Babylonia, Mesopotamia, Approx. 1800 BC

Powers' model

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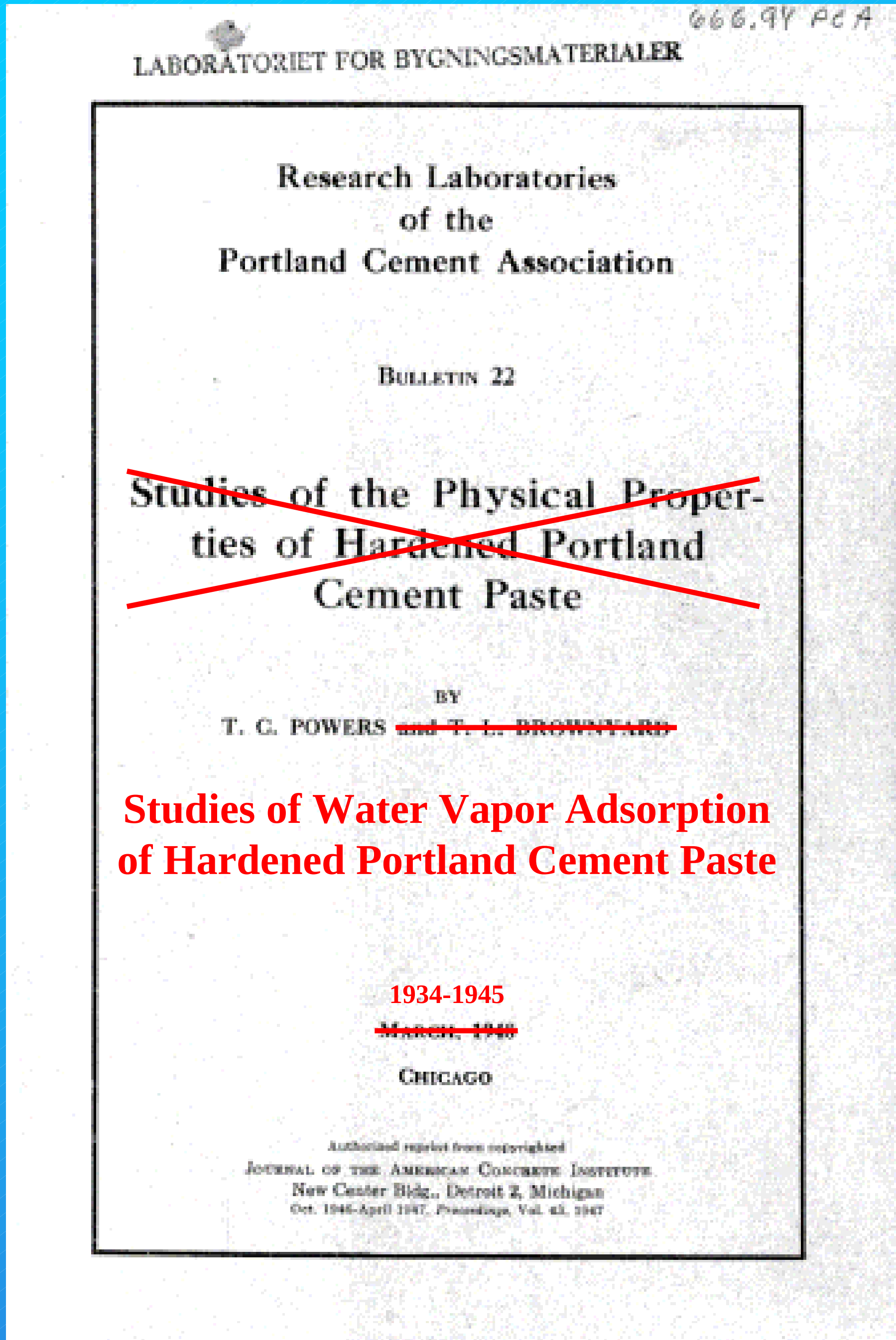
PCA bulletin 22



Research Laboratories
of the
Portland Cement Association

BULLETIN 22

~~Studies of the Physical Properties of Hardened Portland Cement Paste~~

BY

T. C. POWERS ~~and T. L. BROWNYARD~~

Studies of Water Vapor Adsorption of Hardened Portland Cement Paste

1934-1945

~~MARCH, 1948~~

CHICAGO

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JOURNAL OF THE AMERICAN CONCRETE INSTITUTE
New Center Bldg., Detroit 2, Michigan
Oct. 1946-April 1947, *Proceedings*, Vol. 43, 1947

Experimental content

Measurements

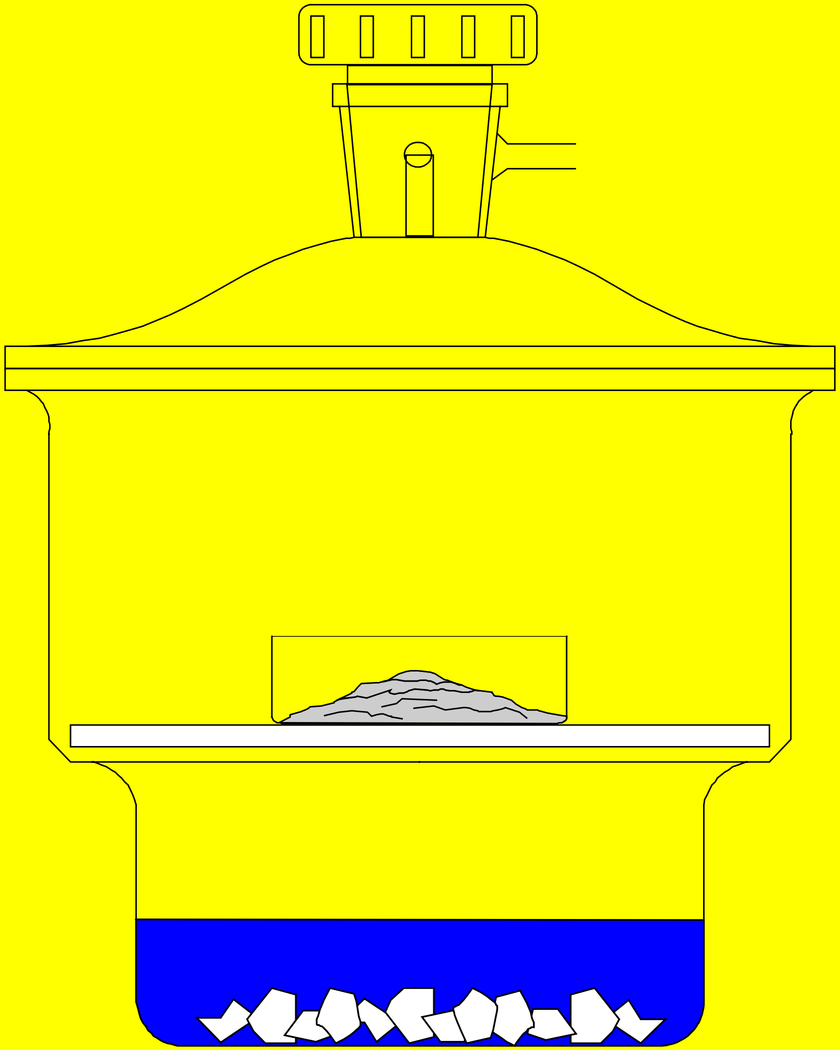
- Adsorption isotherms
  (1st, 2nd, 3rd, ad- & desorption + partial)
- Non-evaporable water

- Strength
- E-modulus
- Heat of hydration
- Heat of water adsorption
- Freezing dilation
- Drying shrikaage
- Termal deformation
- Permeability

Parameters

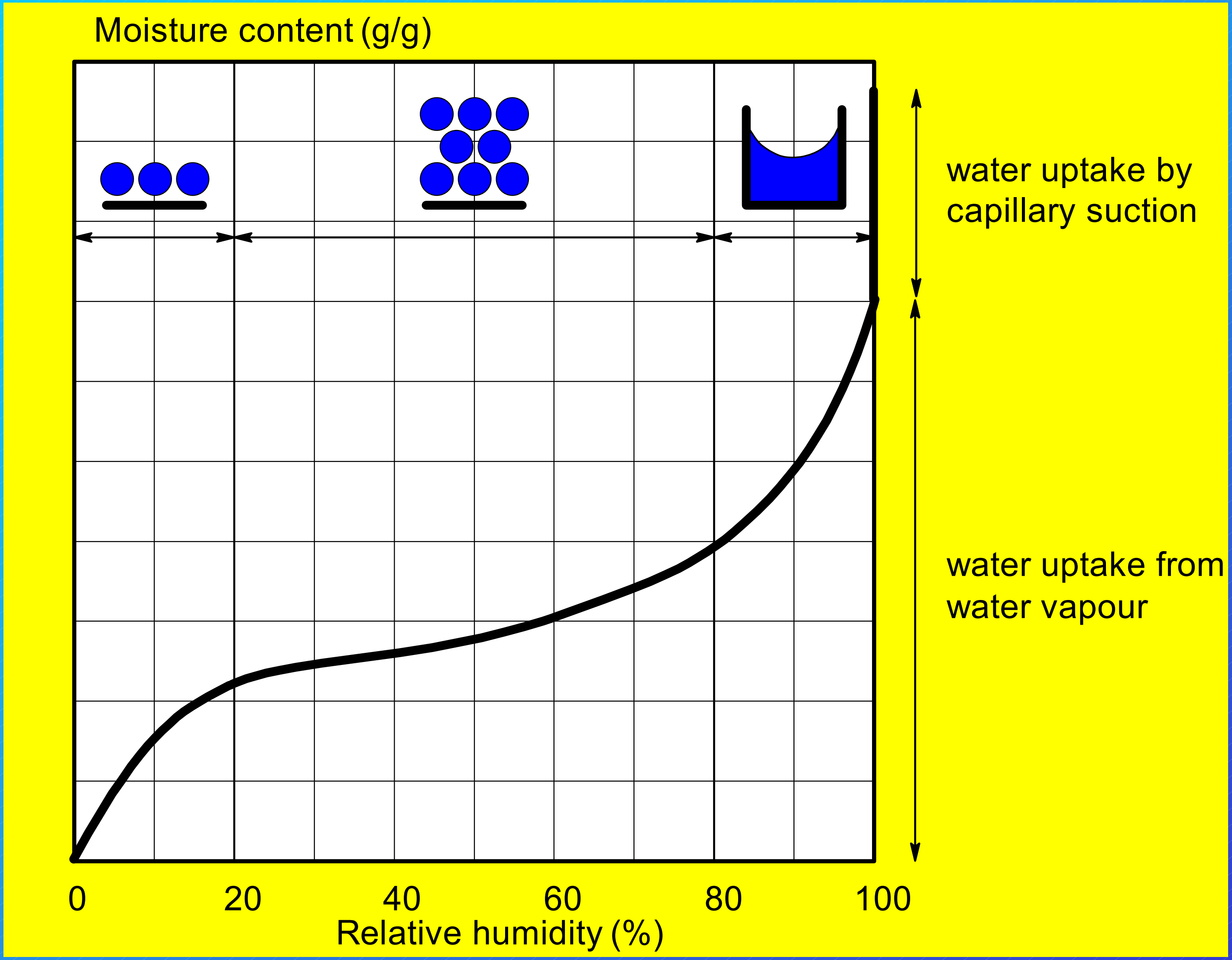
- w/c
- Age
- Cement type
- Curing conditions

Sorption isotherm experiment

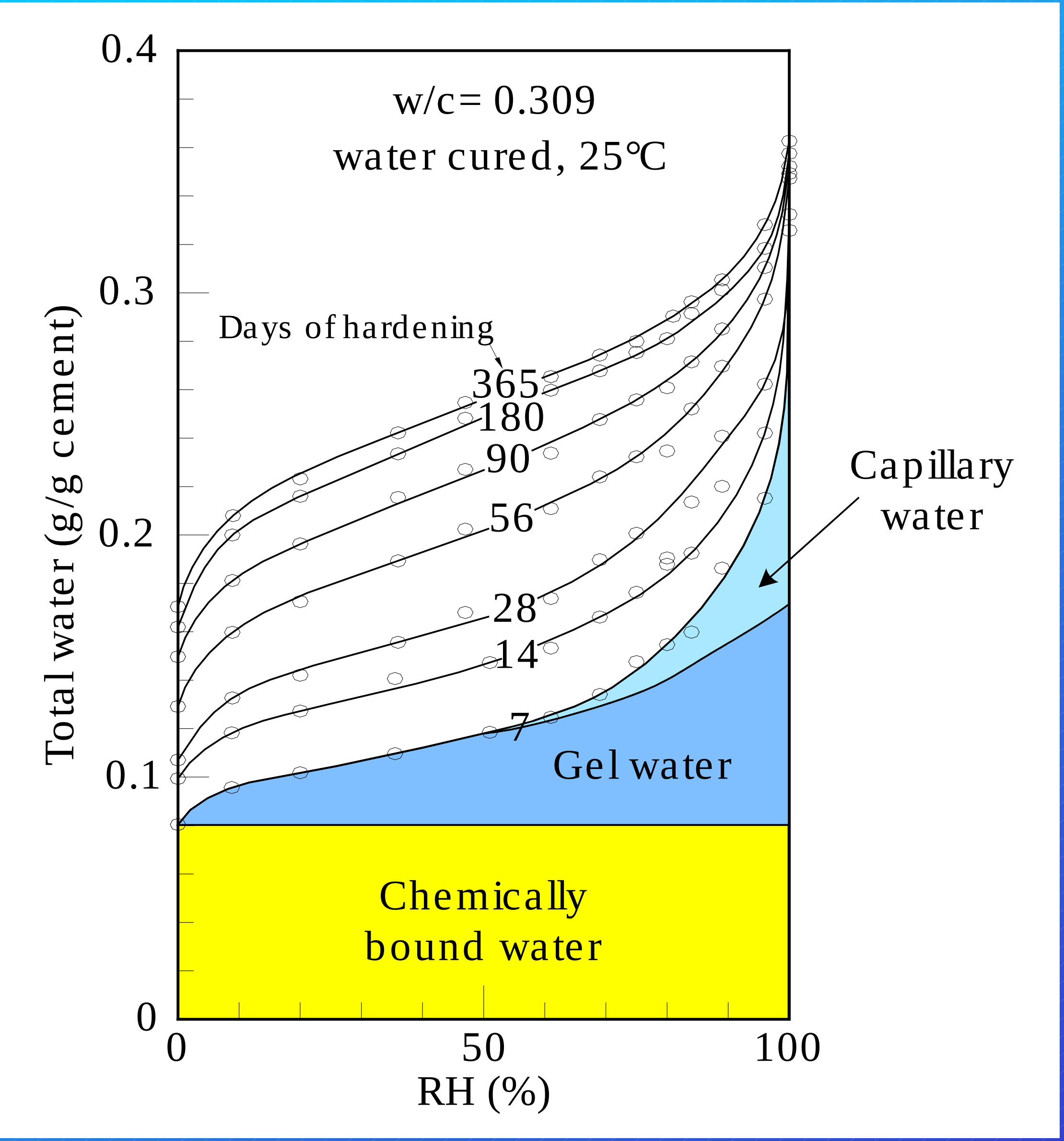


Salt	$RH_{20°C}$
LiCl:	12%
CH_3COOK:	23%
K_2CO_3:	43%
$Mg(NO_3)_2$:	54%
$NaNO_3$:	66%
NaCl:	75%
$(NH_4)_2SO_4$:	81%
KCl:	85%
$BaCl_2$:	91%
KNO_3:	95%
K_2SO_4:	98%

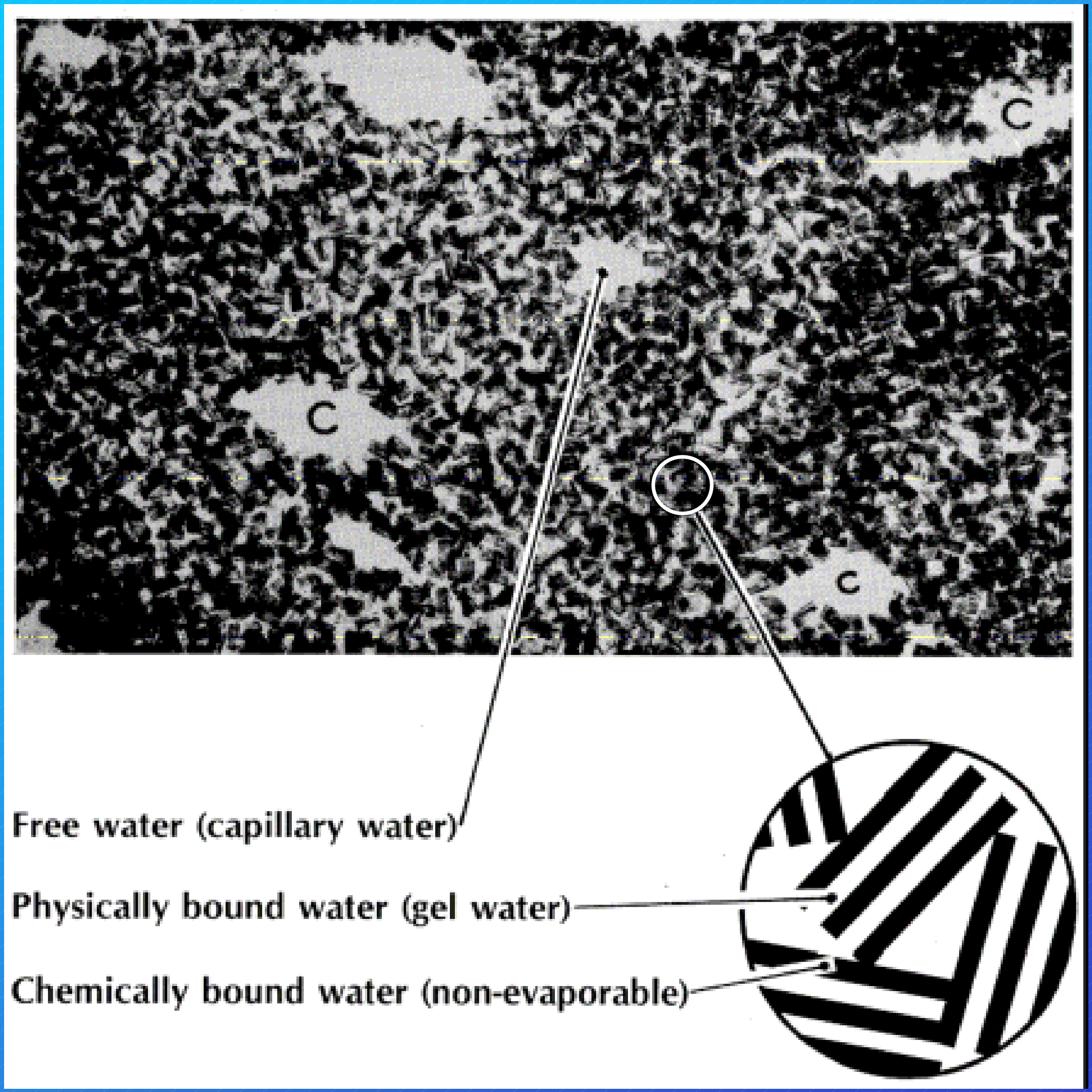
Sorption isotherm



Experimental results



Phases of water in cement paste



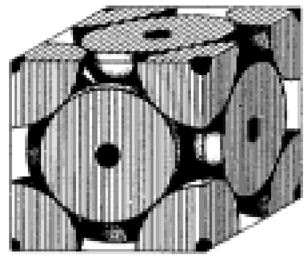
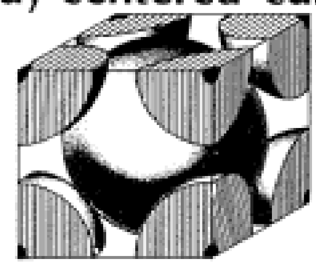
Key figures in Powers' model

Non-evaporable water
~ 0.23 g/g cement reacted

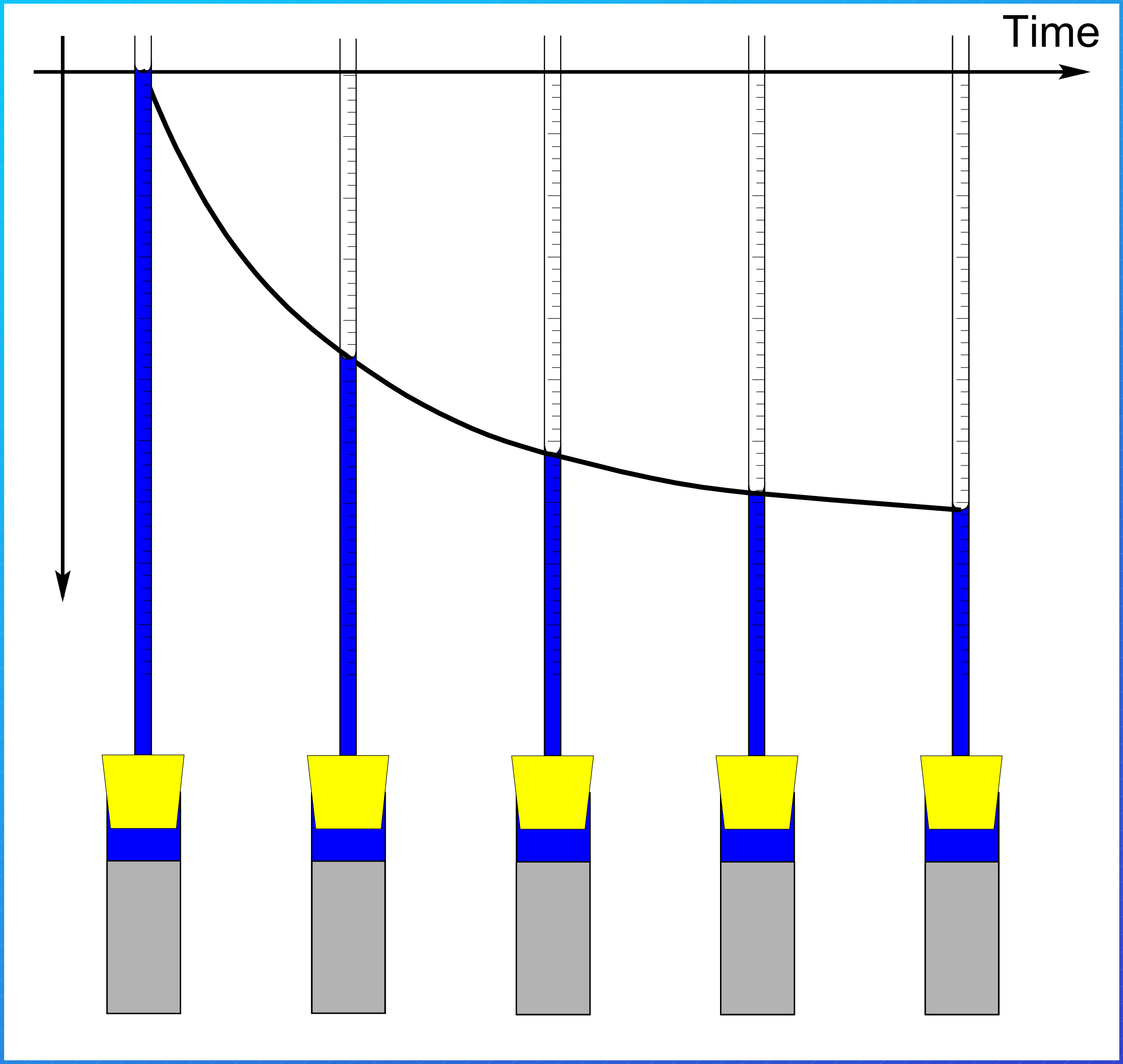
Gel water
~ 0.19 g/g cement reacted

Chemical shrinkage
~ 6.4 ml/100 g cement reacted

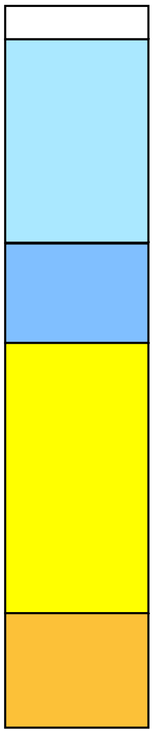
3-D packing of identical spheres

Type	Kissing number	% solid volume
Face-centered cubic 	12	74
Body-centered cubic 	8	68
Random	?	64
Simple cubic	6	52
Lowest density rigid	4	6

Chemical shrinkage



Formulas in Powers' Model



$$V_{c.s} = 0.2\cdot(1-p)\cdot\alpha \quad = \rho_c\cdot 6.4\cdot 10^{-5}\cdot(1-p)\cdot\alpha$$

$$V_{c.w} = p - 1.3\cdot(1-p)\cdot\alpha \quad = p - (\rho_c/\rho_w)\cdot(0.19+0.23)\cdot(1-p)\cdot\alpha$$

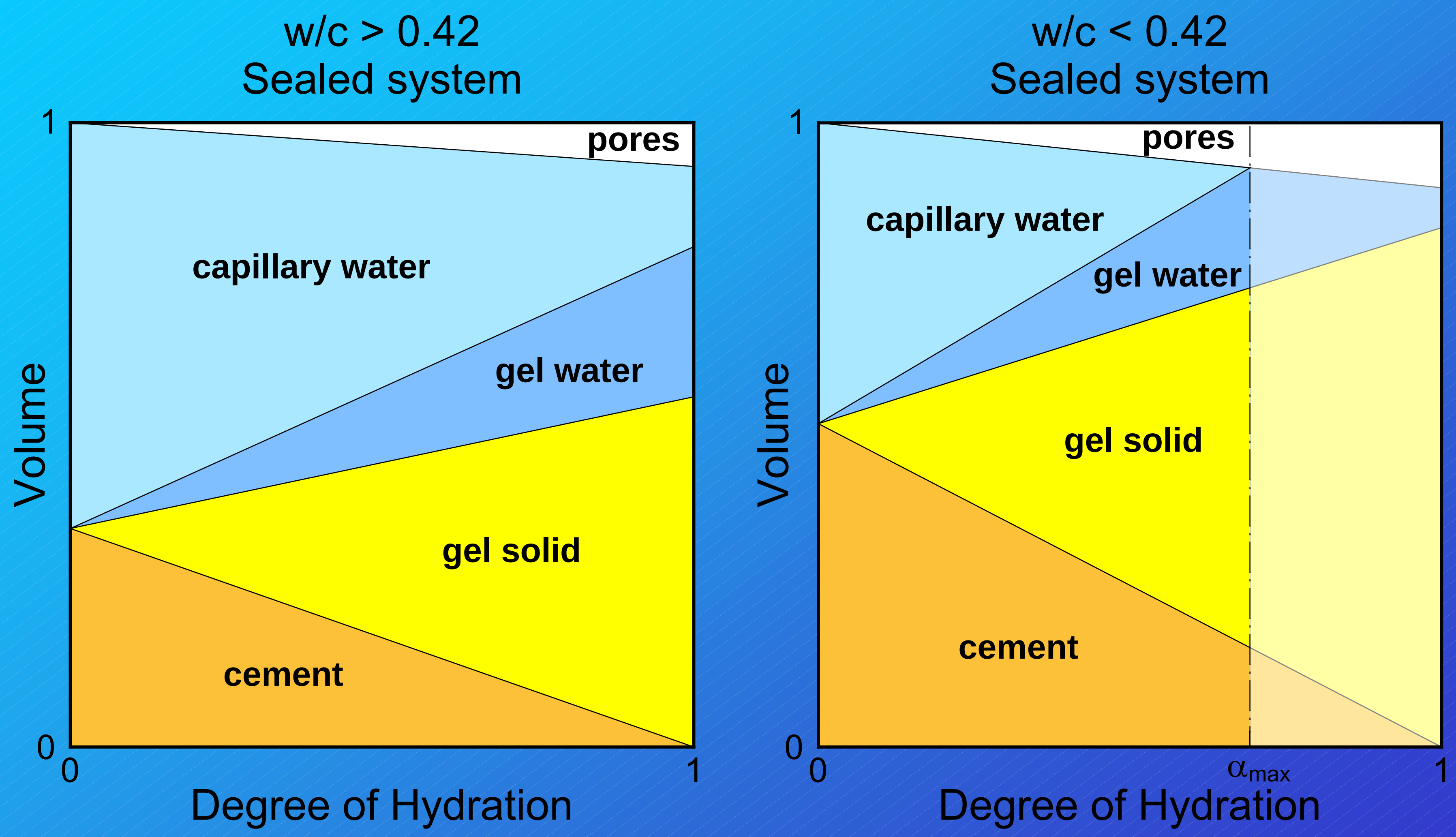
$$V_{g.w} = 0.6\cdot(1-p)\cdot\alpha \quad = (\rho_c/\rho_w)\cdot 0.19\cdot(1-p)\cdot\alpha$$

$$V_{g.s} = 1.5\cdot(1-p)\cdot\alpha \quad = (1-\rho_c\cdot 6.4\cdot 10^{-5}+(\rho_c/\rho_w)\cdot 0.23)\cdot(1-p)\cdot\alpha$$

$$V_c = (1-p)\cdot(1-\alpha)$$

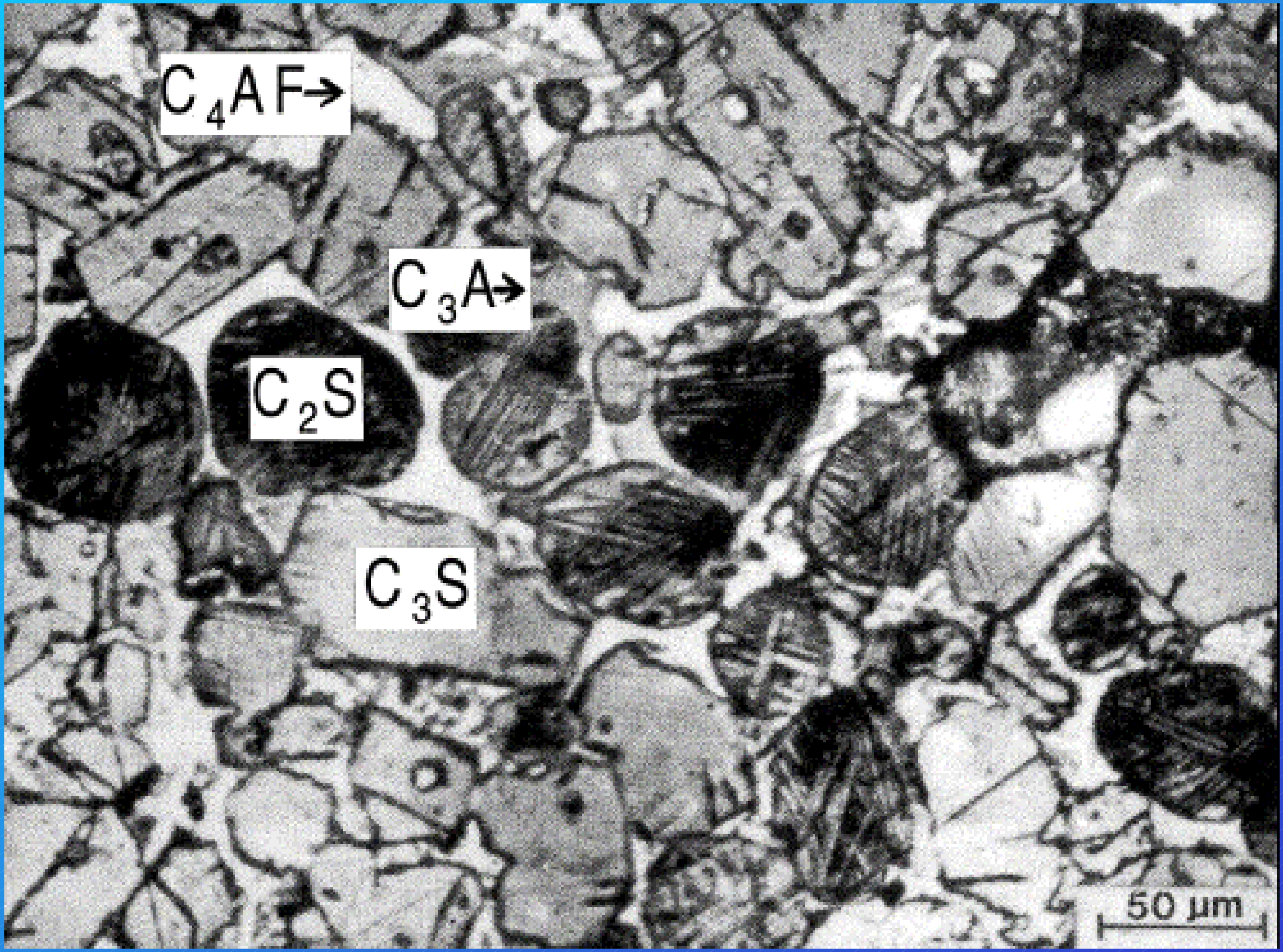
$$p = \frac{w/c}{w/c + \rho_w/\rho_c} \qquad \rho_w = 1000\ \text{kg/m}^3 \qquad \rho_c = 3150\ \text{kg/m}^3$$

Powers' Model



Degree of hydration

$$\alpha = \sum_i w_i \cdot \alpha_i$$



Stability of reaction products

$C_2AH_{7.5}$

CAH_{10}

$C_3AH_{1.43}$

C_2AH_5

$C_{12}A_7H$

$$C_4AH_{19} \underset{\sim 85\%\ RH}{\overset{6H}{\rightleftharpoons}} C_4AH_{13} \underset{\sim 10\%\ RH}{\overset{2H}{\rightleftharpoons}} C_4AH_{11} \underset{\sim 0.01\%\ RH}{\overset{4H}{\rightleftharpoons}} C_4AH_7$$

CAH_4

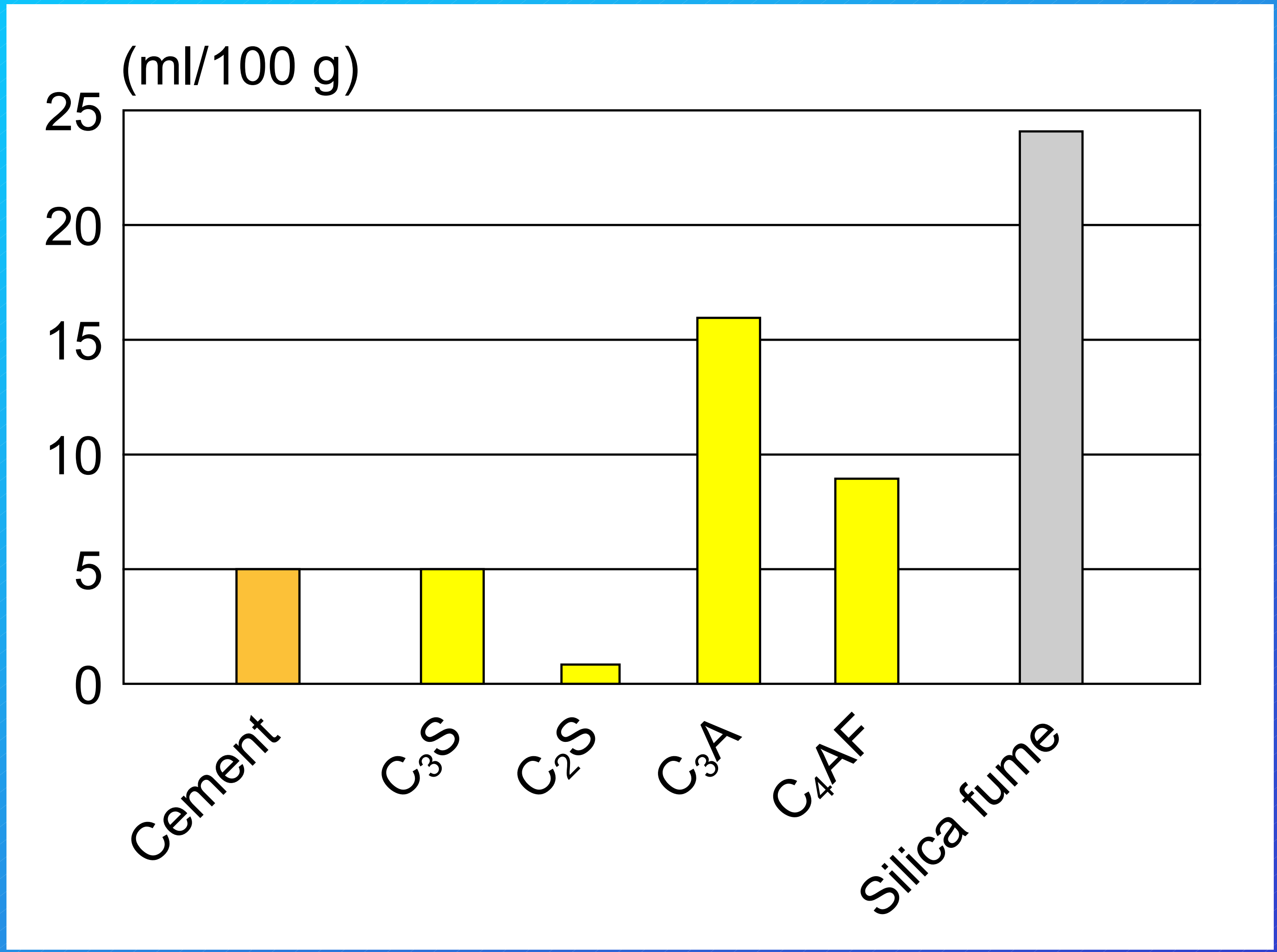
C_3AH_6

CAH_7

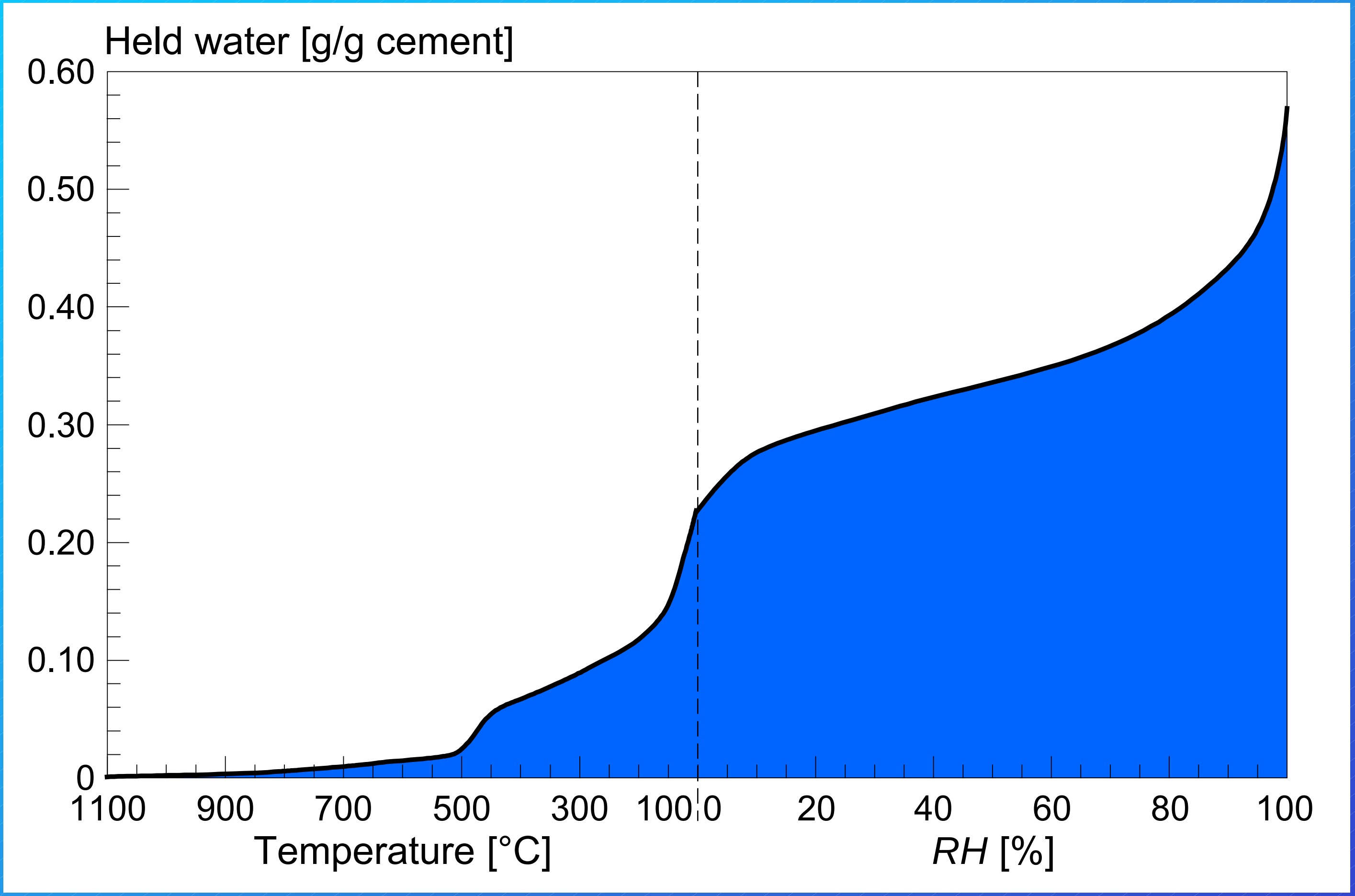
$C_4A_3H_3$

C_2AH_8

Chemical shrinkage of components

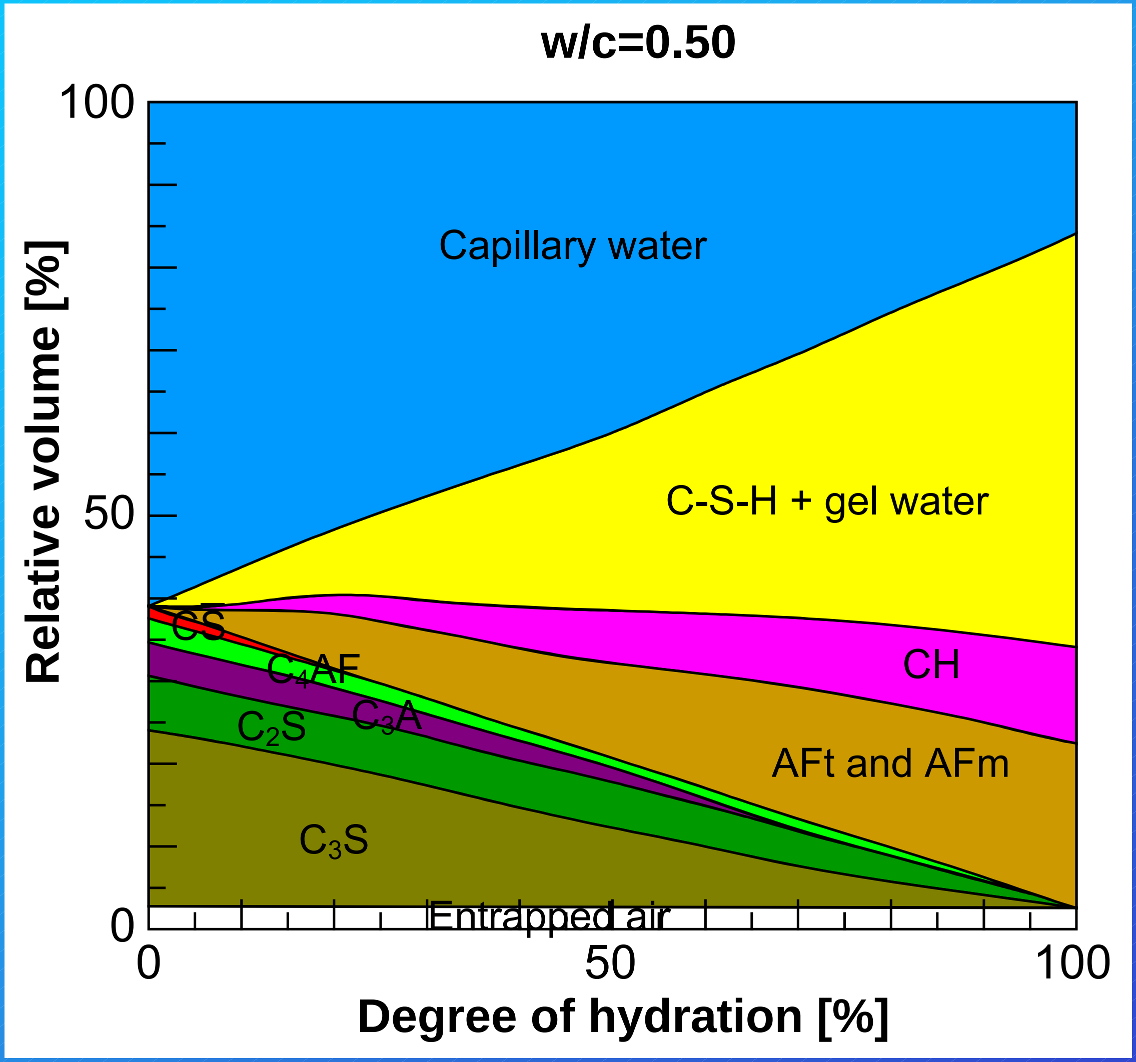


Water bound in cement paste



Jensen (2005)

The true volumes

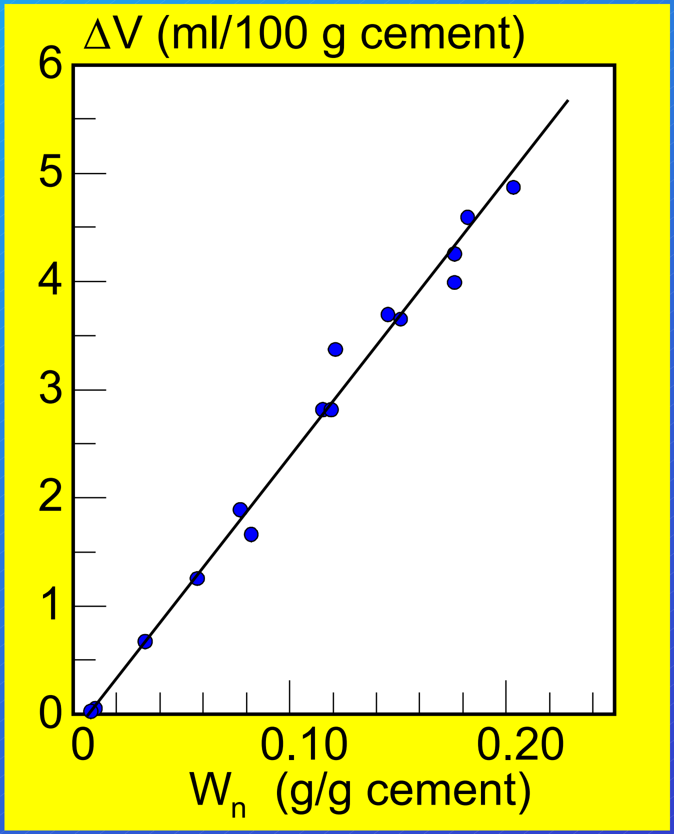


Tennis & Jennings (2002)

Hydration indicators

- Non-evaporable water
- Chemical shrinkage
- BET specific surface area
- Heat evolution
- Calcium hydroxide content

- Compressive strength



Key figures in Powers' model

Non-evaporable water
~ 0 g/g silica fume reacted

Gel water
~ 0.6 g/g silica fume reacted

Chemical shrinkage
~ 24 ml/100 g silica fume reacted