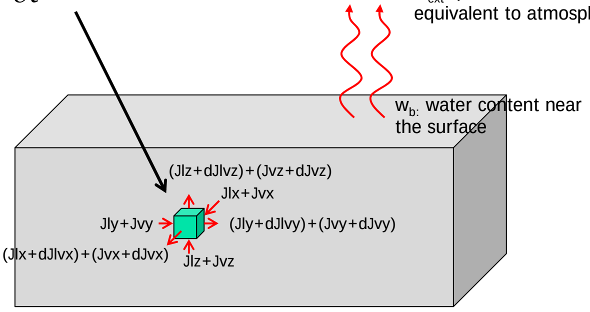


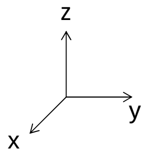
Mass conservation law of water and boundary condition

In concrete: $\frac{\partial w}{\partial t} = -div(J_l + J_v)$

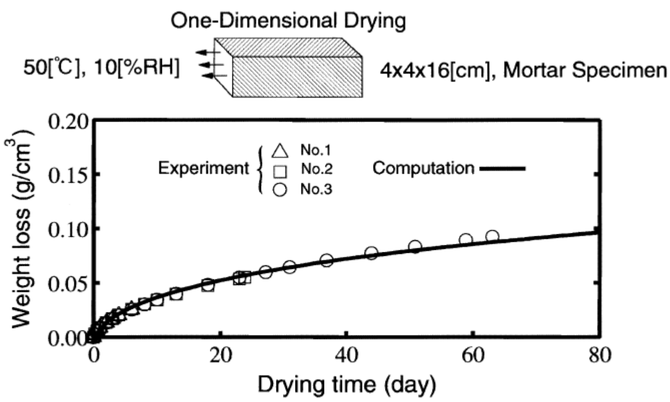
At boundary: $J_b = \alpha(w_b - w_{ext})$

w_{ext}: pseudo water content equivalent to atmospheric humidity



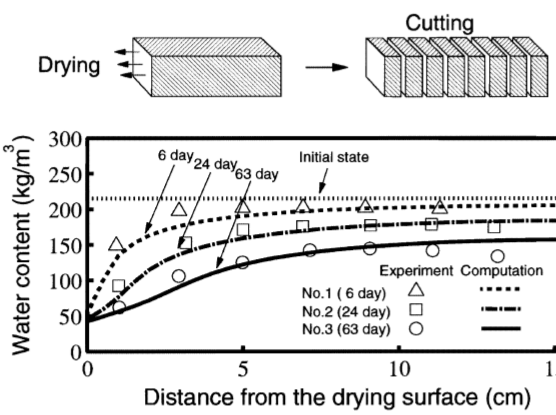


Experimental Verification



Drying Time - Weight Loss of Specimen

Experimental Verification



Moisture Profiles along Drying Direction