Problems of Concrete Structures and Effort toward Durability Design in Thailand

By

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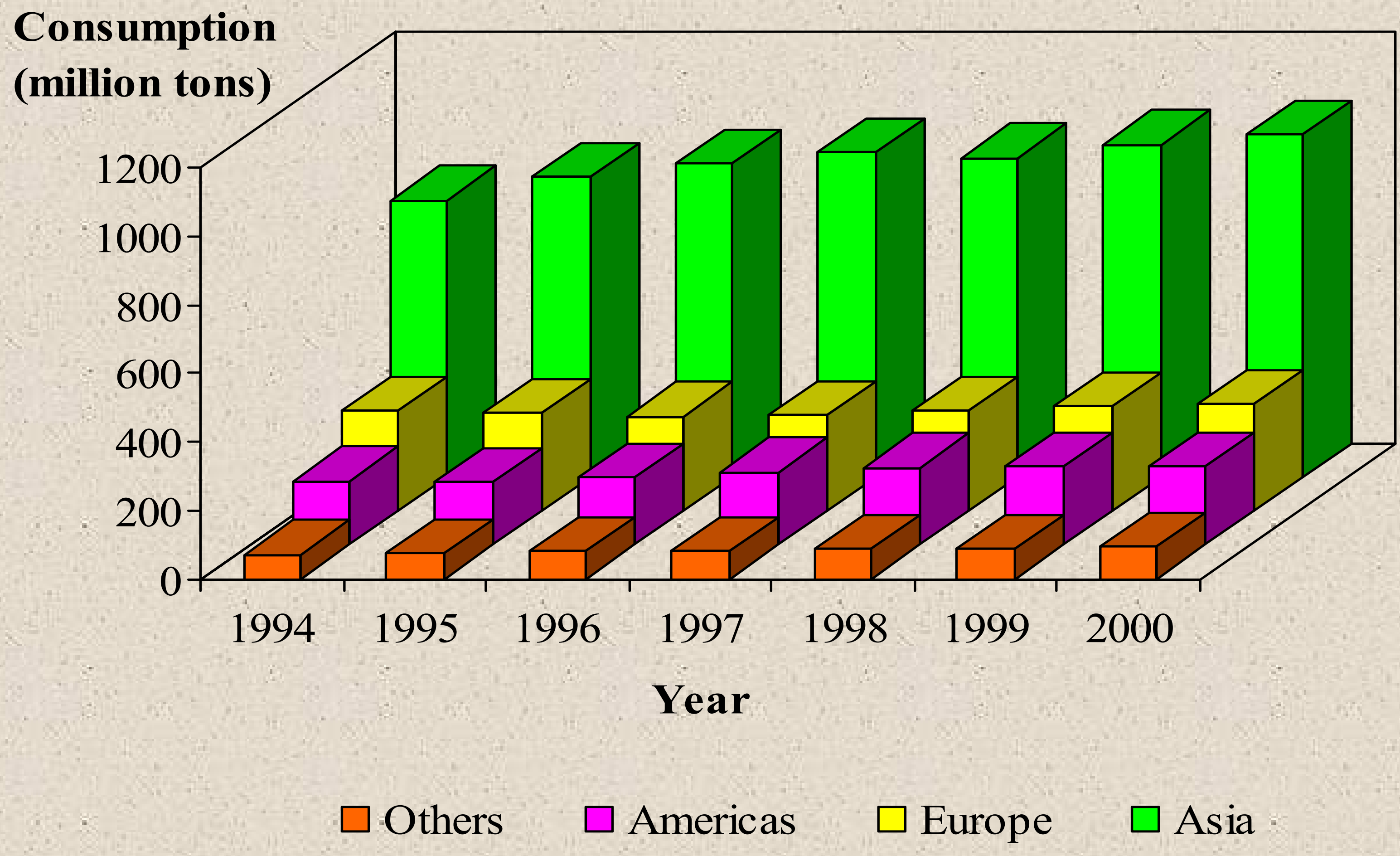
Interesting Statistics about Concrete in Thailand

World Cement Consumption

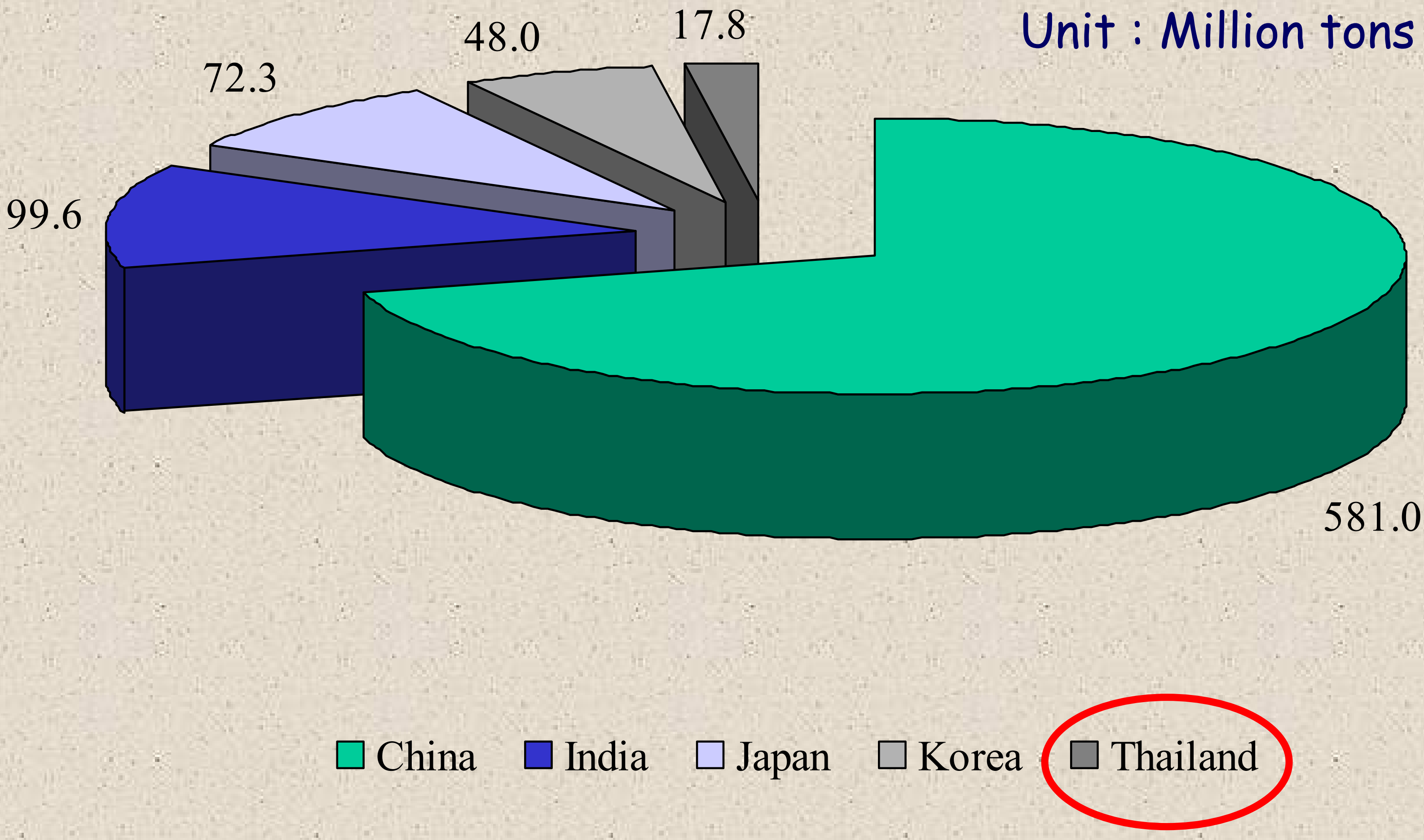


Cement Consumption in Asia

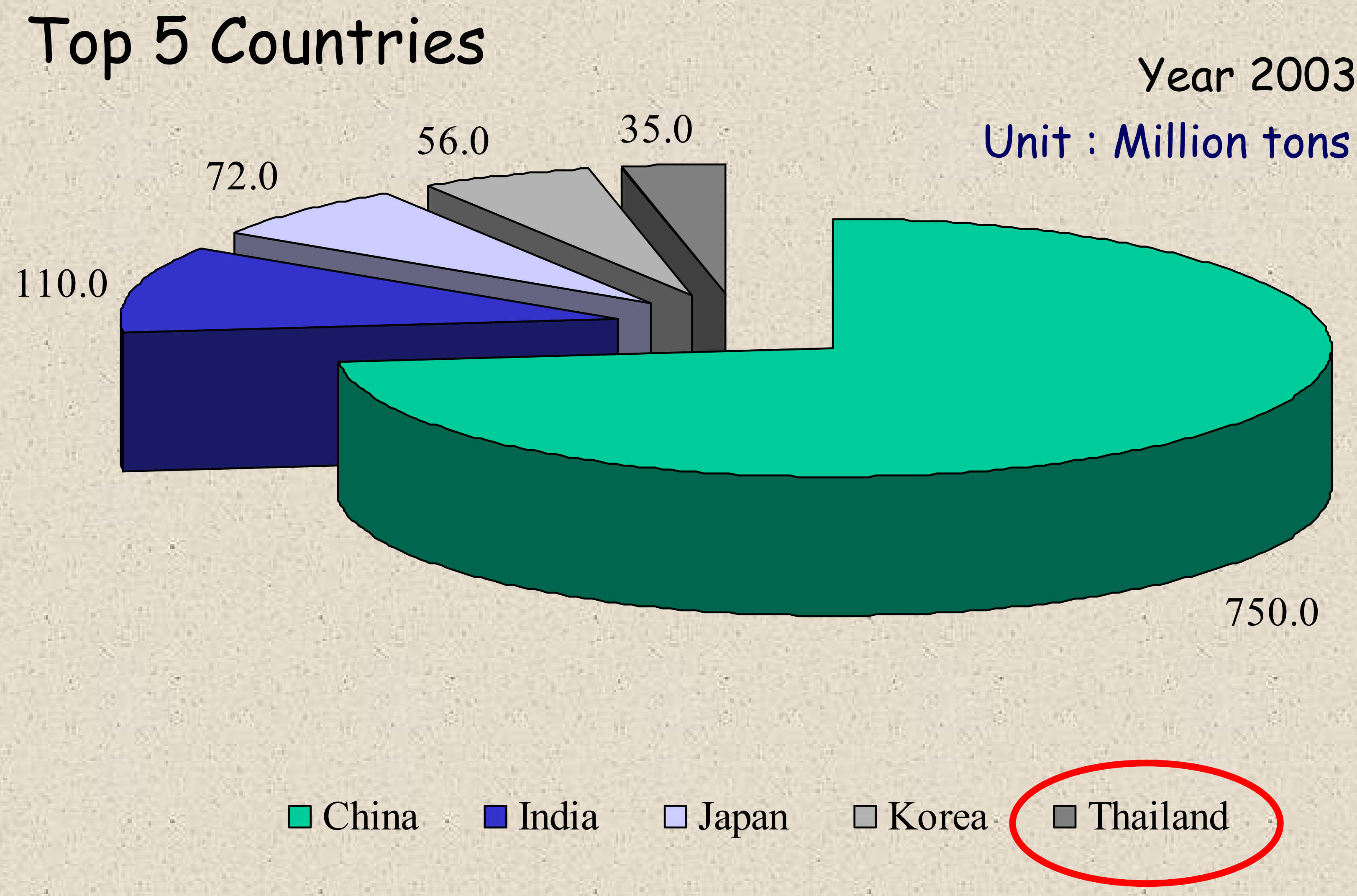
Top 5 Countries

Year 2000

Unit : Million tons



Cement Production in Asia



Per capita consumption in Thailand in 2004

Cement + Fly ash : about 450 - 500 kg

Concrete : about 1 m^3

Growth : about 10-15% or more from 2003

Some World Records in Thailand

Klong Tha Dan Dam

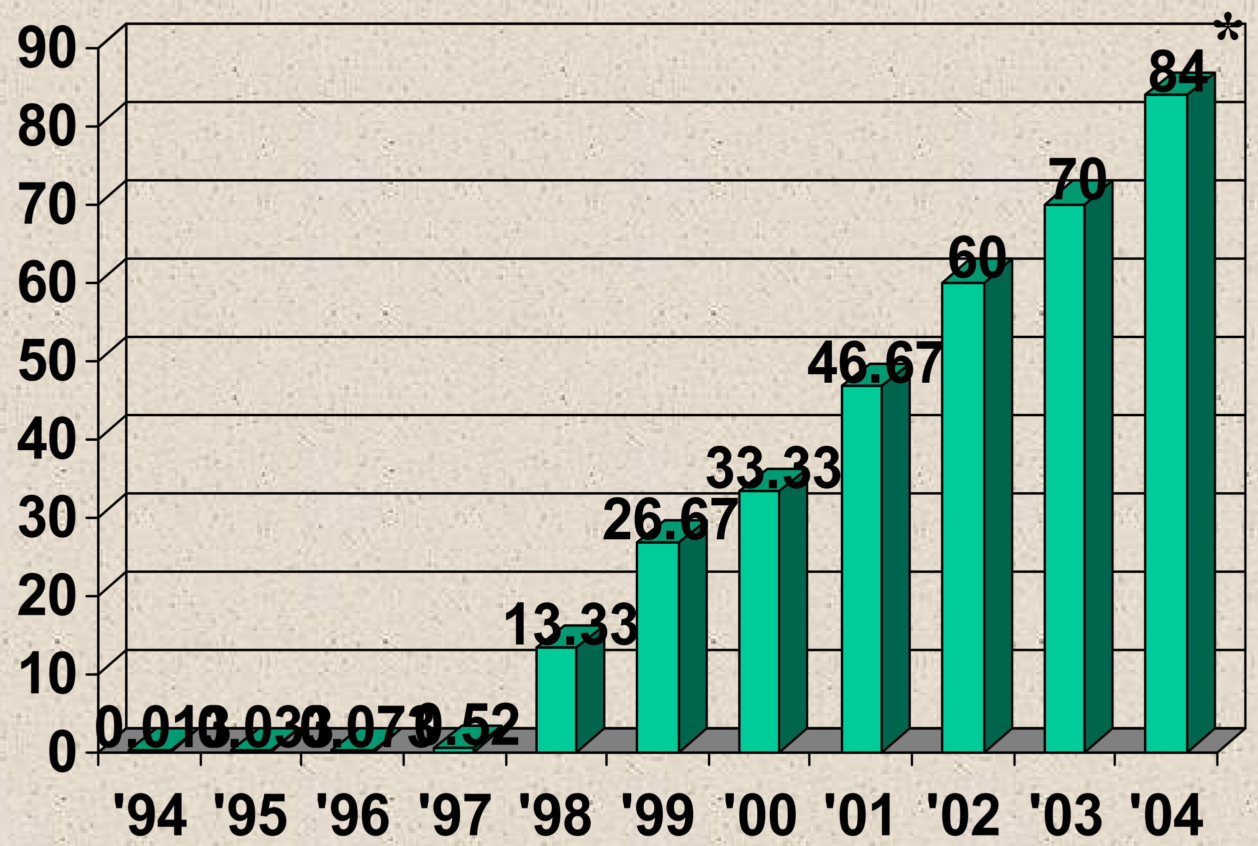
- Highest amount of RCC utilization → 5.5 million m^3
- Highest amount of RCC placing in 1 day → 15,000 m^3

Fly Ash

- Highest effective utilization in concrete → 80% of total fly ash production

Khlong Ta Dan Dam Project with 5.5 million m^3 of RCC

Consumption/Production (%)



Computed based on annual production of 3 million tons

However, those are just in term of quantity.

Still many problems regarding quality.

Research area

Central Thailand

- Bangkok
- Nakornsawan
- Ratchaburi
- Lob-Buri
- Ayudtaya
- Samutsongkarm
- Pathum Thani

Seaside areas

- Samutprakarn
- Cholburi

Environmental condition	Classification	
	Number of structures	Percent
Central Thailand	159	87.85
Seaside area	22	12.15
Total	181	100.00

7-year Surveys on Situation of Concrete Structures in Thailand

- **Location** : central and eastern parts of Thailand (different environment)
- **Age of structures** : from during construction until very aged ones
- **Finding** : Many problems on low quality structures

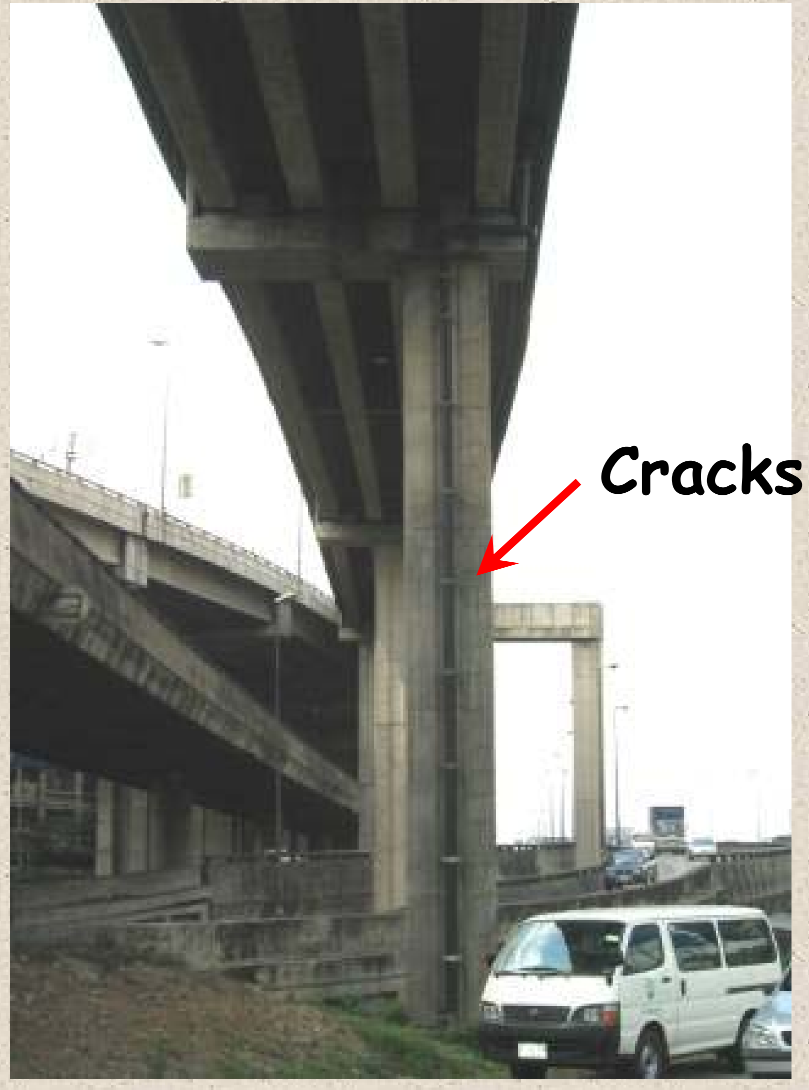
Problems

- Construction of new structures
- Already existing structures

Problems occurs in all Steps of Practice

- Analysis and Design
- Materials
- Construction
- Protection and Maintenance

Analysis and Design Problem



Strength design with no durability consideration

Material Problems

Self-restraint thermal crack

Use Concrete with Segregation

Drying Shrinkage

Alkali-Aggregate Reaction

Biological Degradation

Problems on Poor Construction

Plastic Shrinkage

Cracks due to Plastic Settlement

Early steel corrosion due to Carbonation
(not enough concrete cover)


Steel Corrosion (too small concrete cover)


Maintenance Problems

Chloride Induced Corrosion
(Early Maintenance Program is Required)

Chloride induced Steel Corrosion

Severe Steel Corrosion due to Carbonation


Incompatible repair material

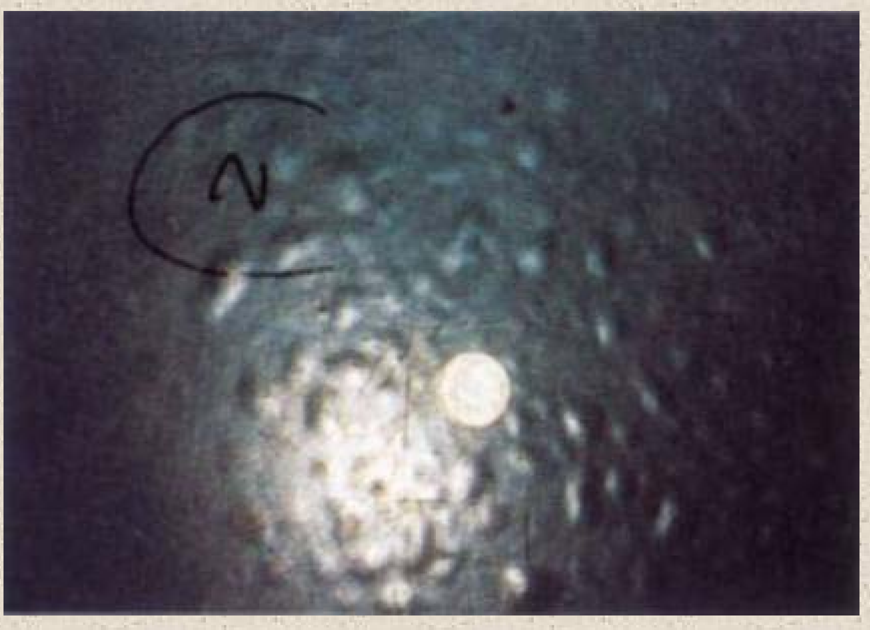
Incipient Anode Problem

Picture from SIKA (Thailand)

Improper active crack repair using epoxy mortar with low deformability

Pictures from SIKA (Thailand)

Failure of Coating



Pictures from SIKA (Thailand)

- Swelling and debonding of the coating material due to moisture behind the coat

Solution

To obtain durable structures

- For New Construction
  - Good Analysis and Design (new PWCP design acts)
  - Good Materials (new TCA material spec.)
  - Good Construction (?)
  - Good Protection and Maintenance
- For Already Existing Structures*
  - Monitoring, Protection, Maintenance, Repair, Strengthening

* Not Today's topic

Analysis and Design

↓

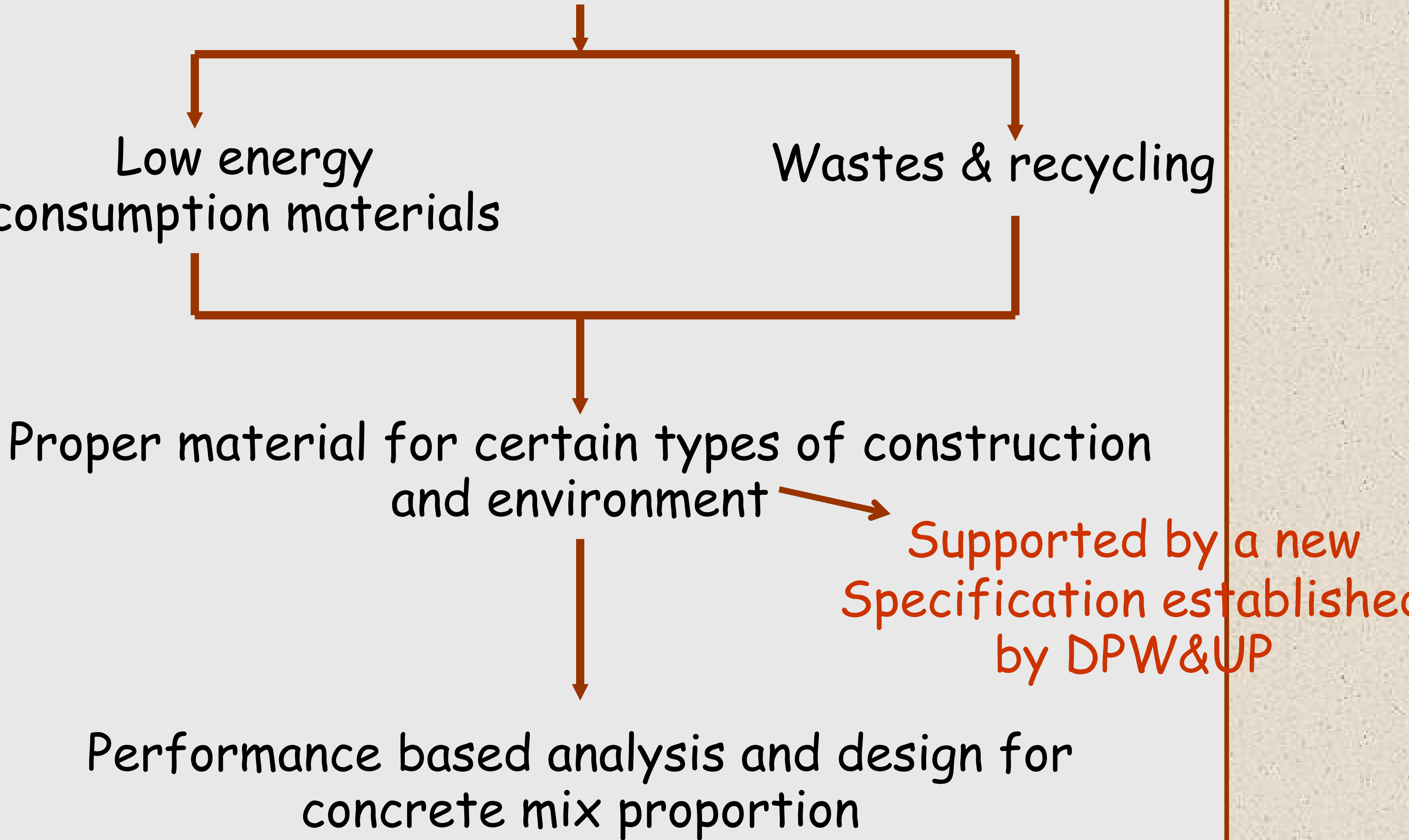
Design considering long term properties (durability, creep, fatigues, ductility), easiness of construction and maintenance

↓

A new building acts enforcing both short term and long term properties of structures by Department of Public Works & Urban Planning

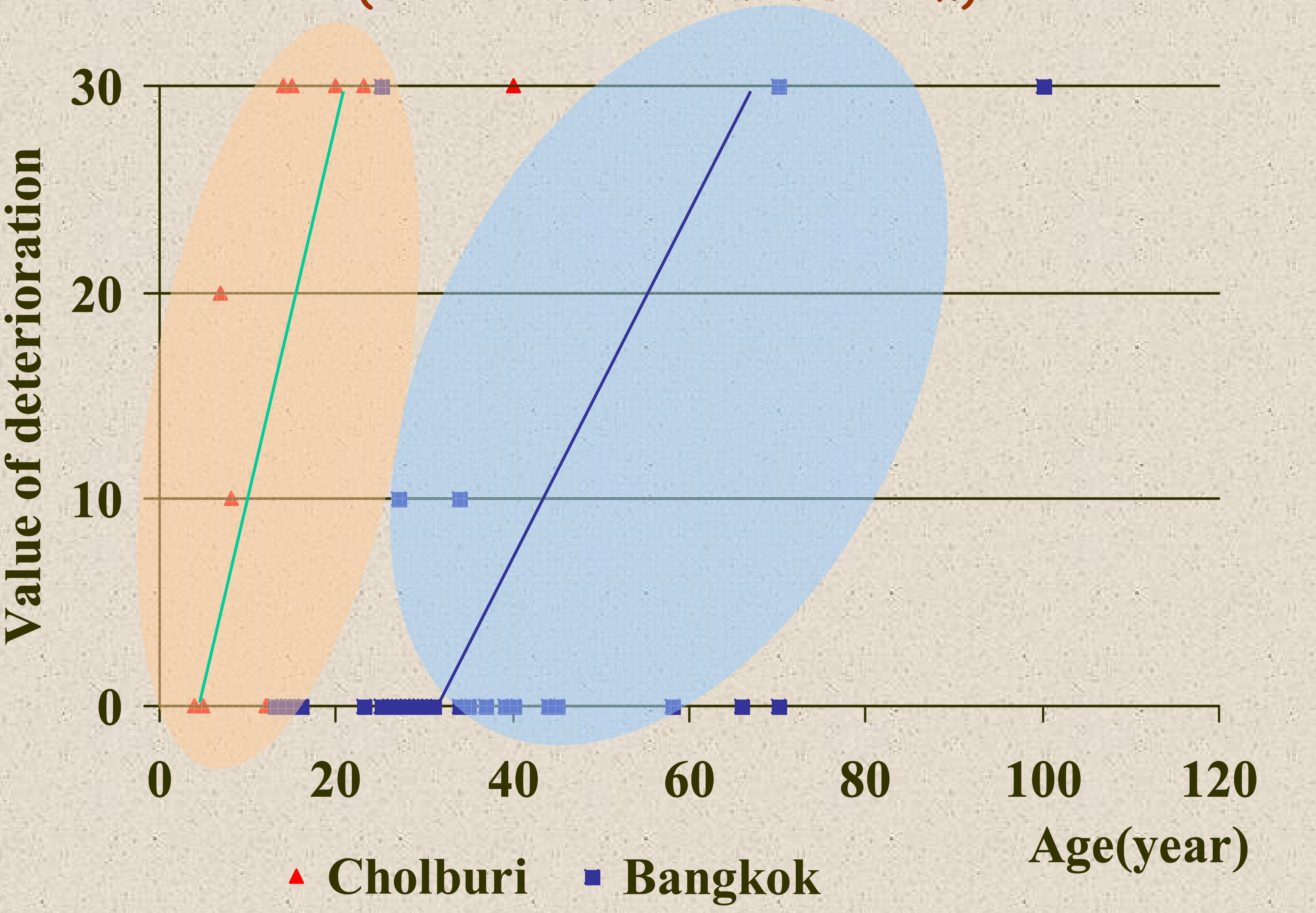
(Effective in 2005)

Materials



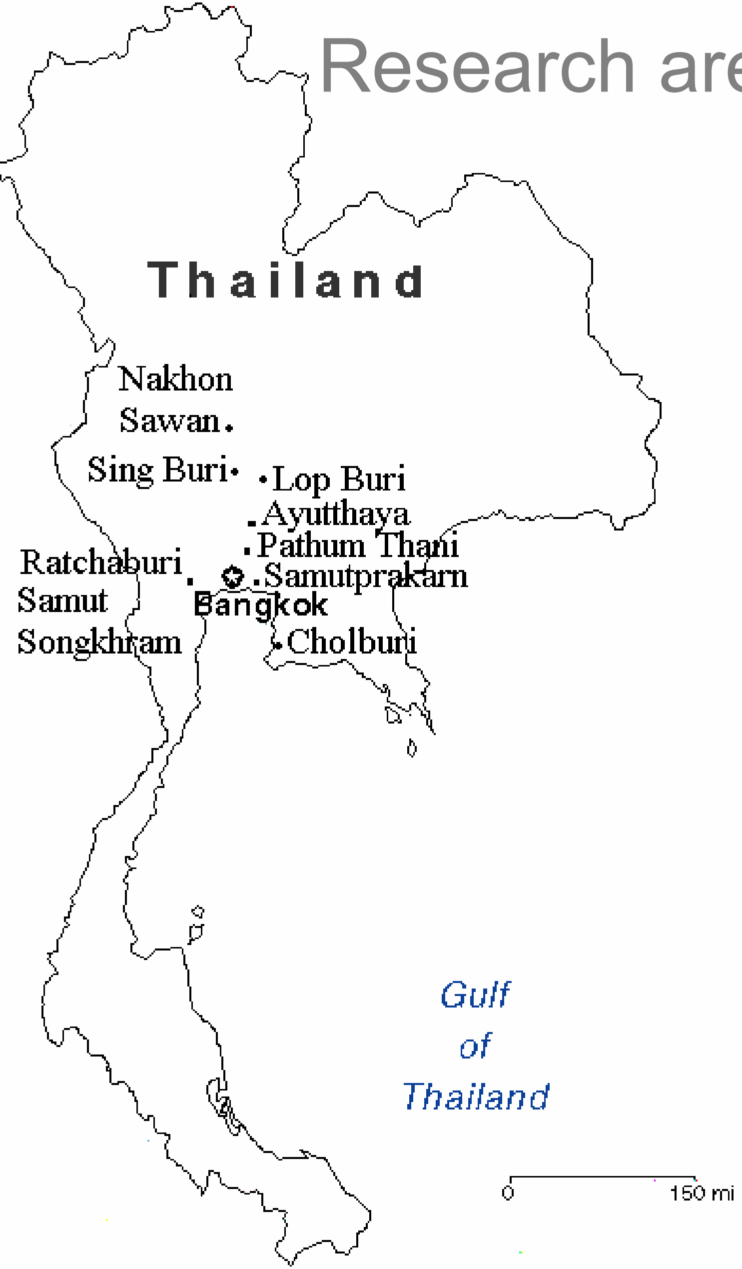
Low energy
consumption materials
Wastes & recycling
Proper material for certain types of construction
and environment
Supported by a new
Specification establishe
by DPW&UP
Performance based analysis and design for
concrete mix proportion

Relation between value of deterioration and age of colum
(Steel Corrosion Problem)



Structures in Cholburi

Research area



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Chloride induced Corrosion

Structures in Bangkok

Carbonation induced steel corrosion


Carbonation induced steel corrosion


Various types of Special Concrete launched by Ready-mixed companies

- Low heat concrete
- Marine concrete (Cl^- and sulfate resistance)
- Sulfate resisting concrete
- Frost resistance concrete
- Self-compacting concrete
- etc.

↓

Extend Service Life

↓

How long ?

Performance Based Analysis and Design of Concrete Mix Proportion (Computer Software for Mix Design)

At SIIT, Thammasat University

Sirindhorn International Institute of Technology
Thammasat University

Performance Prediction Models for Analysis and Design of Concrete Mix Proportion

Overall Concrete Properties

Fresh

- Workability

Plastic

- -Bleeding
- -Settlement
- -Plastic shrink
- -Setting

Early Age

- -Temperature
- -Auto shrink
- -Strength

Hardened

- - f'c
- - ft
- - fr
- - Ec
- – ν

Long term

<u>**Durability**</u>

- - Drying shrink
- - Cl Corrosion
- - Carbonation
- - AAR
- - Sulfate attack
- -Acid attack
- -Freeze-Thaw
- - Erosion

<u>**Others**</u>

- - Creep
- - Fatigue

Previous design practice

Examples of Computer Software for Performance Based Analysis and Design

2001

For workability and strength design

A Workability Prediction Model for Fly Ash Concrete

Overall Concrete Properties

Fresh
- Workability

Plastic
- -Bleeding
- -Settlement
- -Plastic shrink
- -Setting

Early Age
- -Temperature
- -Auto shrink
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Long term

<u>Durability</u>
- - Drying shrink
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- - AAR
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- -Acid attack
- -Freeze-Thaw
- - Erosion

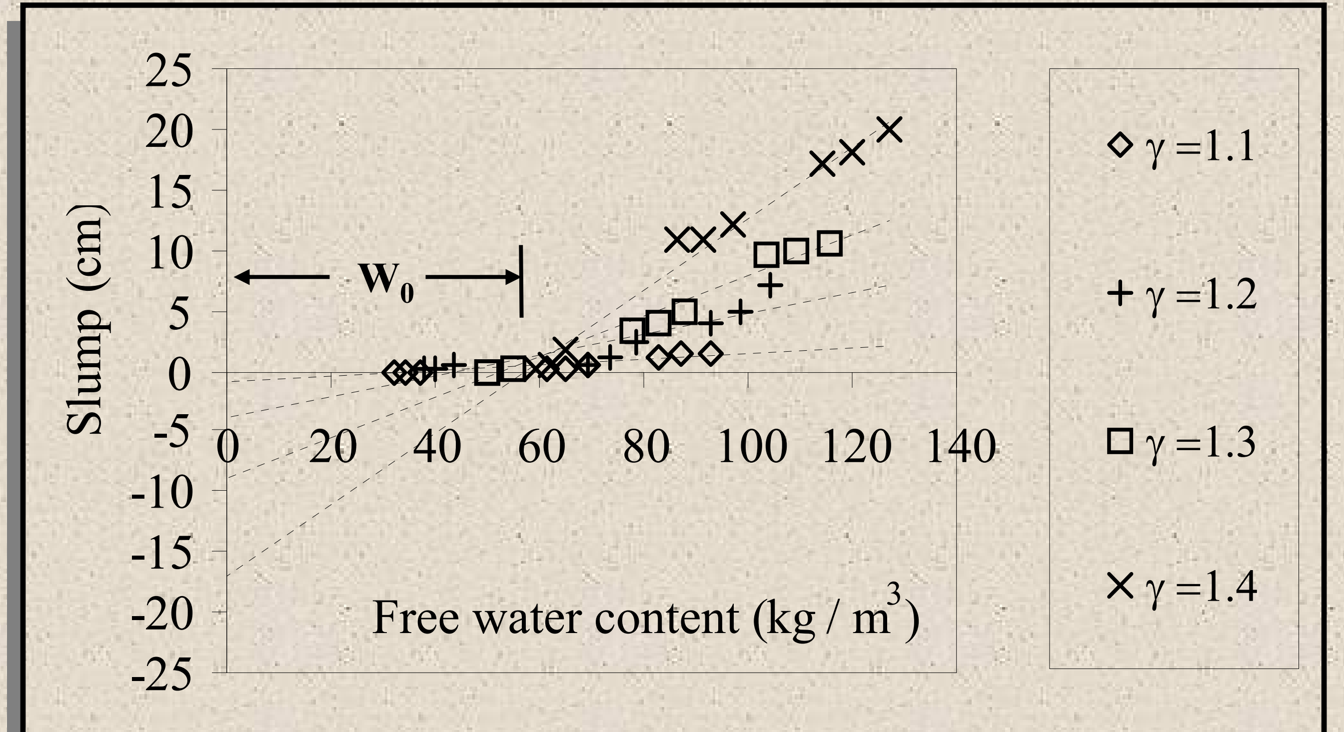
<u>Others</u>
- - Creep

Previous design practice

Factors affecting consistency and workability

Practical factor \ Analytical factor	γ	W_{fr}	S_{ta}	S_{tp}
sand to aggregate ratio	*		*	
Maximum size and gradation of aggregate	*		*	
Gradation of powders and aggregate	*	*	*	*
Size and fineness of powder		*		*
Shape and porosity of powder		*		*
Unit water content	*	*		
Powder content	*	*		*
Concrete temperature		*		
Chemical admixtures		*		*

Model Formulation



$$SL = \alpha_{SL}(W_{fr} - W_0)$$

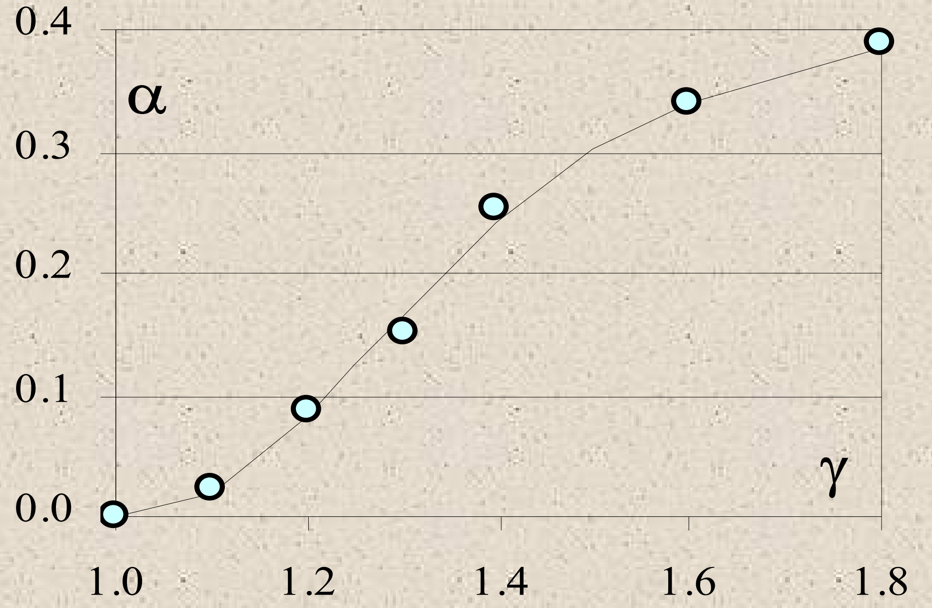
Free water

Minimum free water content required for initiating slump

Slope of slump-free water content curve

The slope of slump-free water content curve

- Concrete with more paste will have higher slump



$$\alpha_{SL} = (3.57\gamma^4 - 21.34\gamma^3 - 46.74\gamma^2 - 43.92\gamma - 14.94)\kappa$$

Effect of void content

Free Water Content in Mixture (W_{fr})

$$SL = \alpha_{SL} (W_{fr} - W_0)$$

Concept : water which has effect on workability is the water not restricted by all solid particles

$$W_{fr} = W_u - W_{rp} - W_{ra}'$$

W_u: *Total water*

W_{rp}: *Water restricted by powders*

$$W_{rp} = \Sigma \beta_{pi} W_{pi}$$

W_{ra}': *Water restricted by aggregates*

$$W_{ra}' = \beta_s' W_s' + \beta_g' W_g'$$

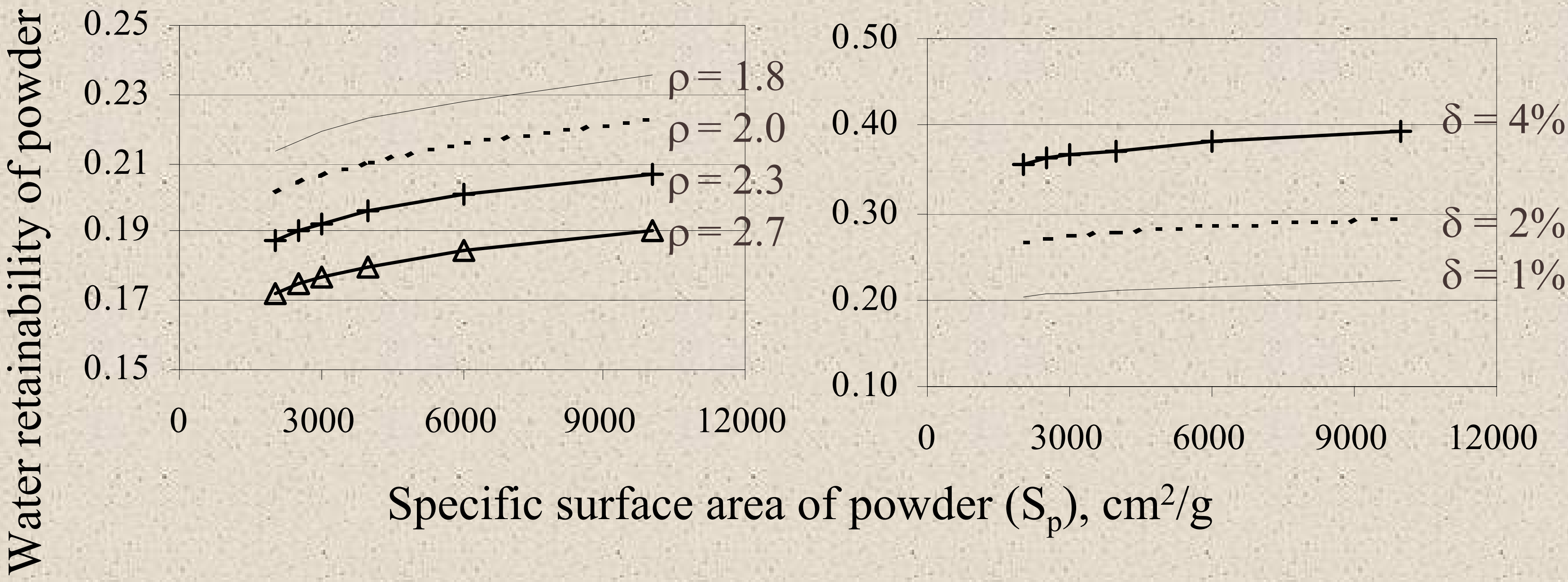
Water Retainability of Powders

Powder will retain more water in and at the surface of the particles when it has larger surface area, porosity and irregularity (shape). For ash-type powders, higher LOI also results in higher water retainability. Higher temperature will increase water retainability of cementitious powders like cement, fly ash, rice husk ash, etc. but affects very little on non-reactive powder like limestone powder.

Water Retainability of Fly Ash

LOI (δ), surface area (S_p), porosity, shape factor

Specific gravity (ρ)

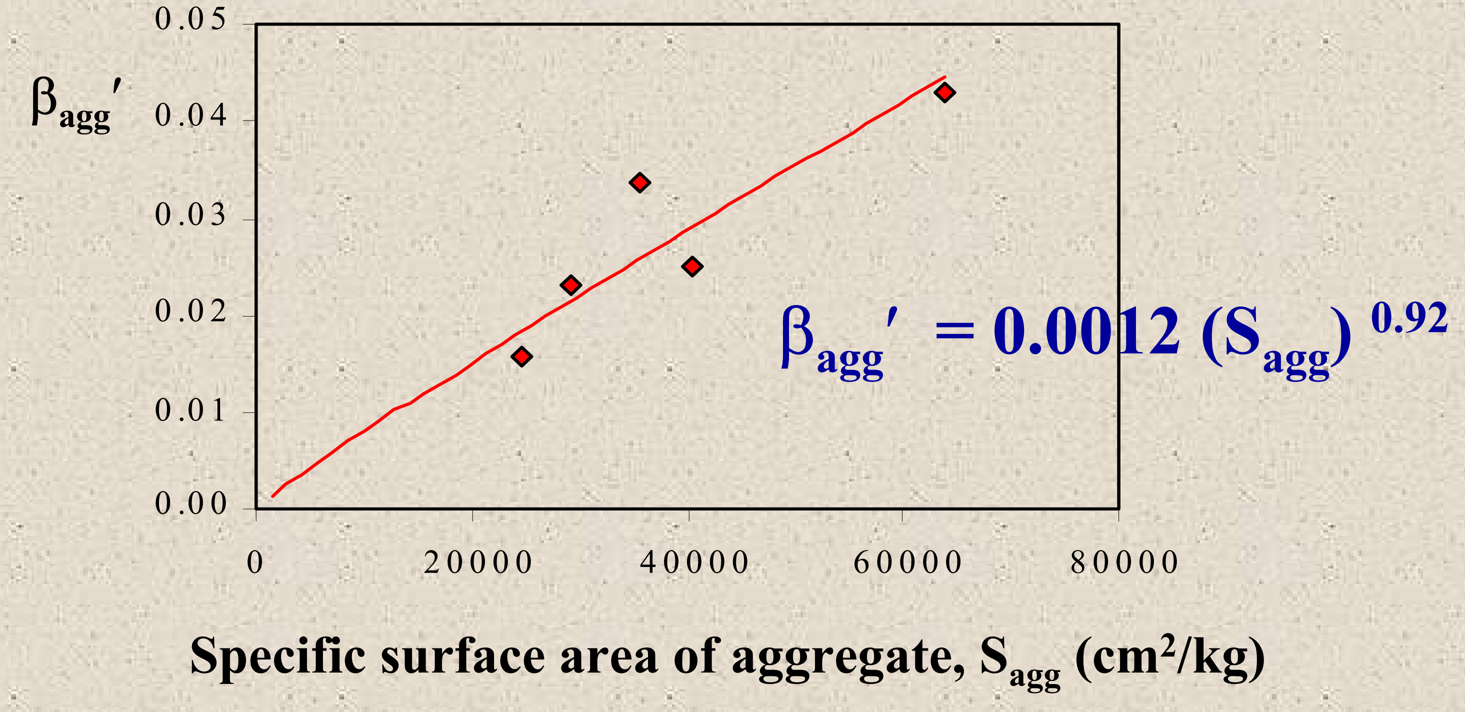


$$\beta_p = 0.185\,\xi\left(\frac{\psi^{0.74}\,S_p^{0.05}\,\delta^{0.41}}{\rho^{0.53}}\right)$$

Water Retainability of Aggregates

$$\beta_p = f\,(\text{porosity}, \underline{\text{surface area}})$$

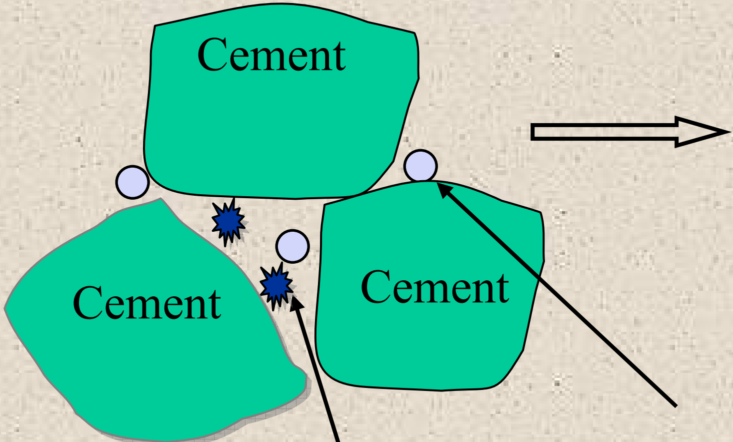
$$\beta_{agg}' = f\,(\text{surface area})$$



Additional free water due to filling effect (W_{aa})

- Fine particles of fly ash can fill in the voids among cement particles, driving out some additional free water

$$W_{fr} = W_u - W_{rp} - W_{ra}' + W_{aa}$$



water (W_{aa})

Spherical particles (lubricating)

Fillable particles (Filling)

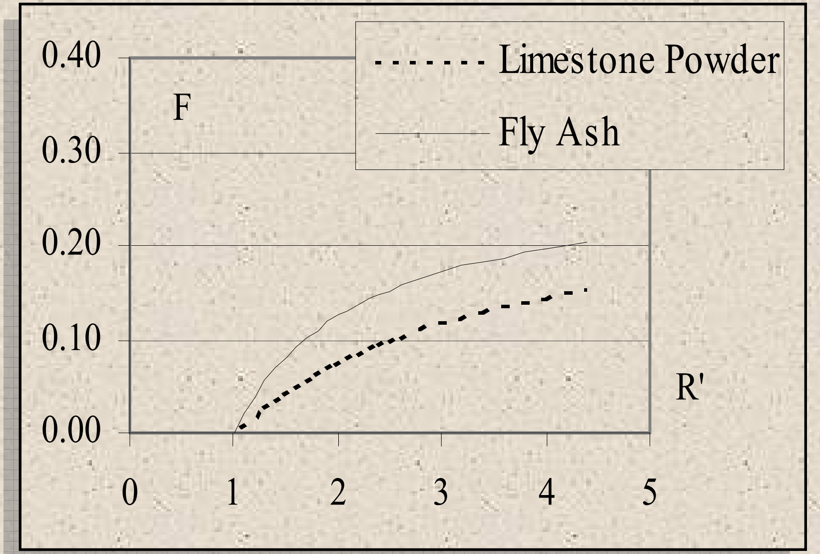
$$V_{fill} = F \times V_c$$

- More amount of cement results in more amount of void for fillable powder to fill

Filling Ability

- **Filling ability depends on**
  - Size : smaller fills easier
  - Shape : spherical fills easier
  - Content : more filler content (in this case fly ash is considered as filler) results in more possibility to fill (but not beyond the capacity of voids among cement).

Filling coefficient (F)



Smaller size

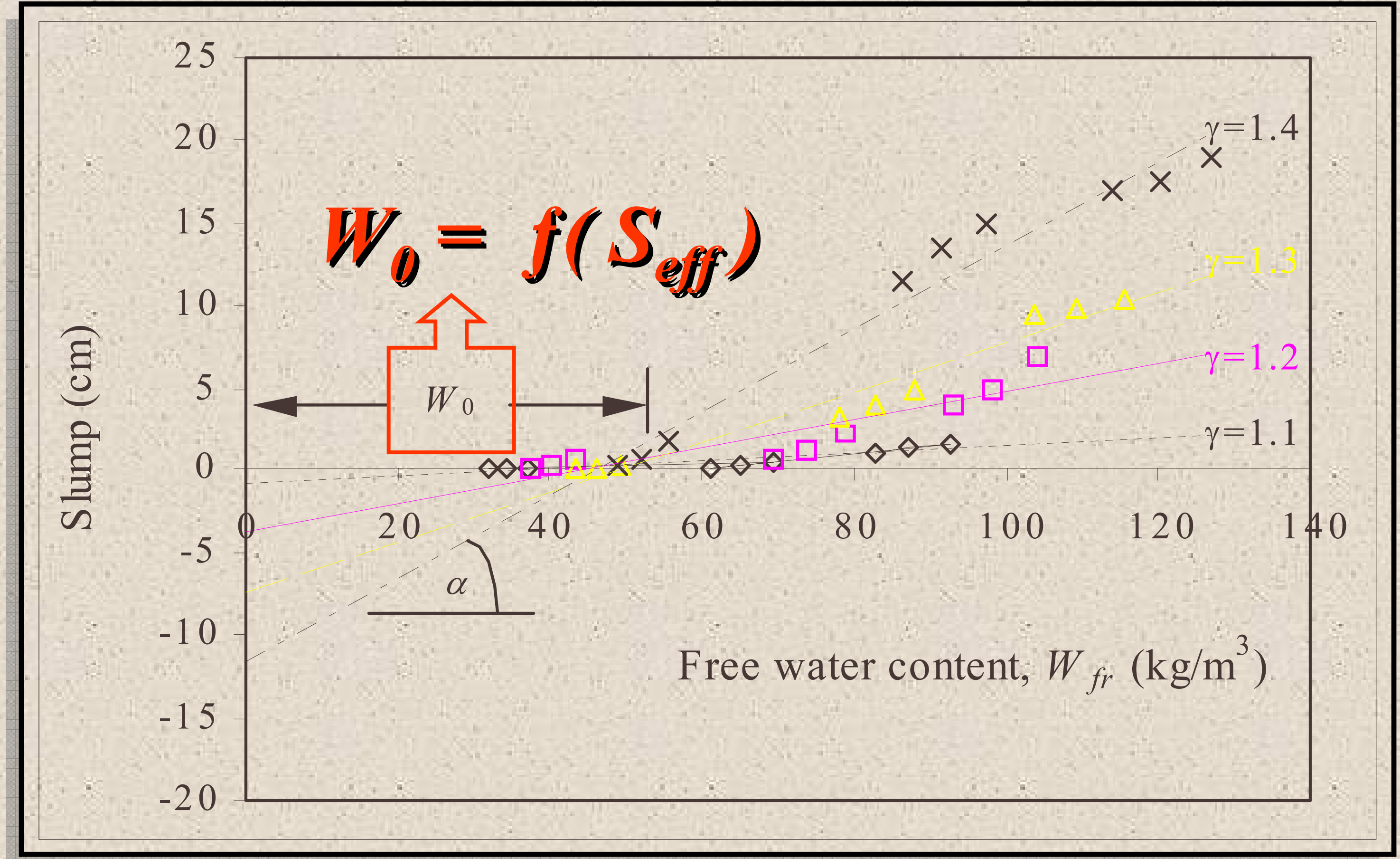
$$F = 0.25 - \frac{0.69}{\exp(R')^{a}}$$

$$R' = 1 + 3\left(\frac{R-1}{\psi^{3.3}}\right)$$

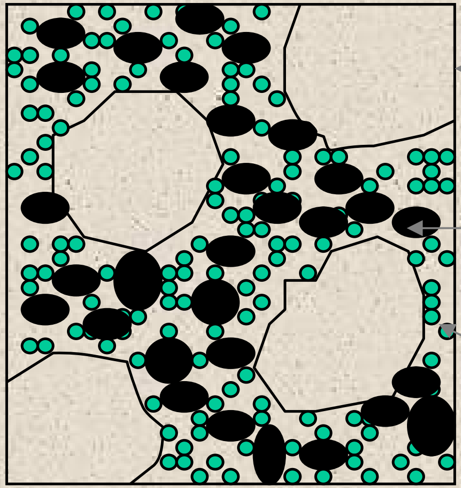
$$a = 0.6\, r^{0.25}$$

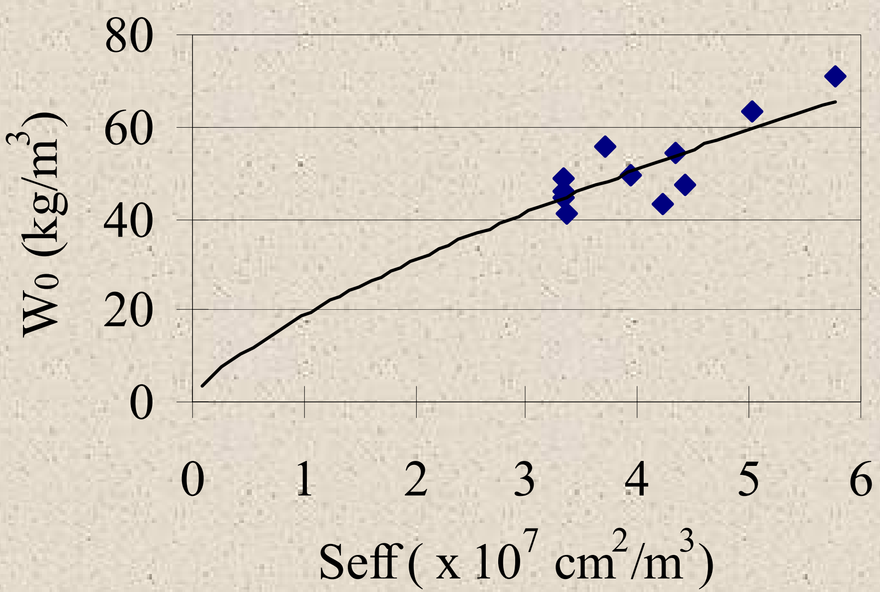
Minimum Free Water Content Required for Initiating slump (W_0)

$$SL = \alpha_{SL} (W_{fr} - W_0)$$



Effective surface area





$$S_{eff} = \eta_a S_{agg} + \eta_p S_{pow}$$

$$W_0 = 8 \times 10^{-5} (S_{eff})^{0.76}$$

$$S_{eff} \begin{cases} (S_{pow}) \times \boxed{\eta_p f(S_{agg})} \\ (S_{agg}) \times \boxed{\eta_a f(V_{pow})} \end{cases}$$

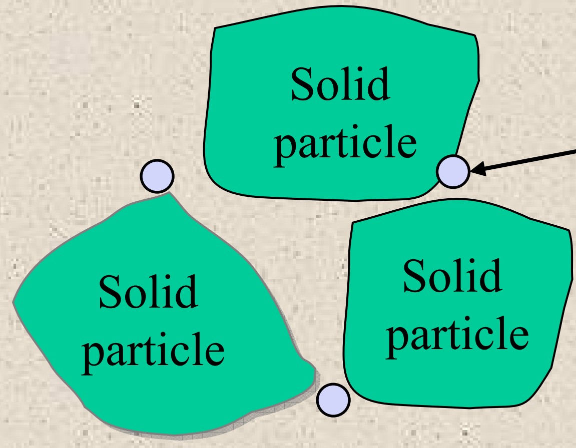
Powder particles contact on aggregate surface

Aggregate contacts can be disturbed by powder particles

Lubrication Effect

Air bubbles and spherical or semi-spherical properties of fly ash particles can introduce lubrication to other solid particles in the concrete mixture. This effect reduces friction among the solid particles and then reduces W_o.

Lubrication of interparticle friction



Spherical particles - fly ash
- Air bubbles

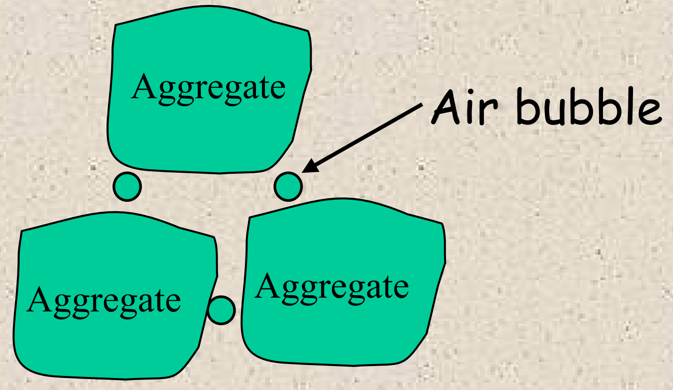
$$W_0' = \frac{W_o}{L}$$

Lubrication coefficient of air bubbles

Lubrication Coefficient, $L = L_a \times L_p$

Lubrication coefficient of powder

Lubrication coefficient of air bubbles

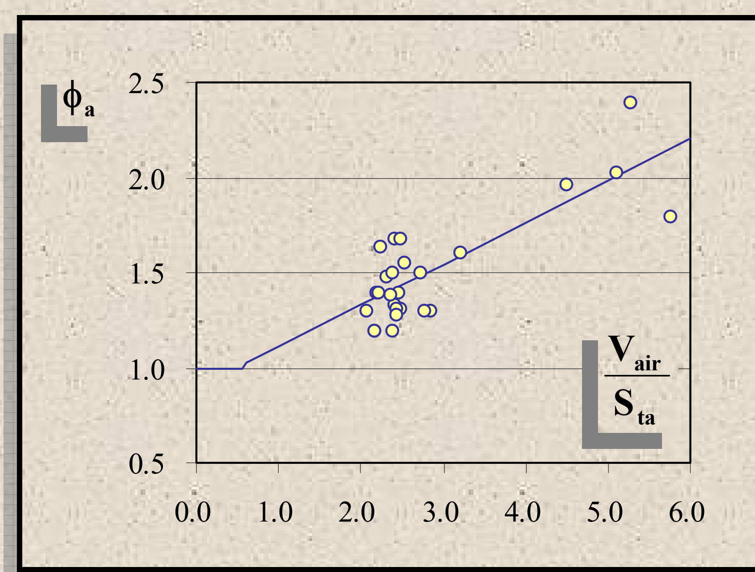


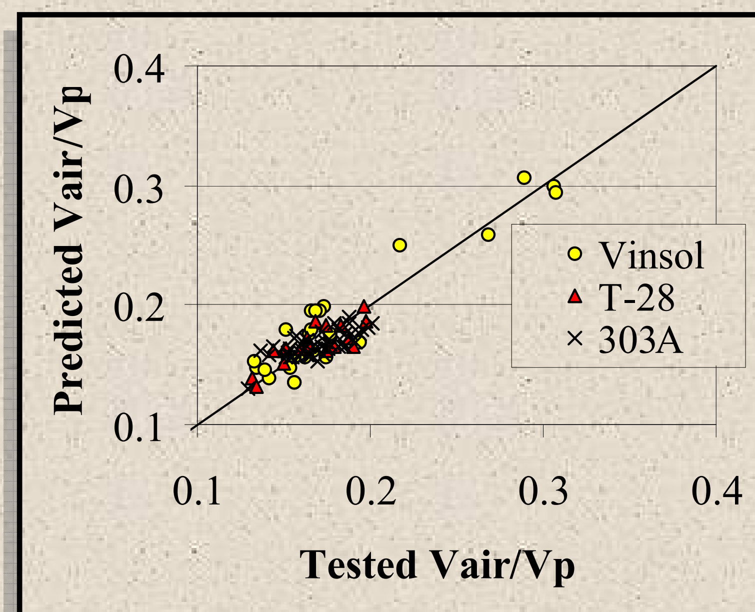
Volume of air

L_a { *Surface area of air* / *Surface area of aggregates*

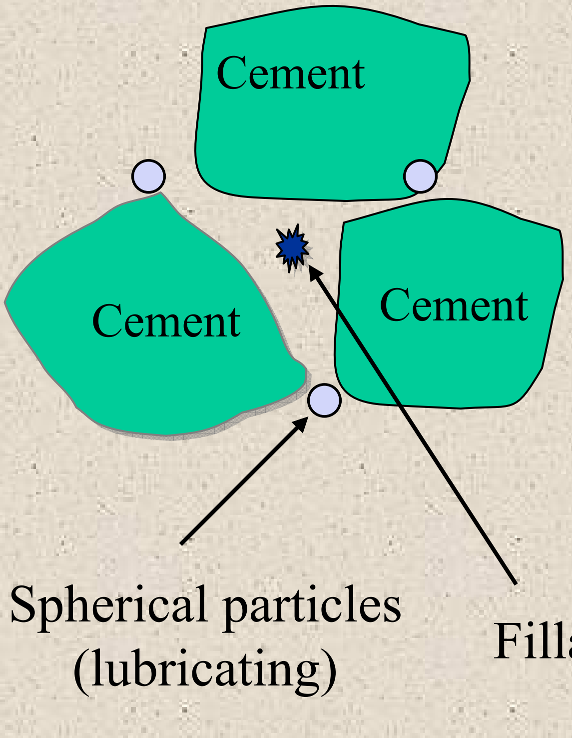
$$L_a = 1.81 \exp\left(3.54 \times 10^7 \times \frac{V_{air}}{S_{ta}}\right) - 0.84$$

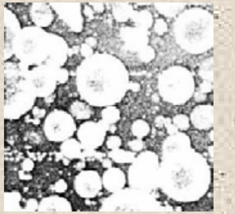
$$V_{air} = f\left(V_{paste}, \frac{w}{b}, \varphi, Loi\right)$$

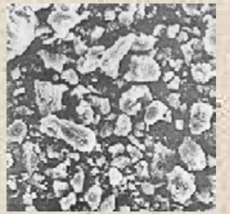


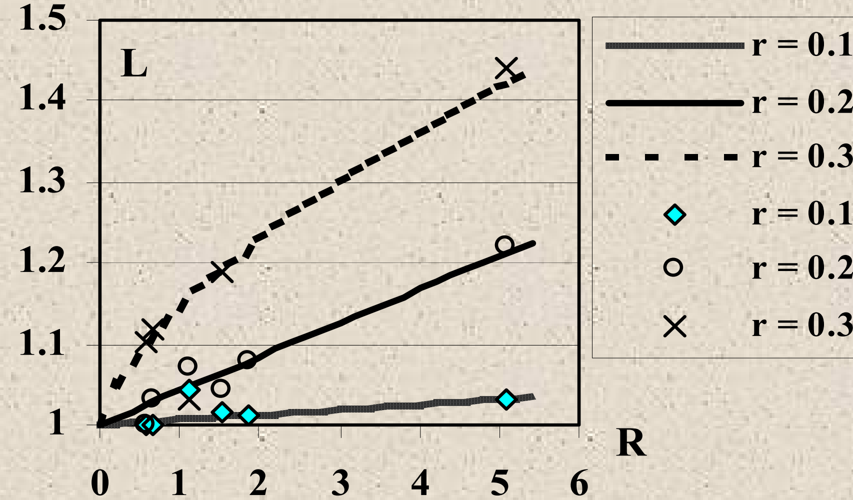


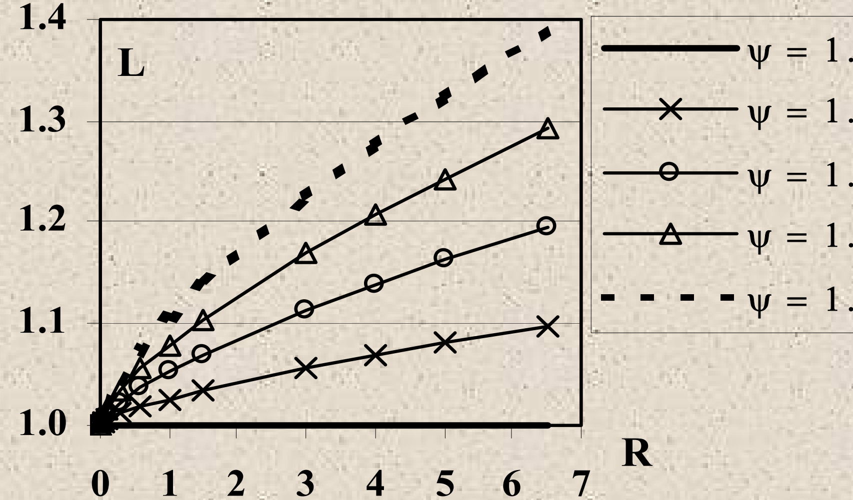
Lubrication coefficient of cement replacing powder





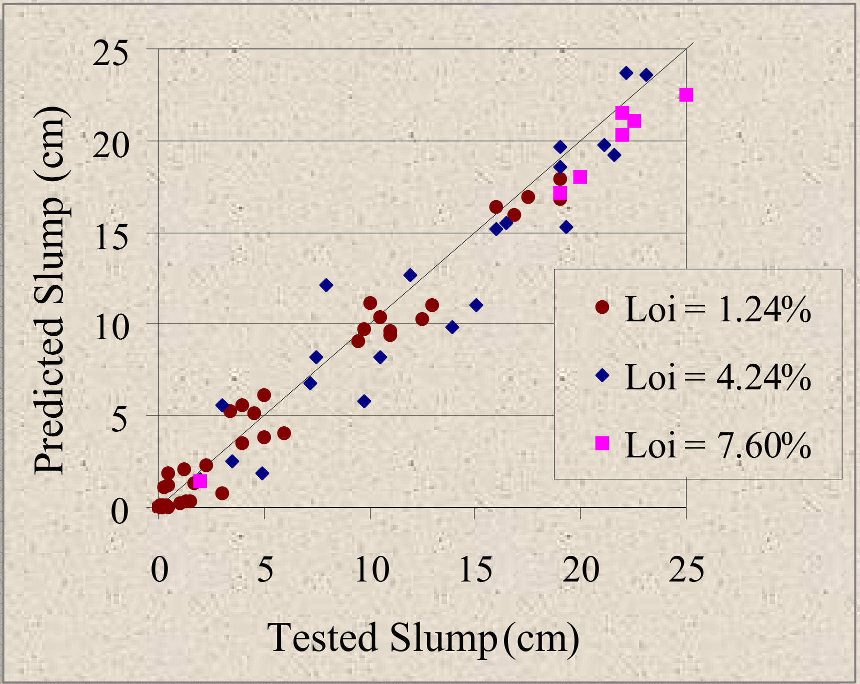


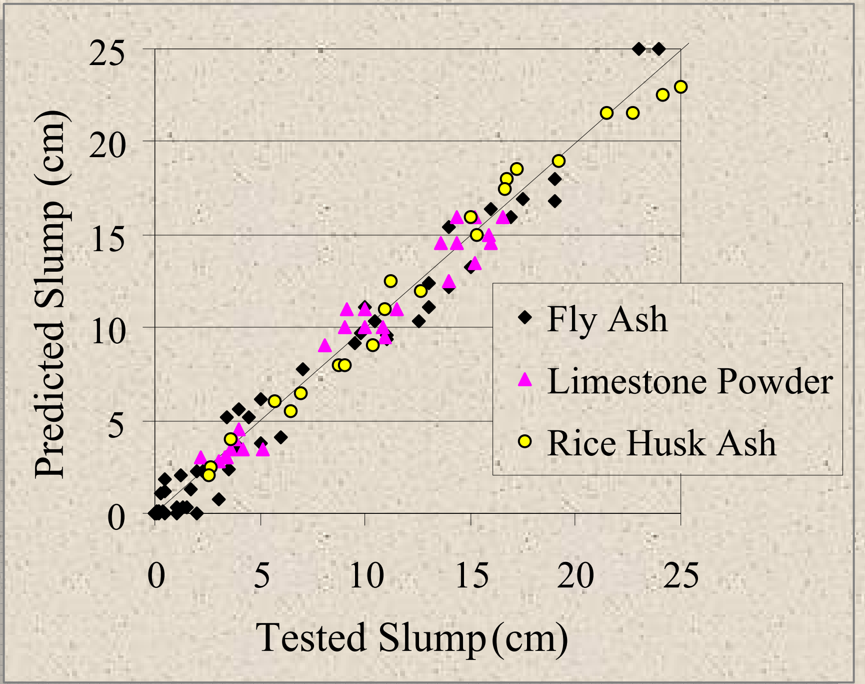




$$L = 1 + (1.4 - \psi)\,(2.27\, r^{1.79})\, R^{(-0.93\, r + 0.98)}$$

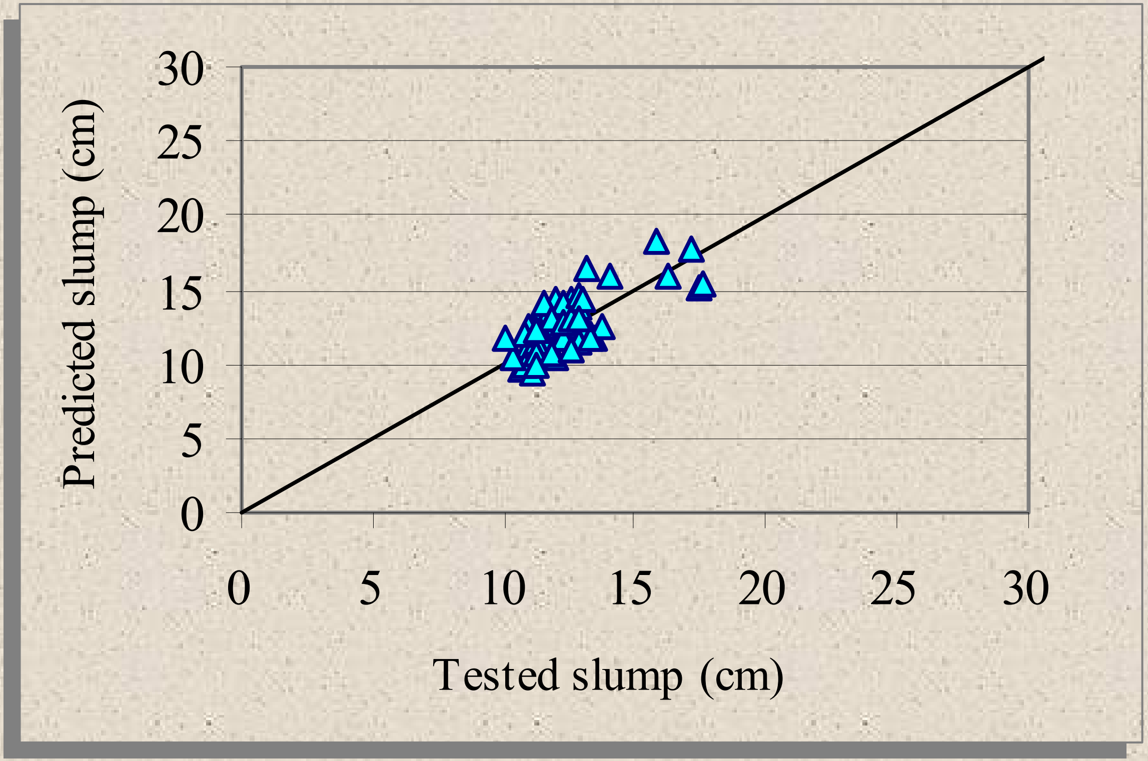
Verifications





Comparison between the predicted and tested slump of concrete containing various type of fly ash

Comparison between the predicted and tested slump of concrete containing various type of powder



Comparison between the predicted and tested slump of concrete with the application of air entraining agent

Use of Water-reducing Efficiency and Setting Time for Time-Dependent Slump Prediction

By

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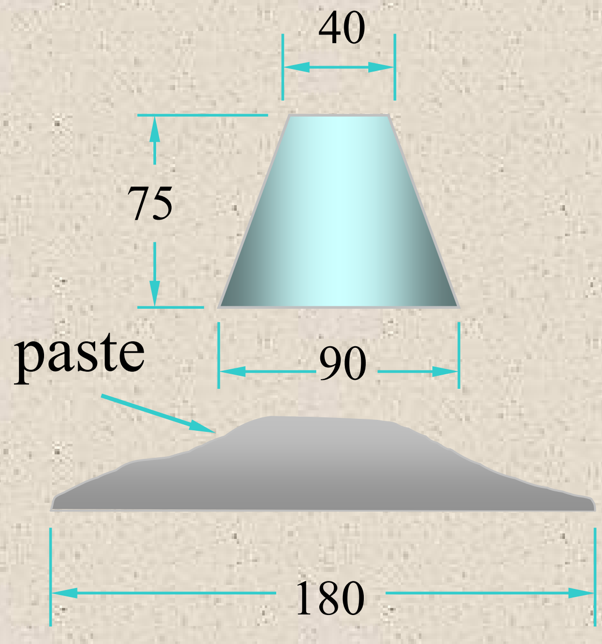
Water Reducing Efficiency (φ') of WRA



$$\varphi' = 1 - \frac{W_{wa}}{W_{woa}}$$

W_{wa}: *quantity of water required to produce a flow diameter of 180 mm with 0.5% dosage of WRA*

W_{woa}: *quantity of water required to produce a flow diameter of 180 mm without WRA*

Water Reducing Efficiency (φ') of WRA

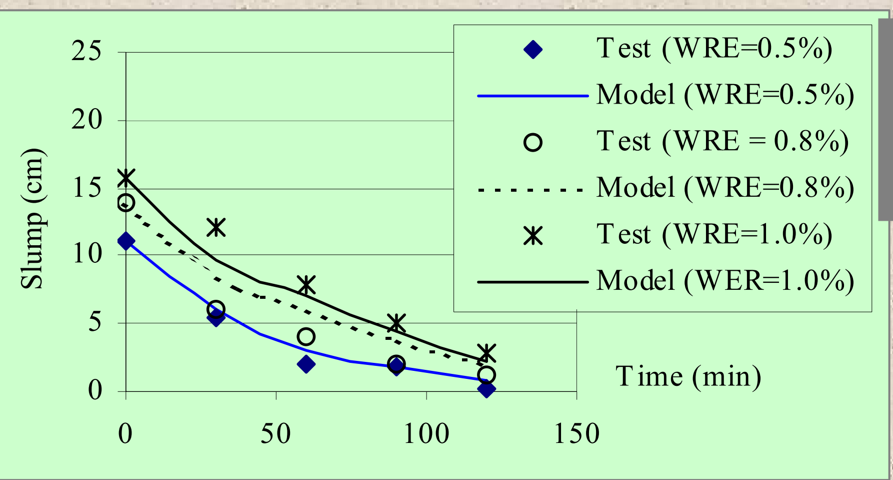
Designation	ASTM Type	Base	Trade Name	Water-reducing efficiency (WRE)
Lignosulfonate (I)	D	Lignosulfonate	Pozzolith 400R	0.20
Lignosulfonate (II)	D	Lignosulfonate	Plastiment R	0.13
Lignosulfonate (III)	D	Lignosulfonate	AS 247R	0.16
Naphthalene (I))	F	Naphthalene	Rheobuild 1000	0.34
Naphthalene (II)	F	Naphthalene	Rheobuild 1000	0.32
Naphthalene (III)	F	Naphthalene	Mighty MX	0.33
Polycarboxylic (1)	F	Polycarboxylic	Glenium™ SP27	0.50
Polycarboxylic (II)	F	Polycarboxylic	Viscocrete	0.44
Polycarboxylic (III)	F	Polycarboxylic	Glenium™ SP27	0.38
Melamine	F	Melamine	Sikament FF	0.27

Initial Setting time of cement with WRA

- *The normal consistency and the initial setting time were determined in accordance with ASTM C 187-98 and C 191-99.*
- *The dosage of WRA was selected at 0.5% by weight of cement, which is the same dosage as the test for water-reducing efficiency*

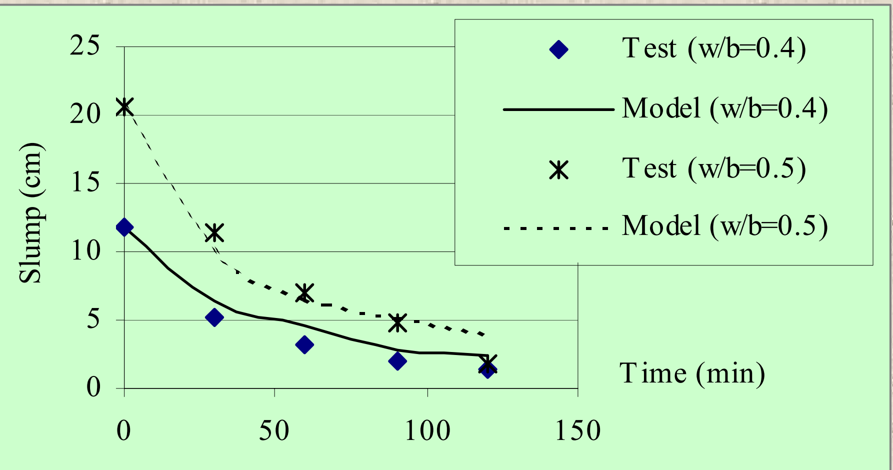
Materials	ASTM type of WRA	Initial Setting Time
Cement only	-	1 hr 34 min
Cement with Lignosulfonate (II)	D	3 hr 35 min
Cement with Lignosulfonate (III)	D	4 hr 13 min
Cement with Naphthalene (II)	F	2 hr 06 min
Cement with Naphthalene (III)	F	2 hr 09 min
Cement with Polycarboxylic (II)	F	3 hr 17 min
Cement with Polycarboxylic (III)	F	2 hr 36 min

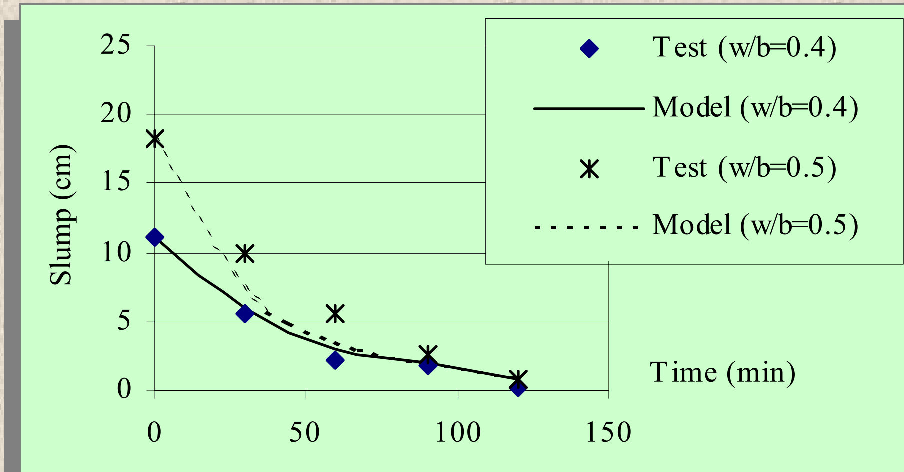
Verifications for Naphthalene



WRA	ASTM type	WRE	Setting time
Lignosulfonate	D	0.15 – 0.20	3.5 – 4.0 hrs
Naphthalene	F	0.30 – 0.35	about 2.0 hrs
Polycarboxylic	F	0.40 – 0.50	2.5 – 3.0 hrs

W/b = 0.4 (No fly ash)

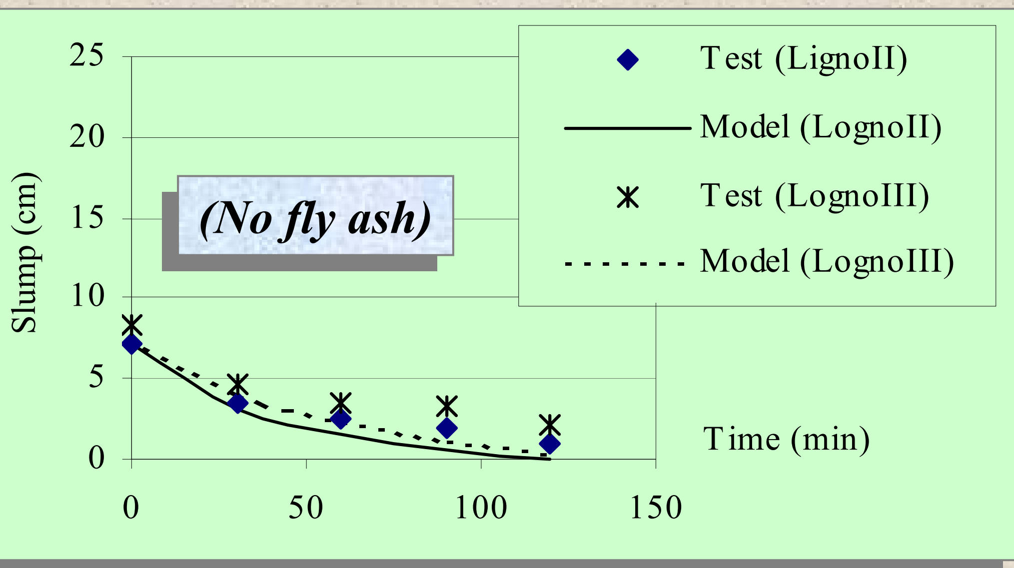


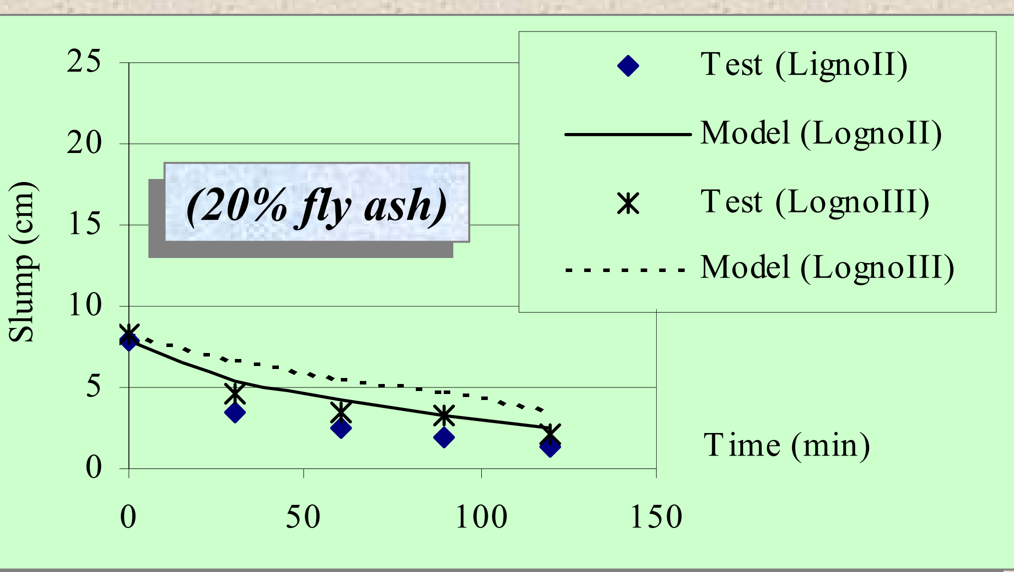


WRA = 0.5% (No fly ash)

WRA = 0.5% (20% fly ash)

Verifications of Lignosulfonate





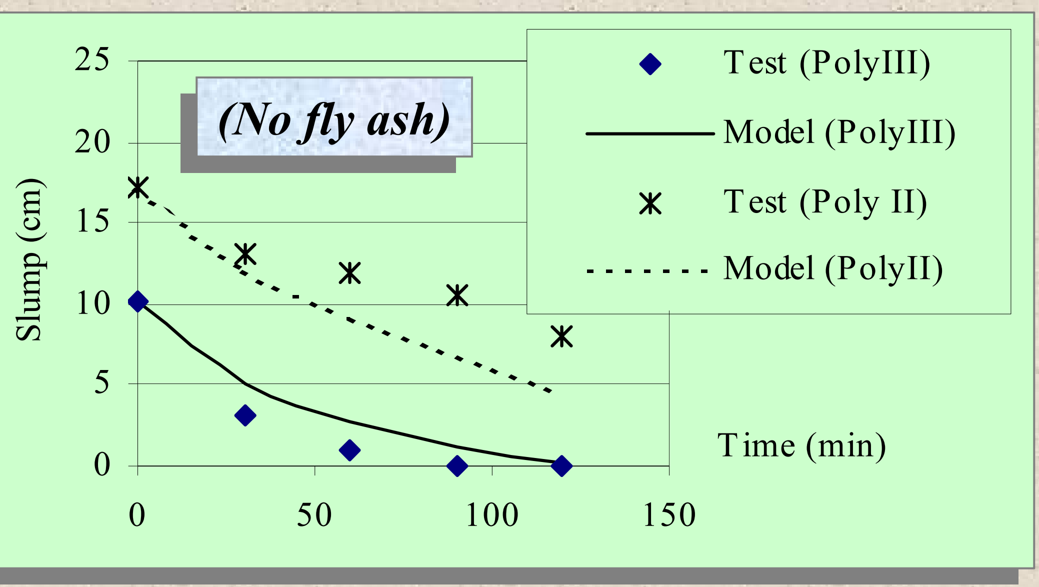
WRA	Setting time	WRE
Lignosulfonate II	3.6 hrs	0.13
Lignosulfonate III	4.2 hrs	0.16

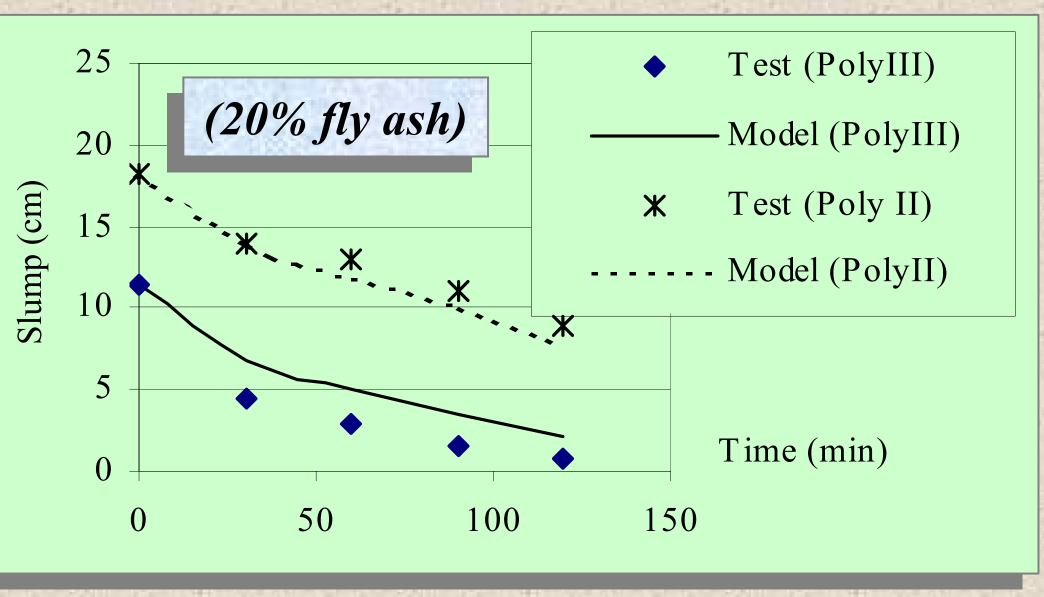
Mixture:

$\gamma = 1.2$, ***W/b = 0.5***

WRA = 0.5%

Verifications of Polycarboxylic





WRA	Setting time	WRE
Polycarboxylic II	3.3 hrs	0.44
Polycarboxylic III	2.6 hrs	0.38

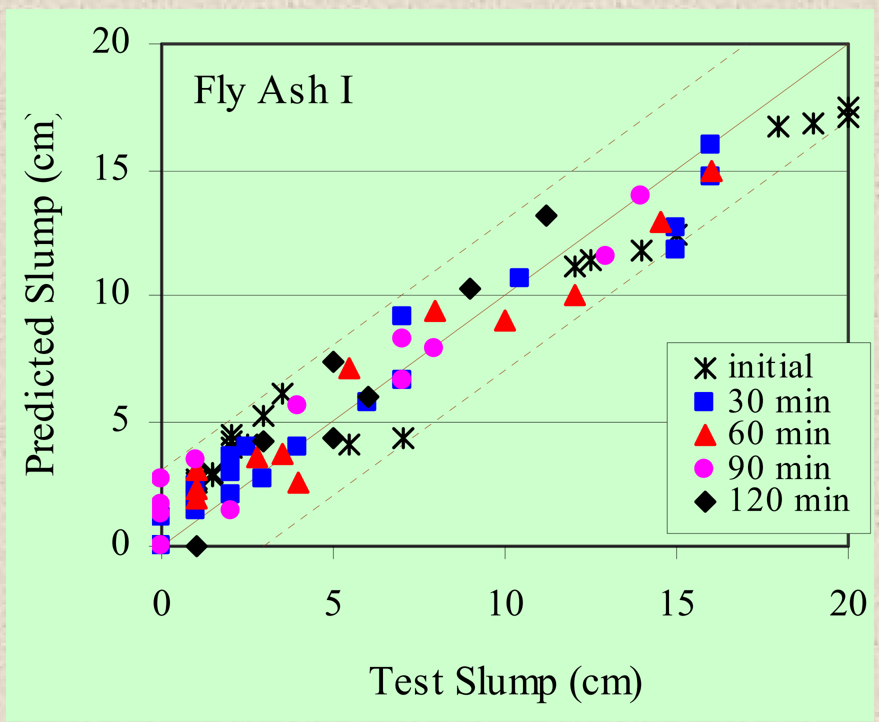
Mixture:

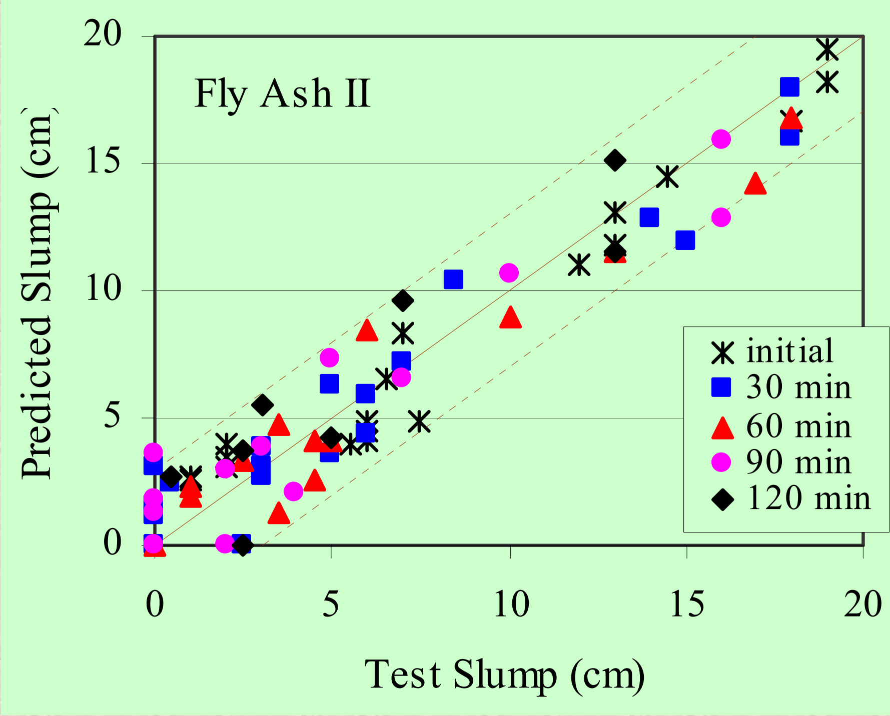
γ = 1.2, W/b = 0.4

WRA = 0.5%

Verification of Initial and Time dependent Slump of Fresh Concrete

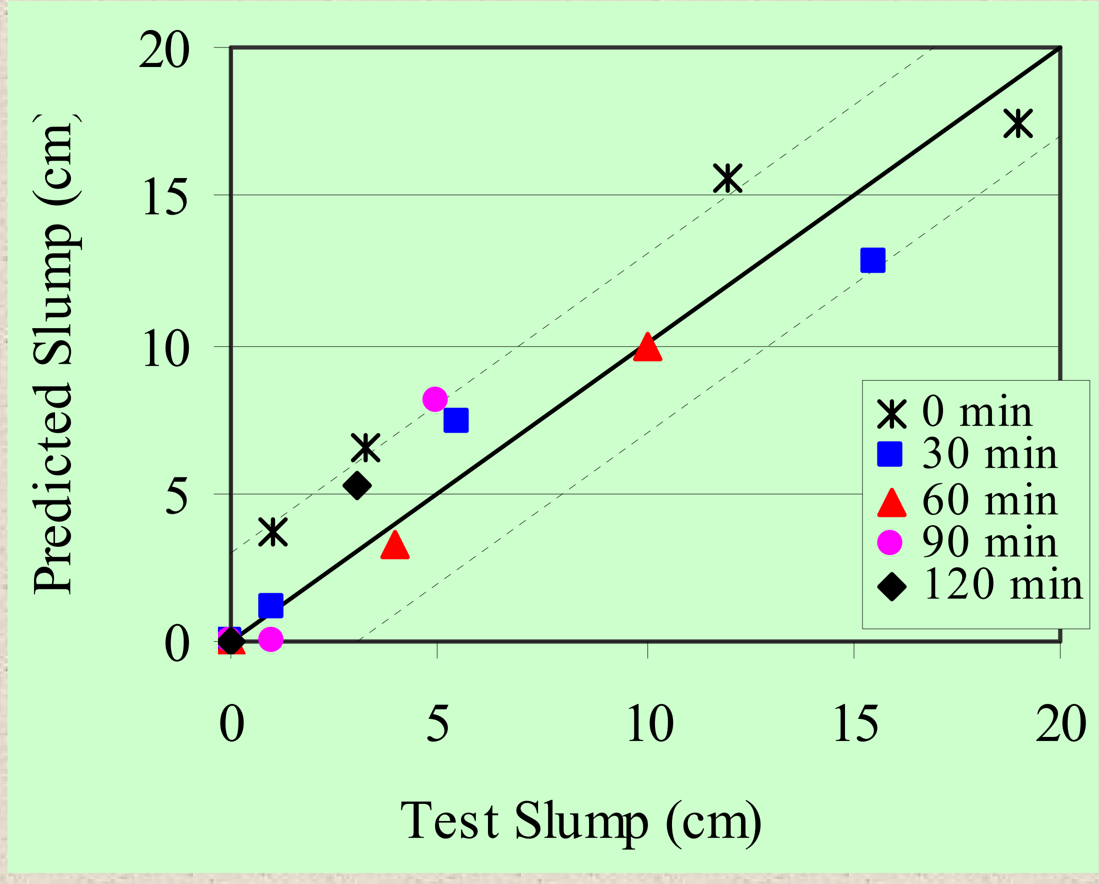
(No admixtures, Normal temperature)





Verification of Slump Loss of Fresh Concrete

(No admixtures, High temperature)



A Compressive Strength Prediction Model for Fly Ash Concrete

MODEL FORMULATION

Compressive strength at 28 days

$$f_c'(28\,\text{days})$$

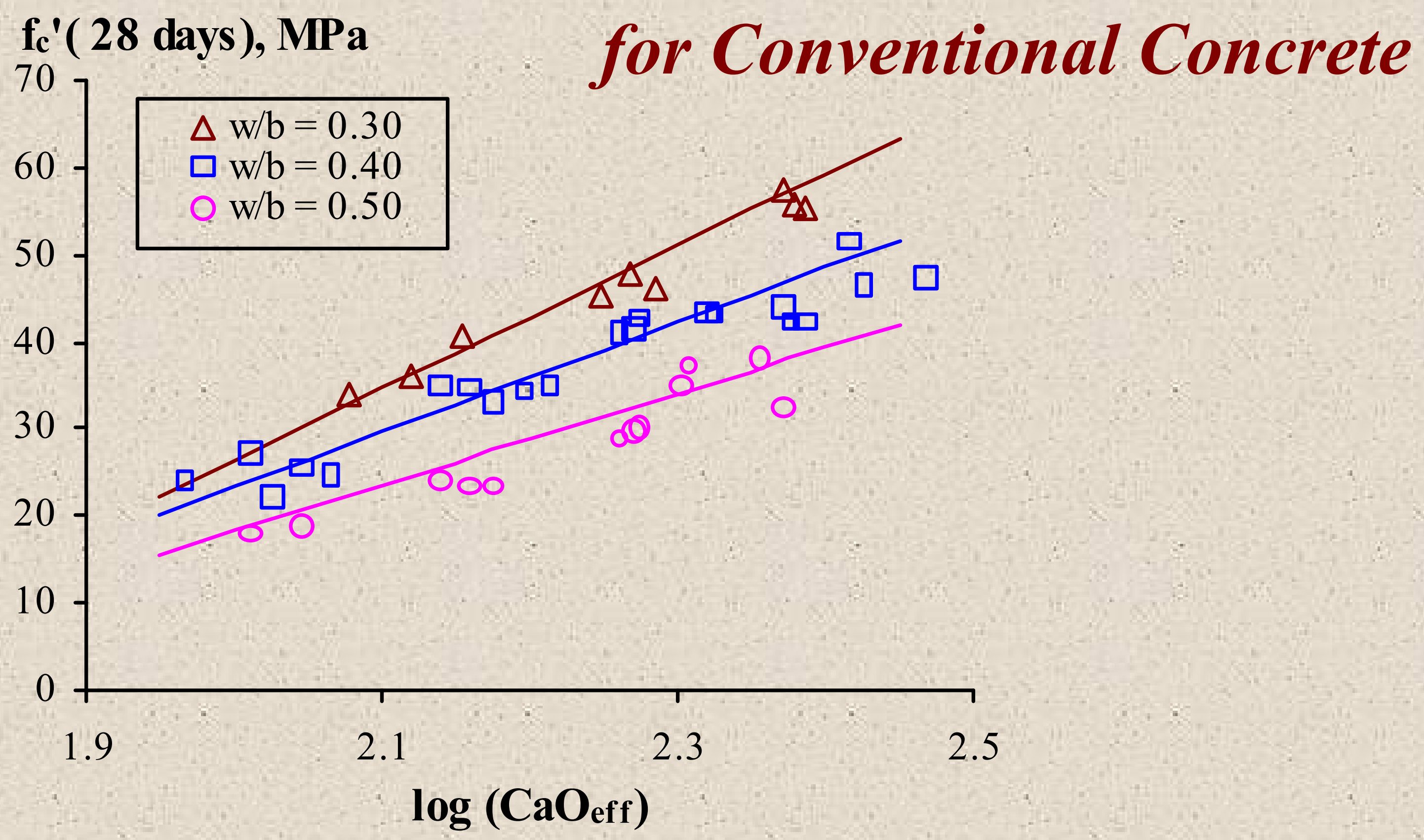
Strength ratio for obtaining compressive strength at other ages

$$\phi(t) = \frac{f_c'(t)}{f_c'(28\,\text{days})}$$

Compressive strength at any ages

$$f_c'(t) = \phi(t) \cdot f_c'(28\,\text{days})$$

Relationships among w/b, CaO_{eff}, and f_c'(28 days)



$$f_c'(28\ \text{days}) = \alpha_1 \log(CaO_{eff}) + \alpha_2$$

Effective Calcium Oxide Content in Binders

$$CaO_{eff} = \frac{(\%CaO_c \times W_c) + \varphi \cdot (\%CaO_f \times W_f)}{100}$$

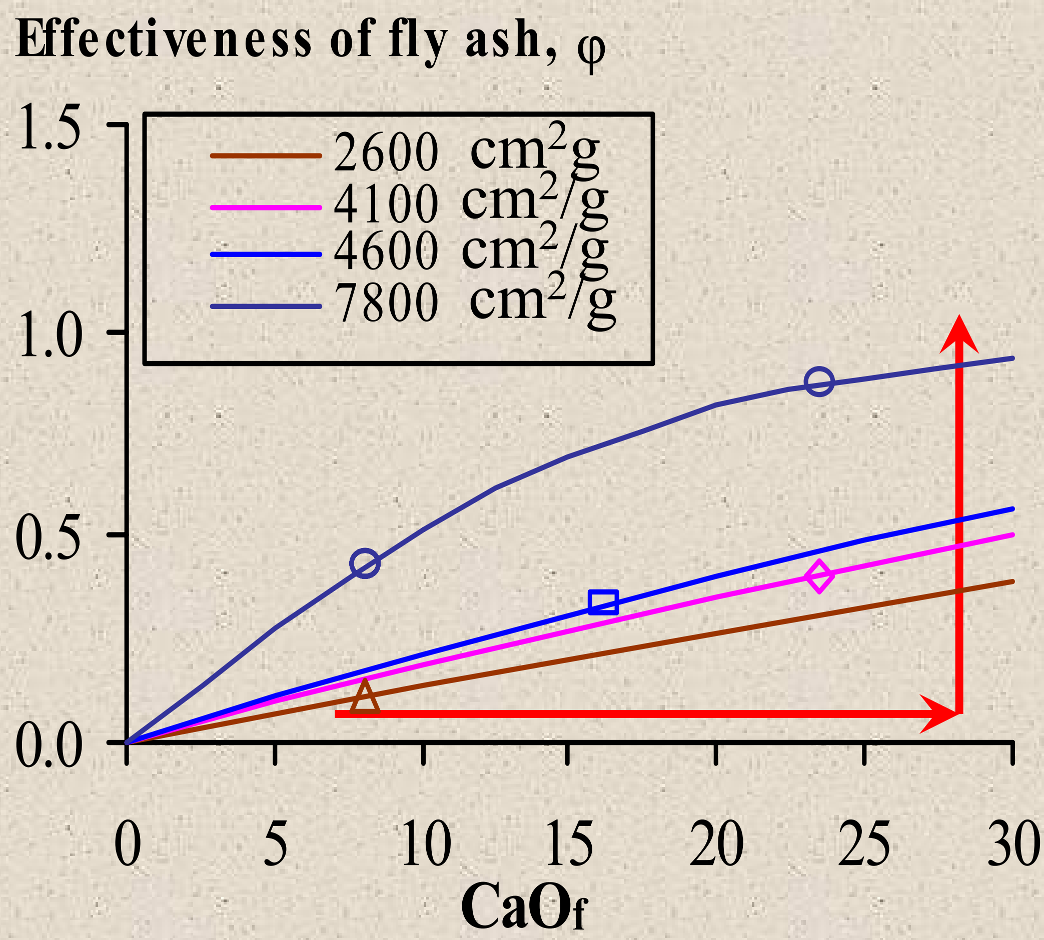
Effectiveness of calcium oxide in fly ash

$$\varphi = \frac{1 - e^{-\kappa(\%CaO_f)}}{1 + e^{-\kappa(\%CaO_f)}}$$

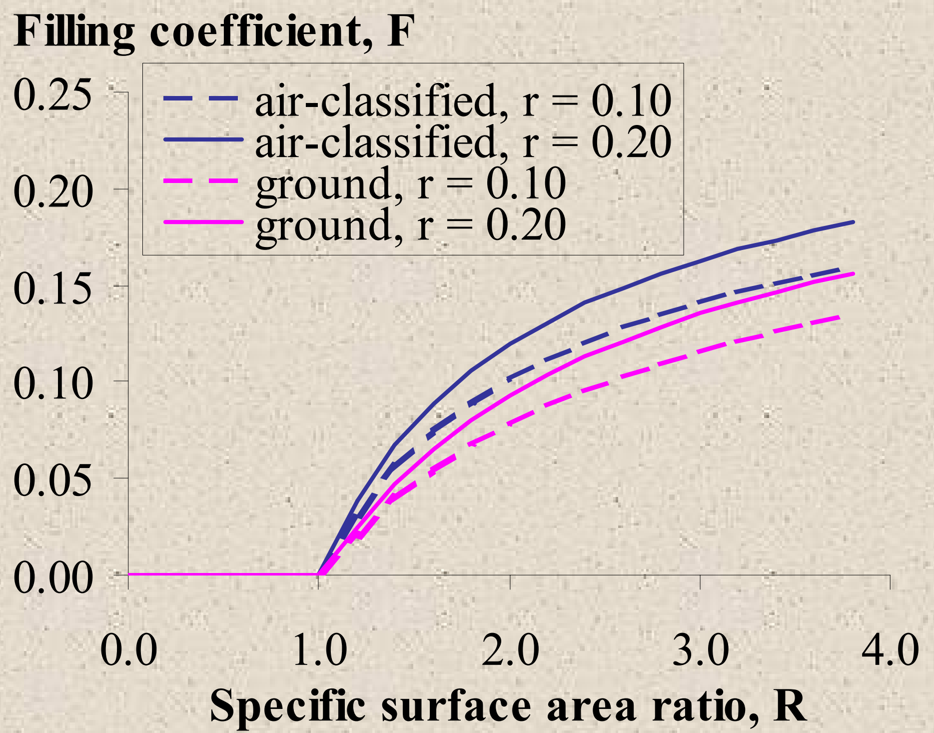
$$\kappa = 0.0048\left(\frac{S_f}{3000}\right)^{3.07} + 0.0245$$

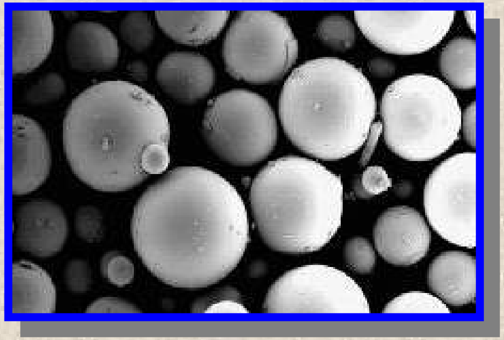
CaO_{eff}	=	effective unit calcium oxide content in concrete (kg/m^3)
$\%CaO_c$	=	calcium oxide content in cement (% by weight)
$\%CaO_f$	=	calcium oxide content in fly ash(% by weight)
W_c	=	cement content in concrete (kg/m^3)
W_f	=	fly ash content in concrete (kg/m^3)

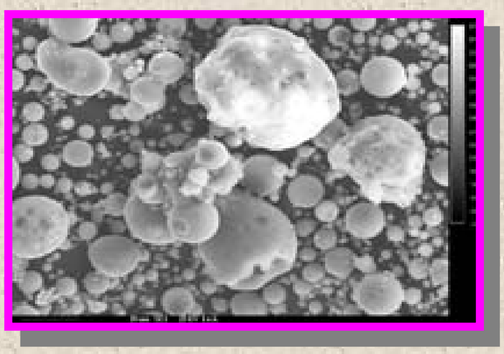
Effectiveness of Fly Ash



Filling Effect of Fly Ash on f_c'(28 days)







in which $$R' = 1 + 3\left(\frac{R-1}{\Psi^{3.3}}\right) \qquad R = \frac{S_p}{S_c} \qquad a = 0.6\,r^{0.25}$$

F = Filling Coefficient

R = Specific surface area

S_c = Specific surface area of cement

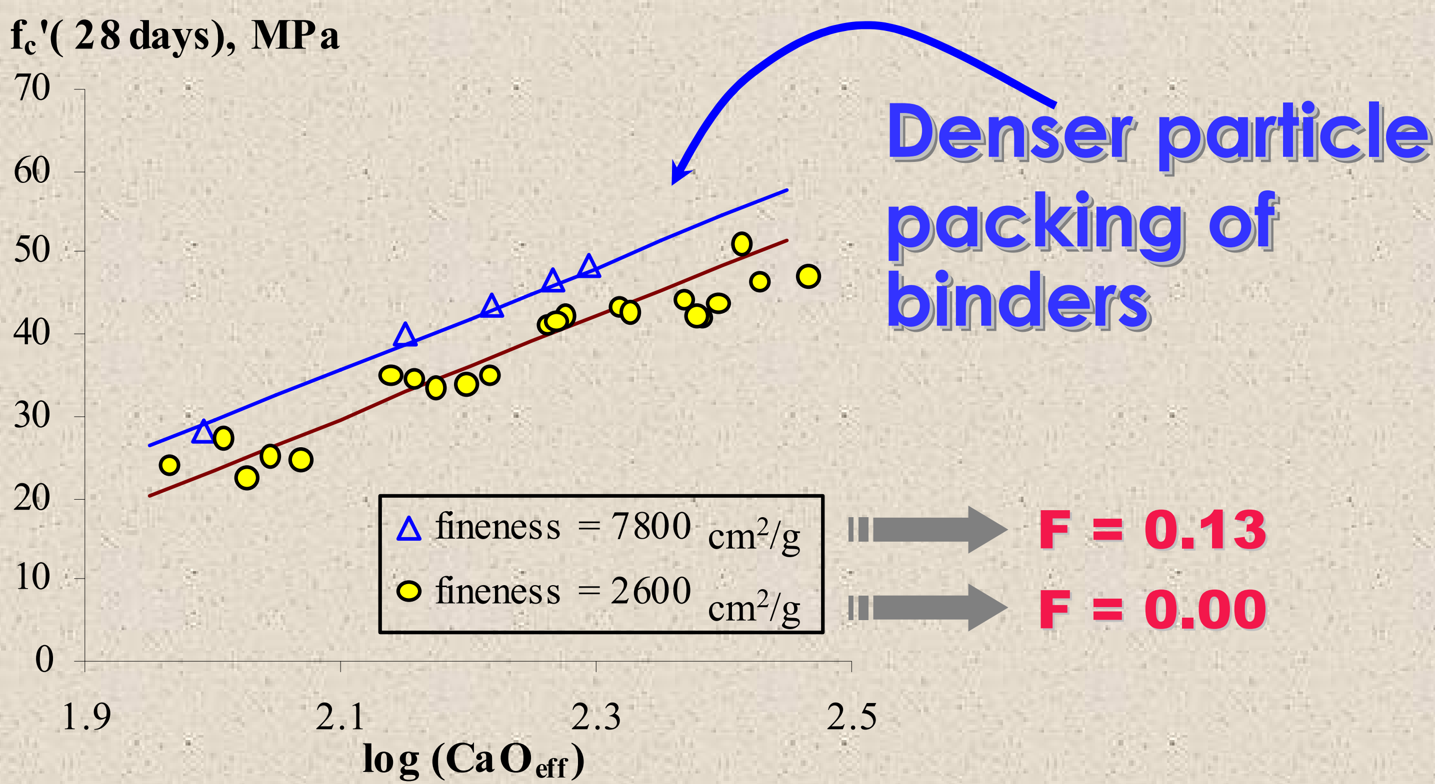
S_c = Specific surface area of filling powder

r = replacement ratio of fly ash

Ψ = Shape factor

(Tangtermsirikul, et al., 2001)

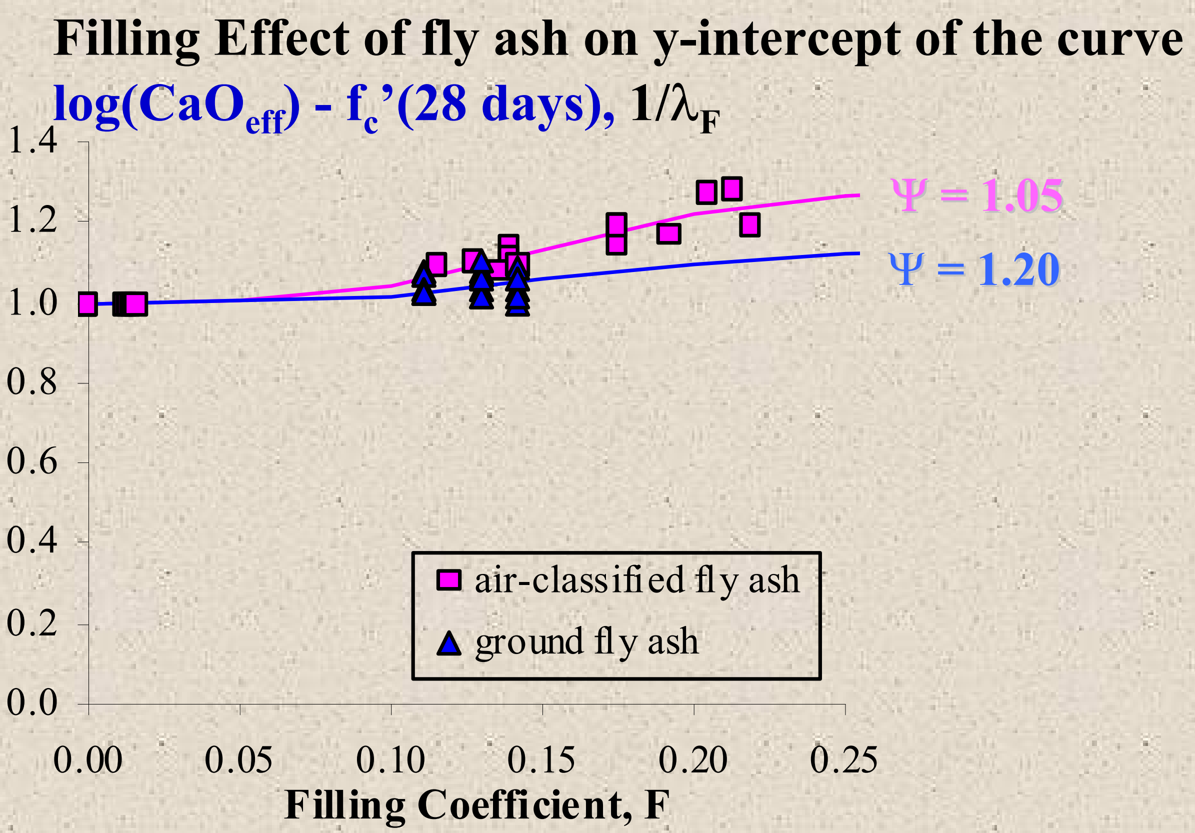
Filling Effect of Fly Ash on f_c'(28 days)

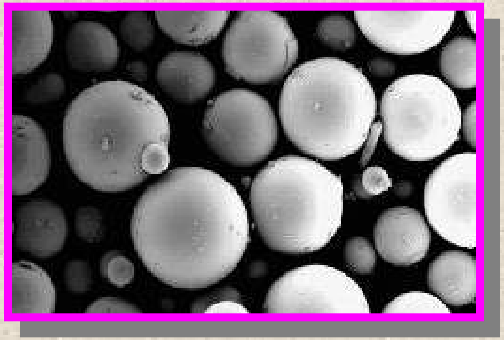


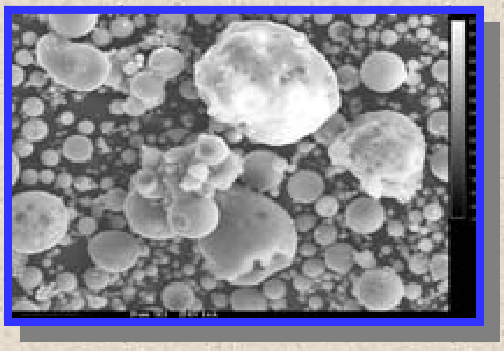
$$f_c'(28\text{ days}) = \alpha_1 \log(CaO_{eff}) + \lambda_F \cdot \alpha_2$$

Filling Effect of fly ash on f_c'(28 days)

Filling Effect of Fly Ash on f_c'(28 days)

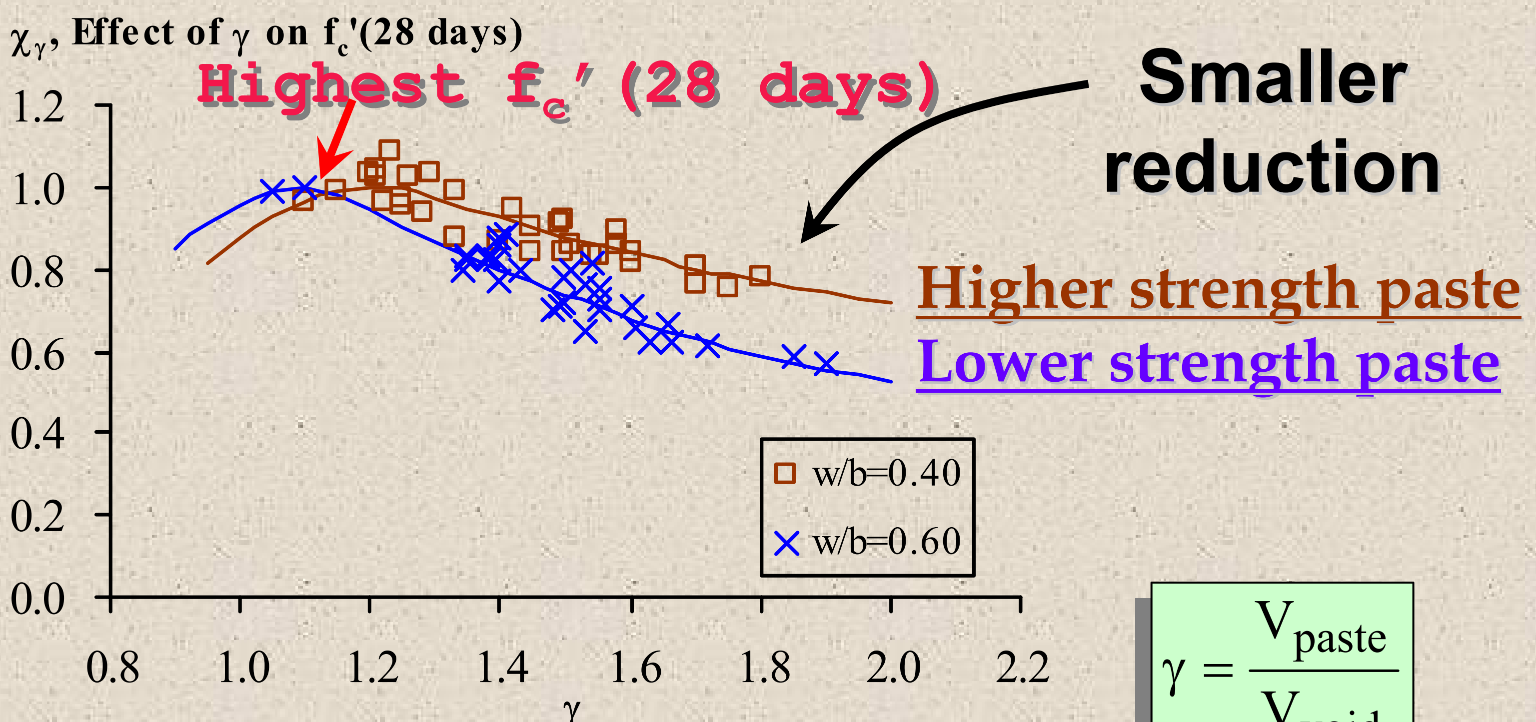






$$\lambda_F = \frac{1}{1 + (0.25\Psi^{-4.91})\tan^{-1}(357F^{3.24})}$$

Effect of ratio of paste to void volume



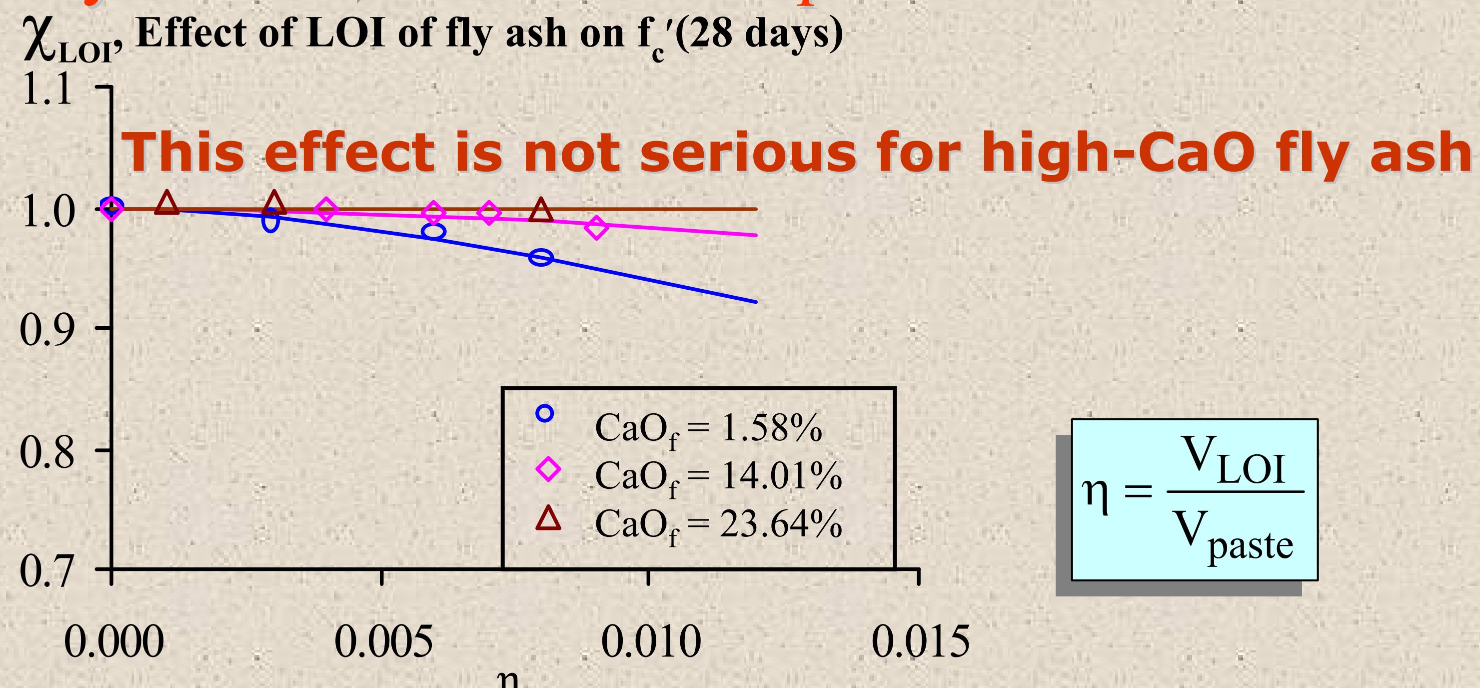
$$\gamma = \frac{V_{paste}}{V_{void}}$$

$$\gamma_{opt} = 0.59^{1.74(w/b)} + 0.55$$

$$\chi_\gamma = \begin{cases} 1-[10.64(w/b)^{3.68}+2.38]\cdot(\gamma_{opt}-\gamma)^{2.21}; \gamma \le \gamma_{opt} \\ 1-\dfrac{[11.97(w/b)^{1.12}]\cdot(\gamma-\gamma_{opt})}{7.57+\exp[1.83(\gamma-\gamma_{opt})]} \quad ; \gamma > \gamma_{opt} \end{cases}$$

Effect of LOI of Fly Ash

LOI in fly ash ⇒ non-reactive part in concrete

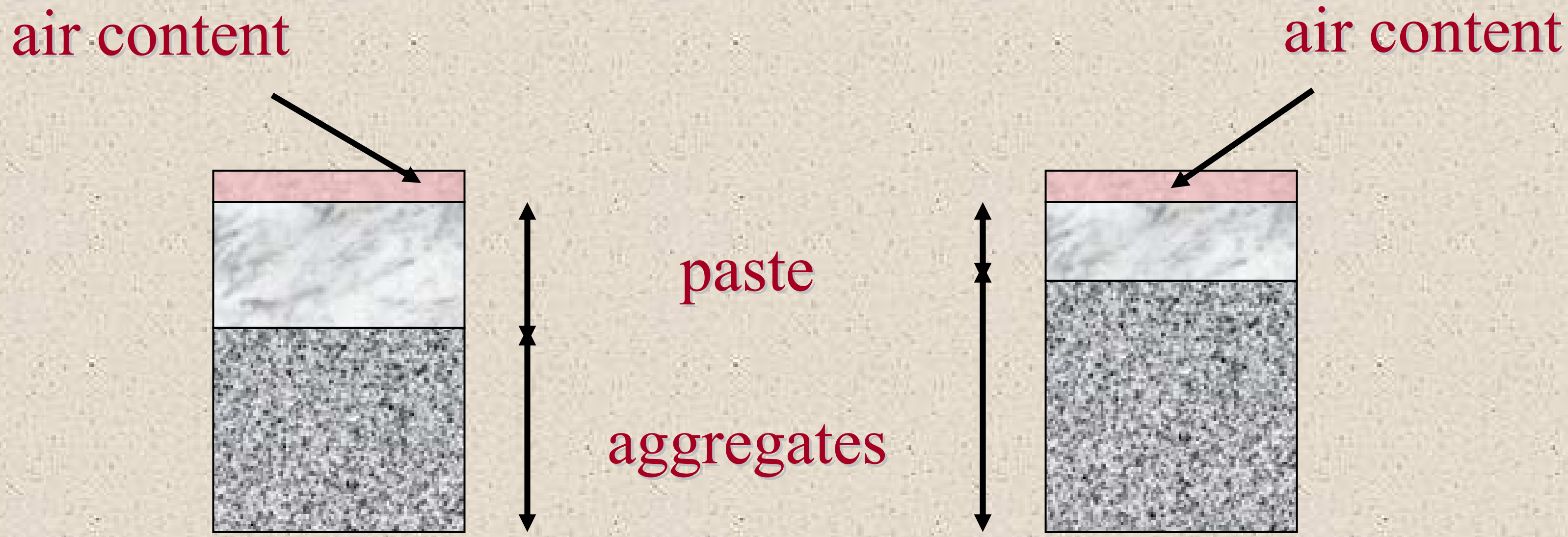


$$\eta = \frac{V_{LOI}}{V_{paste}}$$

$$V_{LOI} = \frac{(\%LOI \times W_f / \rho_{uc})}{100} \approx \frac{(\%LOI \times W_f / \rho_f)}{100}$$

$$\chi_{LOI} = 1 - 155.75 \ \ [\exp(-0.15 \cdot CaO_f)] \ \ \eta^{1.66}$$

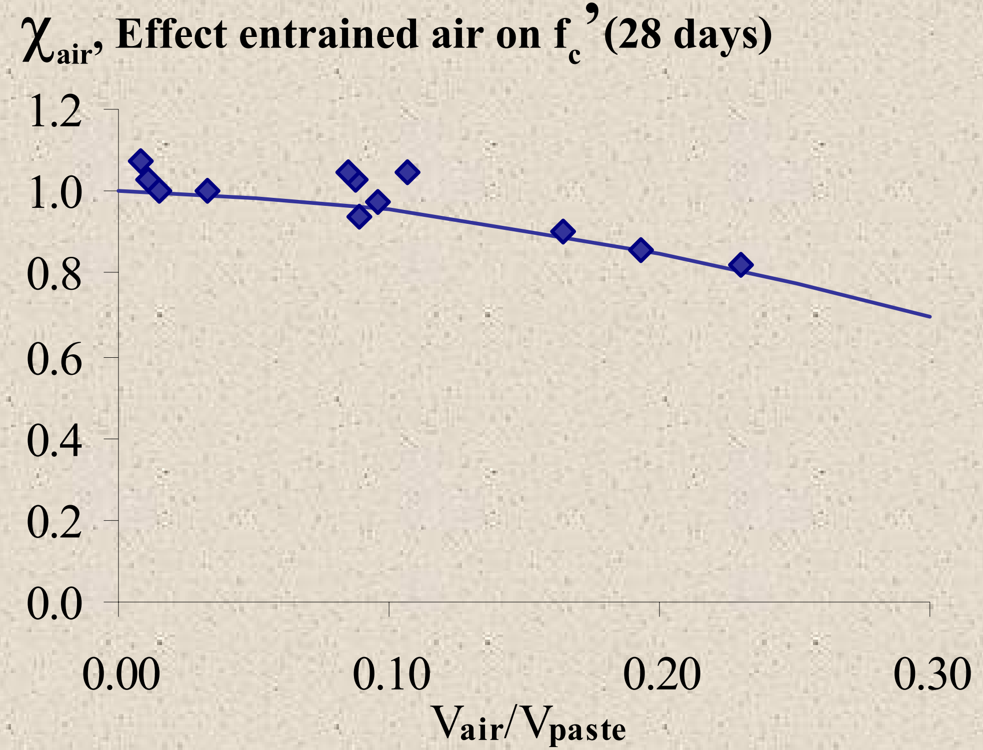
Effect of Entrained Air



Same air content **BUT** gives different effect on f_c'(28 days)

$$\xi = \frac{V_{air}}{V_{paste}}$$

Effect of Entrained Air



$$\chi_{air} = 1 - 2.35 \quad \xi^{1.70}$$

28-DAY COMPRESSIVE STRENGTH MODEL

for Conventional Concrete

$$f_c'(28days) = [\alpha_1 \log(CaO_{eff}) + \lambda_f \cdot \alpha_2] \cdot \chi_\gamma \cdot \chi_{LOI} \cdot \chi_{wr} \cdot \chi_{air}$$

$$\lambda_F = \frac{1}{1 + (0.25\Psi^{-4.91}) \tan^{-1}(357F^{3.24})}$$

$$\chi_\gamma = \begin{cases} 1 - [10.64(w/b)^{3.68} + 2.38] \cdot (\gamma_{opt} - \gamma)^{2.21}; \gamma \le \gamma_{opt} \\ 1 - \dfrac{[11.97(w/b)^{1.12}] \cdot (\gamma - \gamma_{opt})}{7.57 + \exp[1.83(\gamma - \gamma_{opt})]} \quad ; \gamma > \gamma_{opt} \end{cases}$$

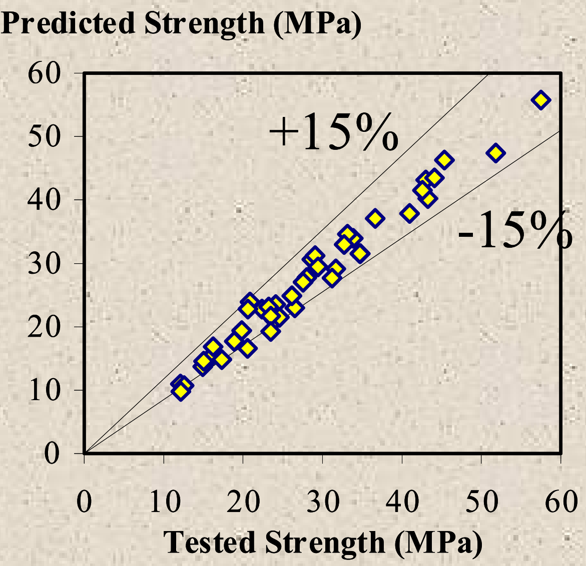
$$\chi_{LOI} = 1 - 155.75 \quad [\exp(-0.15 \cdot CaO_f)] \quad \eta^{1.66}$$

$$\chi_{air} = 1 - 2.35 \quad \xi^{1.70}$$

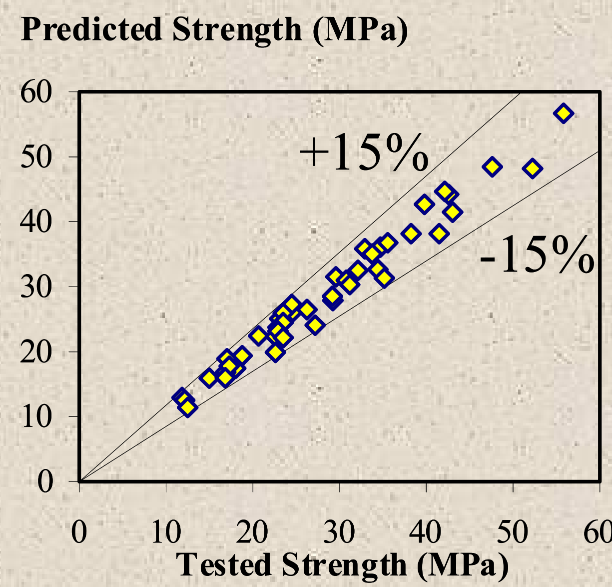
$$\chi_{wr} = 1 + (3.52\Omega - 0.27) \cdot (0.005(w/b)^{-2.07}) \cdot \tan^{-1}(3.90\nu)$$

Verifications for Conventional Concretes Model

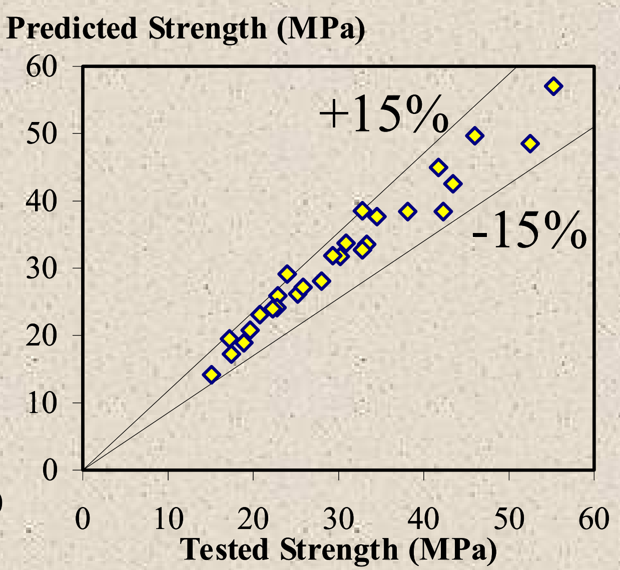
Concrete containing original fly ash



Fineness = 2600 cm^2/g



Fineness = 4100 cm^2/g

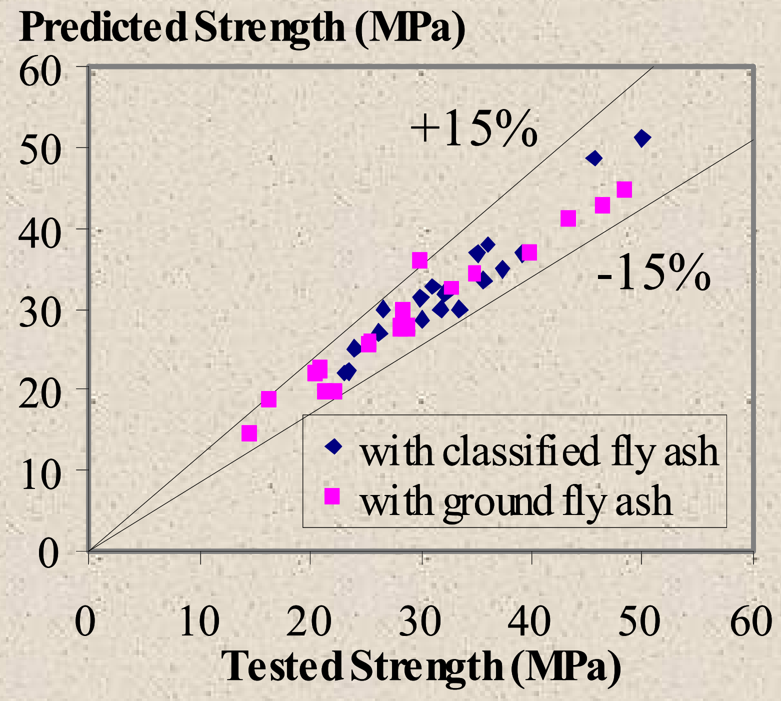


Fineness = 4600 cm^2/g

Verifications for Conventional Concretes Model

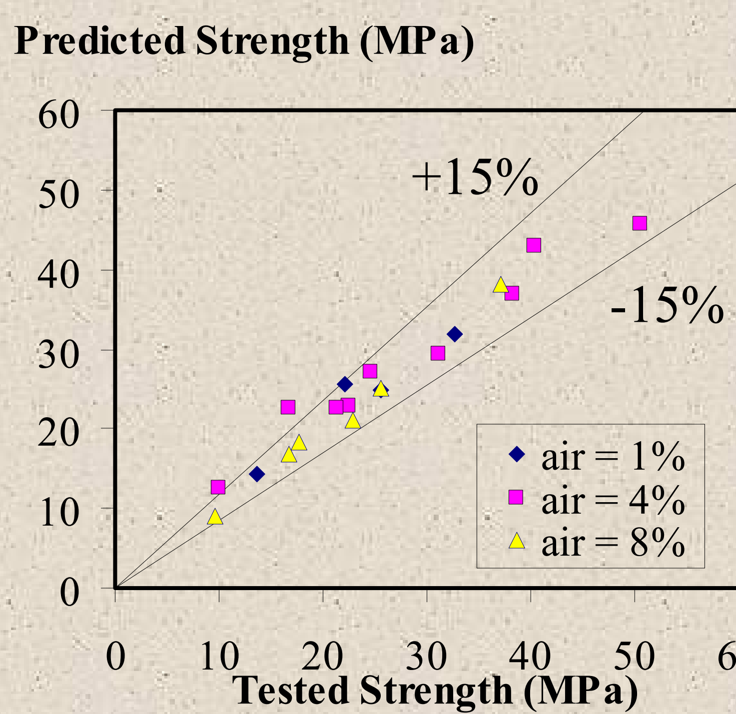
Concrete with classified fly ash ($\Psi = 1.05$)

Concrete with ground fly ash ($\Psi = 1.20$)

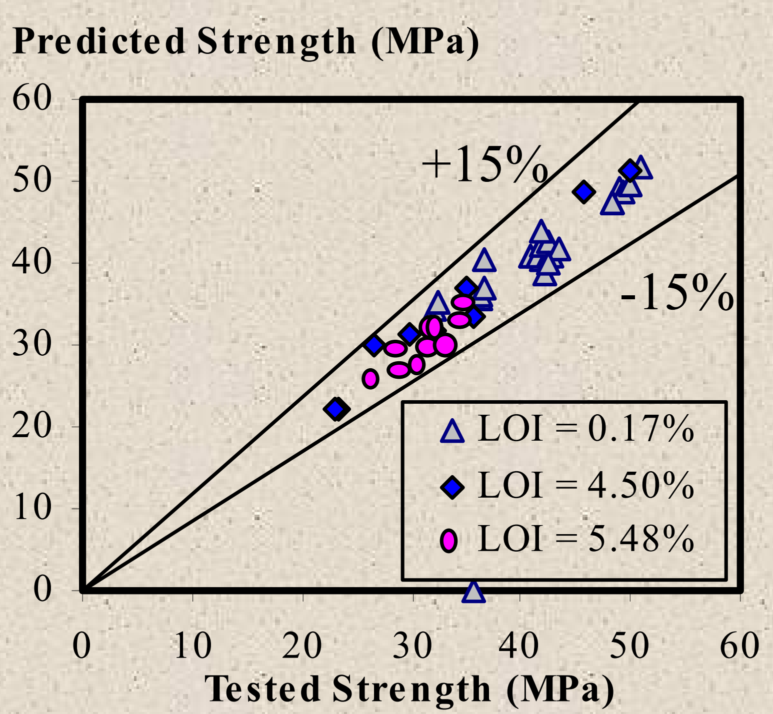


Verifications for Conventional Concretes Model

Air Entrained Concrete



High LOI Fly Ash Concrete



Compressive Strength Development Model

Strength Ratio

$$\phi(t) = \frac{f_c'(t)}{f_c'(28days)}$$

Factor Effecting Strength Development of Concrete

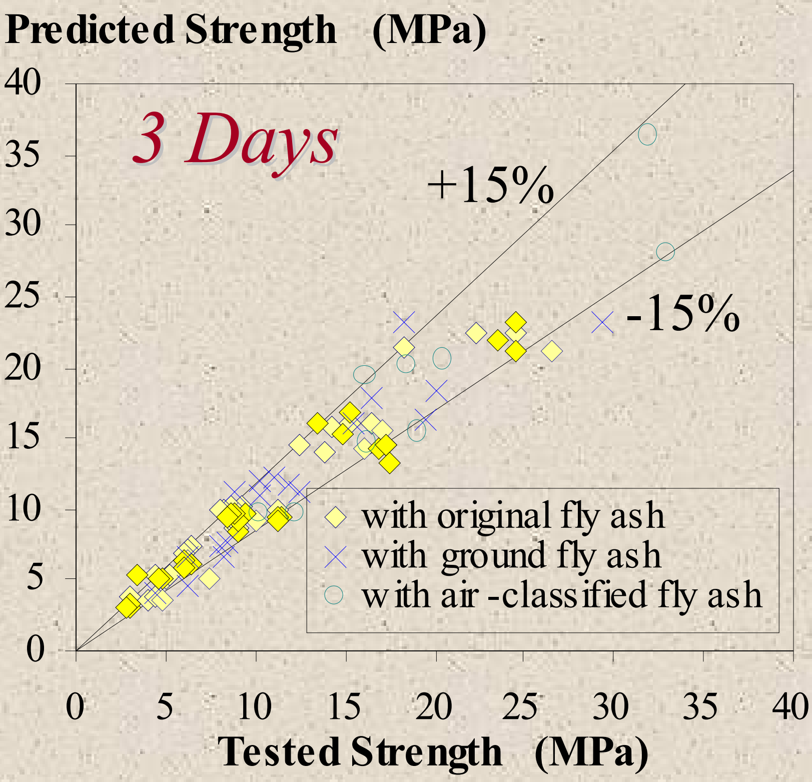
SiO_2/CaO

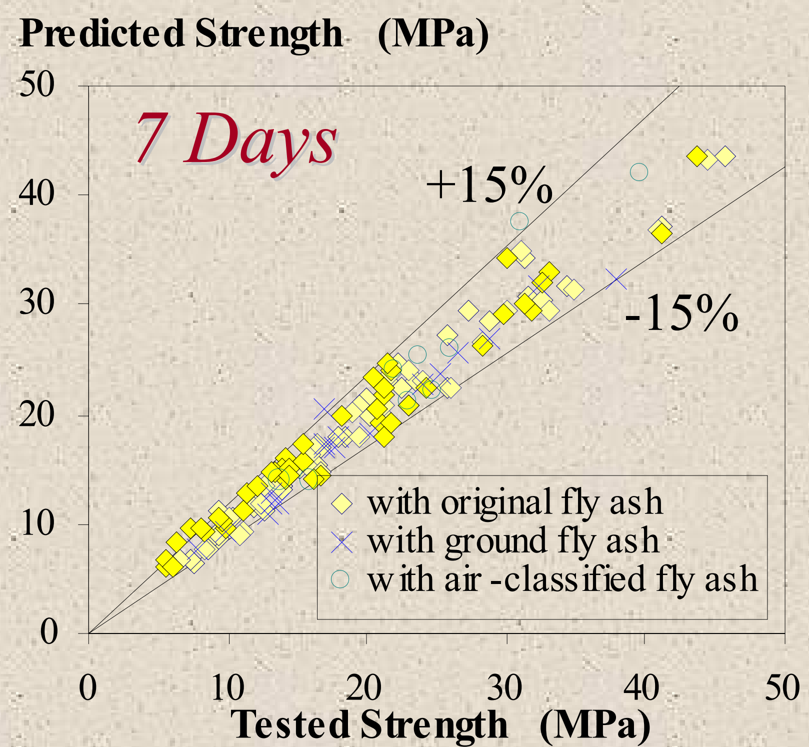
w/b

Filling Effect of fly ash

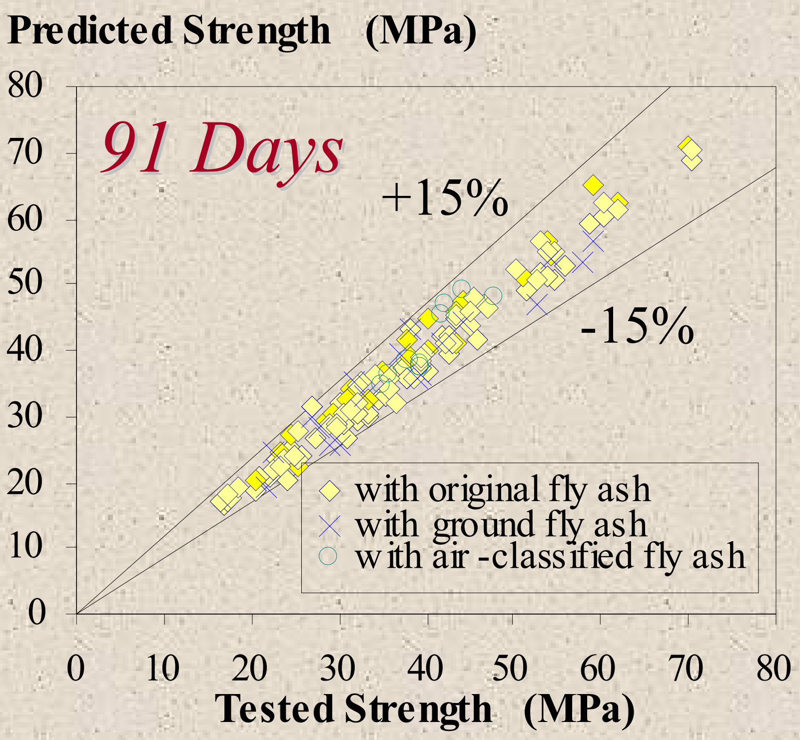
Effect of water-reducing admixture

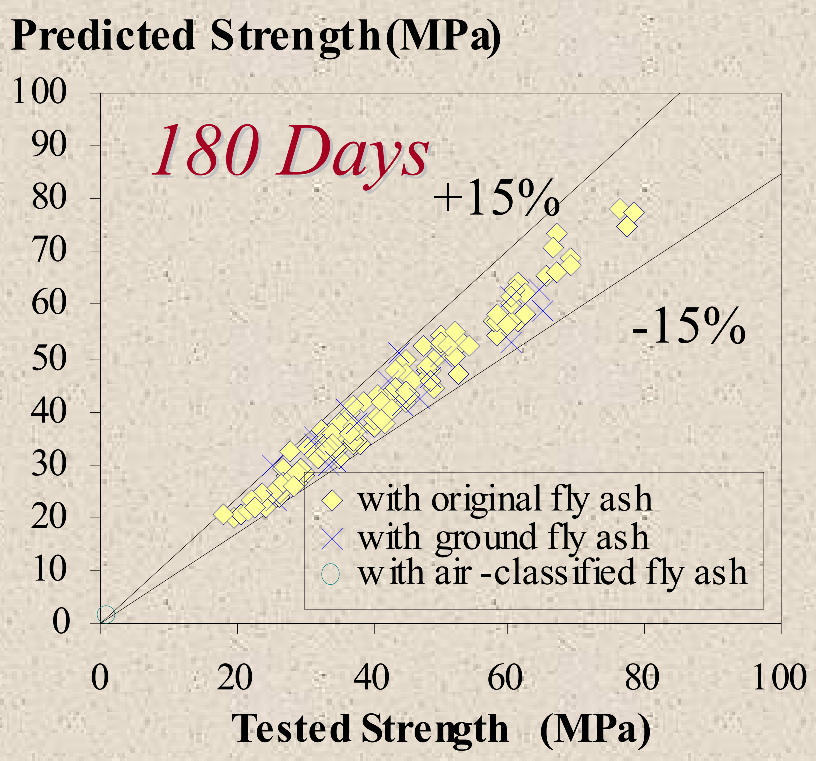
Verifications for the Strength Development Model



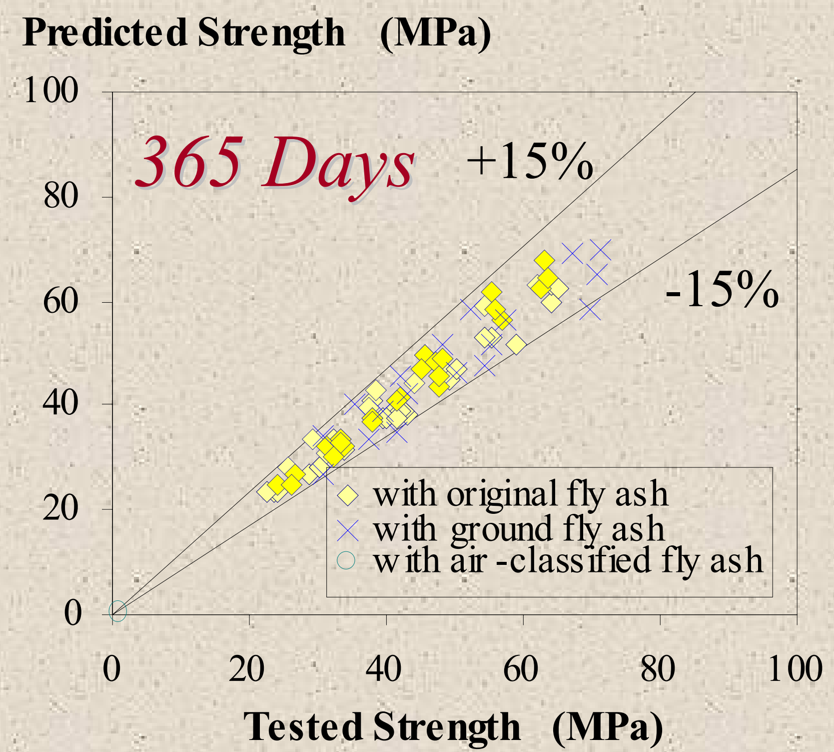


Verifications for the Strength Development Model





Verifications for the Strength Development Model



PERFORMANCE BASED PREDICTION MODEL

:Temperature of Concrete

Sirindhorn International Institute of Technology

Thammasat University

Total Heat Generation of Concrete

↓

Specific Heat

$$Q = \int H dt = s \rho \Delta T$$

s : Specific Heat

ρ : Specific Gravity

H : Heat Generation rate per unit volume

T : Temperature of concrete

Temperature of Concrete

↓

Heat Conductivity

$$s\rho\left(\frac{dT}{dt}\right) = K\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + H$$

Heat Transfer Coefficient

$$\left(-k\nabla^2 T + H\right) n = m\left(T - T_{ext}\right)$$

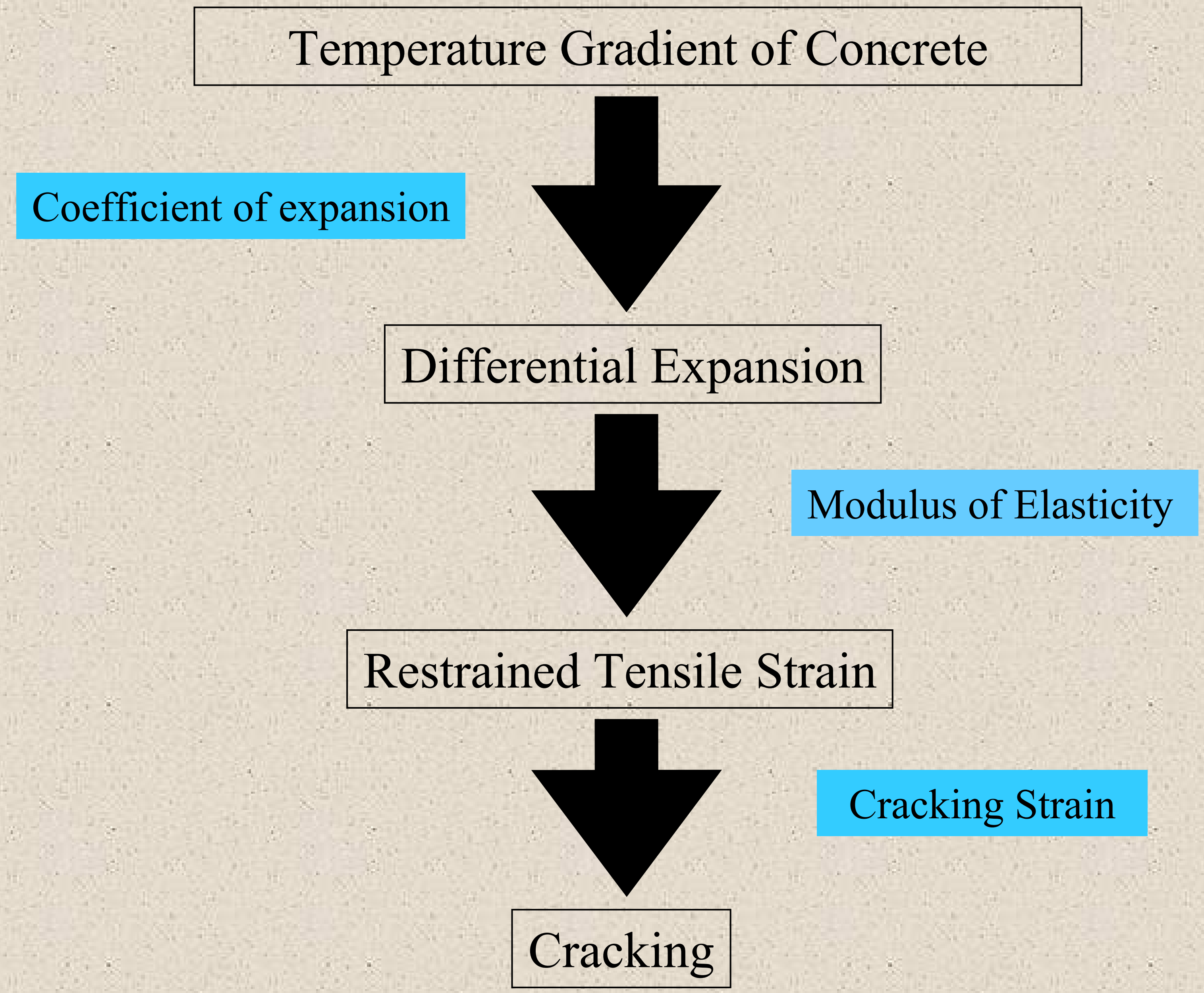
K : Heat conductivity

H : Heat generation rate per unit volume

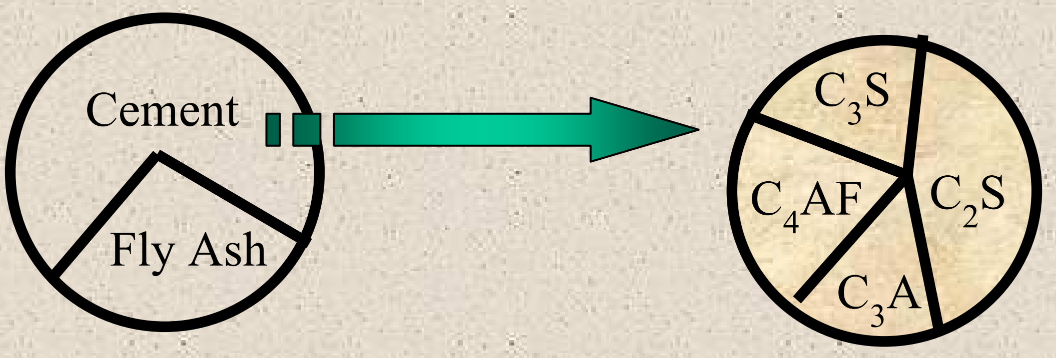
n : Outward unit vector normal to the surface

m : Heat transfer coefficient

Temperature Gradient of Concrete


Temperature Gradient of Concrete
Coefficient of expansion
Differential Expansion
Modulus of Elasticity
Restrained Tensile Strain
Cracking Strain
Cracking

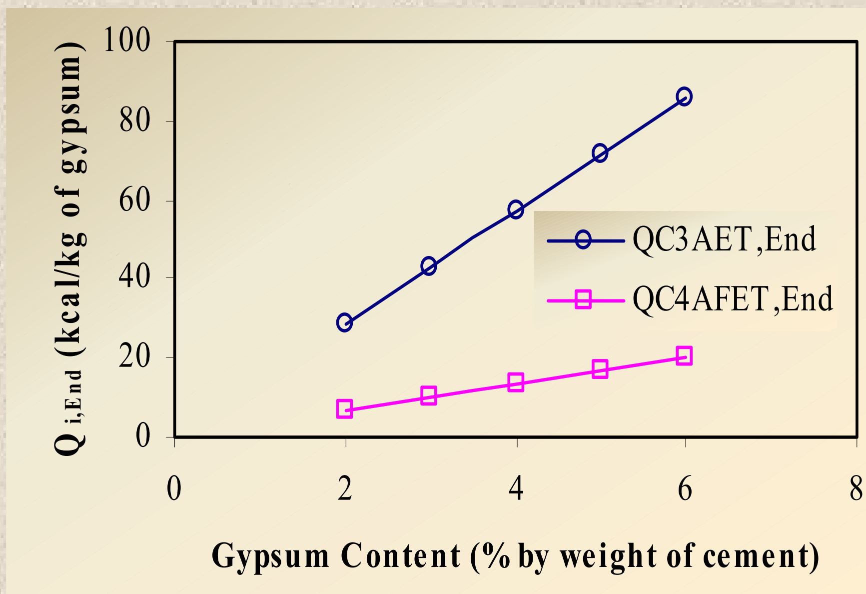
Total Heat Generation of Concrete

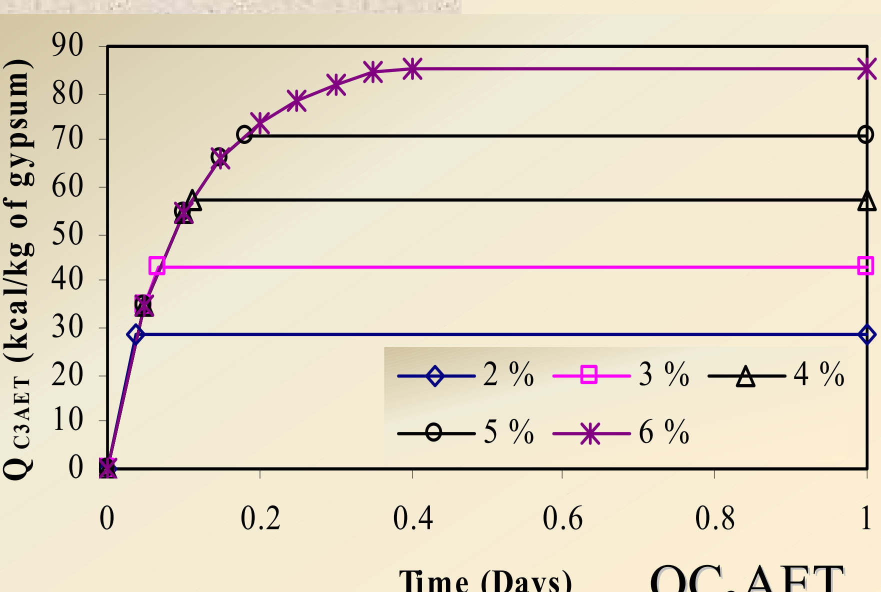


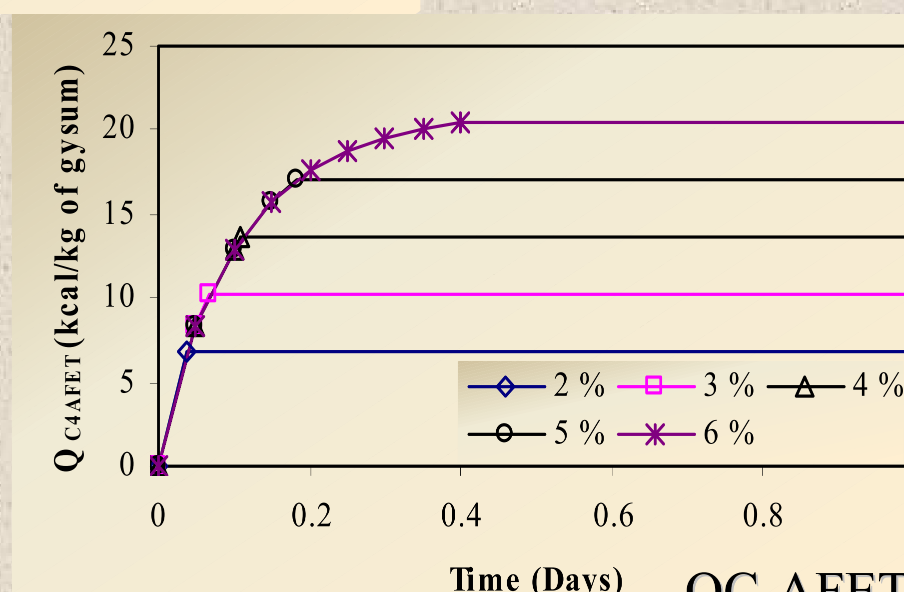
$$Q(t) = Q_{C_3S}(t) + Q_{C_2S}(t) + Q_{C_3A}(t) + Q_{C_4AF}(t) + Q_{C_3AET}(t) + Q_{C_4AFET}(t) + Q_{FA}(t)$$

- Cumulative Heat Generation of Ettringite and Monosulphate
- Cumulative Heat Generation of Cement Compounds
- Cumulative Heat Generation of Fly Ash

Heat Generation of Ettringite and Monosulfate Formation Reactions



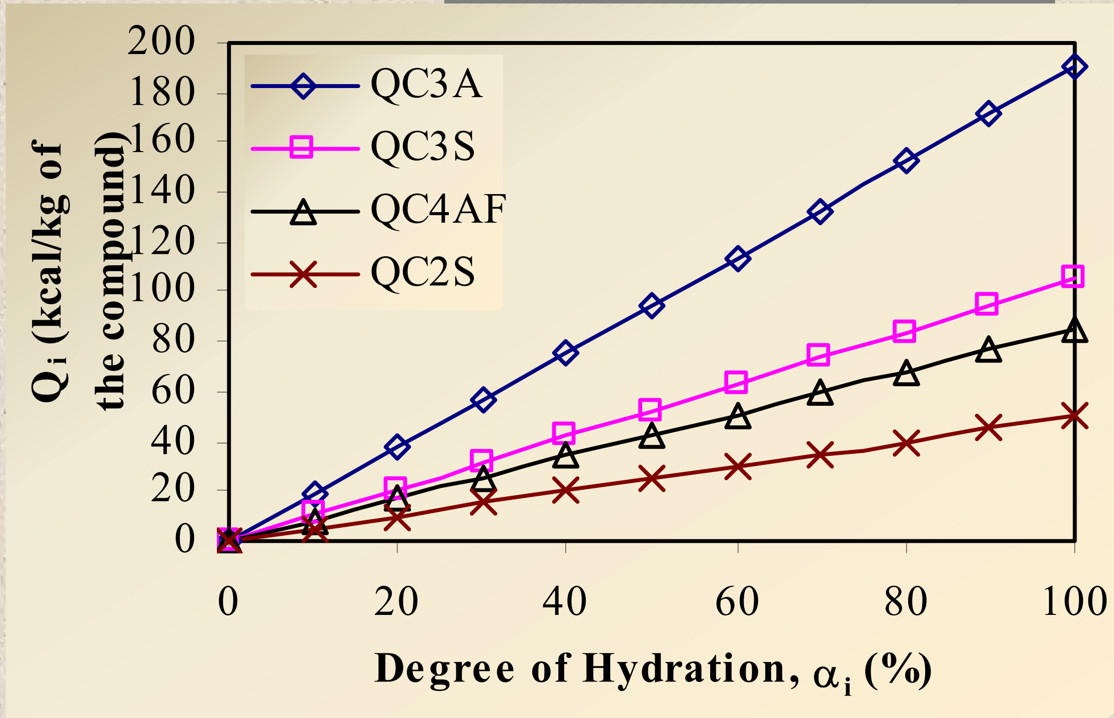




Heat Generation of Cement

Degree of Hydration

$$Q_i(t) = \frac{\alpha_i(t)}{100} \cdot Q_{i,max} \cdot w_i$$



$QC_3A = 190$ kcal/kg

$QC_3S = 105$ kcal/kg

$QC_4AF = 85$ kcal/kg

$QC_2S = 50$ kcal/kg

For C_3S and C_2S $\quad w_i = w_{io}$

For C_3A and C_4AF $\quad w_i = w_{io} - w_{iET} - w_{iMN}$

Heat Generation of Fly Ash

$$Q_{FA}(t) = \frac{\alpha_{poz}(t)}{100} \cdot Q_{FA,max} \cdot w_{fa}$$

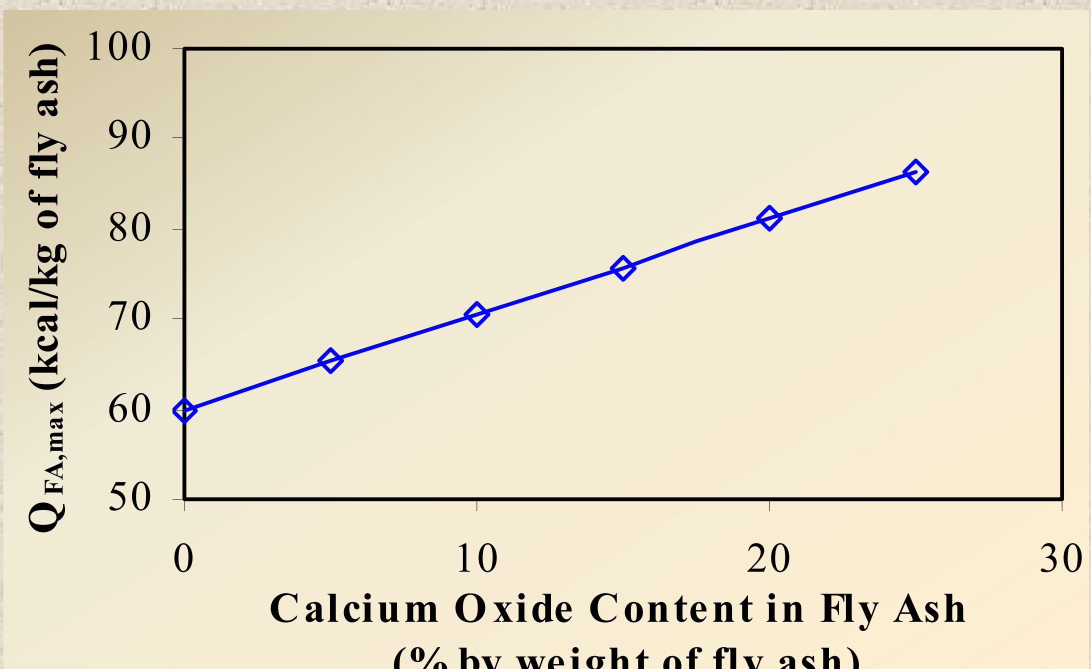
Degree of Pozzolanic Reaction

Fly Ash Content

At max degree of pozzolanic reaction

$$Q_{FA,max} = 36 + 0.63 \cdot \%CaO_f$$

Calcium Oxide in Fly Ash



Thermal Properties

Specific Heat Model

$$c(t) = w_g c_g + w_s c_s + w_{fw}(t) c_w + w_{uc}(t) c_c + w_{ufa}(t) c_{fa} + w_{hp}(t) c_{hp}(t)$$

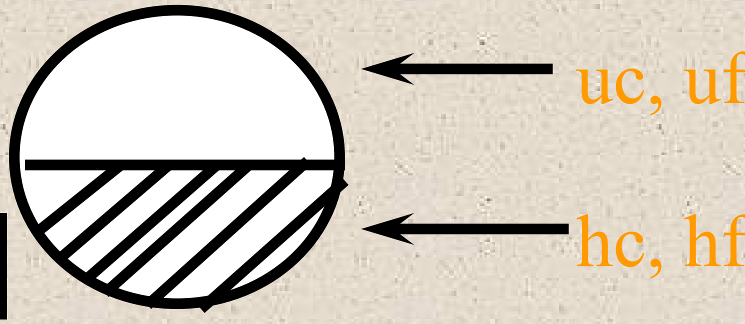
$c(t)$: specific heat of concrete at any time.

c_i : specific heat of i-th component of concrete

w_i : weight of i-th component of concrete

$$w_{uc}(t) = \left(1 - \alpha_{hy}(t)\right) w_{c0}$$

$$w_{ufa}(t) = \left(1 - \alpha_{poz}(t)\right) w_{fa0}$$

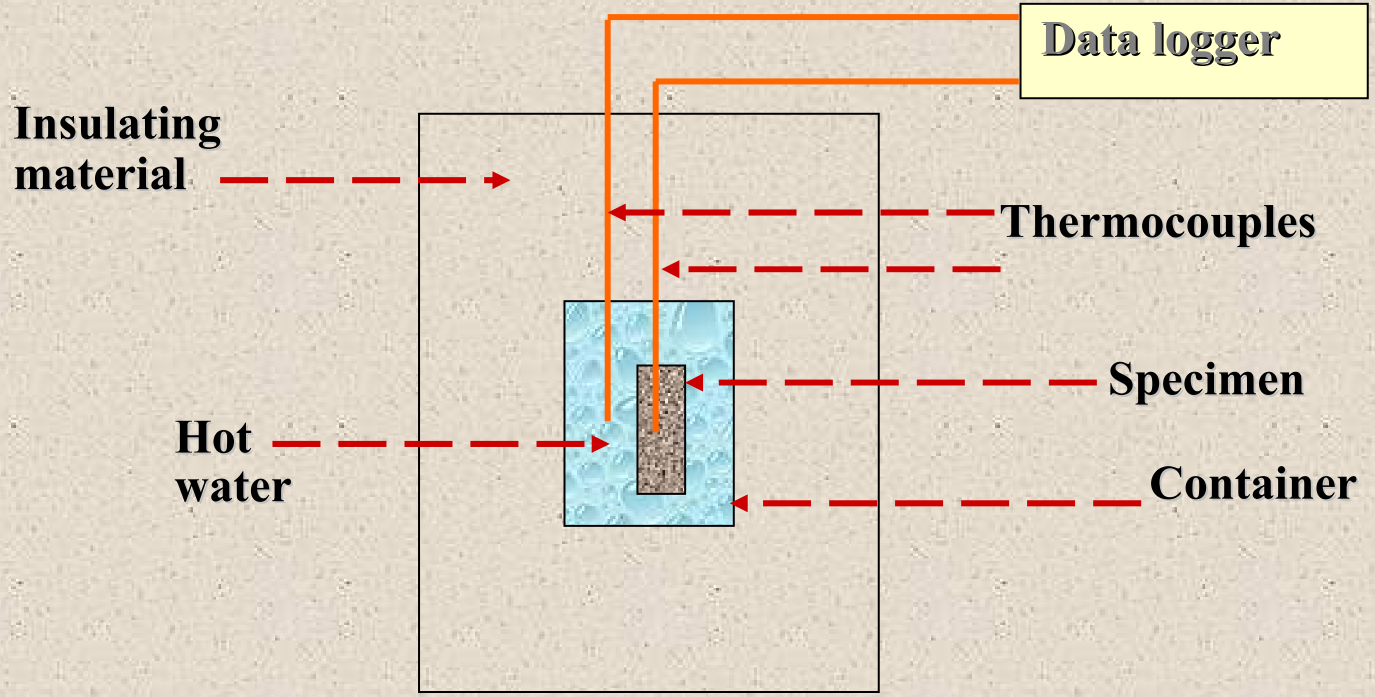


Thermal Coefficients	Coarse aggregate (Lime Stone)	Fine aggregate (Sand)	Water	Cement	Fly Ash	Air	Hydrated Product *
Specific Heat (kcal/kg/ °C)	0.20	0.19	1.0	0.18	0.17	0.24	0.13

* Back analysis

ASHRAE: American Society of Heat Refrigerating and Air Conditioning Engineering

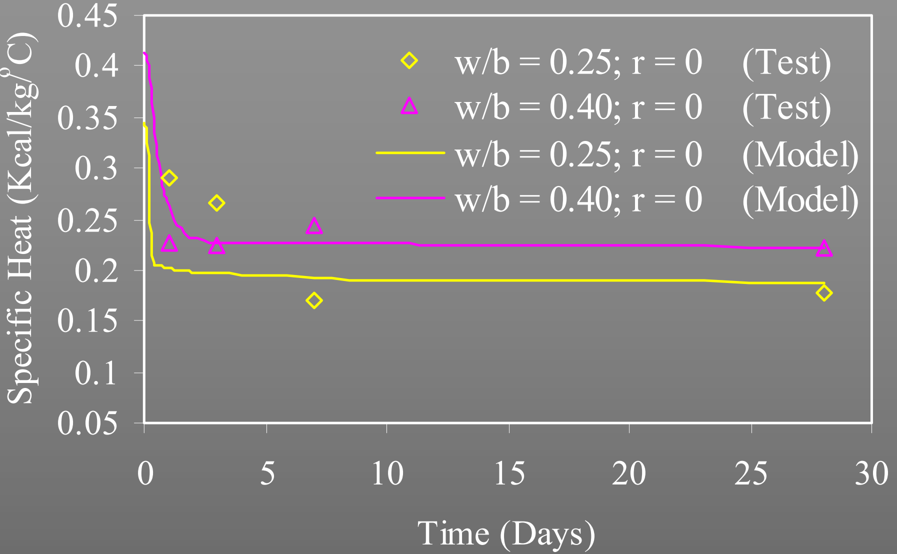
Apparatus for testing specific heat

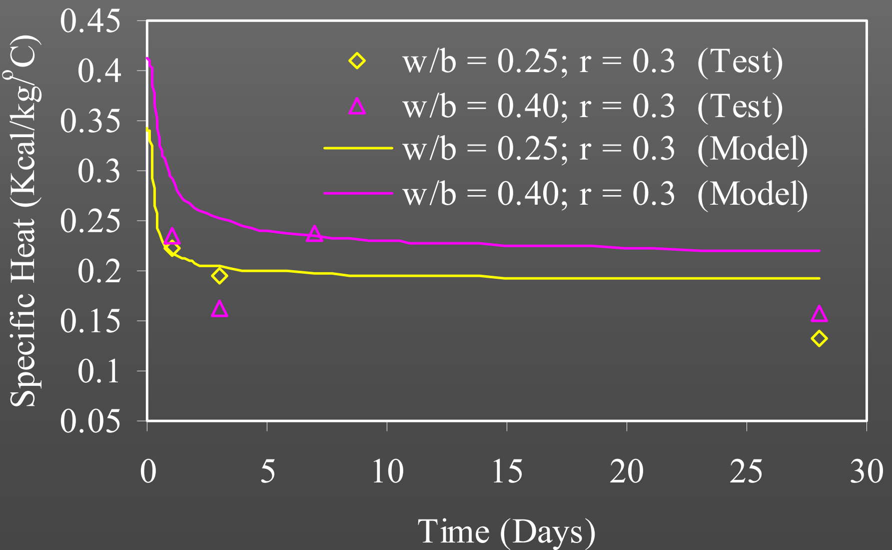


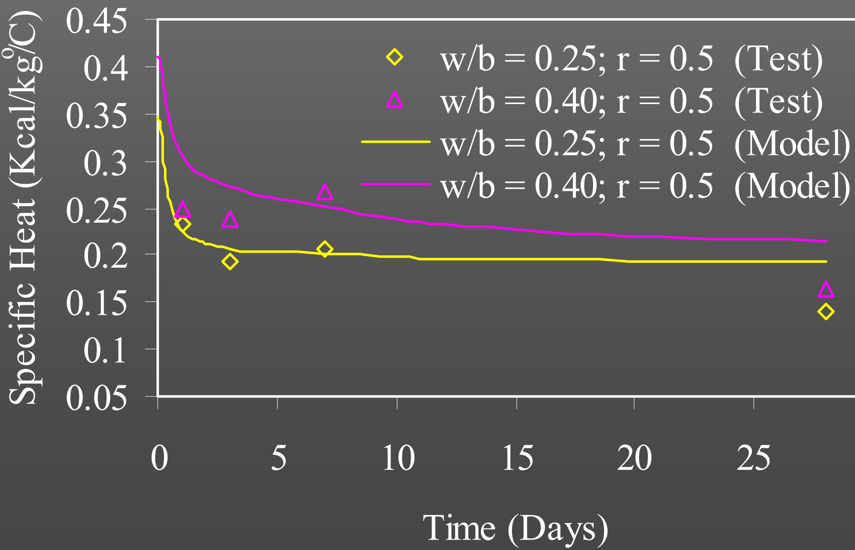
Data Logger

Insulated Container

Verification of Specific Heat Model







Thermal Conductivity Model

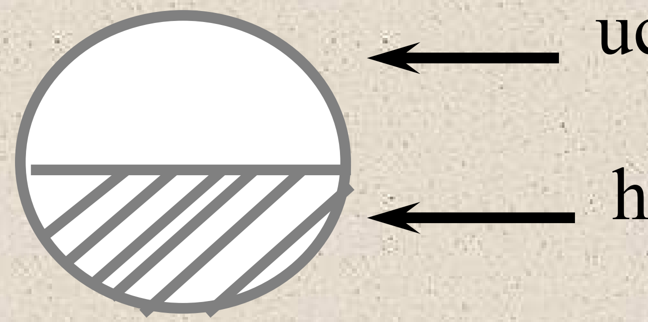
$$Z(t) = n_g z_g + n_s z_s + n_{fw}(t) z_w + n_{uc}(t) z_c + n_{ufa}(t) z_{fa} + n_{hp}(t) z_{hp}$$

$Z(t)$: conductivity of concrete at any time.

Z_i : conductivity of i-th component of concrete

n_i : volume metric ratio of i-th component of concrete

$$n_{uc}(t) = \left(1 - \alpha_{hy}(t)\right) n_{c0}$$

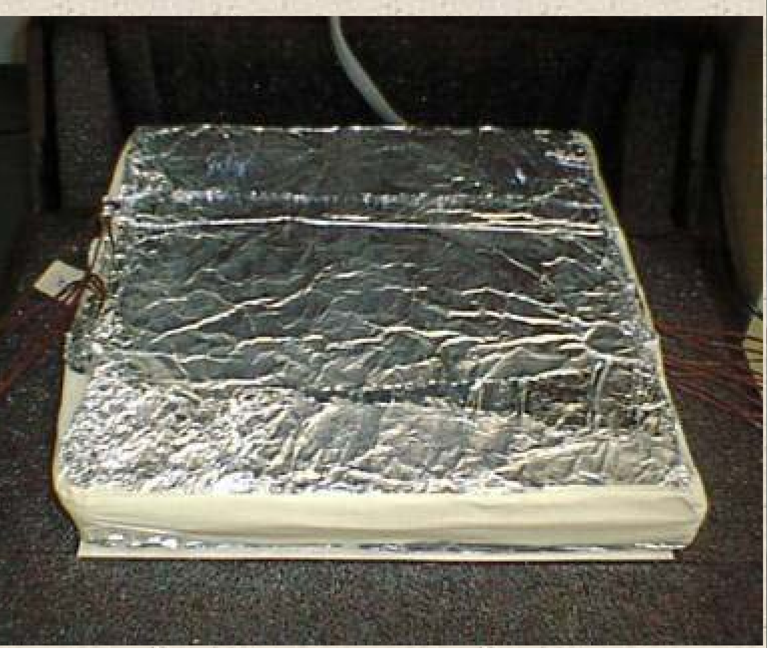


Thermal Coefficients	Coarse aggregate (Lime Stone)	Fine aggregate (Sand)	Water	Cement	Fly Ash	Air	Hydrated Product *
Heat Conductivities (Kcal/m.day.C)	20.50	7.50	12.44	0.62	1.16	0.54	23.5

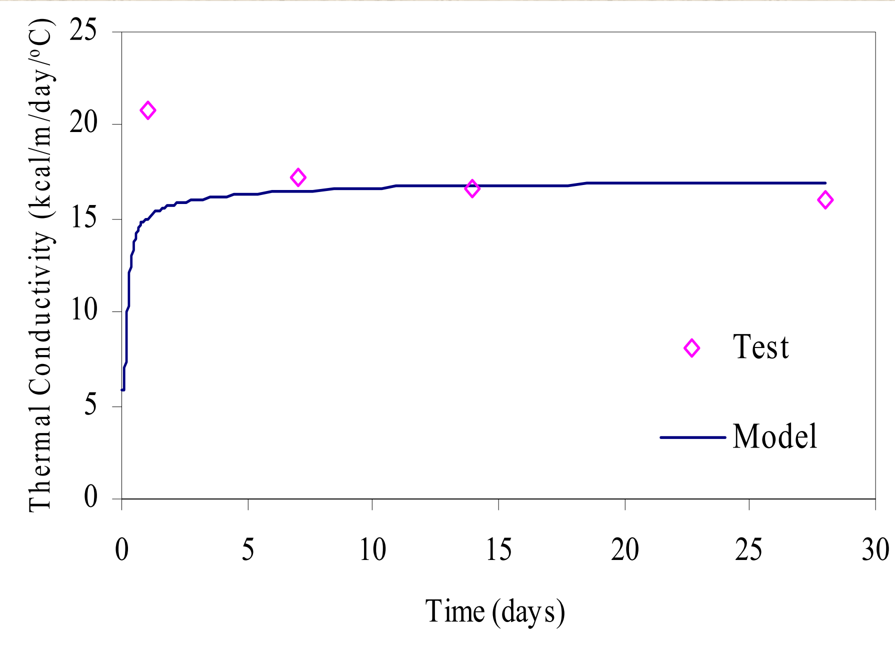
* Back analysis

ASHRAE: American Society of Heat Refrigerating and Air Conditioning Engineering

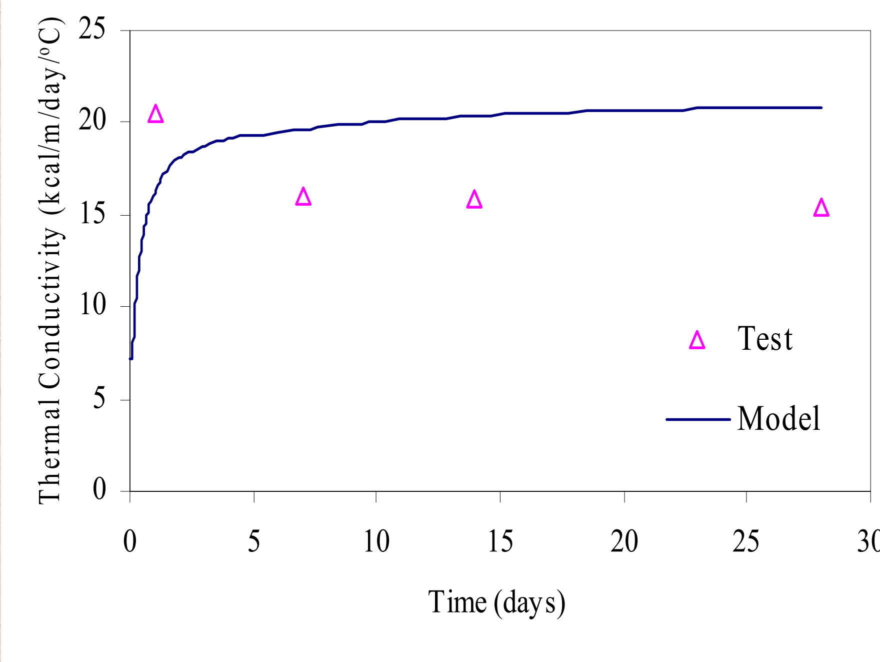
Thermal Conductivity Test



Verification of Thermal Conductivity Model



Thermal conductivity of w25r0.



Thermal conductivity of w40r0.

Total Heat Generation of Concrete

Specific Heat

$$Q = \int H dt = s \rho \Delta T$$

s : Specific Heat

ρ : Specific Gravity

H : Heat Generation rate per unit volume

T : Temperature of concrete

Temperature of Concrete

Heat Conductivity

Heat Transfer Coefficient

$$s\rho\left(\frac{dT}{dt}\right) = K\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + H$$

$$\left(-k\nabla^2 T + H\right)n = m\left(T - T_{ext}\right)$$

K : Heat conductivity

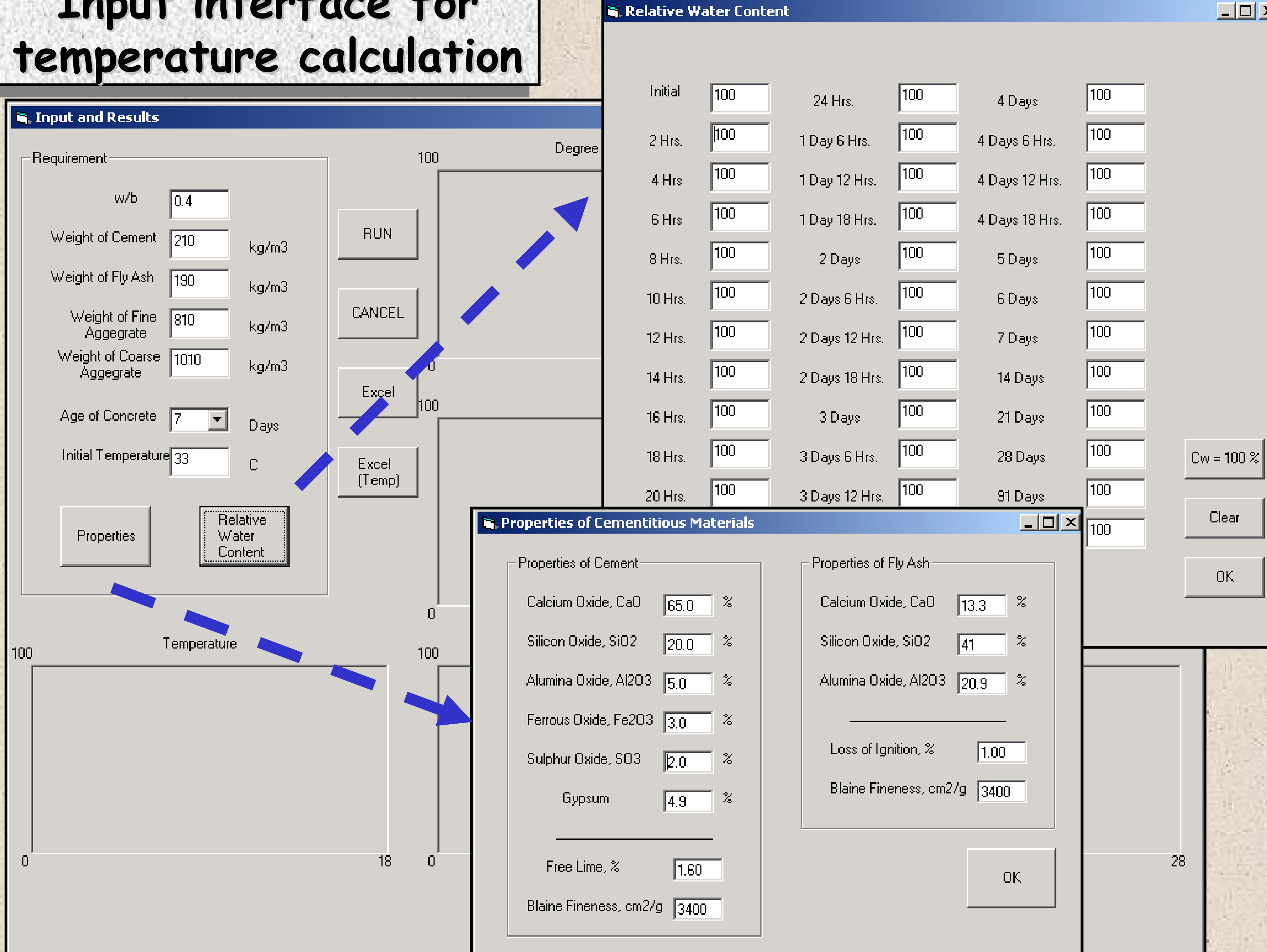
H : Heat generation rate per unit volume

n : Outward unit vector normal to the surface

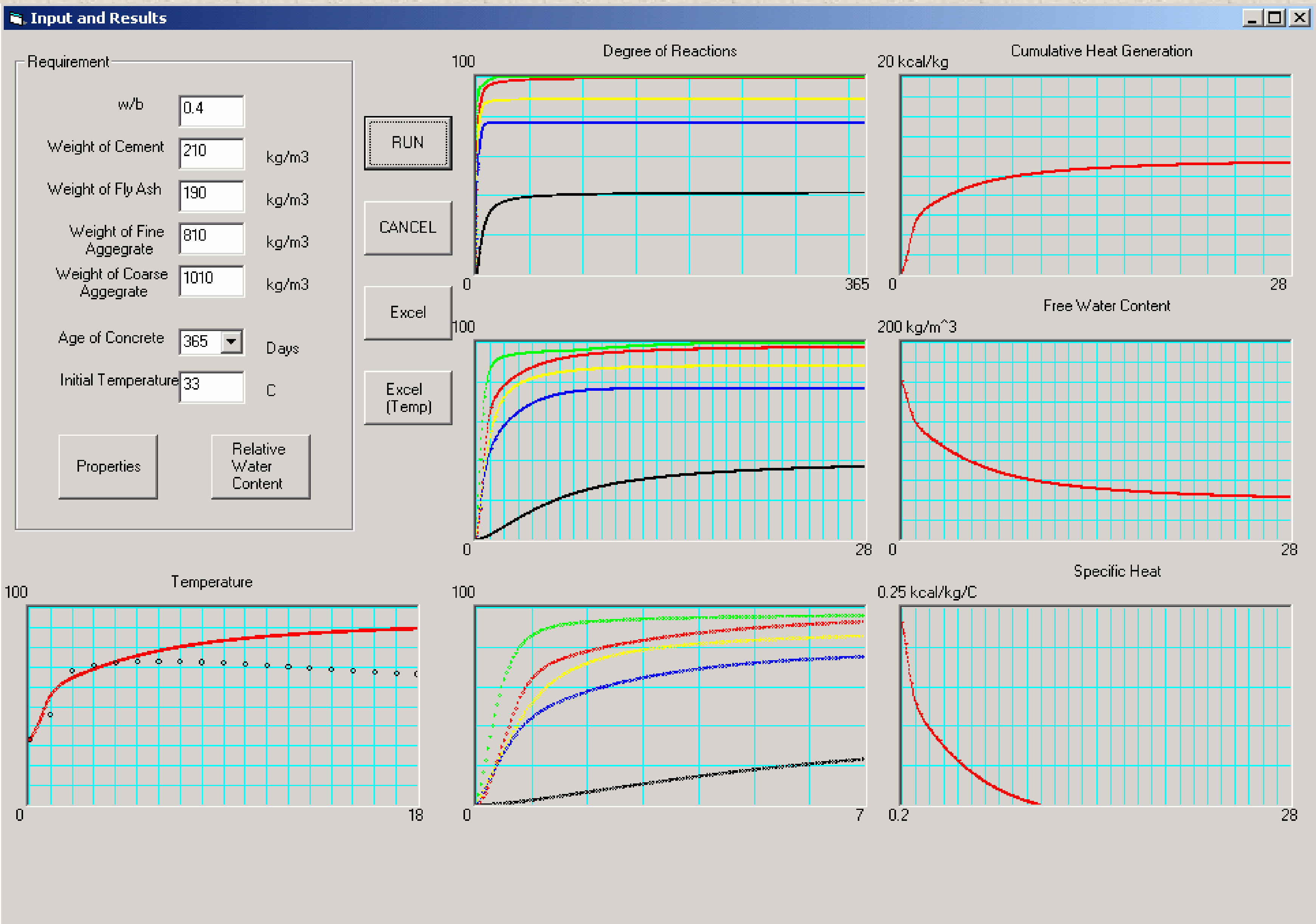
m : Heat transfer coefficient

Temperature Gradient of Concrete

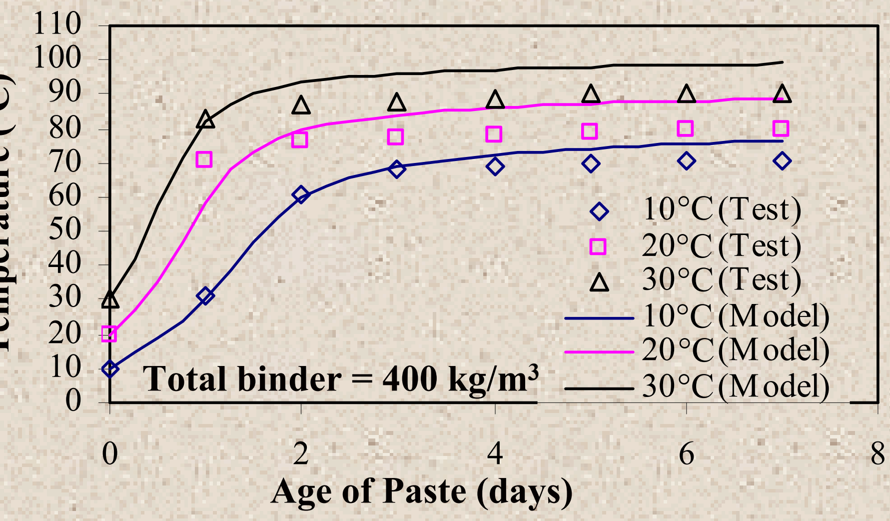
Input interface for temperature calculation

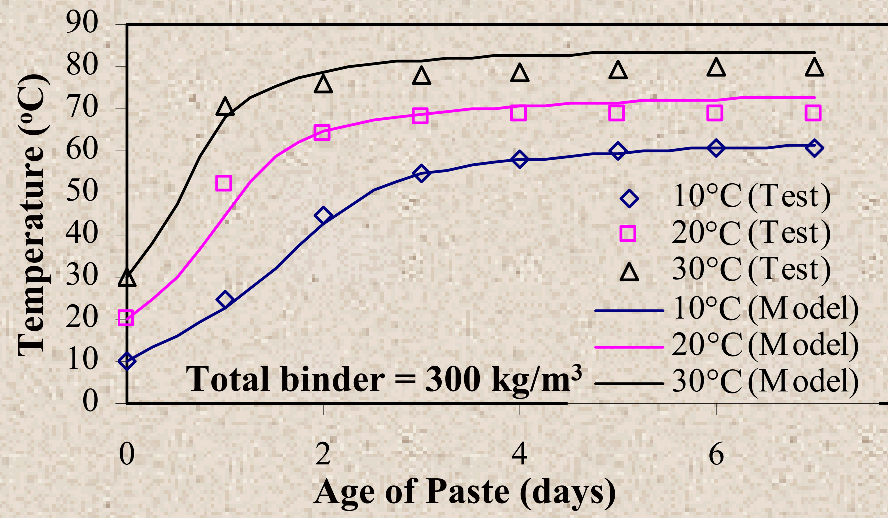


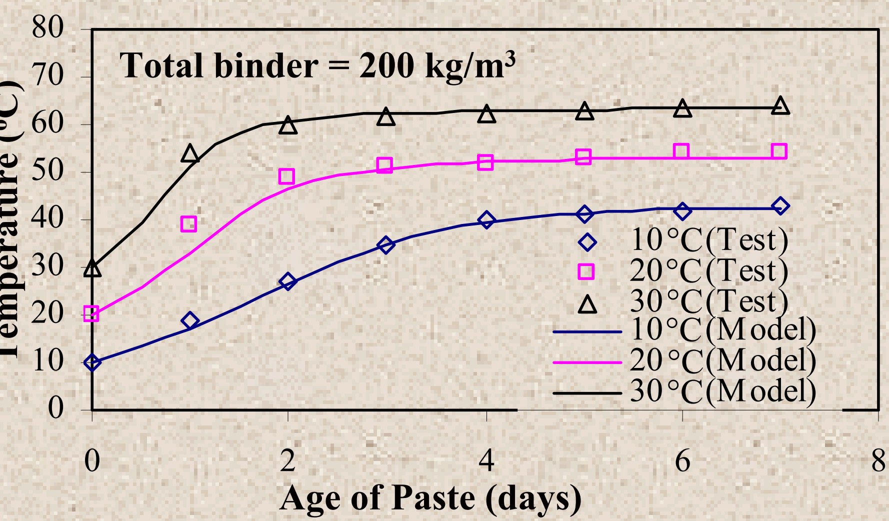
Output interface for temperature calculation



Verification by Adiabatic Test Results

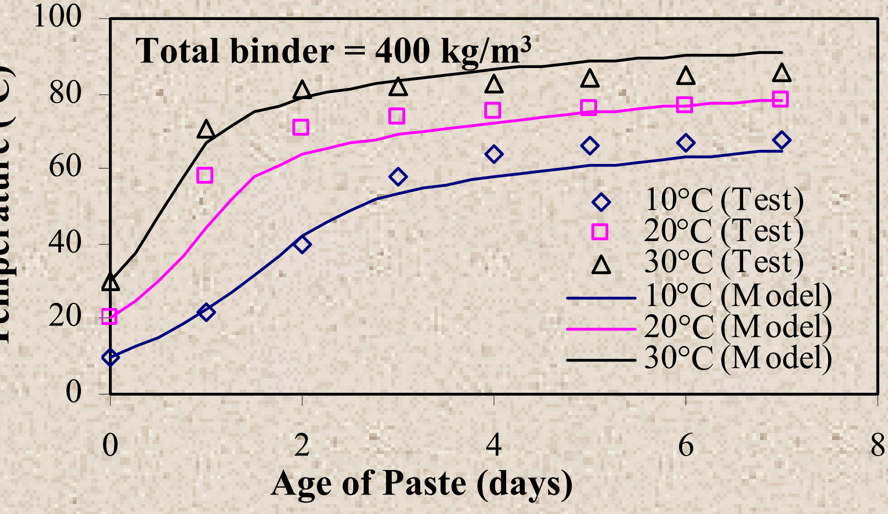


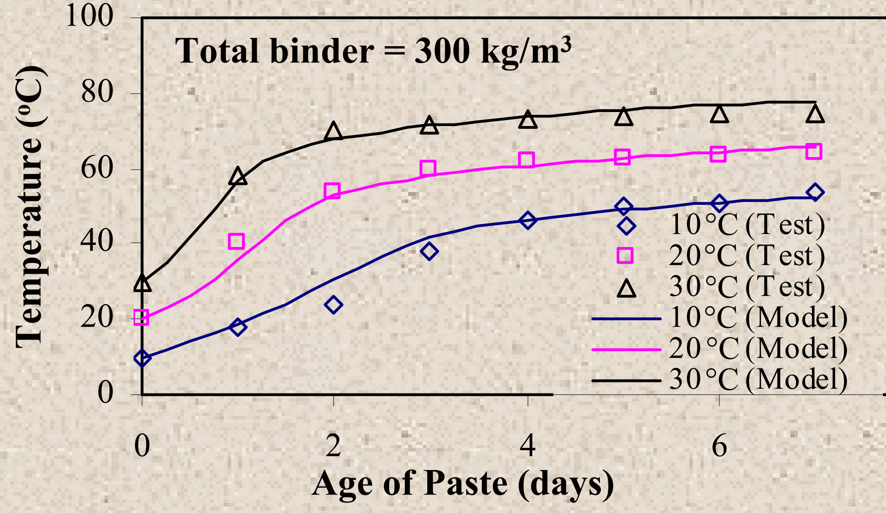


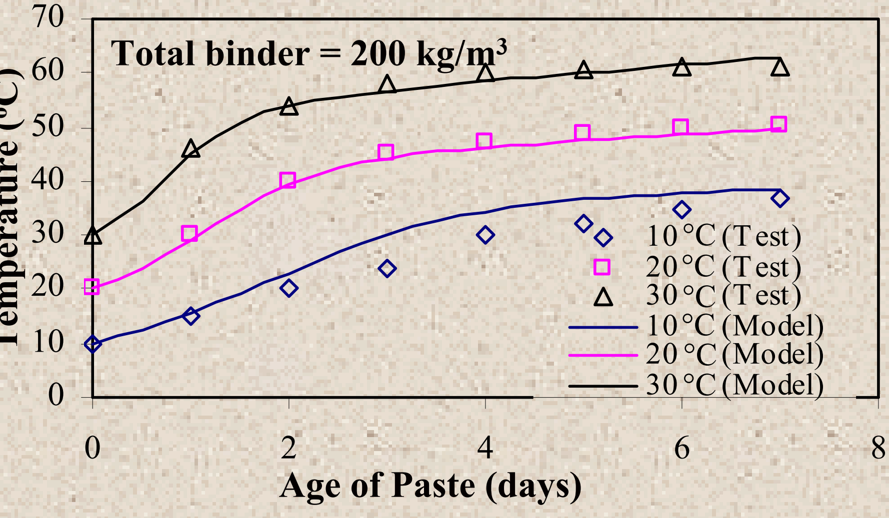


Adiabatic temperature rise of Portland cement mixture (Suzuki et al. 1990)

Verification by Adiabatic Test Results

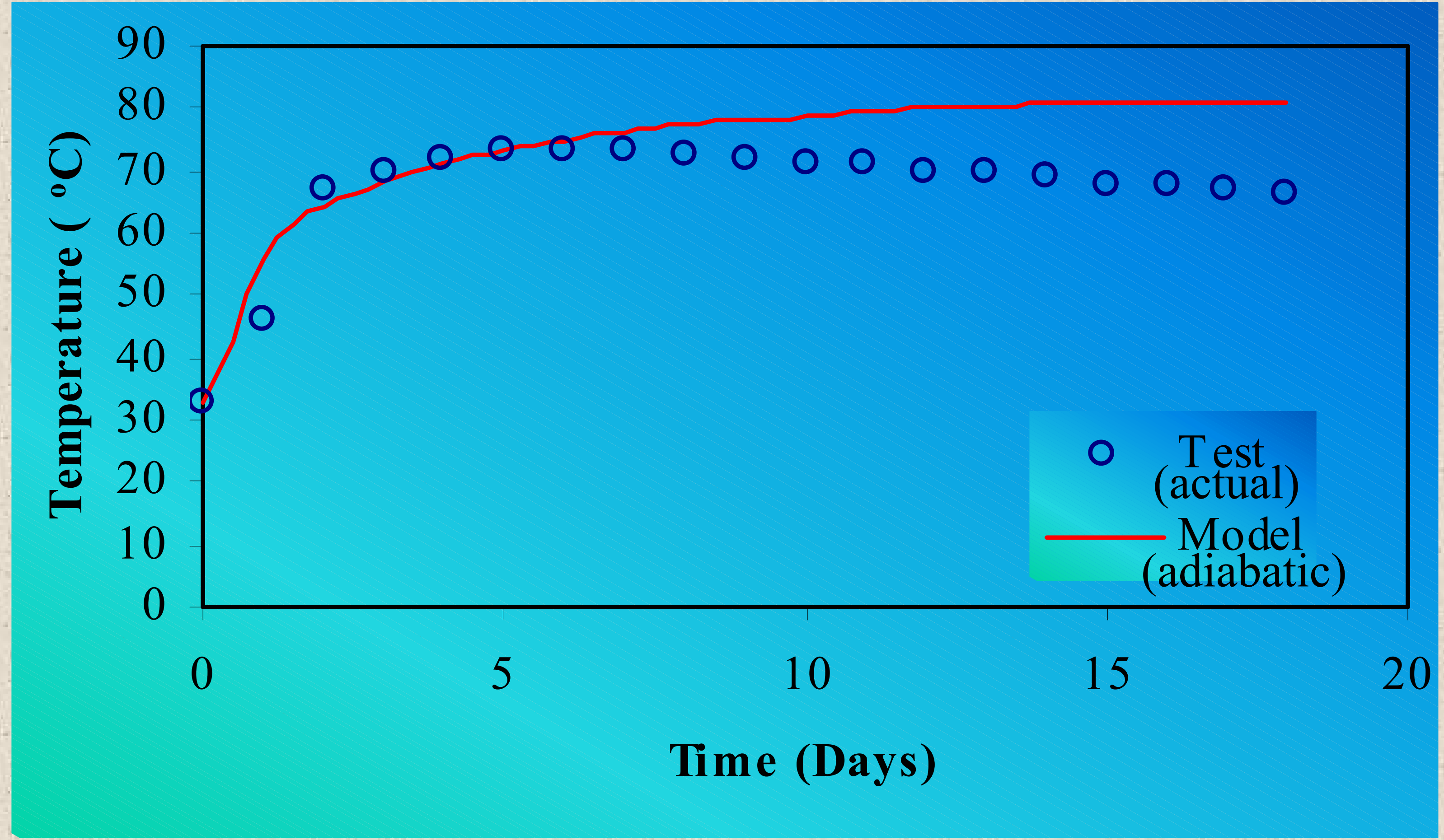






Adiabatic temperature rise of blend cement mixture with 20 % fly ash replacement (Suzuki et al. 1990)

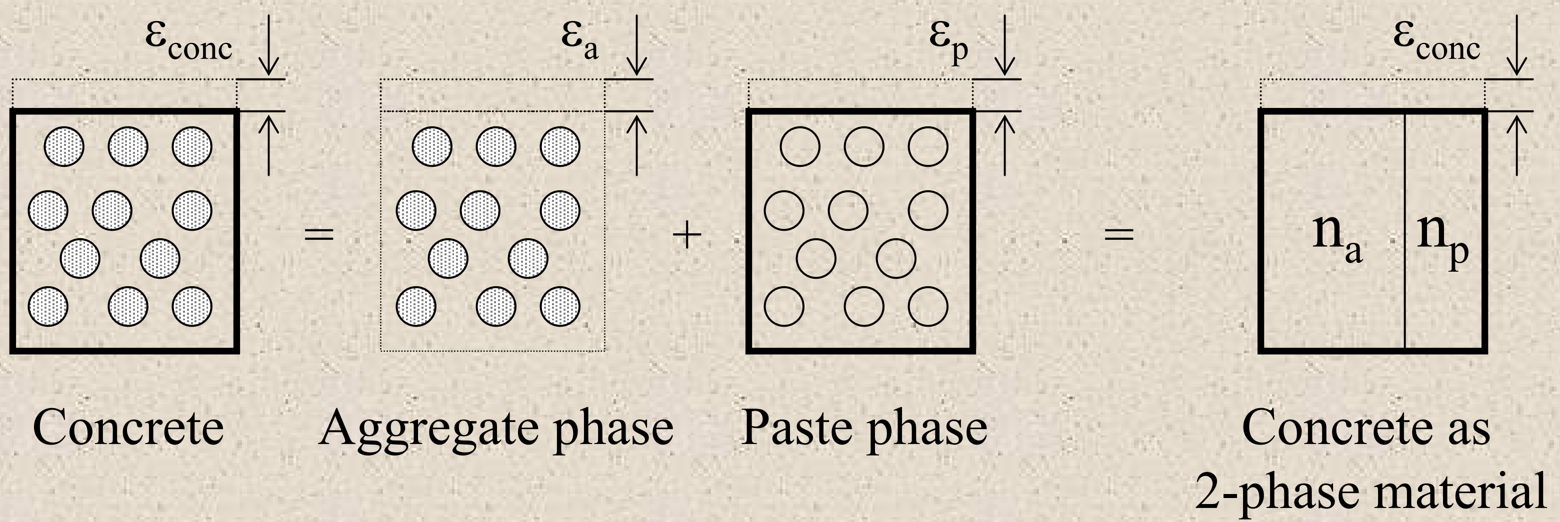
Verification of the Program



Temperature rise in a footing (38.4×8.4×4.75 m)

Autogenous Shrinkage Model

Concrete as a 2-Phase Material



Paste phase undergoes shrinkage

Aggregate phase resists the shrinkage

Equilibrium Condition

$$\sum \sigma_i = \sigma_{(p-a)} + \sigma_{(a-p)} = 0$$

Stress-Strain Relation

$$\sigma_i = E_i \times \varepsilon_i$$

Strain Compatibility

$$\varepsilon_a = \varepsilon_{par} = \varepsilon_{conc}$$

Model for paste of concrete

$$\varepsilon_{conc} = \frac{\varepsilon_{po} \cdot E_p \cdot (1 - n_a)}{E_p + E_a}$$

$$n_a = \frac{V_a}{V_{conc}}$$

Model for aggregate restrain

$$E_p = 1.05 \times 10^4 \times (f_c)^{0.474}$$

Model for Paste Shrinkage (ε_{p0})

Principle of Modelling

$$\varepsilon_{as}(t) = \varepsilon_{as,chem}(t) + \varepsilon_{as,phy}(t) - \varepsilon_{exp}(t)$$

$$\varepsilon_{as,chem}(t) = \left(A \cdot m_{C_3A} \cdot \alpha_{C_3A}(t)\right) + \left(B \cdot m_{C_4AF} \cdot \alpha_{C_4AF}(t)\right) + \left(C \cdot m_{C_3S} \cdot \alpha_{C_3S}(t)\right) + \left(D \cdot m_{C_2S} \cdot \alpha_{C_2S}(t)\right) + \left(E \cdot m_{FA} \cdot \alpha_{FA}(t)\right)$$

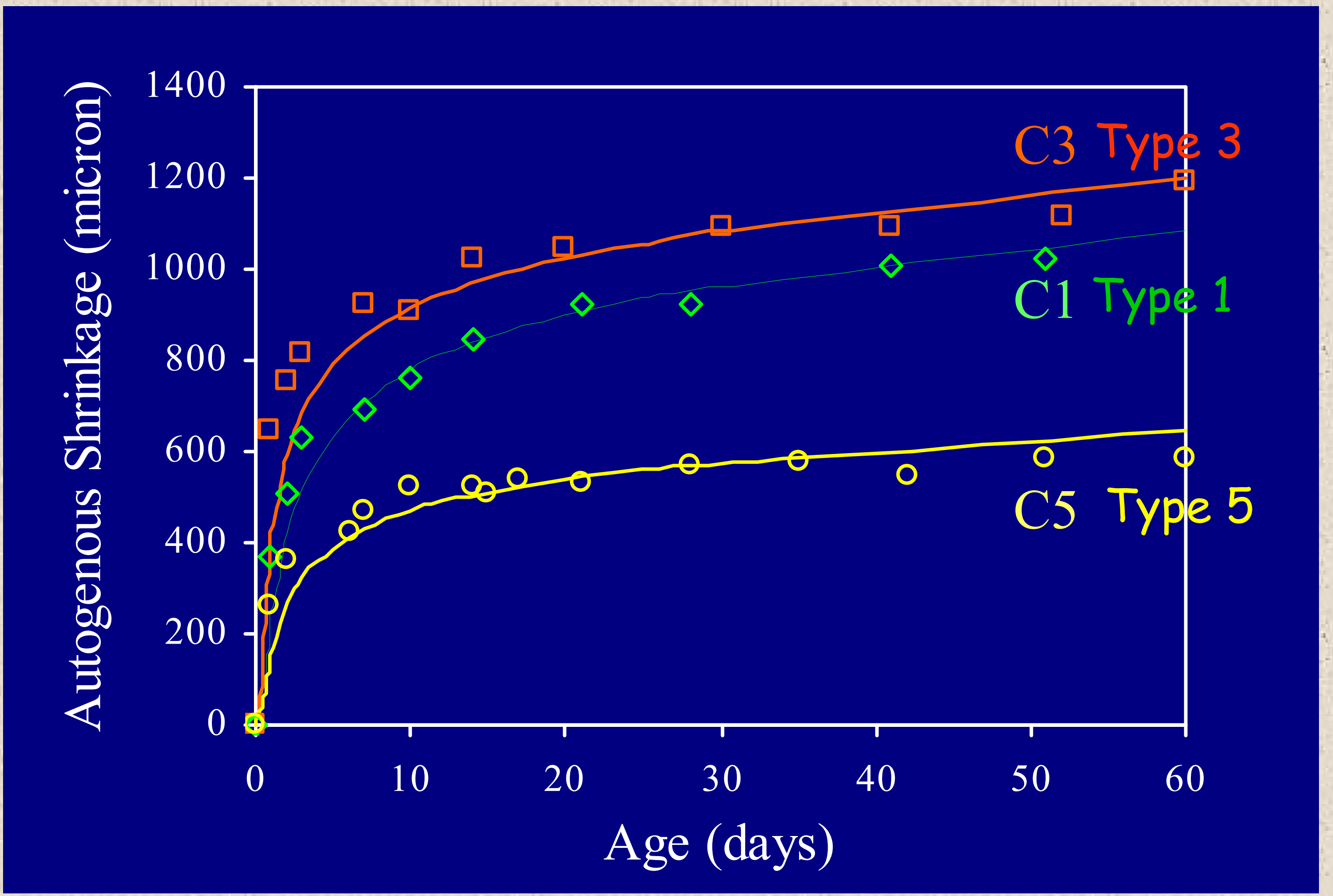
Cement

Fly Ash

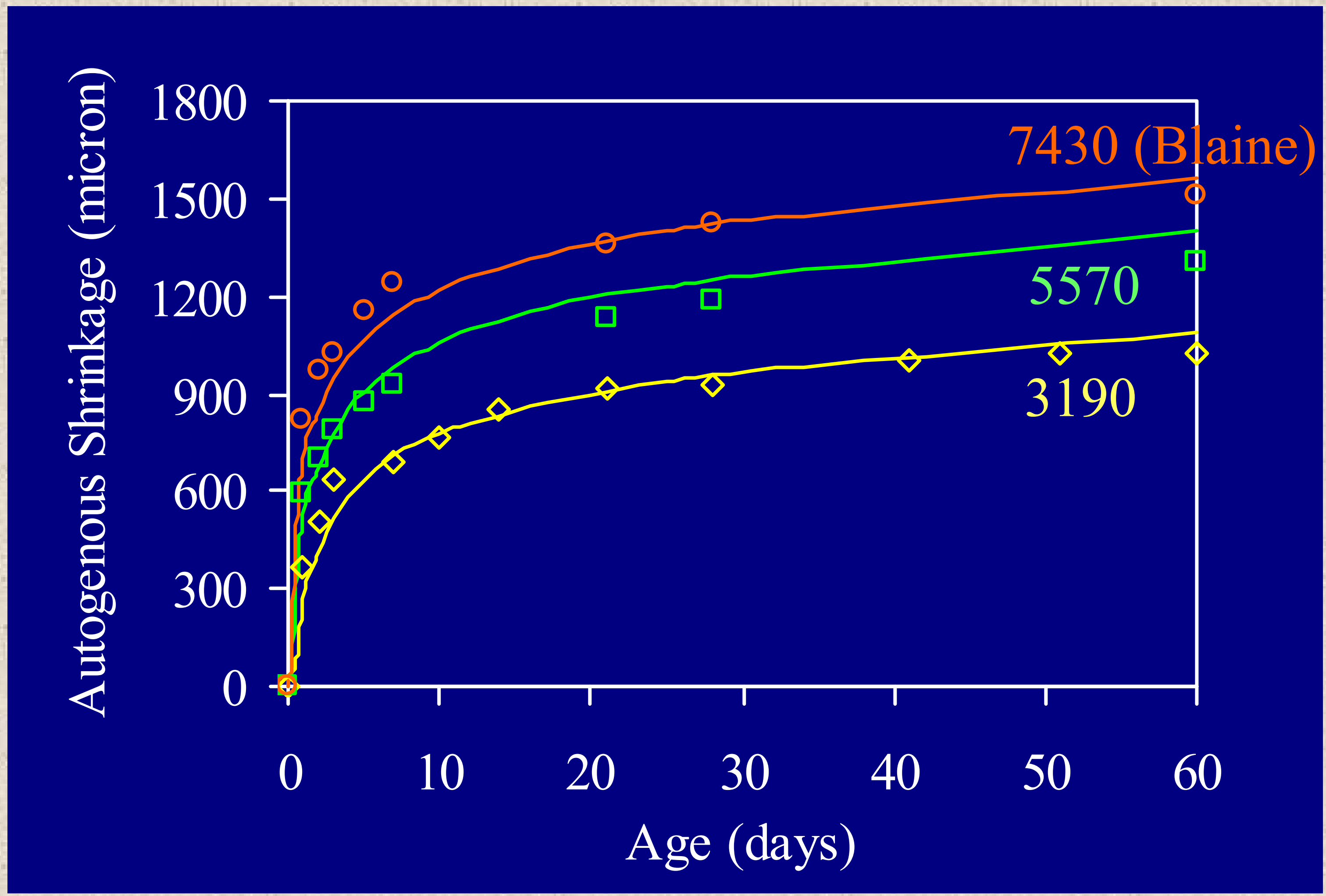
Capillary Surface Tension Stress

$$\varepsilon_{as,phy}(t) = \frac{2\gamma \cdot A_s(t)}{r_{ave}(t)} \Big/ E_s$$

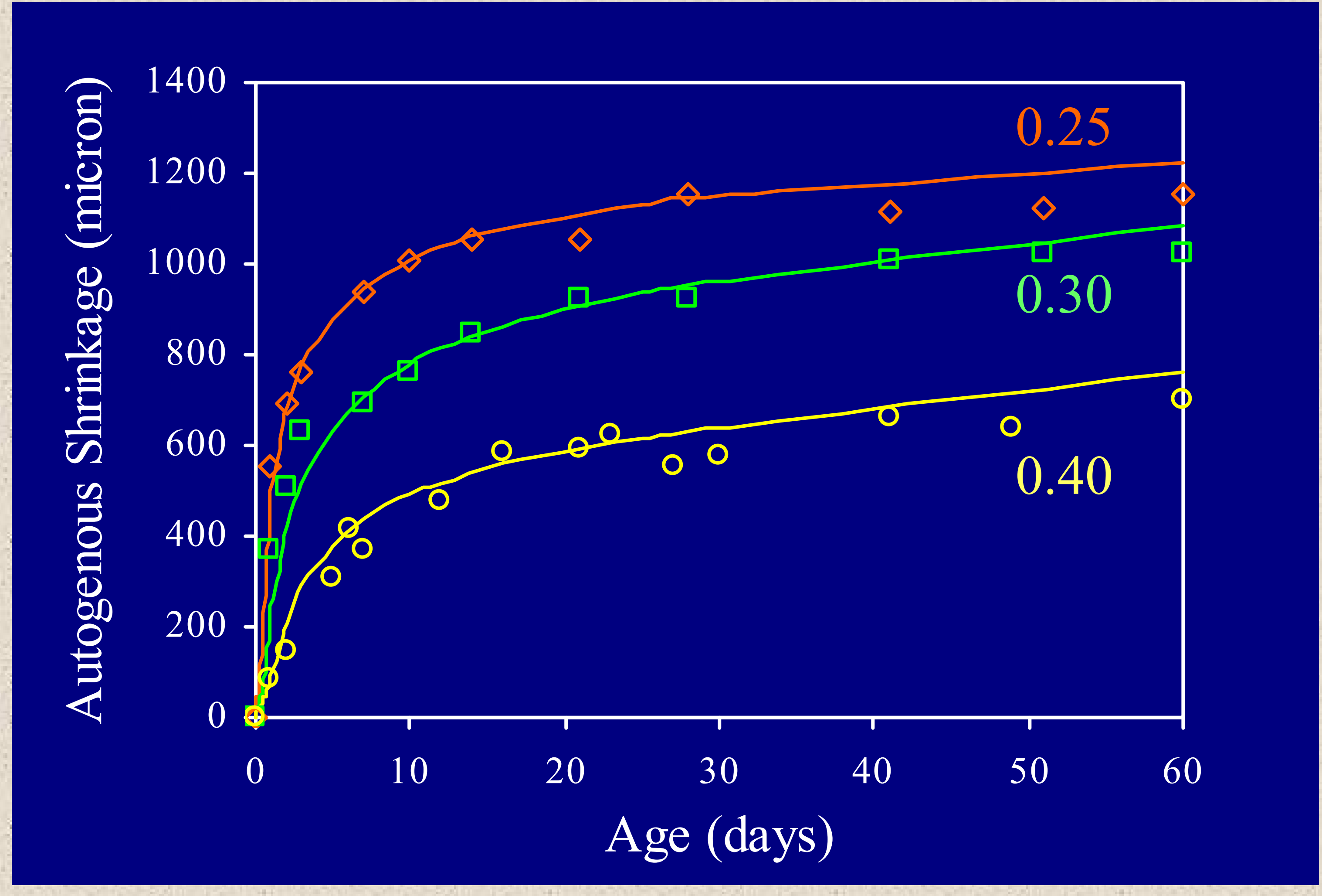
Effect of Types of Cement on Autogenous Shrinkage of Paste



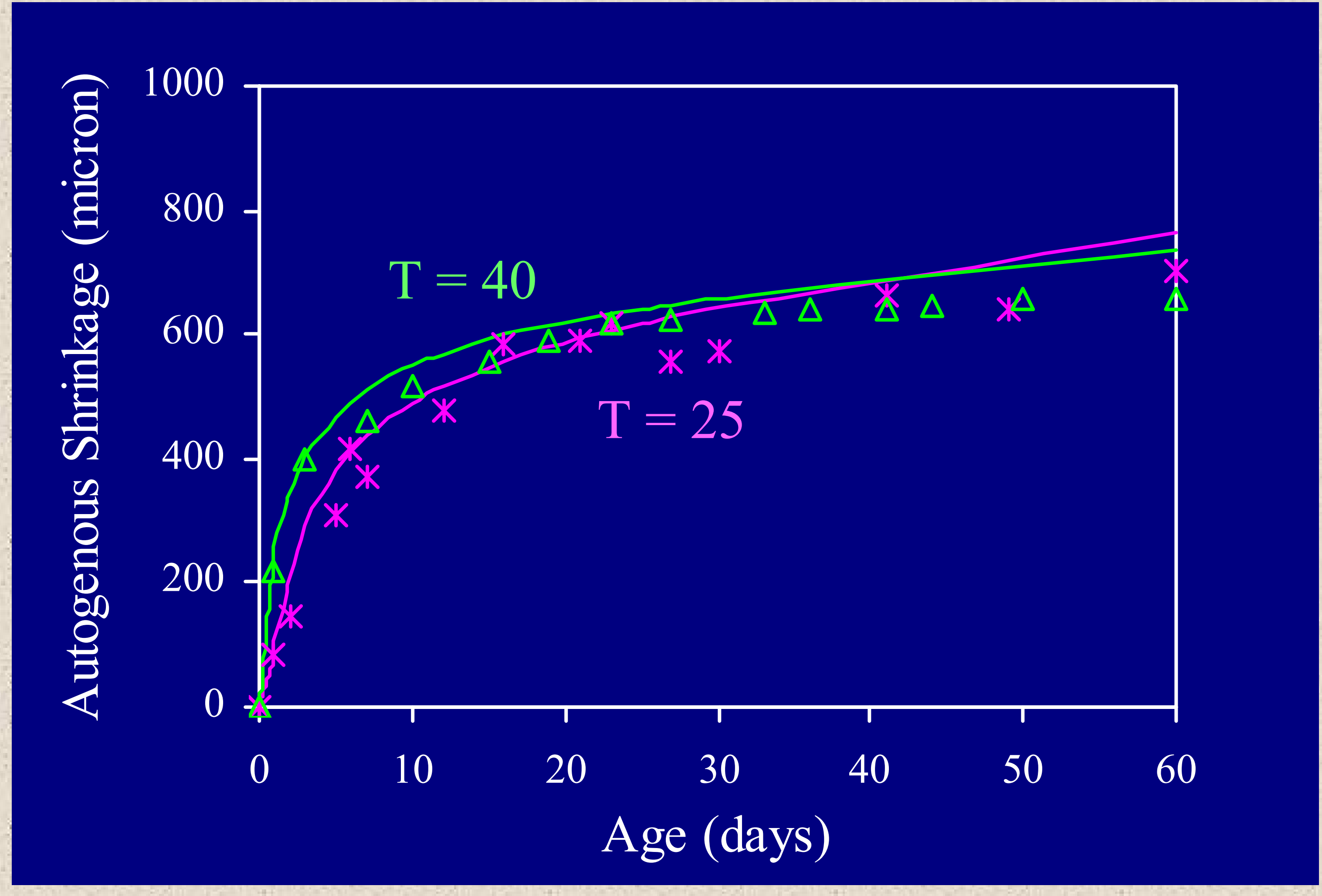
Effect of Fineness of Cement on Autogenous Shrinkage of Paste



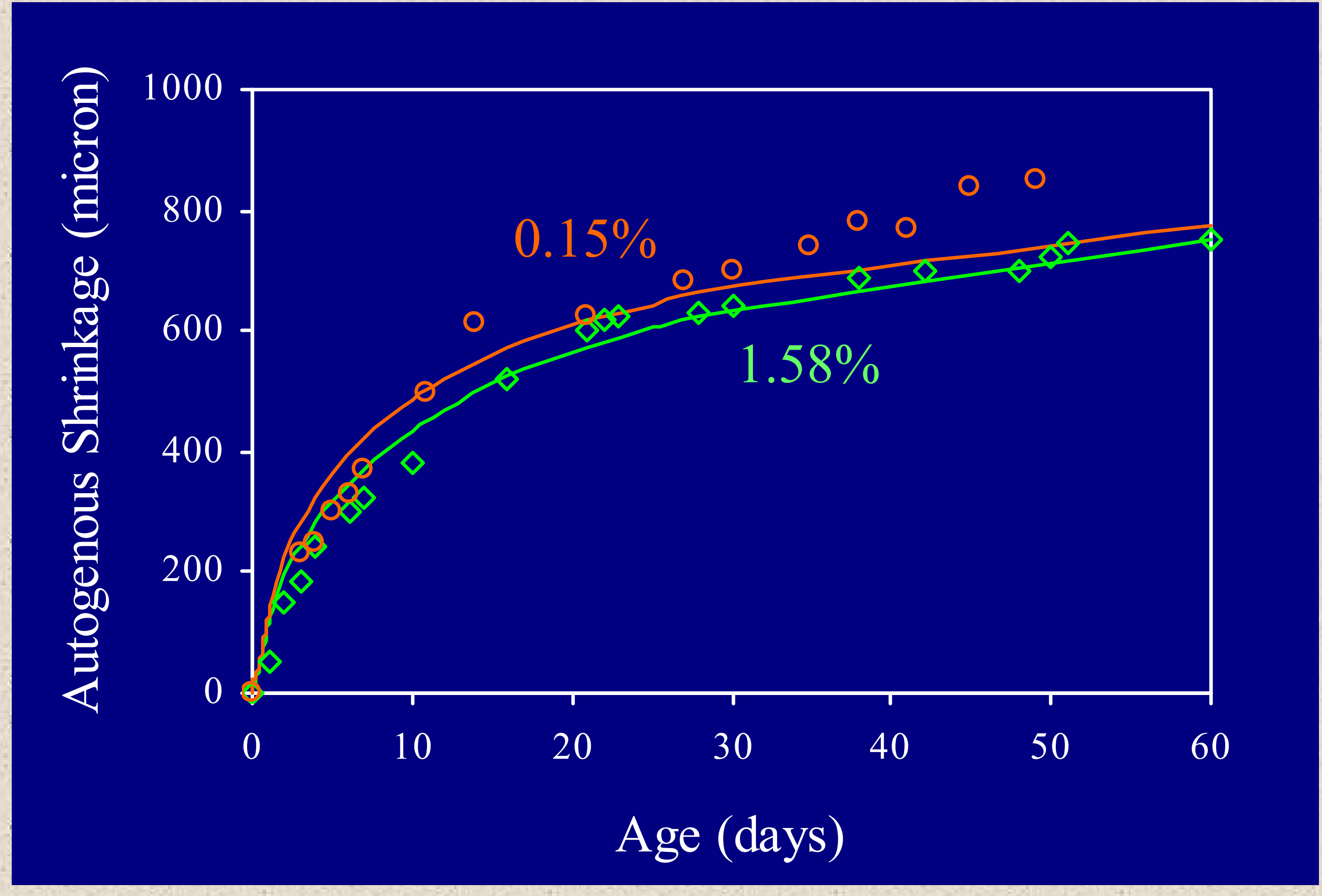
Effect of Water to Binder Ratio on Autogenous Shrinkage of Paste



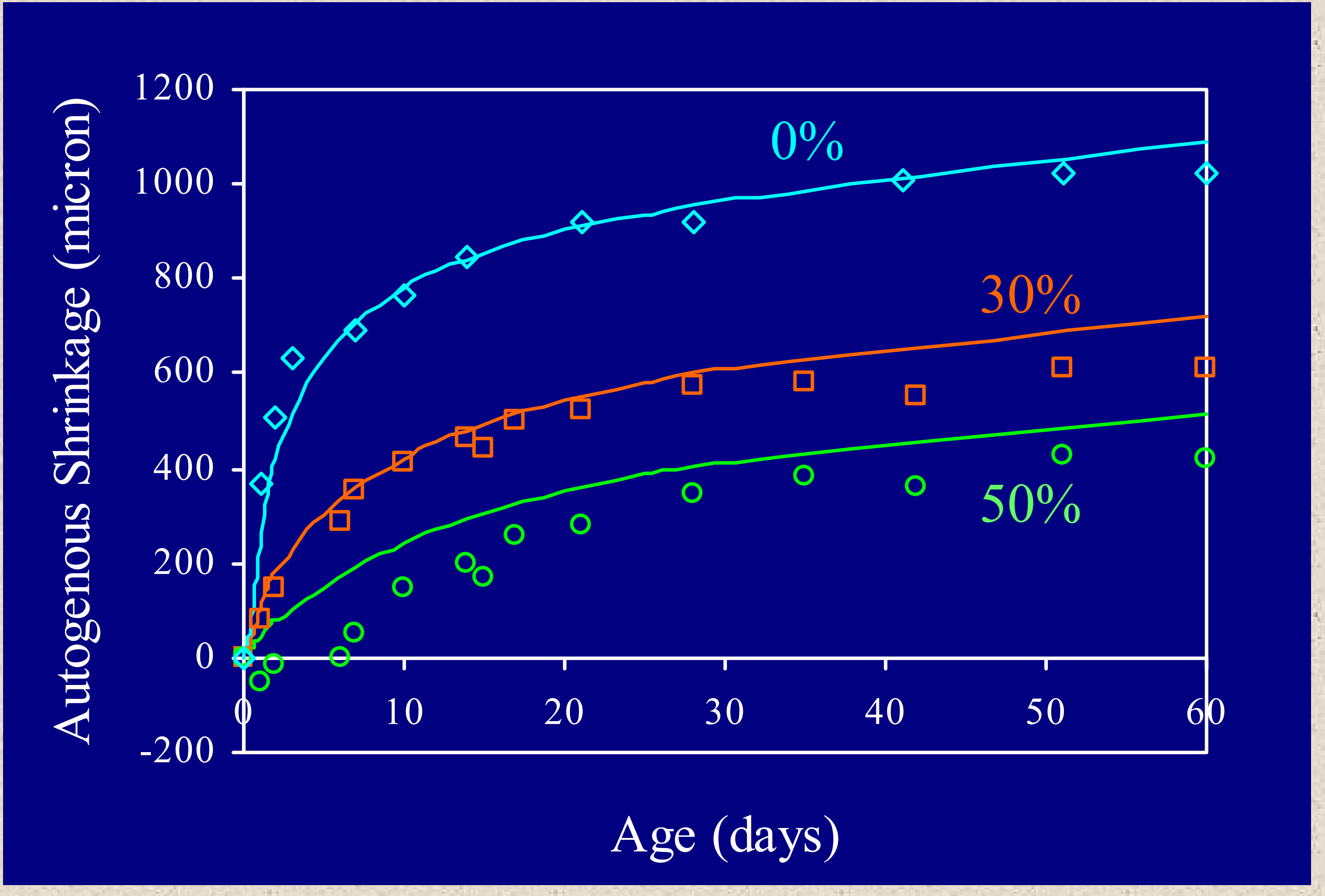
Effect of Curing Temperature on Autogenous Shrinkage of Paste



Effect of Type of Fly Ash (SO_3 content) on Autogenous Shrinkage of Paste



Effect of Fly Ash Content on Autogenous Shrinkage of Paste

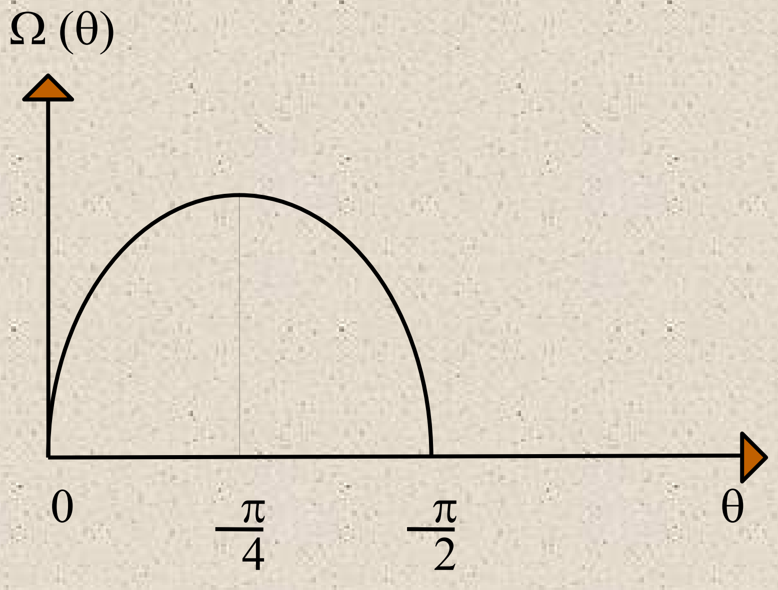


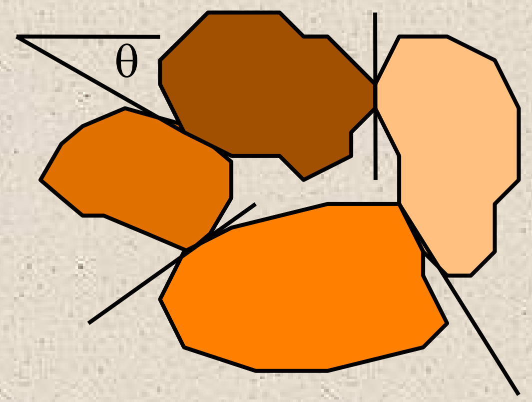
Model for Aggregate Restraint (E_a)

Concept :

Stress is transferred at the aggregate contacts

Density Function For Contact Angle





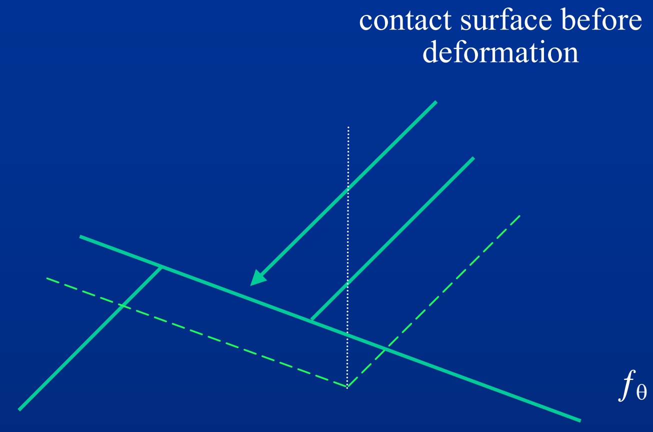
$$\Omega(\theta) = \sin(2\theta)$$

$$\int_0^{\pi/2} \Omega(\theta)d\theta = 1.0$$

Constitutive Relation for Normal Directio

$$\sigma_{c\theta} = E_c' \cdot \omega_\theta$$

$2.5 \times 10^5 \ \mathrm{kgf/cm^2}$



Stress in Direction Parallel to Contact Plan

$$f_\theta = \mu \cdot \sigma_{c\theta}$$

Coefficient of Contact Friction of Aggregate Regarding Effect of Water Lubrication

For Coarse Aggregate

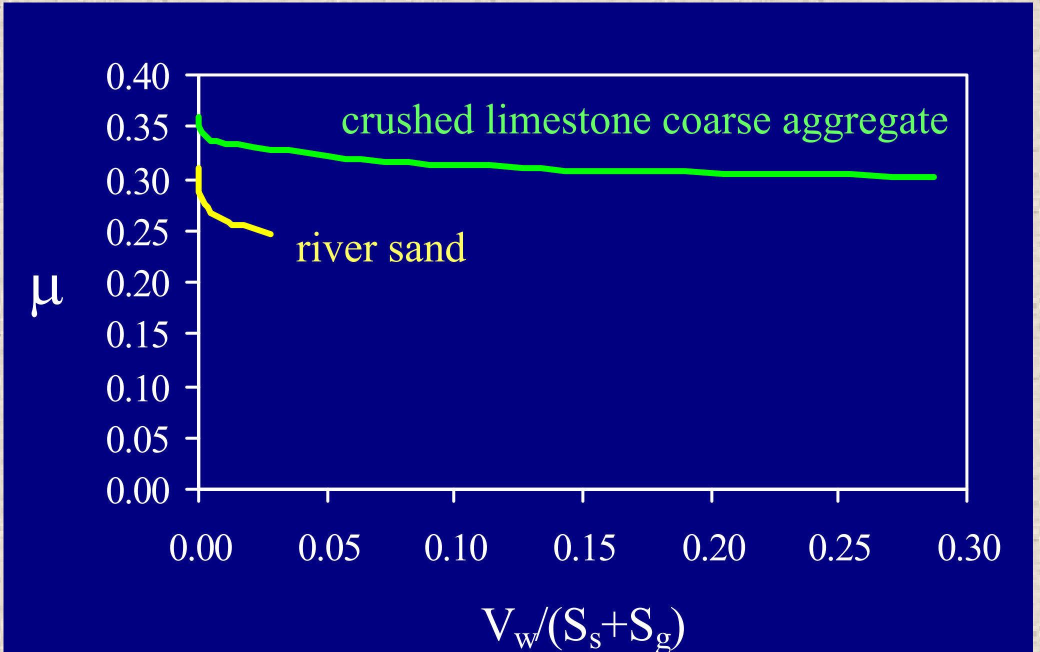
$$\mu_g = \mu_{g,SSD} - 0.15 \cdot \left(\frac{V_w}{S_s + S_g} \right)^{0.24}$$

0.36 for dry crushed limestone

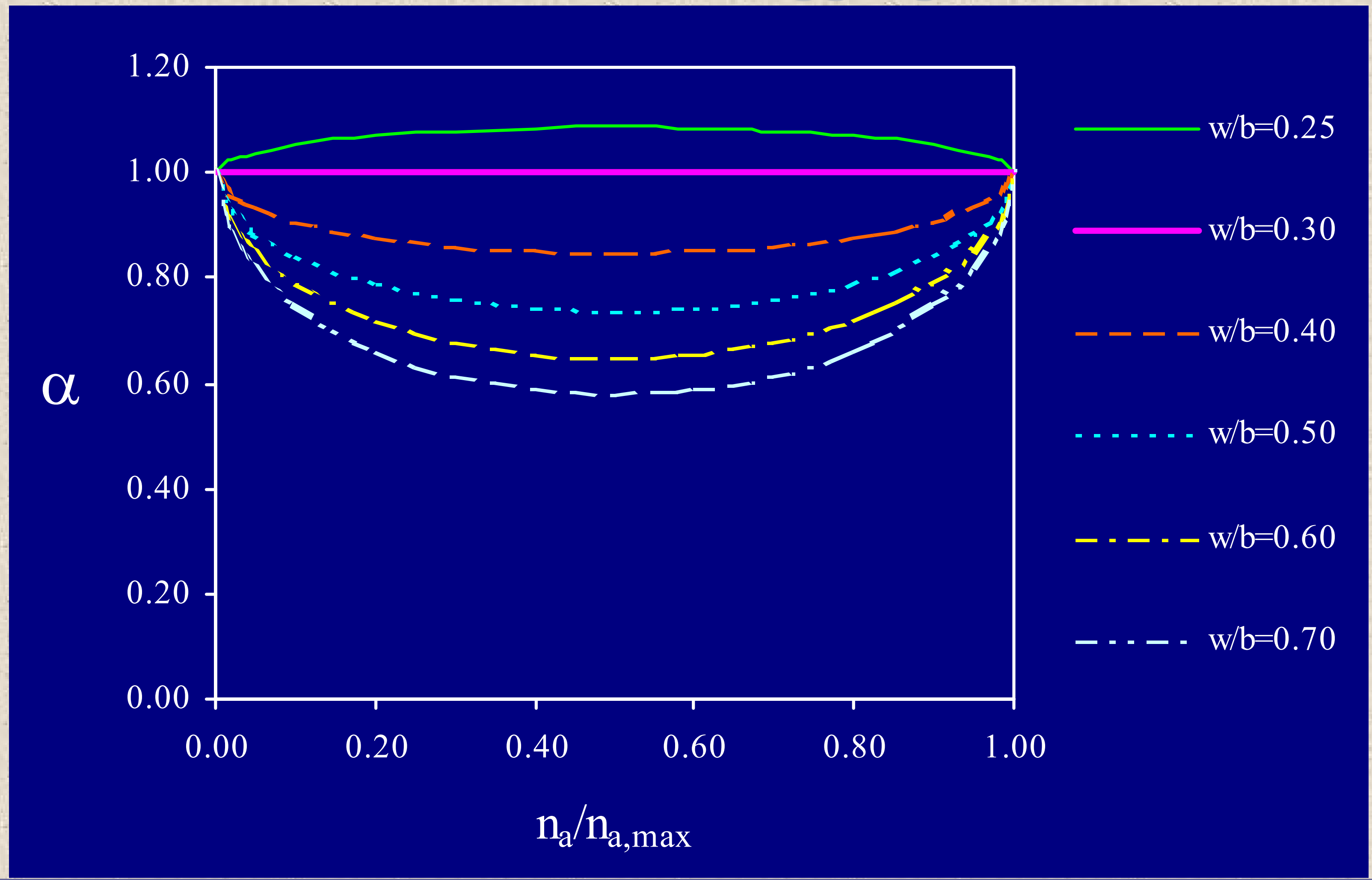
For Fine Aggregate

$$\mu_s = \mu_{s,SSD} - 0.28 \cdot \left(\frac{V_w}{S_s + S_g} \right)^{0.24}$$

0.31 for dry river sand



Effect of Water Content on Aggregate Contact Area



$$\alpha = 1 - \left[\sqrt{1 - \left(\left(\frac{n_a}{n_{a,max}} - 0.5 \right) \Big/ 0.5 \right)^2} \cdot \left(0.497 \cdot \ln\left(\frac{w}{c} \right) + 0.602 \right) \right]$$

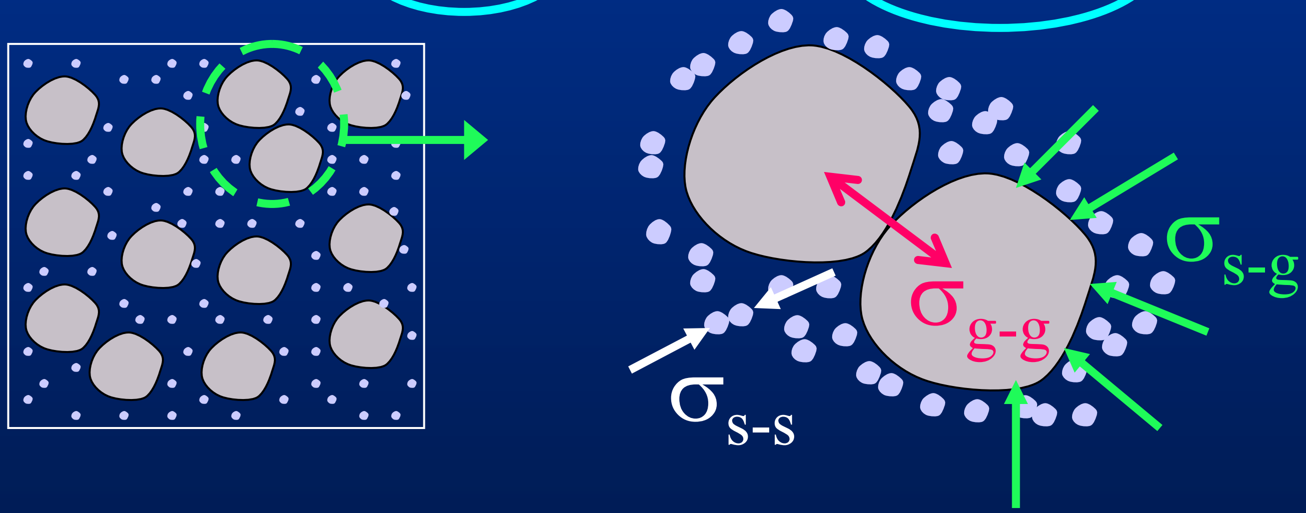
Model for Aggregate Stiffness

(Mixtures of Coarse and Fine Aggregates)

Stress Contributed by Each Materials

Stress Produced by Coarse Aggregate

$$\sigma_g = \sigma_{g-g} + \sigma_{s-g} = \sigma_{g-g} + n_g.\sigma_{s-s}$$



Stress Produced by Fine Aggregate

$$\sigma_s = (1 - n_g).\sigma_{s-s}$$

Total Stress of the Combined Aggregates

$$\sigma_a = \sigma_g + \sigma_s = \sigma_{g-g} + \sigma_{s-s}$$

$$\sigma_{a(z)} = \int_0^{\pi/2} \Omega(\theta) \cdot (\sigma_{c\theta(g)} \cdot \cos\theta + f_{\theta(g)} \cdot \sin\theta) \cdot A_{c\theta(g)} \cdot d\theta$$

$$+ \int_0^{\pi/2} \Omega(\theta) \cdot (\sigma_{c\theta(s)} \cdot \cos\theta + f_{\theta(s)} \cdot \sin\theta) \cdot A_{c\theta(s)} \cdot d\theta$$

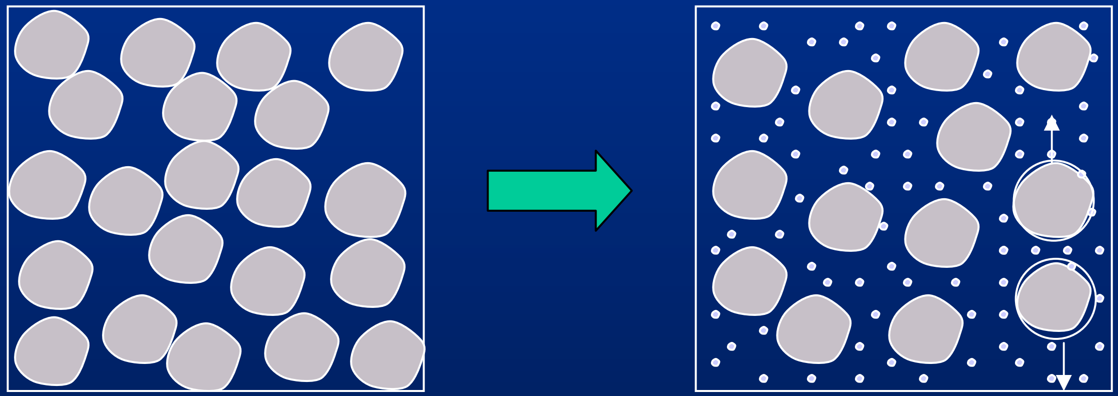
$$\sigma_{a(y)} = \int_0^{\pi/2} \Omega(\theta) \cdot (\sigma_{c\theta(g)} \cdot \sin\theta - f_{\theta(g)} \cdot \cos\theta) \cdot A_{c\theta(g)} \cdot d\theta$$

$$+ \int_0^{\pi/2} \Omega(\theta) \cdot (\sigma_{c\theta(s)} \cdot \sin\theta - f_{\theta(s)} \cdot \cos\theta) \cdot A_{c\theta(s)} \cdot d\theta$$

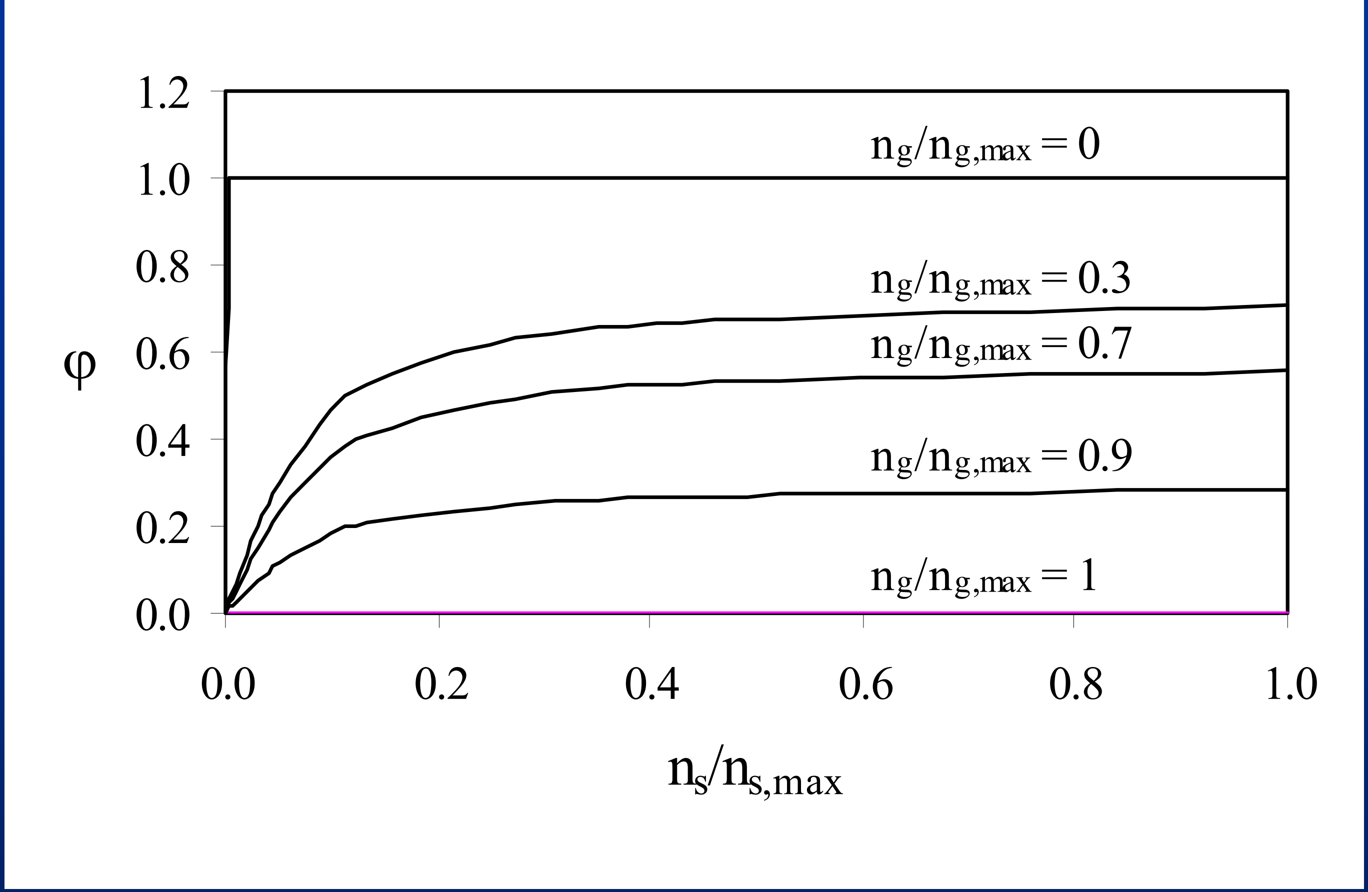
Effect of Particle Interference on Contact Area of Coarse Aggregate

$$A_{c\theta(s)} = (A_{co(s)} + \int dA_{c\theta(s)} \cdot \phi) \cdot \alpha$$

$$A_{c\theta(g)} = (A_{co(g)} + \int dA_{c\theta(g)} \cdot \phi) \cdot \alpha \cdot (1 - \varphi)$$



Particle interference caused by fine aggregate reduces the contact area of coarse aggregate

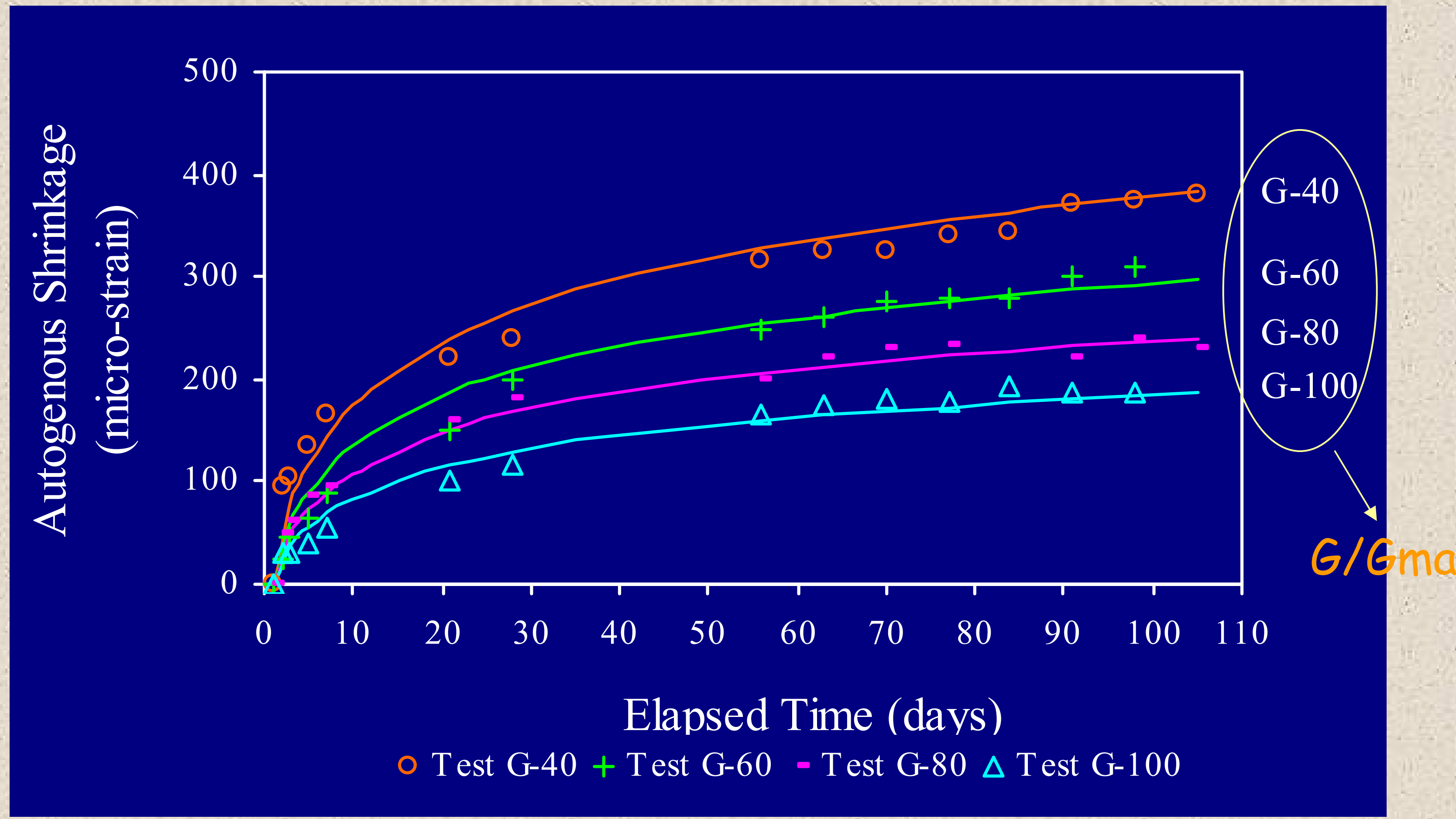


$$\varphi = \left[\tan^{-1}\left(15\cdot\frac{n_s}{n_{s,max}}\right)\right]^{\left(1.024\cdot\left(\frac{n_g}{n_{g,max}}\right)^{0.016}\right)}$$

$$\times\left[0.429+\exp\left(-0.561-8.538\cdot\frac{n_g}{n_{g,max}}\right)\right]\times\left[1-\left(\frac{n_g}{n_{g,max}}\right)^{5.402}\right]$$

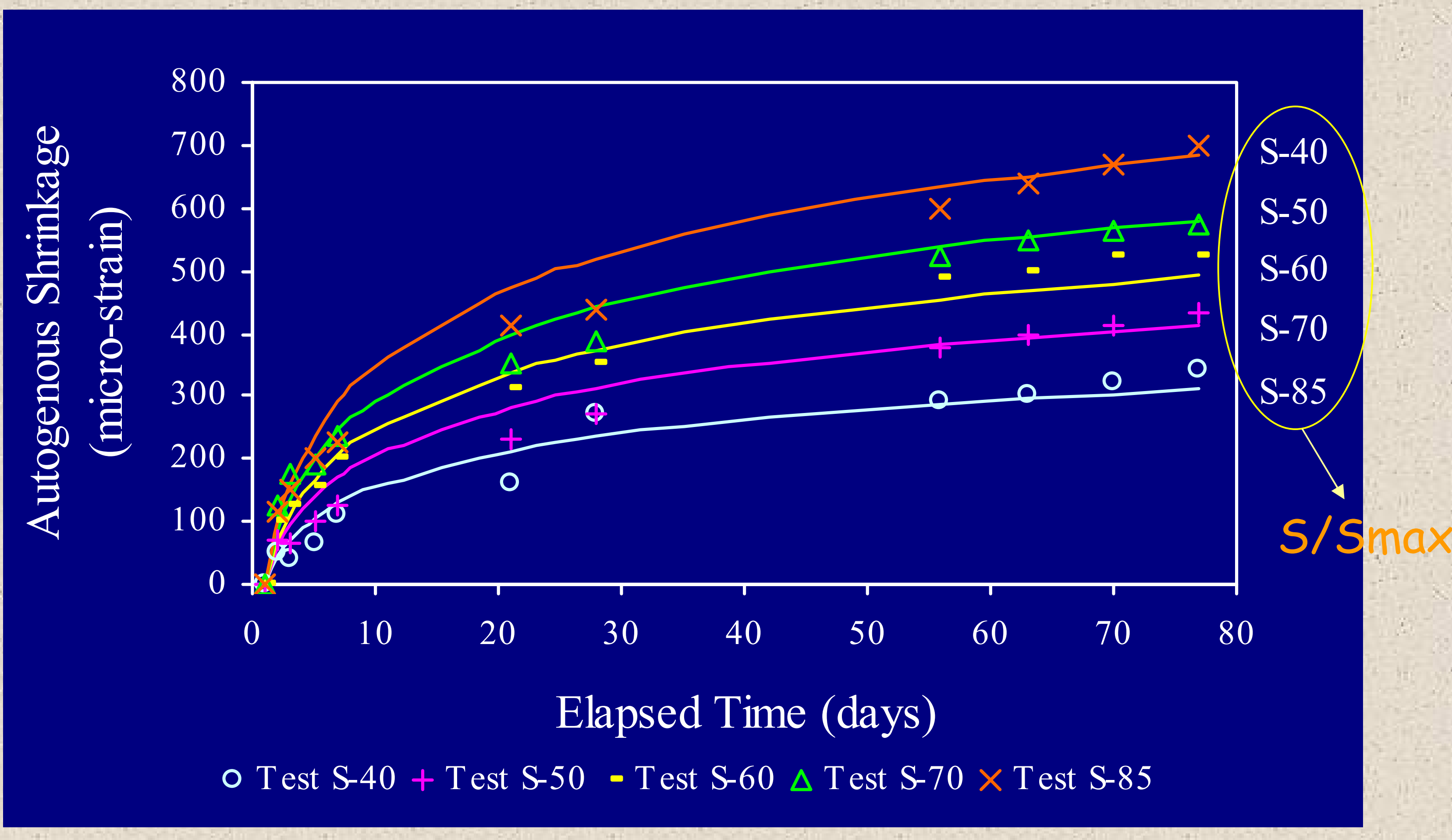
Test and Analytical Results of Autogenous Shrinkage of No-Fine Concrete

(Effect of Coarse Aggregate Content)



Test and Analytical Results of Autogenous Shrinkage of Mortar

(Effect of Fine Aggregate Content)



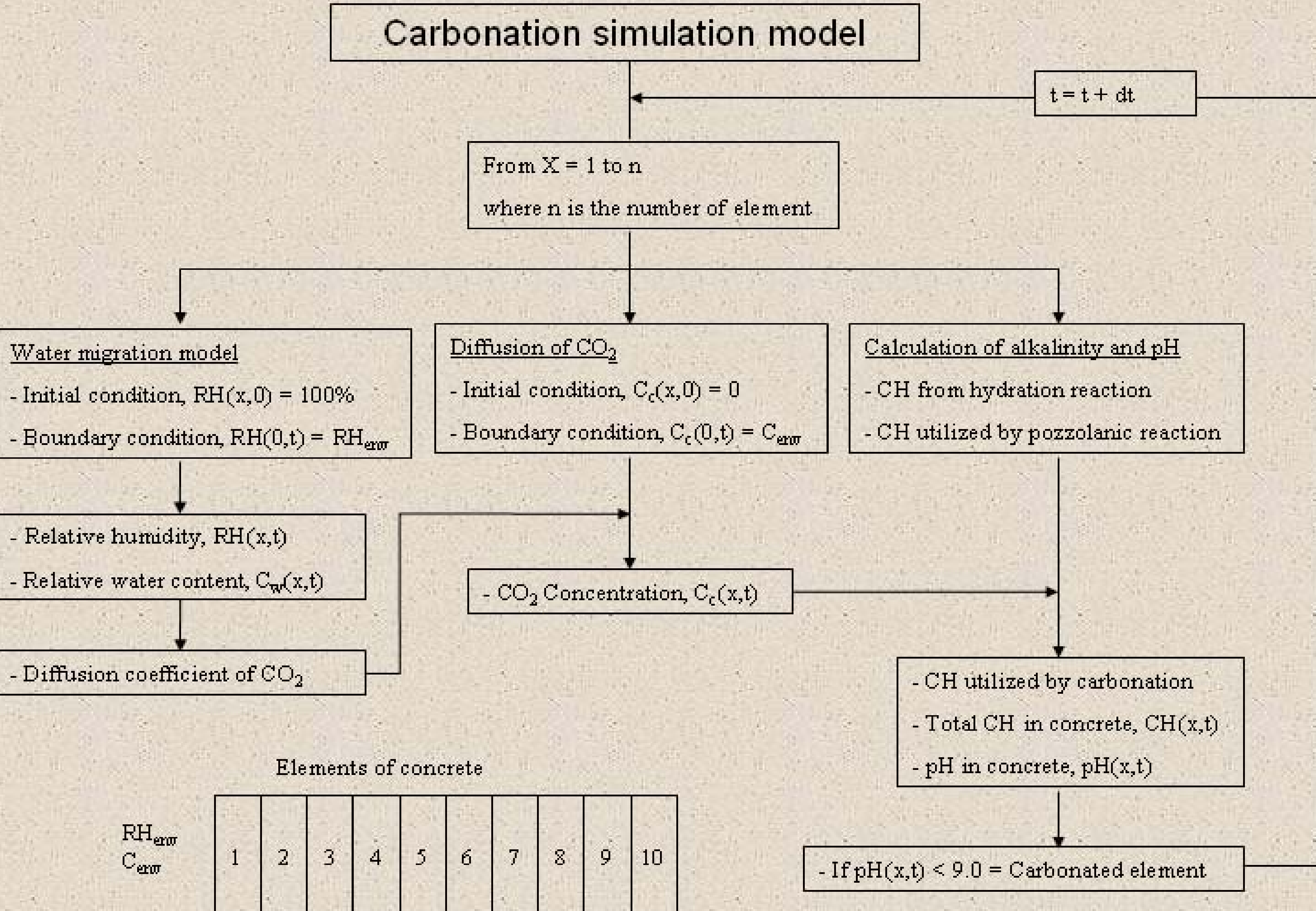
PERFORMANCE BASED PREDICTION MODEL

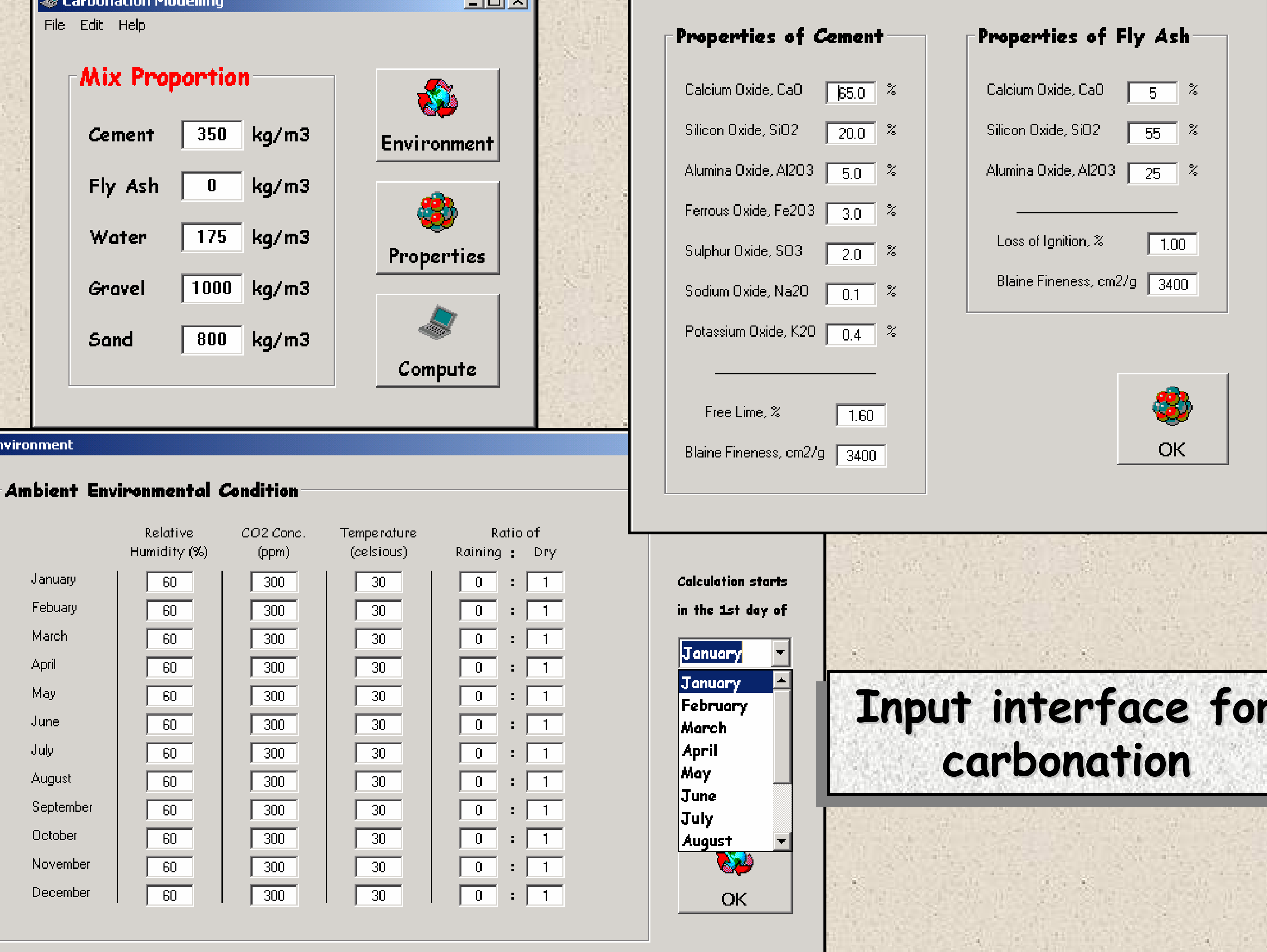
:Carbonation of Fly Ash Concrete

Sirindhorn International Institute of Technology

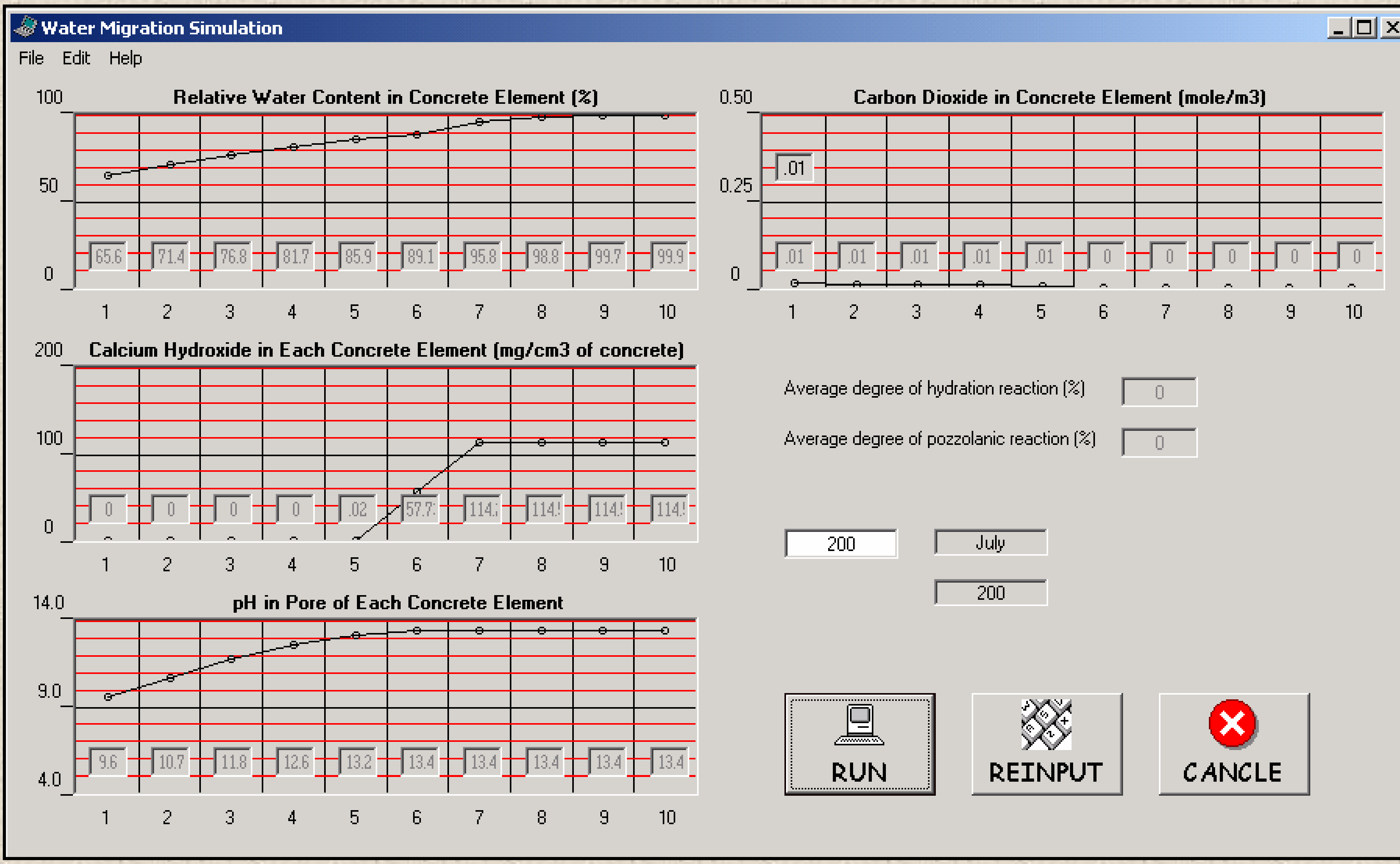
Thammasat University

(ii) Flow chart of the model




Carbonation Modelling
File Edit Help
Mix Proportion
Cement 350 kg/m3
Fly Ash 0 kg/m3
Water 175 kg/m3
Gravel 1000 kg/m3
Sand 800 kg/m3
Environment
Properties
Compute
Properties of Cement
Calcium Oxide, CaO 65.0 %
Silicon Oxide, SiO2 20.0 %
Alumina Oxide, Al2O3 5.0 %
Ferrous Oxide, Fe2O3 3.0 %
Sulphur Oxide, SO3 2.0 %
Sodium Oxide, Na2O 0.1 %
Potassium Oxide, K2O 0.4 %
Free Lime, % 1.60
Blaine Fineness, cm2/g 3400
Properties of Fly Ash
Calcium Oxide, CaO 5 %
Silicon Oxide, SiO2 55 %
Alumina Oxide, Al2O3 25 %
Loss of Ignition, % 1.00
Blaine Fineness, cm2/g 3400
OK
nvironment
Ambient Environmental Condition
Relative Humidity (%)
CO2 Conc. (ppm)
Temperature (celsious)
Ratio of Raining : Dry
January 60 300 30 0 : 1
Febuary 60 300 30 0 : 1
March 60 300 30 0 : 1
April 60 300 30 0 : 1
May 60 300 30 0 : 1
June 60 300 30 0 : 1
July 60 300 30 0 : 1
August 60 300 30 0 : 1
September 60 300 30 0 : 1
October 60 300 30 0 : 1
November 60 300 30 0 : 1
December 60 300 30 0 : 1
Calculation starts in the 1st day of
January
January
February
March
April
May
June
July
August
OK
Input interface for carbonation

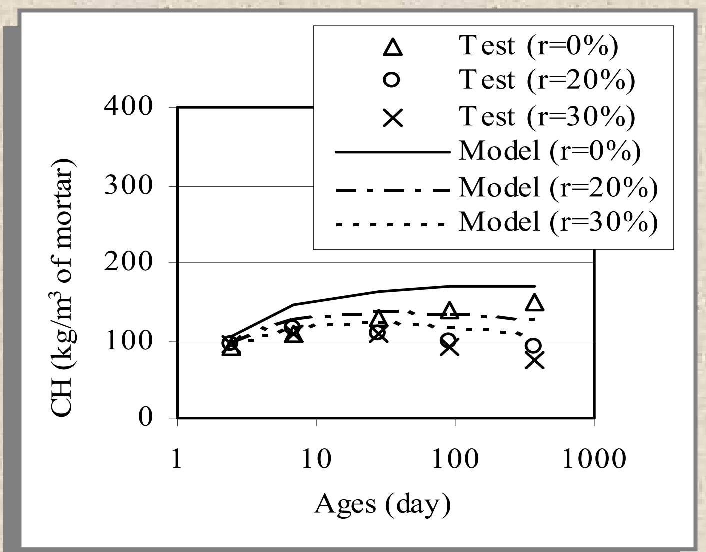
Output interface for carbonation prediction

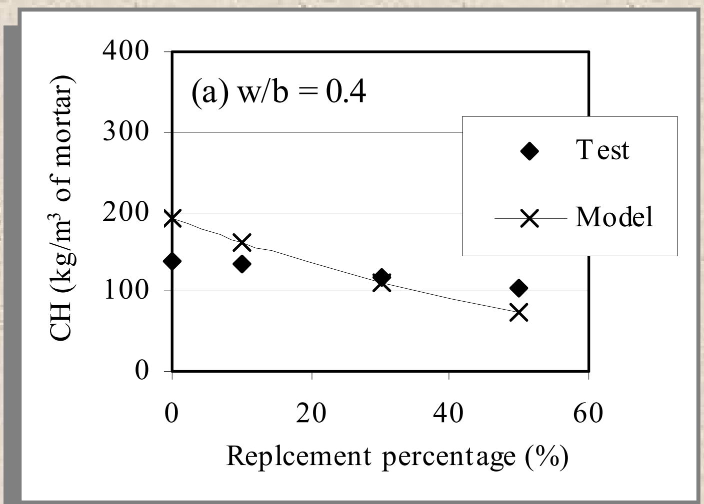


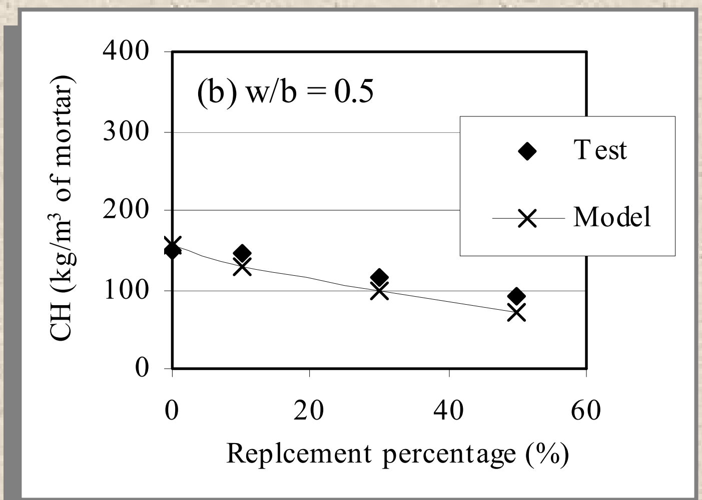
2.5 Verifications

(i) Verification of CH

CH in mortar specimen (Papadakis's data)
: w/b = 0.5 and A/B = 3.0



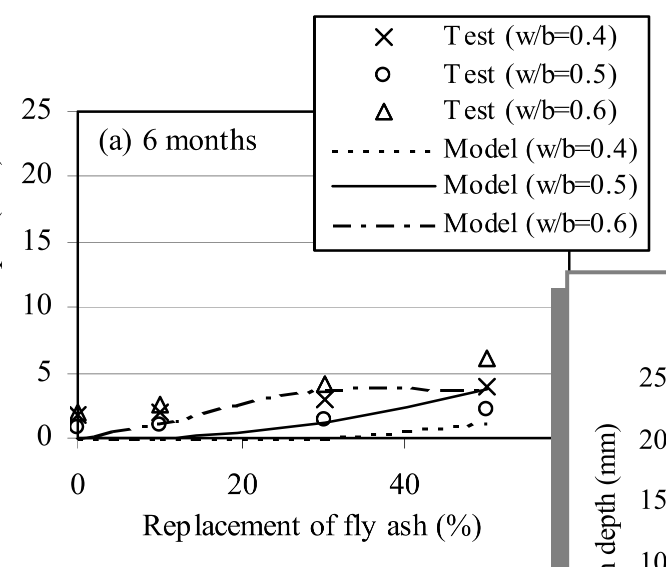


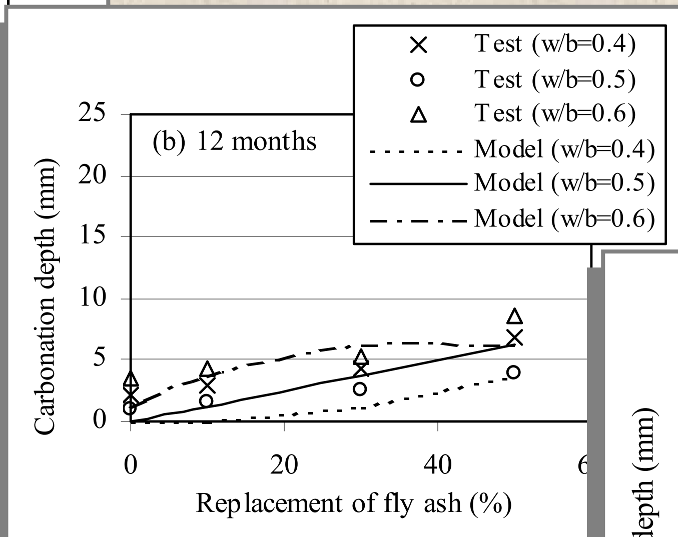


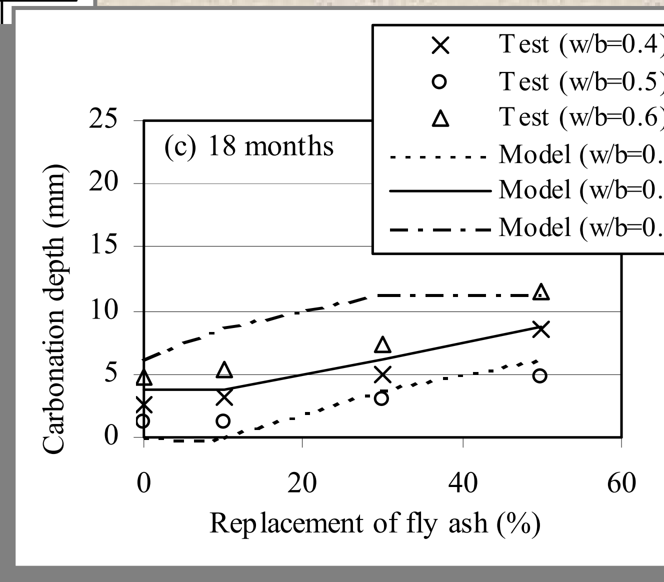
CH in mortar specimen (Author's data) at 28 days

(ii) Verification of carbonation depth (real environment)

- Carbonation depth was the distance from concrete surface to center of the innermost concrete element that has the pH value less than 9

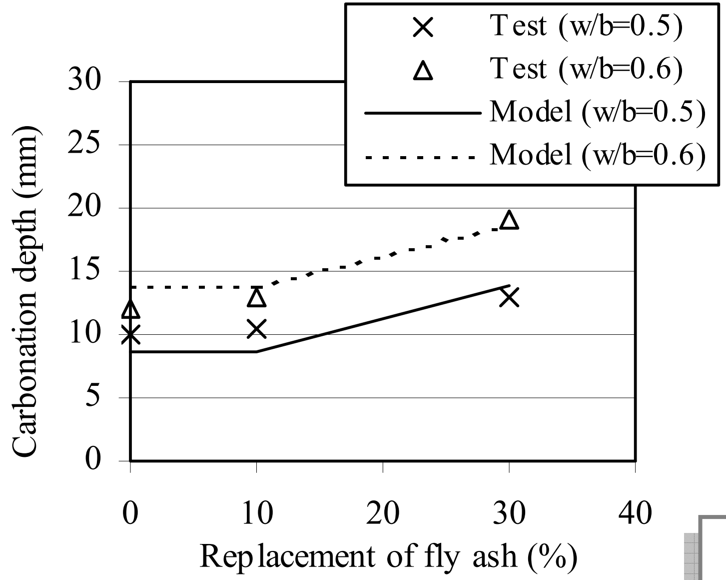






Average CO_2 concentration = 650 ppm.
Average relative humidity = 70%
Average temperature = 29 °C

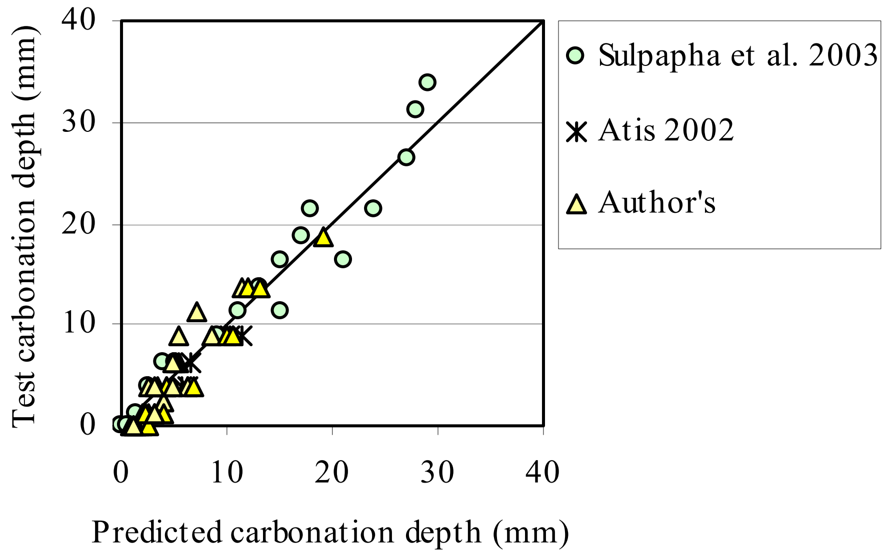
(iii) Verification of carbonation depth (accelerated environment)



Average CO_2 concentration = 4%

Average relative humidity = 55%

Average temperature = 40 °C



CO_2 concentration

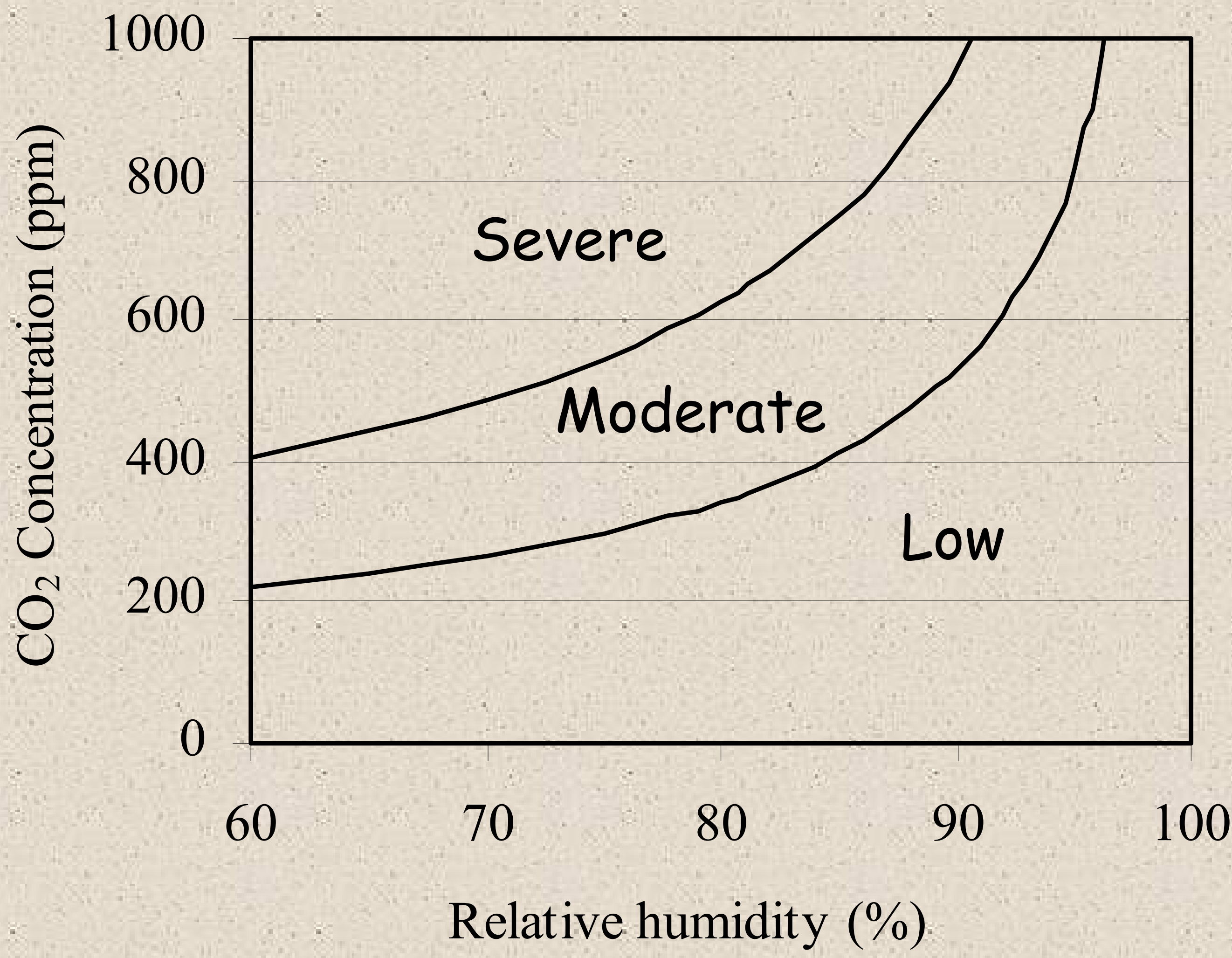
Sulapha = 6.0 %

Atis = 4.7 %

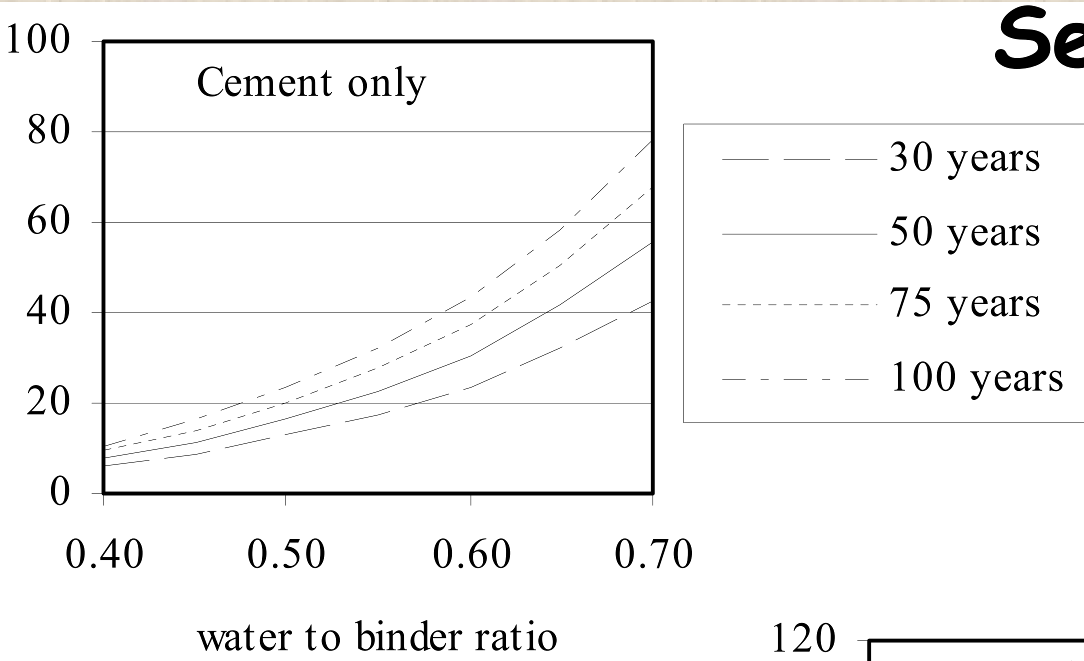
Author's = 4.0 %

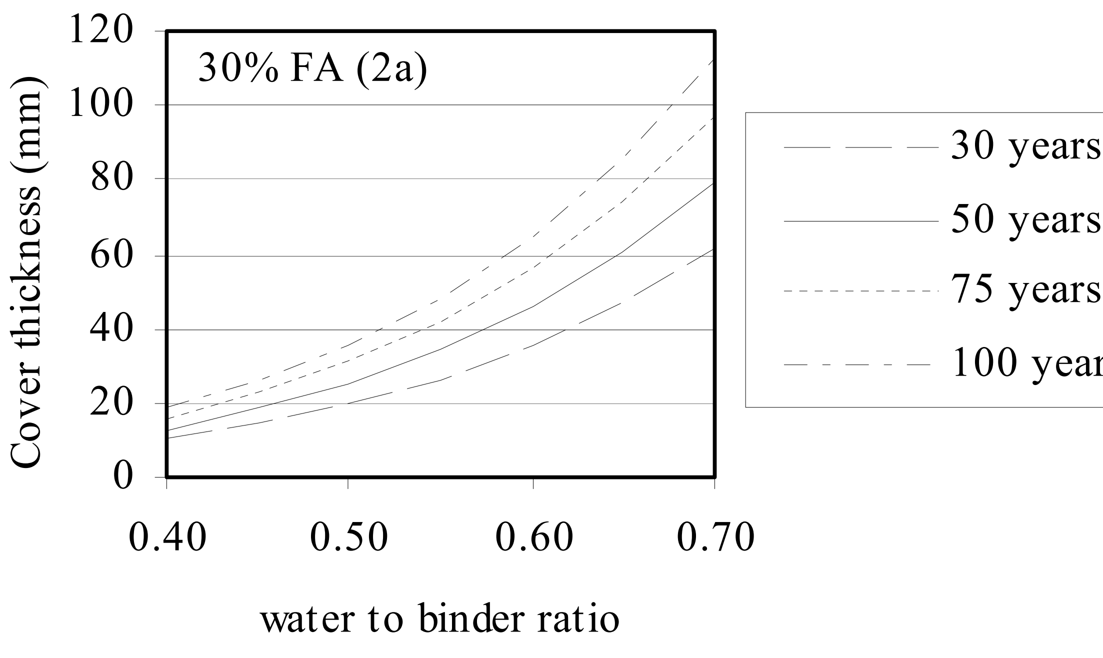
3. Mix Design of Concrete Subjecting to Carbonation

Proposed Three Zones based on Severity of Environment



Design Chart for Severe Environment



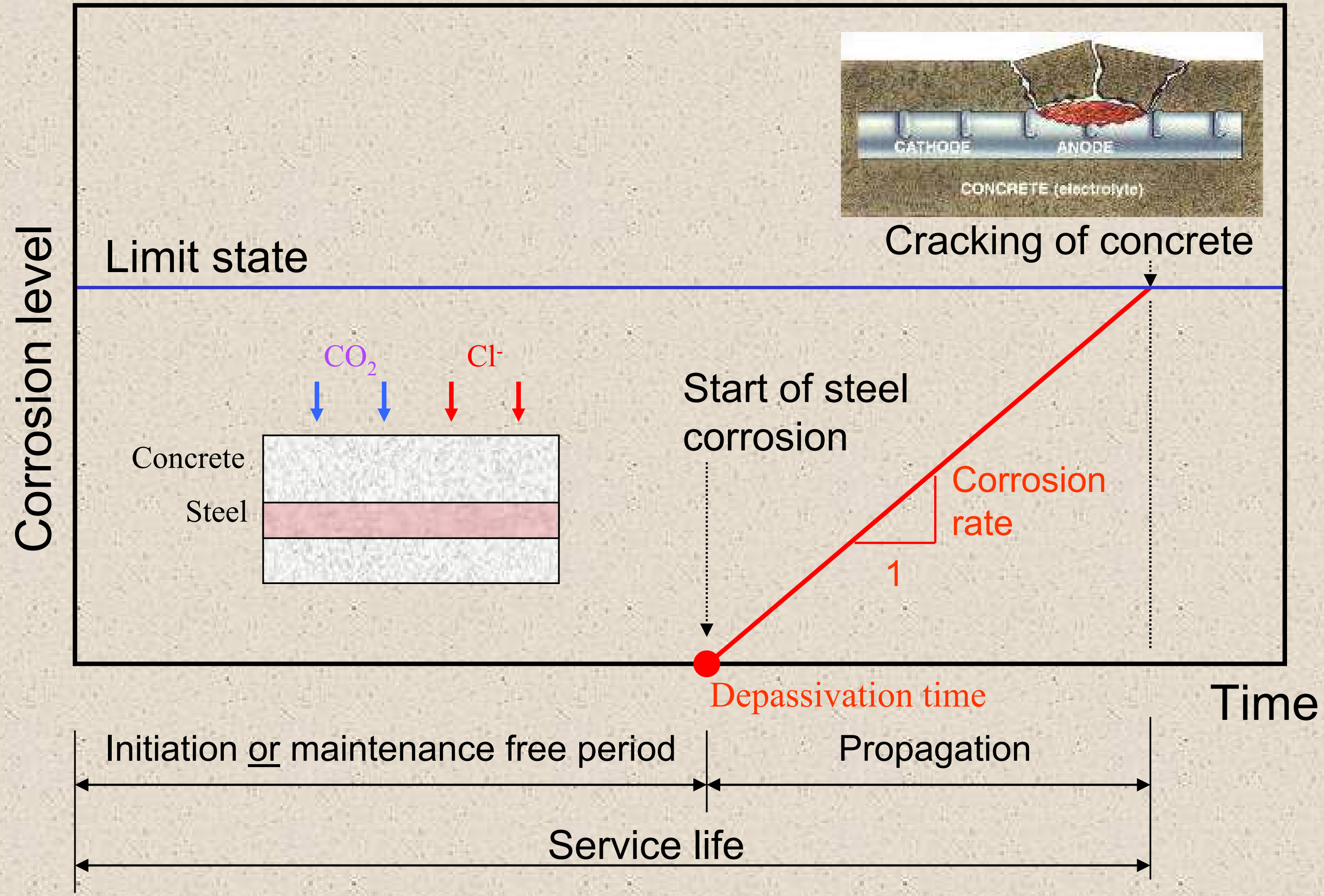


PERFORMANCE BASED PREDICTION MODEL

:Chloride induced steel corrosion

Sirindhorn International Institute of Technology
Thammasat University

Conceptual Service Life Model of Steel in Concrete



Simulation of Chloride-Induced Corrosion of Steel in Concrete

Models :

- ***Movement of chloride and water vapor (Fick's second law of diffusion)***
- ***Chloride binding capacity***
- ***Carbonation***
- ***Cyclic wetting and drying***
- ***Ion adsorption and surface condensation***
- ***Ion exchange***
- ***Depassivation criteria***

Chloride Binding

Chlorides in Concrete

Chloride binding capacity

Total chlorides

This chloride attacks the steel

Fixed chlorides

Free chlorides

By cementitious materials

1. Chlorides chemically bound in the structure of hydration products

   $3CaO.Al_2O_3.CaCl_2.10H_2O$ (Calcium Chloroaluminate, Friedel's Salt)
   $3CaO.Fe_2O_3.CaCl_2.10H_2O$ (Calcium Chloroferrite)
   } Absorbed chlorides

2. Chlorides physically bound to the surface of hydration and pozzolanic products

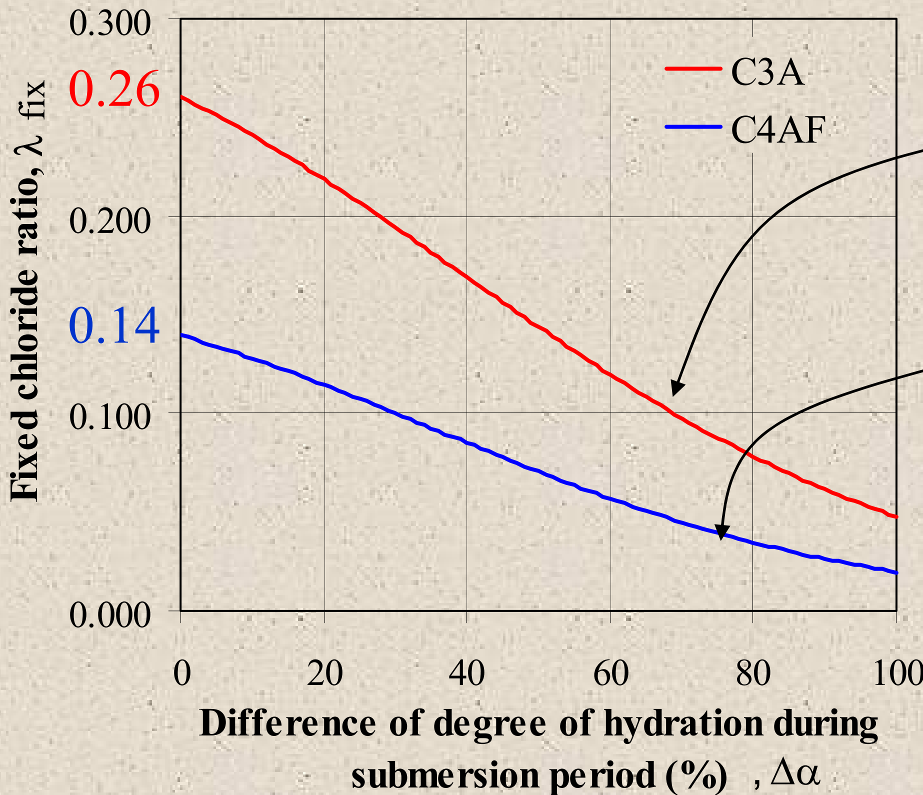
   C-S-H from hydration of C_3S , C_2S
   C-S-H and CAH from pozzolanic reaction
   CAH and CAFH from hydration of C_3A , C_4AF
   } Adsorbed chlorides on the pore walls

3. Chlorides physically bound by other hydration products; monosulfate, ettringite, etc.

By non - reactive materials

Finer, fine and coarse aggregates → Adsorbed chlorides on the surface

Relationship between fixed chloride ratios of C_3A and C_4AF and their degrees of hydration

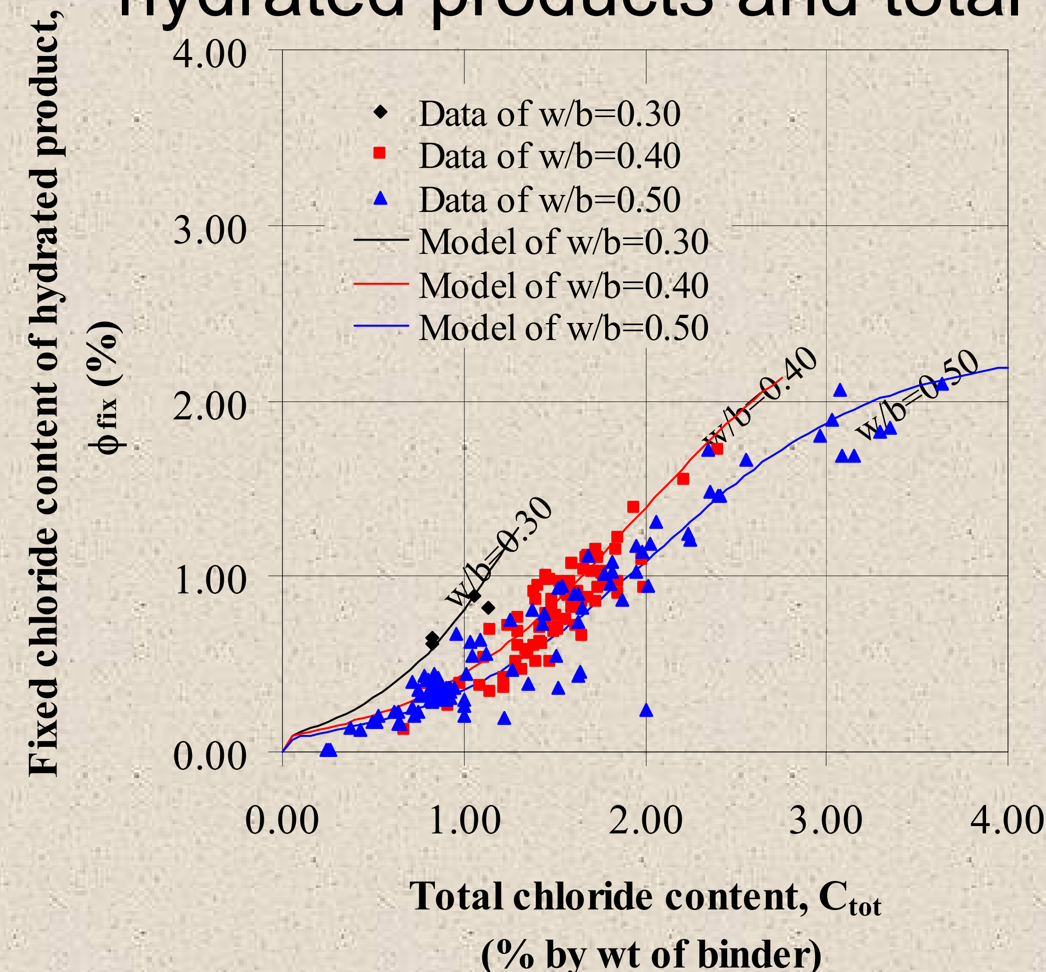


$$\lambda_{fix,C_3A} = \frac{1.12}{3.30 + e^{3.0 \times \left(\frac{\Delta\alpha_{C_3A}}{100}\right)}}$$

$$\lambda_{fix,C_4AF} = \frac{0.60}{3.30 + e^{3.3 \times \left(\frac{\Delta\alpha_{C_4AF}}{100}\right)}}$$

$\Delta\alpha_{C_3A \text{ or } C_4AF}$ ↑ ⇨ Paste is denser. ⇨ Less amount of C_3A and C_4AF to catch chlorides. (Low fixed chloride ratio)

Relationship between fixed chloride content of hydrated products and total chloride content



C_{tot} ↑

⇩

More amount of chlorides in pore.

⇩

More fixed chloride content

$$\phi_{fix} = \left[\frac{-0.093 \times w/b + 0.135}{0.037 + e^{(-0.0002 \times w/b - 1.572) \times C_{tot}}}\right] \times \left(\frac{C_{tot}}{C_{tot} + 0.01}\right) \times \left(\frac{F_c}{3190}\right)^{0.5}$$

$$FixCl^{-}_{by\ physical\ binding} = \phi_{fix} \times \sum M_{products}(t_e)$$

Program of Chloride Binding Capacity

Output

Material case (MC) = 2

Data number (N) = 1

Binder content 1.394 g/cm^3

Ettringite, mono, CAH, CAFH .411

CSH .684

Diff. hydrated C3A / 2 .008

Diff. hydrated C4AF / 2 .012

Total chloride content (Test) 1.42 % by wt of binder

Fixed chloride content (Test) .73 % by wt of binder

Fixed chloride content (Model) .74 % by wt of binder

Run Again

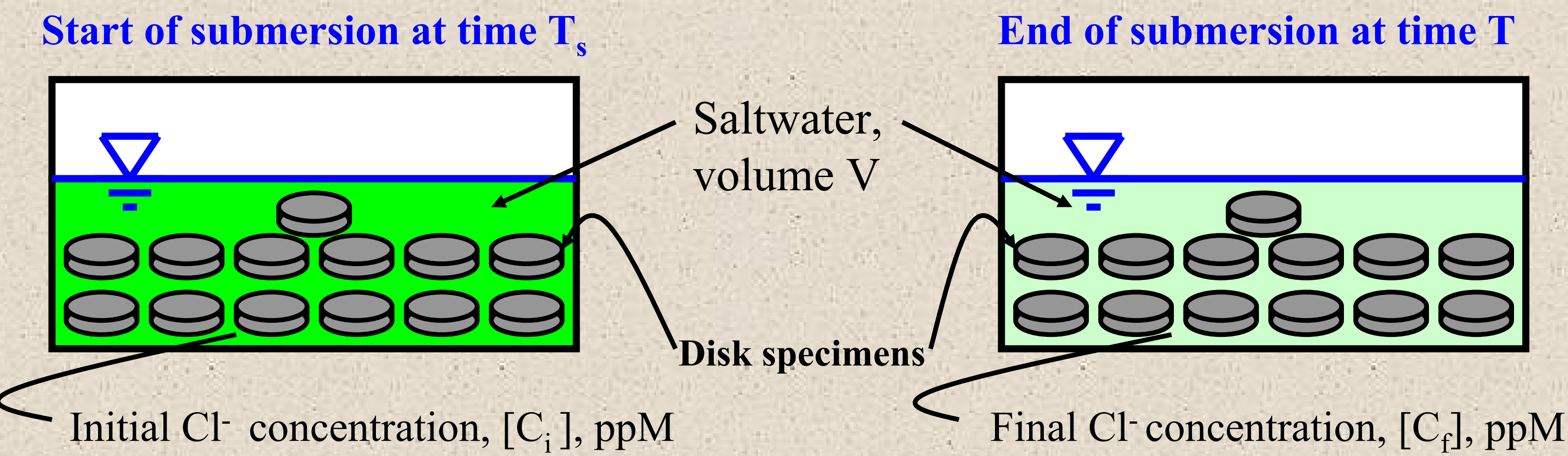
Exit

Time at end	-	Time at start	=	Submersion period (day)
29		1		28

Binders	Major compound	Mass of each compound (g/cm^3)	Mass for ettringite and monosulfo. formation (g/cm^3)	Remain Mass (g/cm^3)	Percentage of reaction (%)			Hydrated mass of each compound (g/cm^3)	Fixed CL by hydrated mass of each compound (g/cm^3) Physical	Fixed CL by hydrated mass of each compound (g/cm^3) Chemical	Fixed CL by hydrated mass of each compound (% by wt of binder) Physical	Fixed CL by hydrated mass of each compound (% by wt of binder) Chemical
Cement	C3A	.116	.041	.075	89.4	68.2	21.2	.016	.0017	.0011	.121	.08
	C4AF	.136	.055	.08	80.2	50.2	30	.024	.0011	.0008	.076	.056
	C3S	.79			83.7			.661	.0042		.299	
	C2S	.244			78			.19	.0016		.113	
Fly ash		0			0			0	0		0	
		Summation 1.286						Summation .892	Summation .0104		Summation .745	

เริ่ม Start | Microsoft PowerPoint ... | Exploring - Dr. Somnu... | Project1 - Microsoft V... | Output | En | 2:15

Experimental Setup of Chloride Binding Capacity



Calculation:

Total Cl^- = $\{[C_i] - [C_f]\} * V$

Free Cl^- is known from Expressed Pore Solution

So, Fixed Cl^- = Total Cl^- - Free Cl^-

Chloride binding capacity = Fixed Cl^- / Total Cl^-

Mix Designation

Cement paste

C1: Type I cement, w/c=0.30
C2: Type I cement, w/c=0.40
C3: Type I cement, w/c=0.50
C4: Type III cement, w/c=0.40
C5: Type V cement, w/c=0.40

Cement - fly ash paste

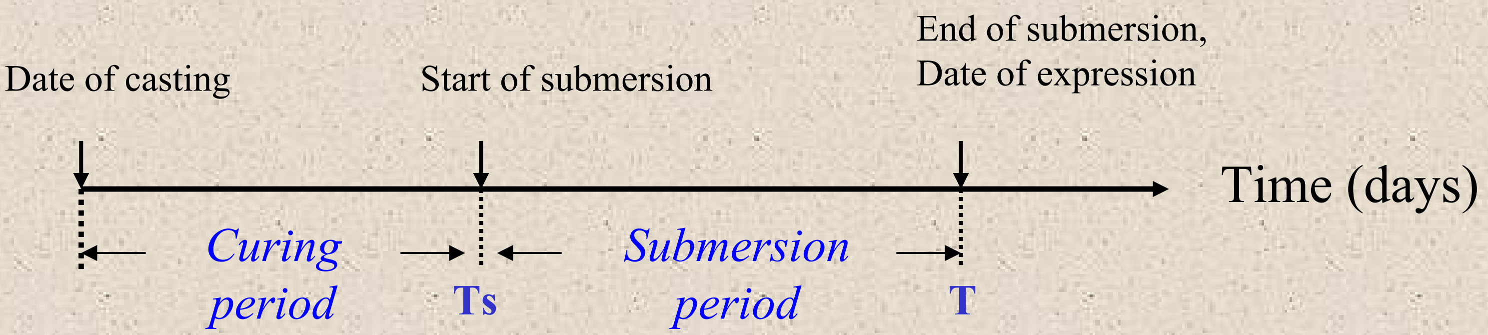
Cement+Fly Ash A (Low calcium)

FA1: Type I cement + Fly ash A (30%), w/c=0.40
FA2: Type I cement + Fly ash A (50%), w/c=0.40
FA3: Type I cement + Fly ash A (70%),w/c=0.40

Cement+Fly Ash B (High calcium)

FB1: Type I cement + Fly ash B (30%), w/c=0.40
FB2: Type I cement + Fly ash B (50%), w/c=0.40
FB3: Type I cement + Fly ash B (70%), w/c=0.40

Curing and submersion period



Curing period: 1, 7 and 28 day
Submersion period: 28, 56 and 91 day

Experiment Details

(External Chlorides)

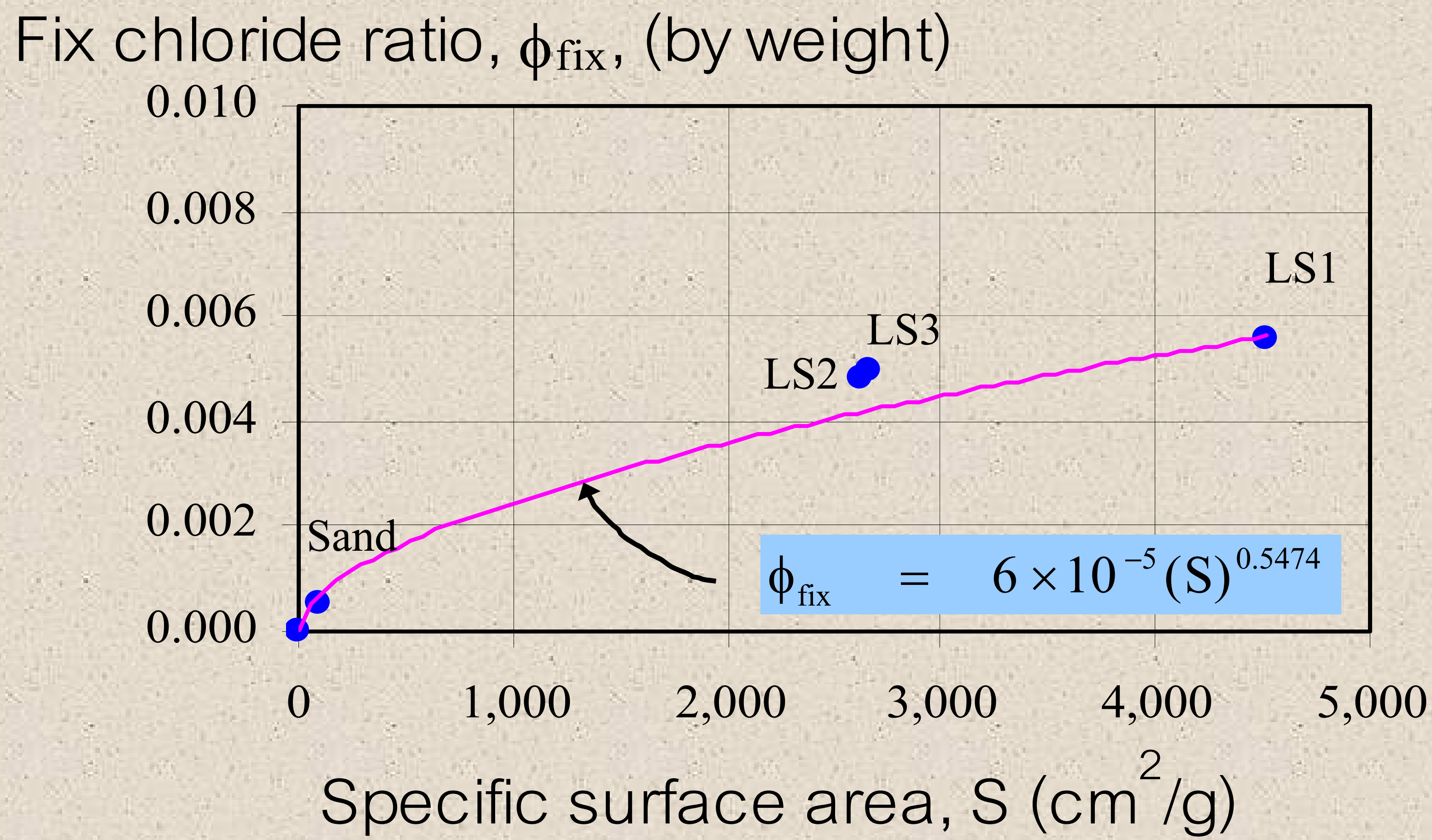
3.00 % of Cl^- for saltwater

Pore-expressed method

Measurement of $[OH^-]$ by pH meter

Measurement of $[Cl^-]$ by potentiometric titration with $AgNo_3$ solution and chloride ion selective electrode

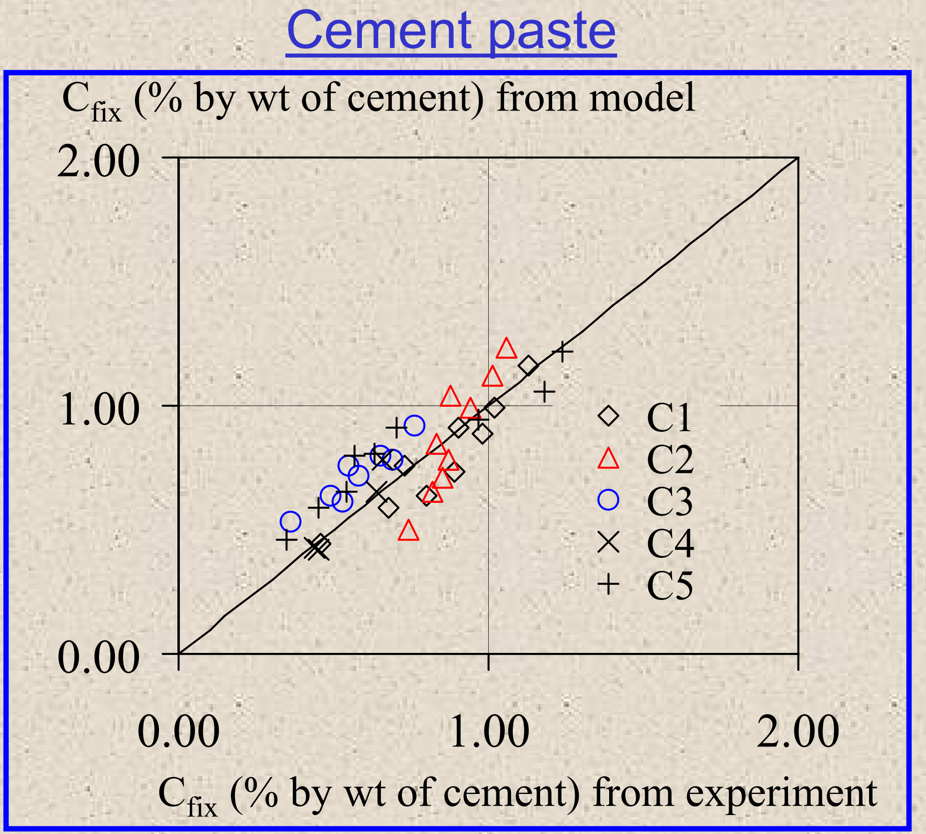
Model of Chloride Binding Capacity of Fine Aggregate and Finer Aggregate

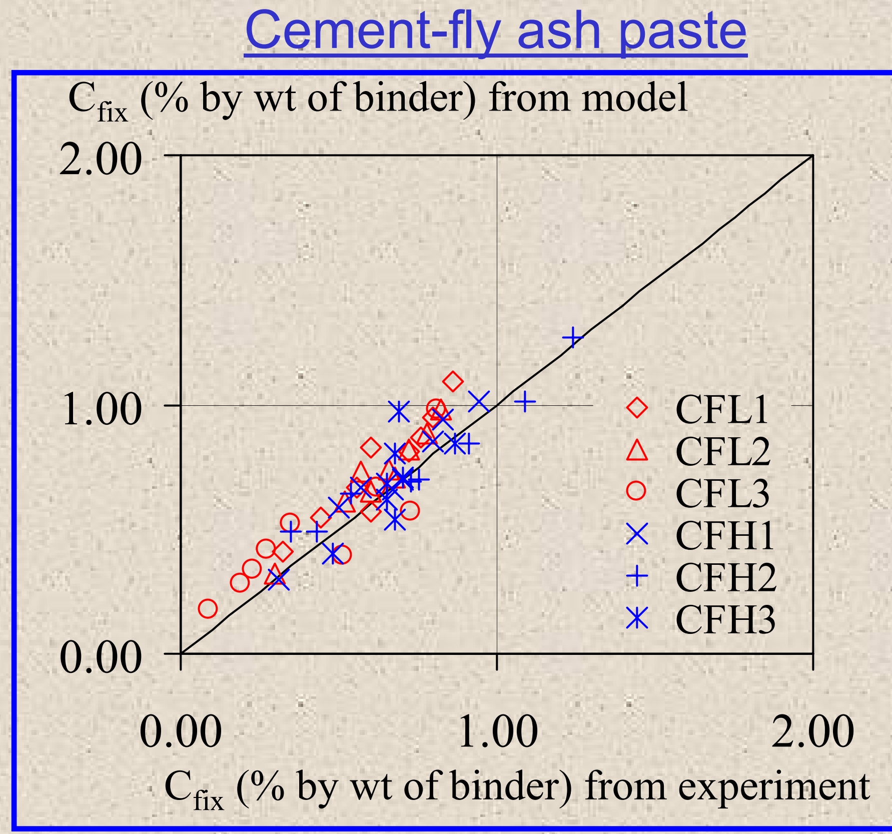


From Plangngeon and Tangtermsiriul

Verification of CBC Model (External Chlorides)

Sumranwanich et.al.





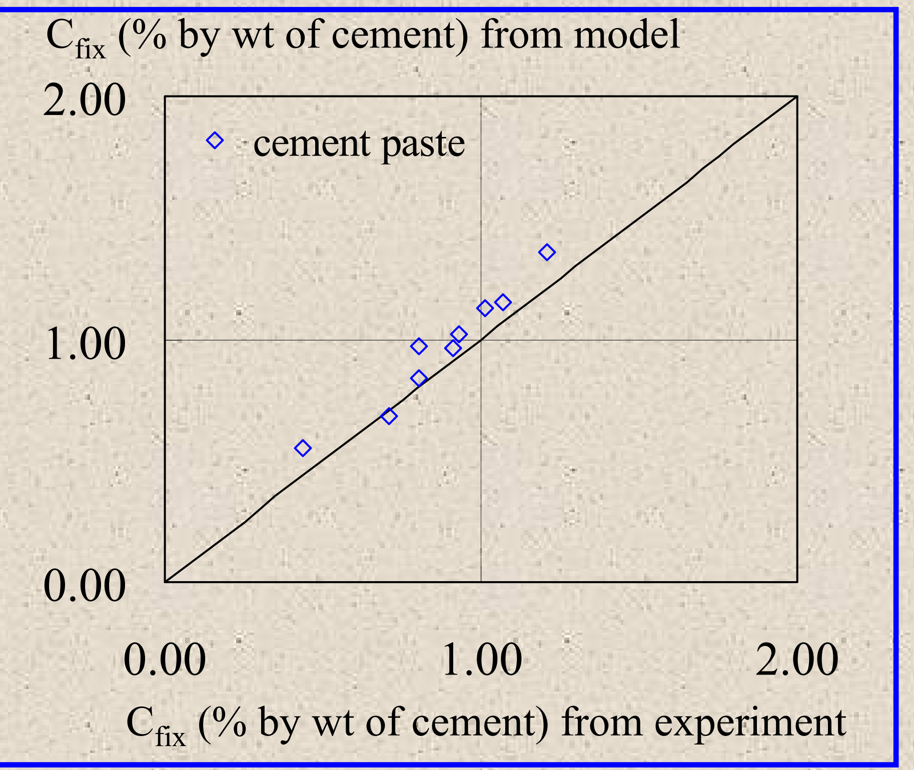
Age at start of submersion: t_s = 1, 7, 28 days

Submersion period: t_e-t_s = 28, 56, 91 days

Verification of CBC Model (External Chlorides)

Arya et. al.

Cement paste



Age at start of submersion:

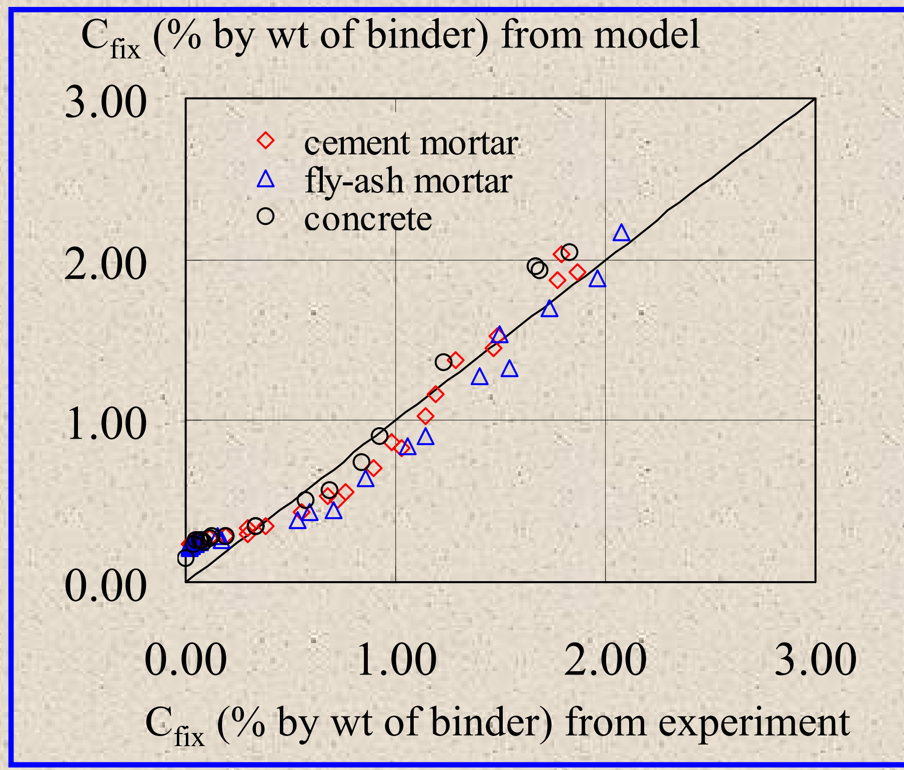
t_s = 2, 28, 84 days

Submersion period:

t_e-t_s = 28, 56, 84 days

Maruya et. al.

Mortar and concrete



Age at start of submersion:

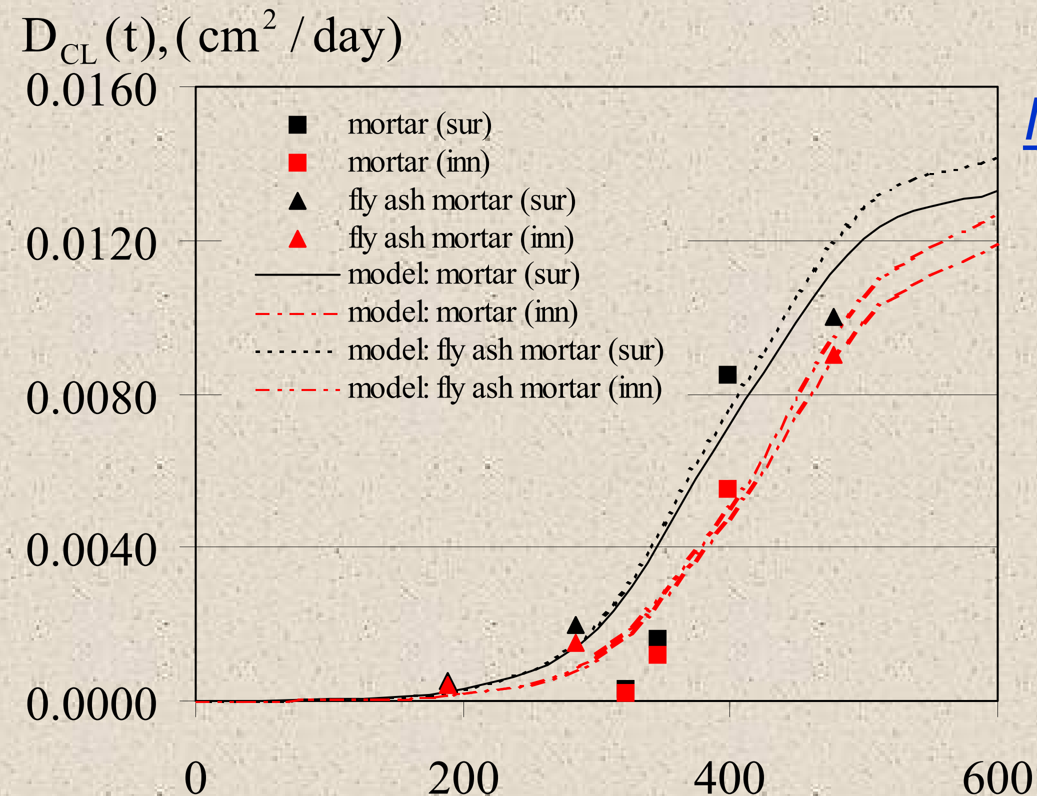
t_s = 28 days

Submersion period:

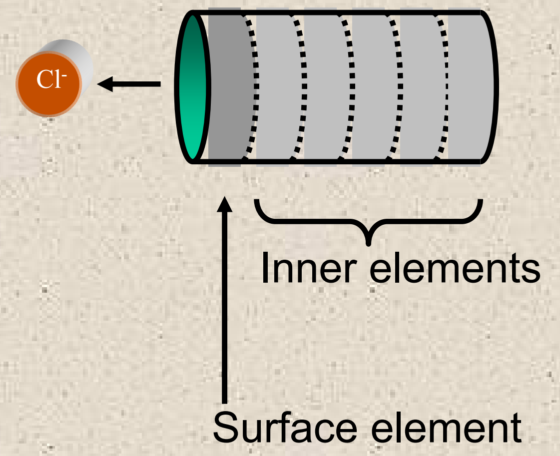
t_e-t_s = 28, 91, 182, 365 days

Chloride Diffusion Coefficient

Model of Time-Dependent Chloride Diffusion Coefficient



Maruya and Tangtermsiriku



$$200 \times d_{ave}^{2.1}(t) \times \left(\frac{n(t)}{100}\right)^{3.5}$$

For surface element;

$$D_{CL}(1,t) = \frac{0.000012}{0.00043 + e^{-0.0197 \times \left(200 \times d_{ave}^{1.5}(t) \times \left(\frac{n(t)}{100}\right)^{3.5}\right)}} \times (R_p^3 + 0.375) \times \left(0.25 \times \left(\frac{f}{b}\right) + 1\right) \times \left(\frac{C_W(1,t)}{100}\right)$$

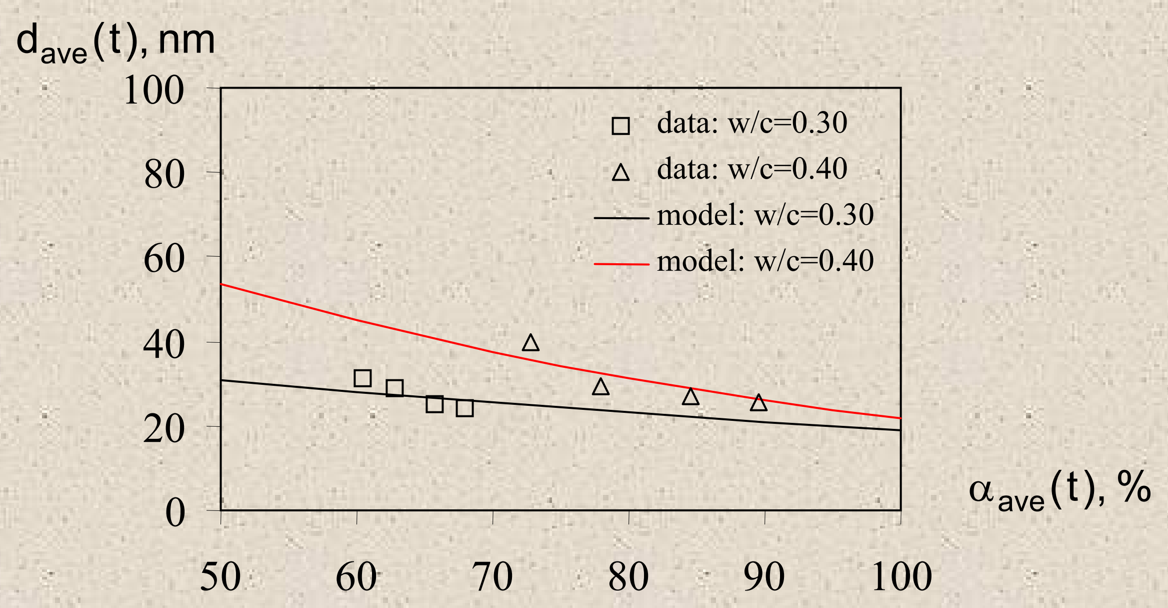
For inner element;

$$D_{CL}(x,t) = \frac{0.000010}{0.00039 + e^{-0.0184 \times \left(200 \times d_{ave}^{1.5}(t) \times \left(\frac{n(t)}{100}\right)^{3.5}\right)}} \times (R_p^3 + 0.375) \times \left(0.25 \times \left(\frac{f}{b}\right) + 1\right) \times \left(\frac{C_W(x,t)}{100}\right)$$

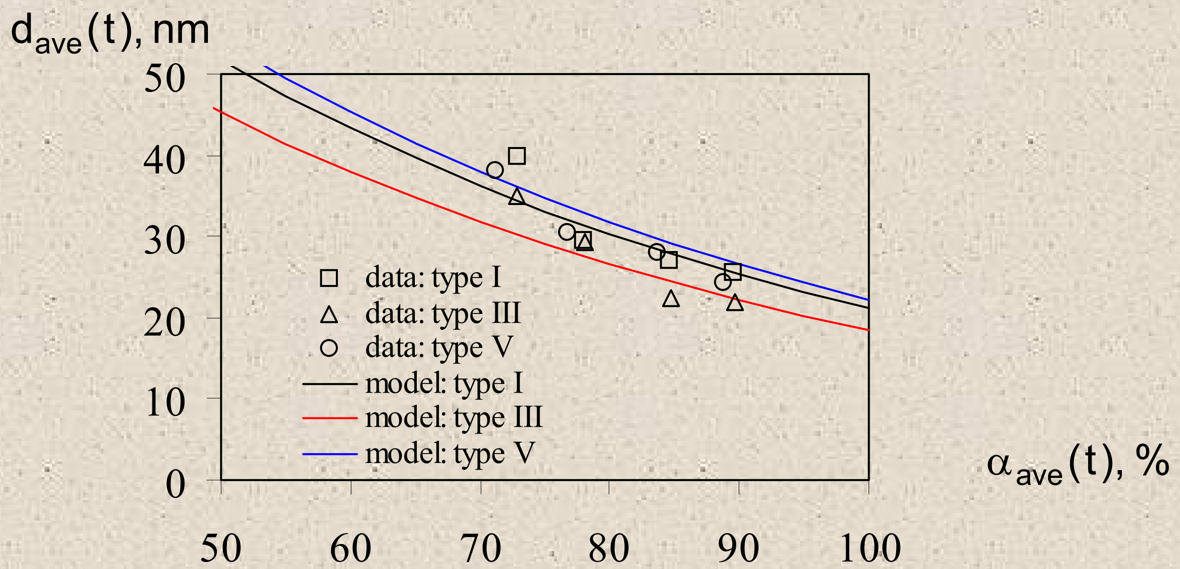
Pore Structures
(Average pore diameter and Total porosity)

Average Pore Diameter of Paste

Effect of water to cement ratio

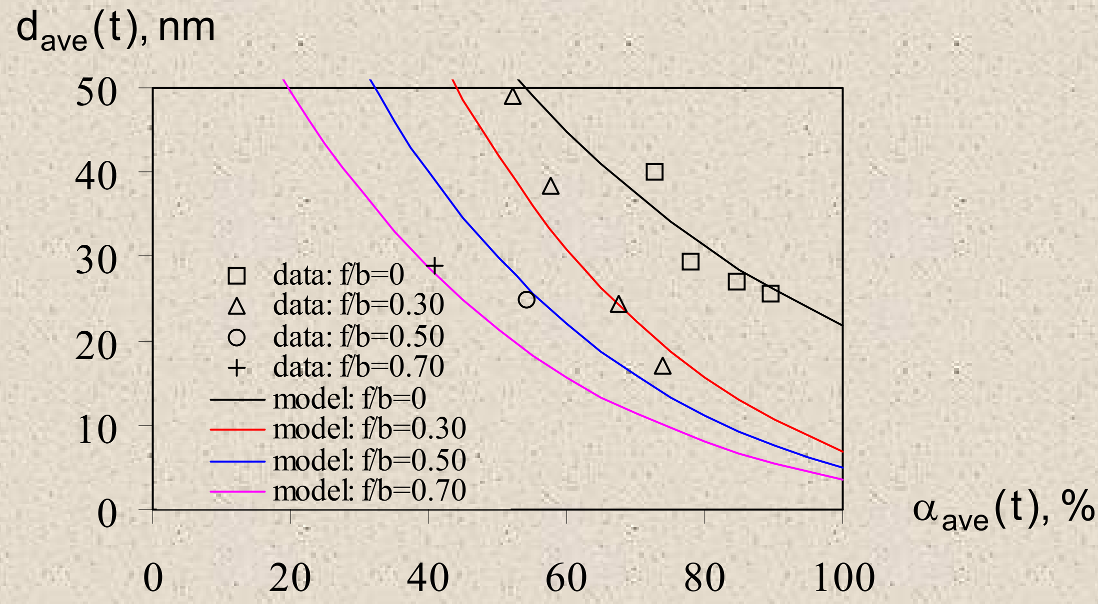


Effect of type of cement



Average Pore Diameter of Paste *(continued)*

Effect of fly ash



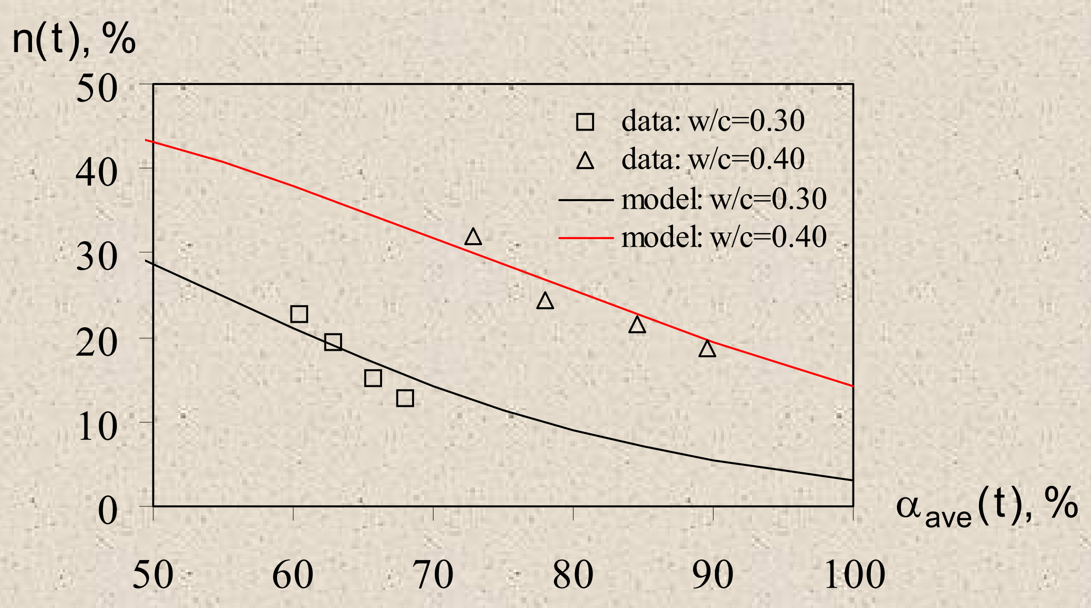
Model of average pore diameter, $d_{ave}(t)$

$$d_{ave}(t) = e^{\left(\left(8.2\times(w/b-0.19)^{0.78}+2.45\right)+\left(-6.5\times(w/b-0.19)^{0.56}+0.92\right)\times\frac{\alpha_{ave}(t)}{100}\right)} \times\left(\frac{1602}{F_c^{1.02}}+0.57\right)\times\left(\left(\frac{C_3A}{100}\right)^{-0.065}-0.21\right)$$

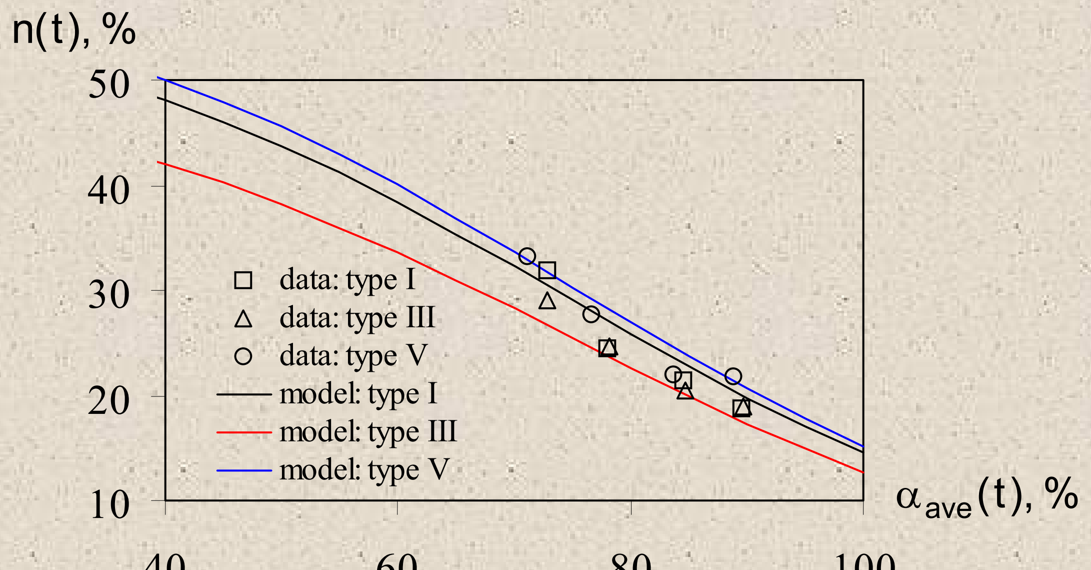
$$\times\left(1-\left(\frac{f}{b}\right)\times\left(-0.68\times\left(\frac{f}{b}\right)+1.45\right)\right)\times\left(-1.5\times\frac{\alpha_{ave}(t)}{100}+2\right)$$

Total Porosity of Paste

<u>Effect of water to cement ratio</u>

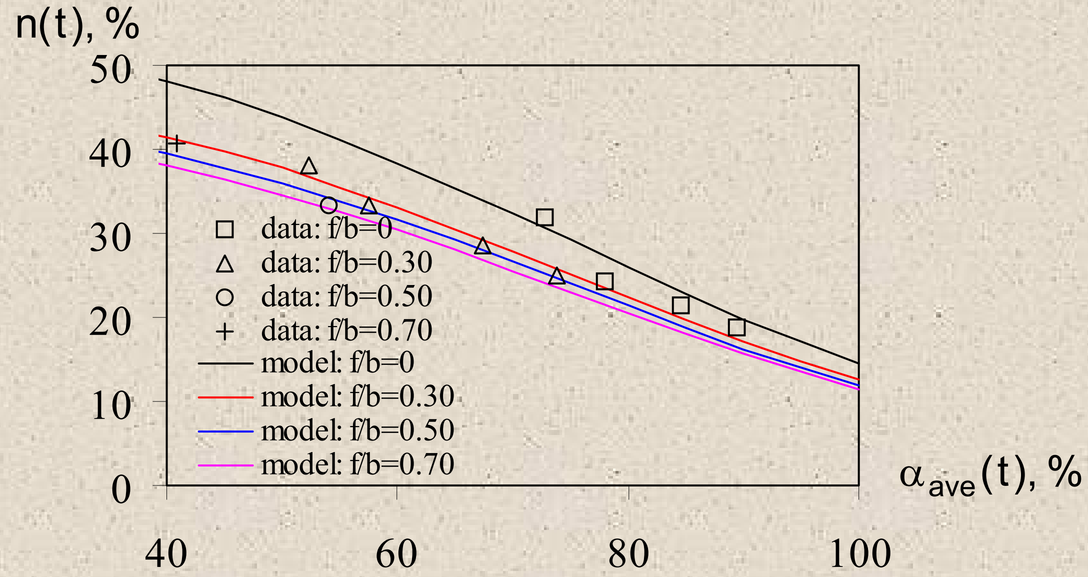


<u>Effect of type of cement</u>



Total Porosity of Paste *(continued)*

Effect of fly ash



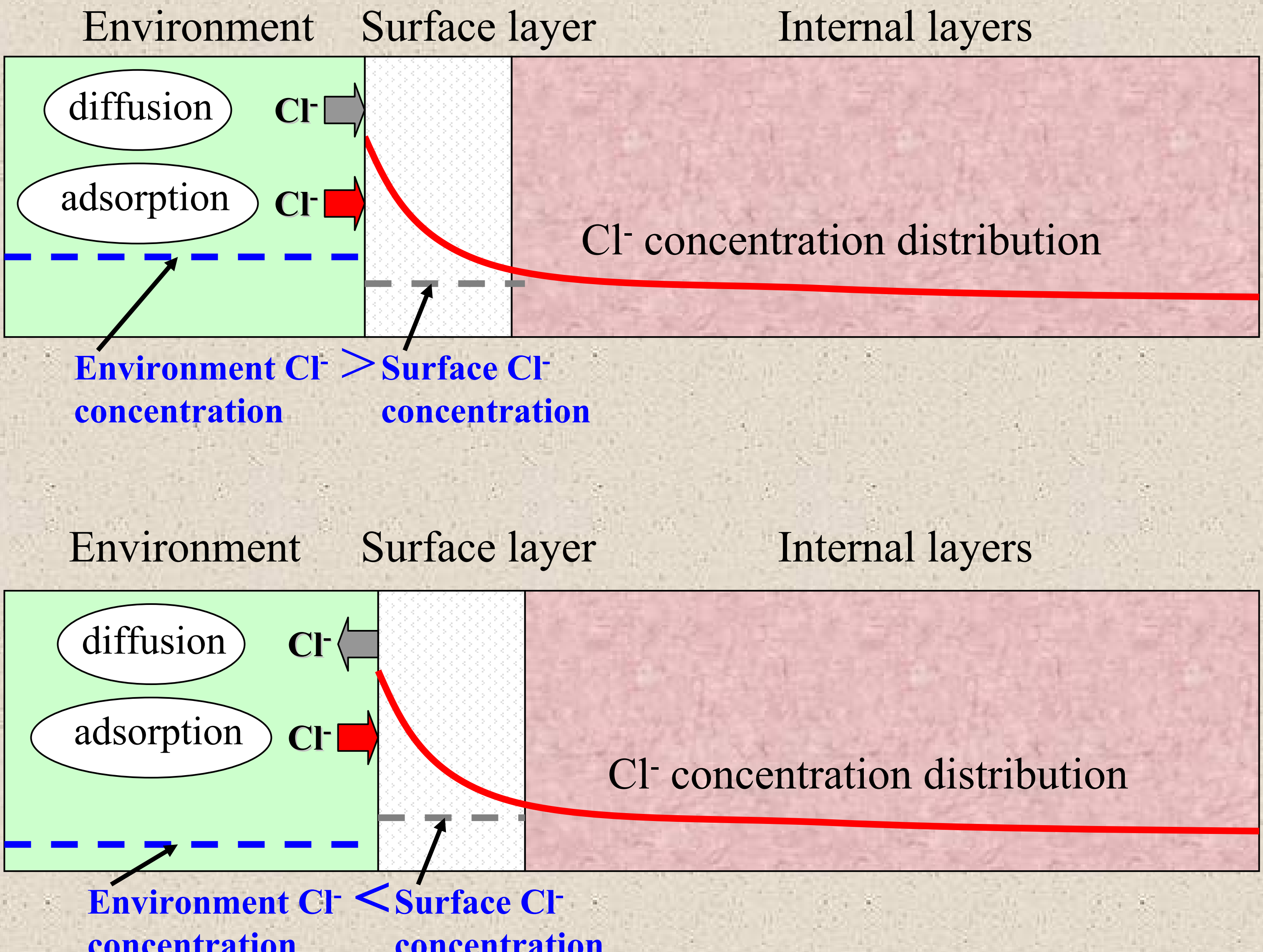
Model of total porosity, n(t)

$$n(t)=\left(23.9\times\ln\left(\frac{w}{b}\right)+77.4\right)\times\frac{27.6}{26.5+e^{\left(0.86\times(w/b)^{-1.43}+1.2\right)\times\frac{\alpha_{ave}(t)}{100}}}\times\left(\frac{1602}{F_c^{1.02}}+0.57\right)$$

$$\times\left(\left(\frac{C_3A}{100}\right)^{-0.065}-0.21\right)\times\left(-0.25\times\left(\frac{f}{b}\right)^{0.5}+1\right)$$

Chloride condensation in submerged zone

Chloride Condensation in Surface Layer



Model of Time-Dependent Ion Adsorption

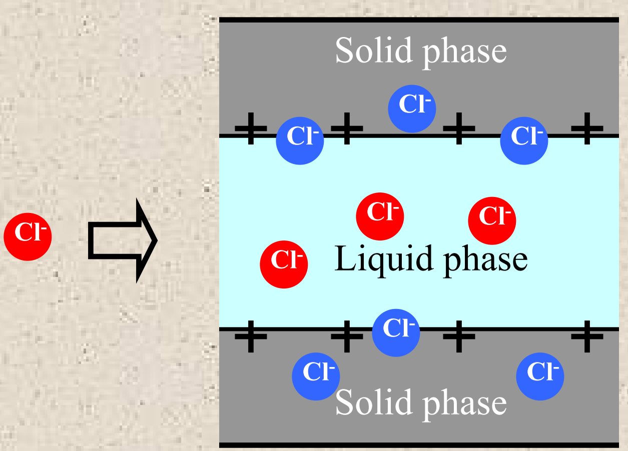
$$F_{ad}(1,t) = \left(0.0000034 \times B^{0.443}\right) \times R_p^{0.05} \times \left(-0.35 \times C_{f,b}^{0.5}(1,t) + 1\right) \times \frac{n(t)}{100} \times e^{-C_{f,b}(1,t)}$$

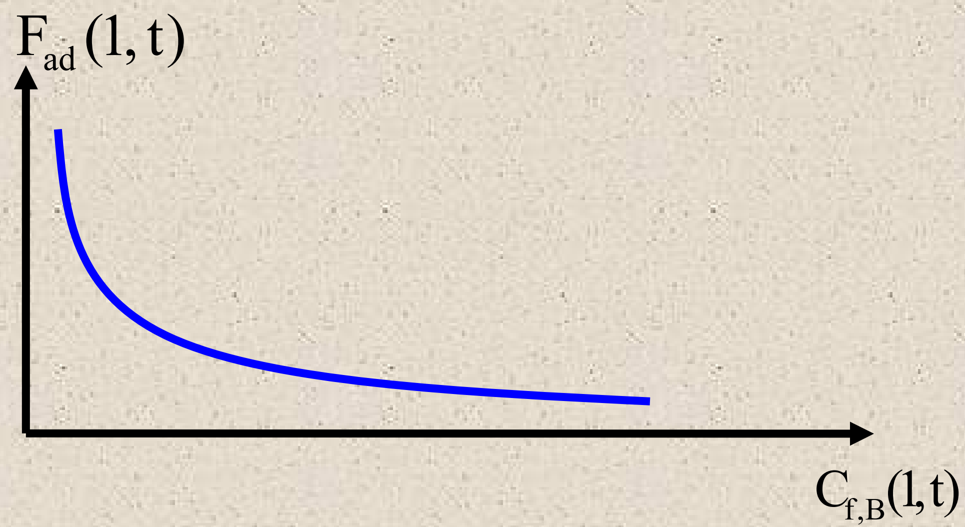
where, $F_{ad}(1,t)$ = Ion adsorption flux of surface element, mol/(cm^2/day)

$C_{f,B}(1,t)$ = Free chloride content of surface element, % by wt of binde

B = Binder content (kg/m^3) R_p = Paste ratio

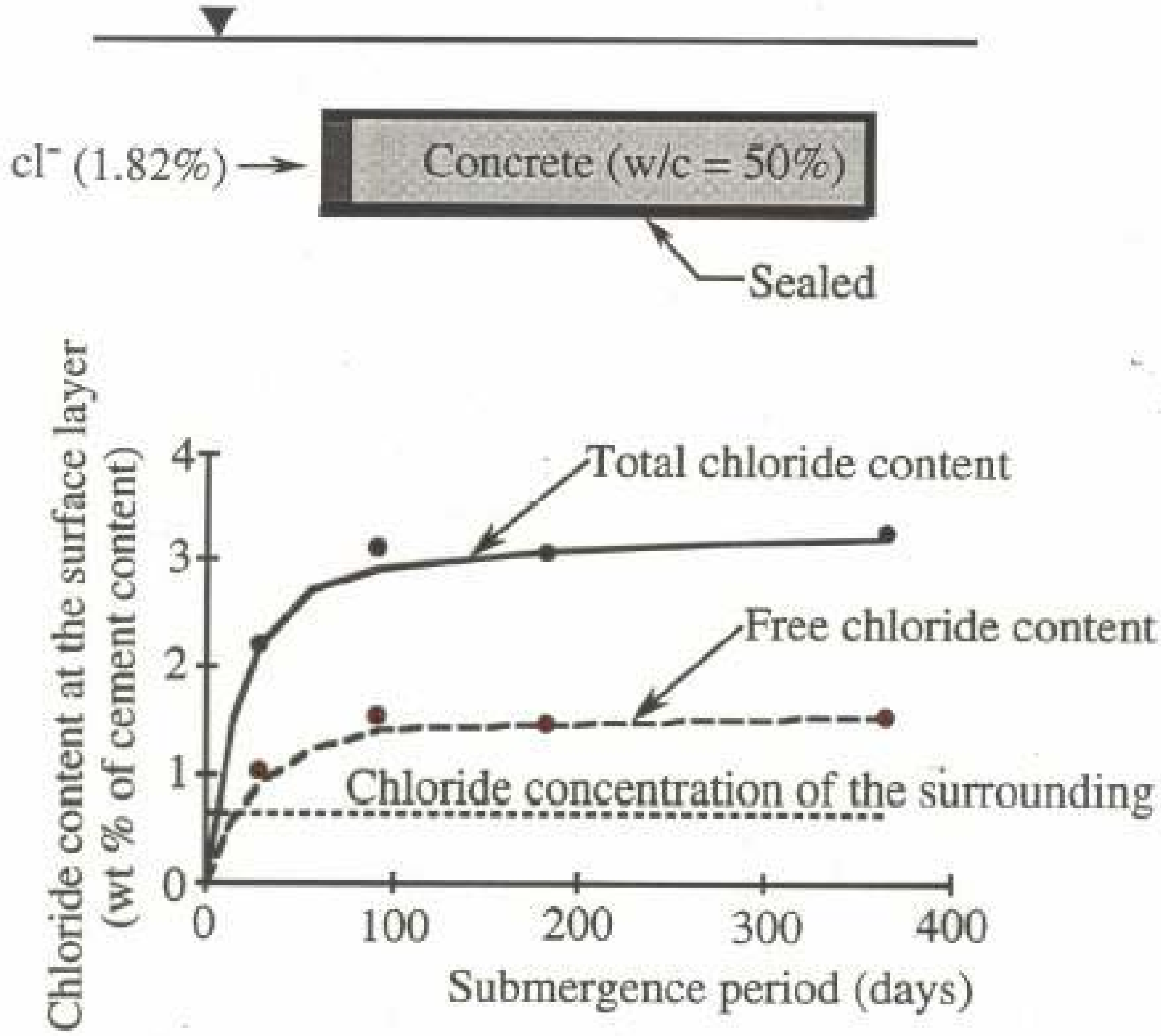
n(t) = Porosity, %





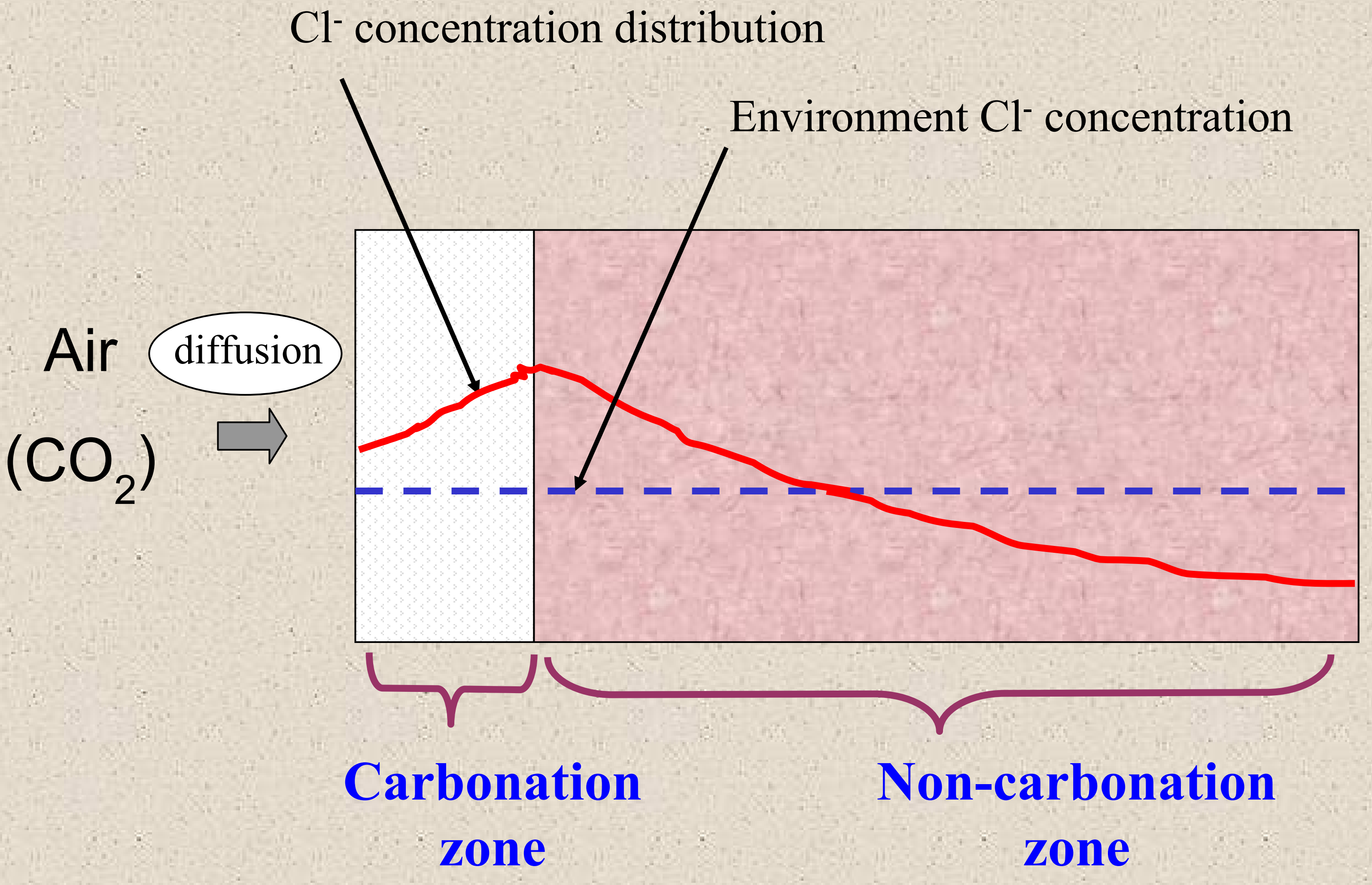
Cl- free chloride Cl- fixed chloride

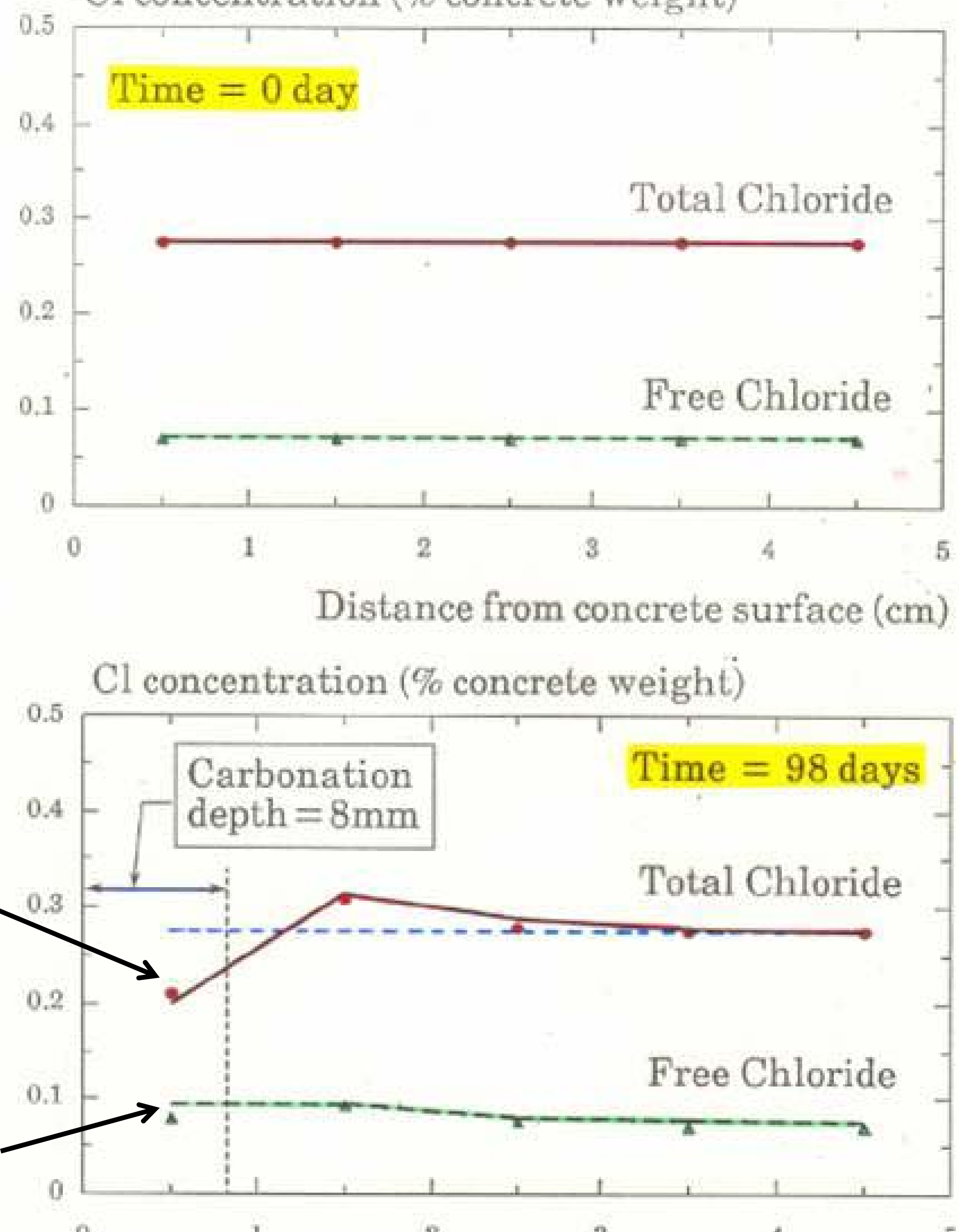
Chloride Penetration Test Results



Chloride condensation due to Carbonation

Effect of Carbonation



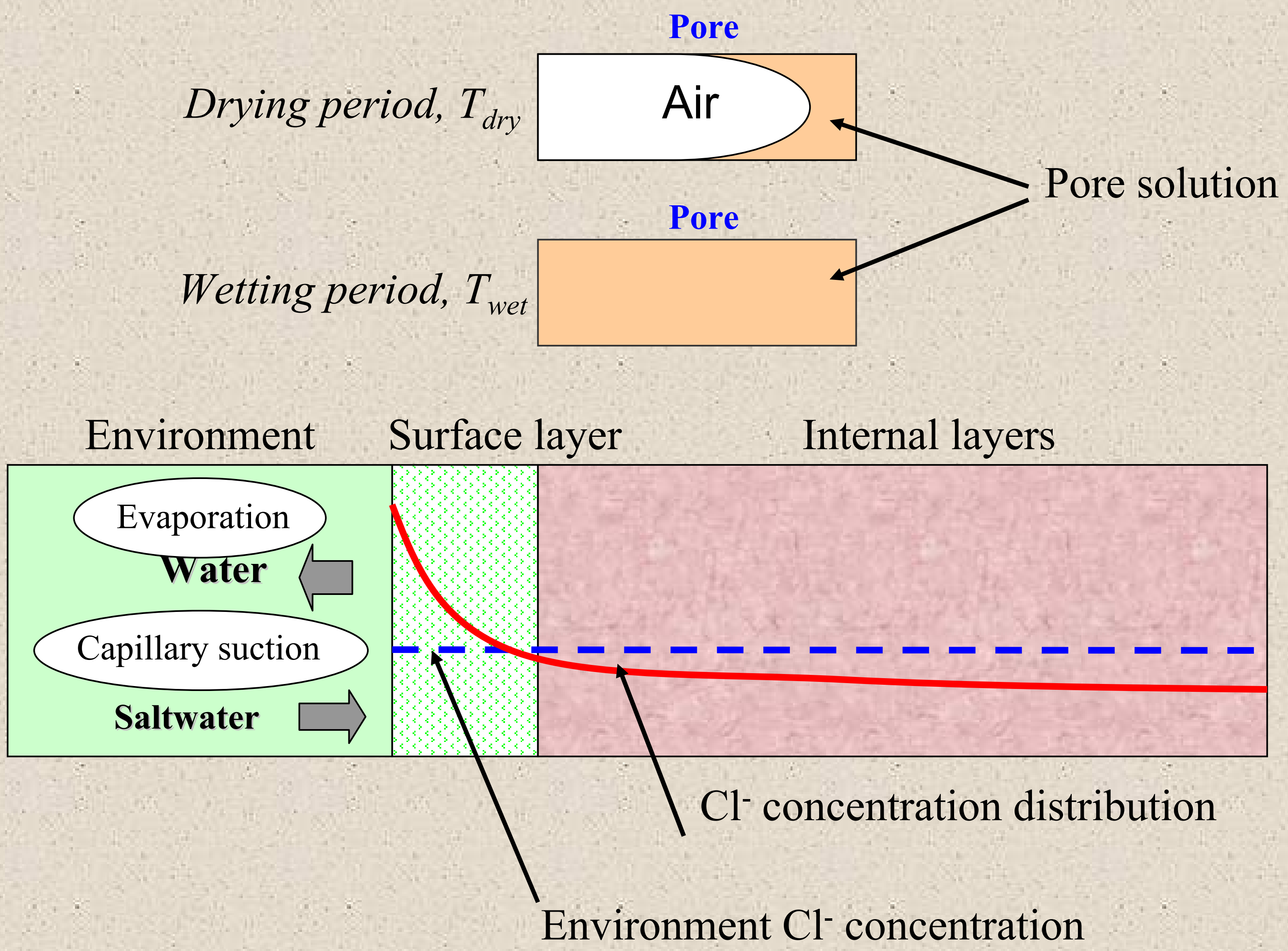


Total chloride reduces

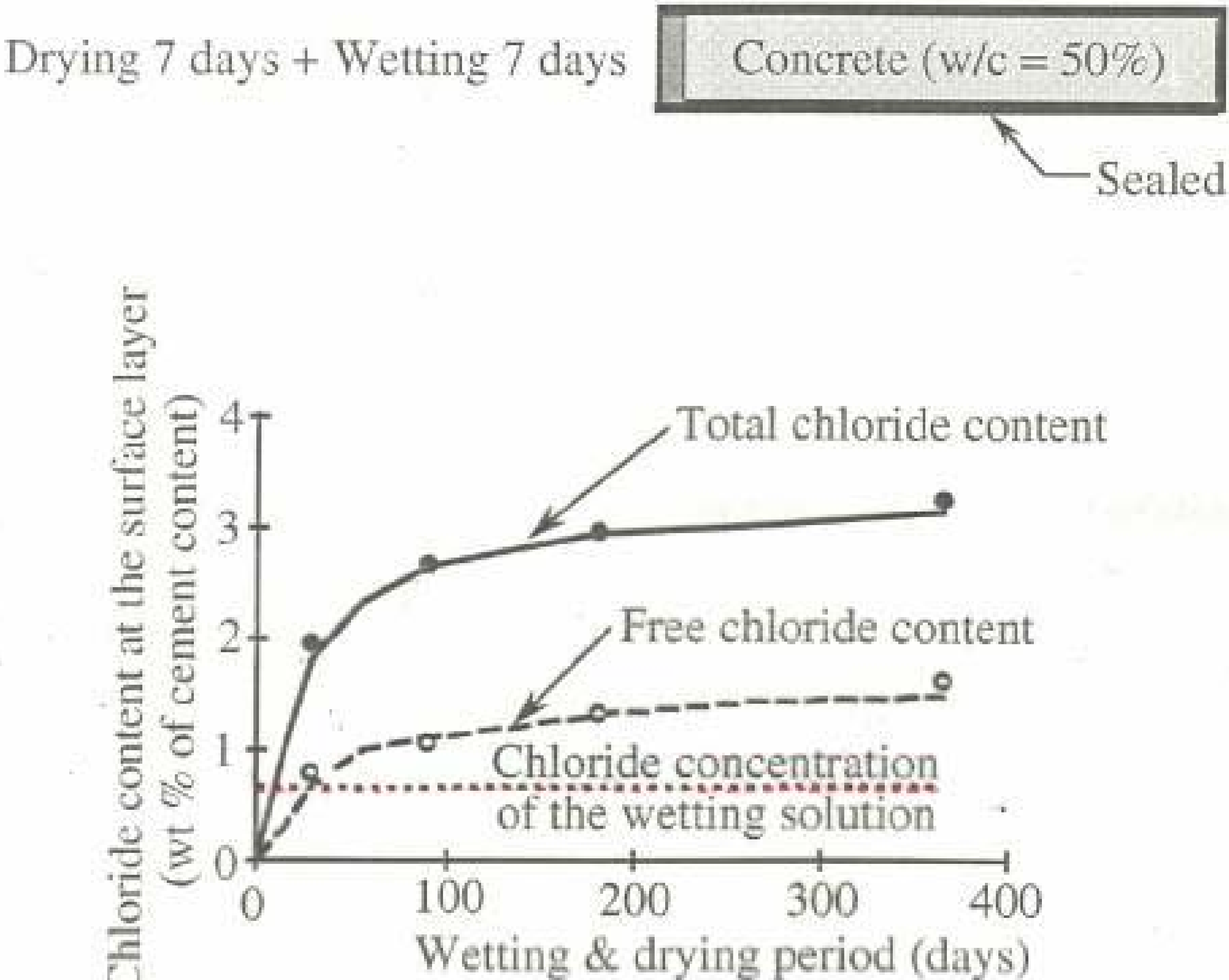
Free chloride increases

Chloride condensation due to effect of wetting & drying

Effect of Cyclic Wetting and Drying

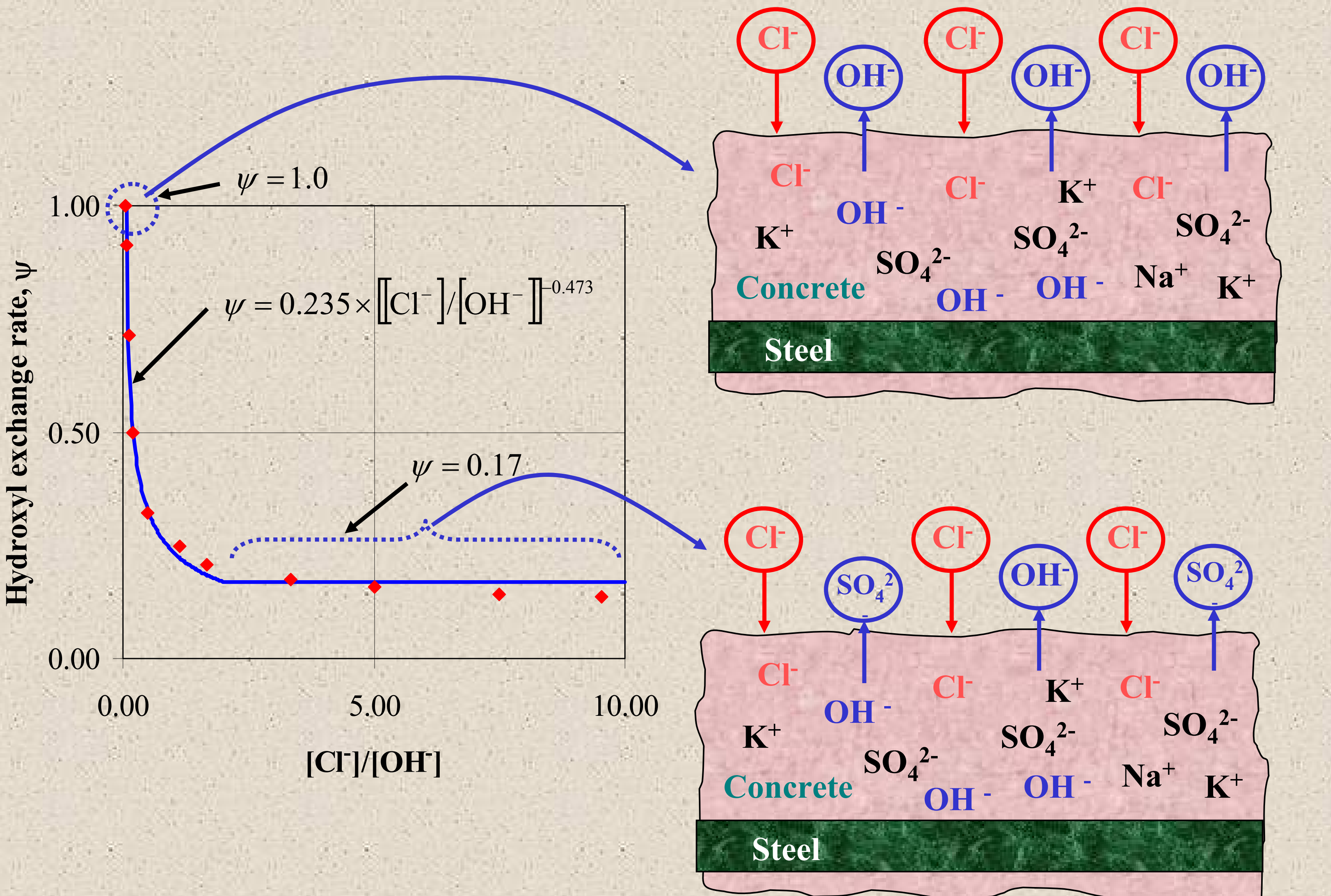


Wetting & Drying Test Results



Ion Equilibrium

Mechanism of Ion Exchange



Depassivation Criteria

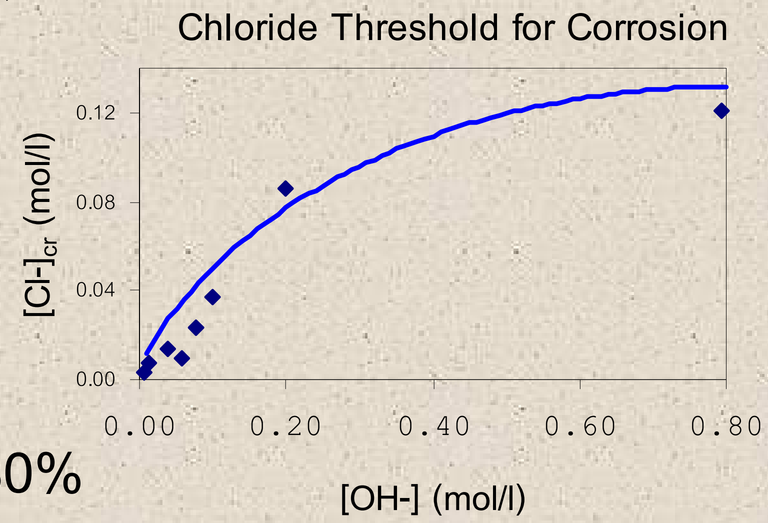
Depassivation Criteria

1. Chloride corrosion threshold
   - Depend on the hydroxyl concentration in pore solution
   - $[Cl^-]_{cr} = 0.1716\ [OH^-]^{0.7619}$

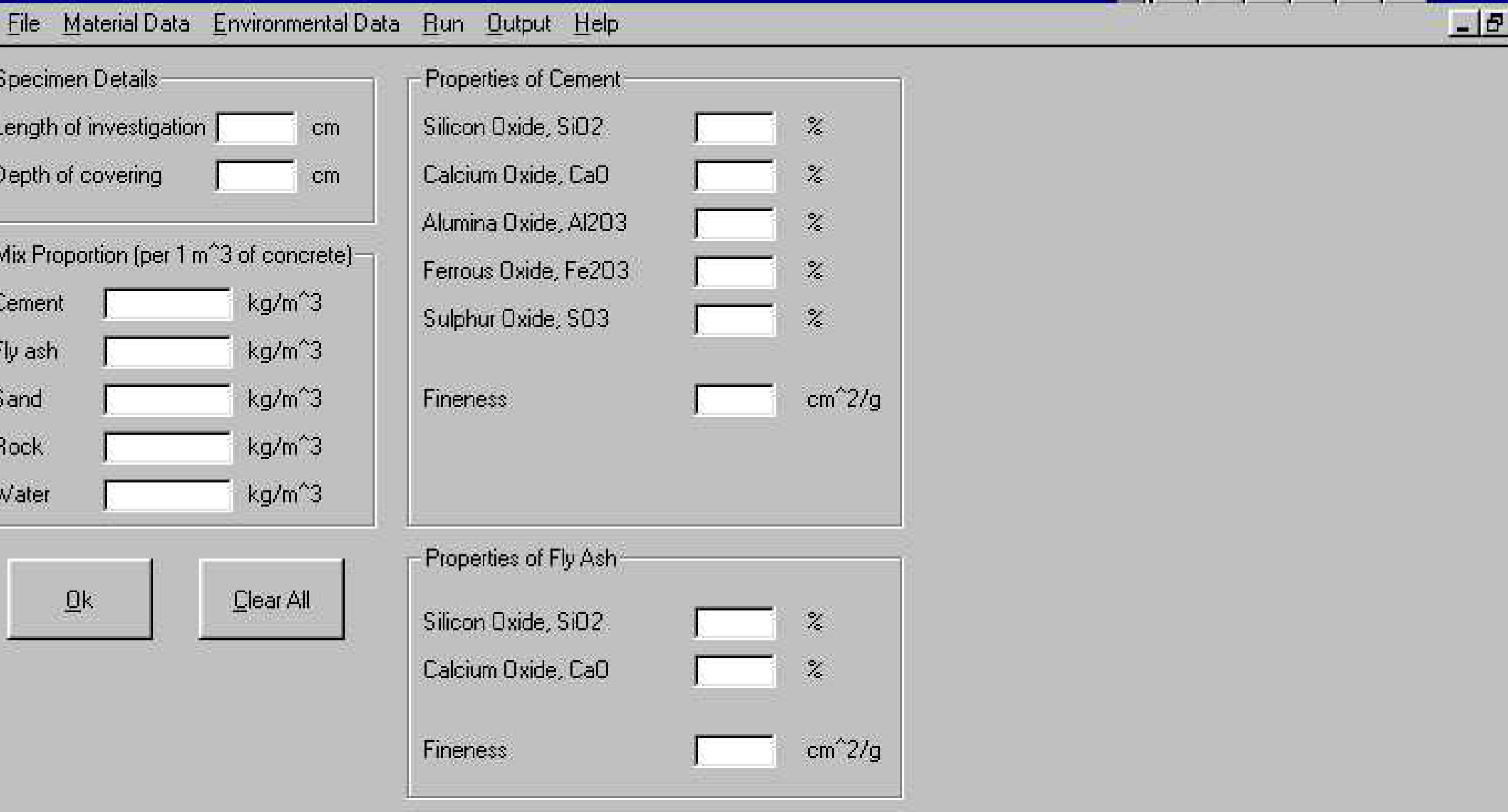
     where,

     $[Cl^-]_{cr}$ = critical chloride concentration, mol/l

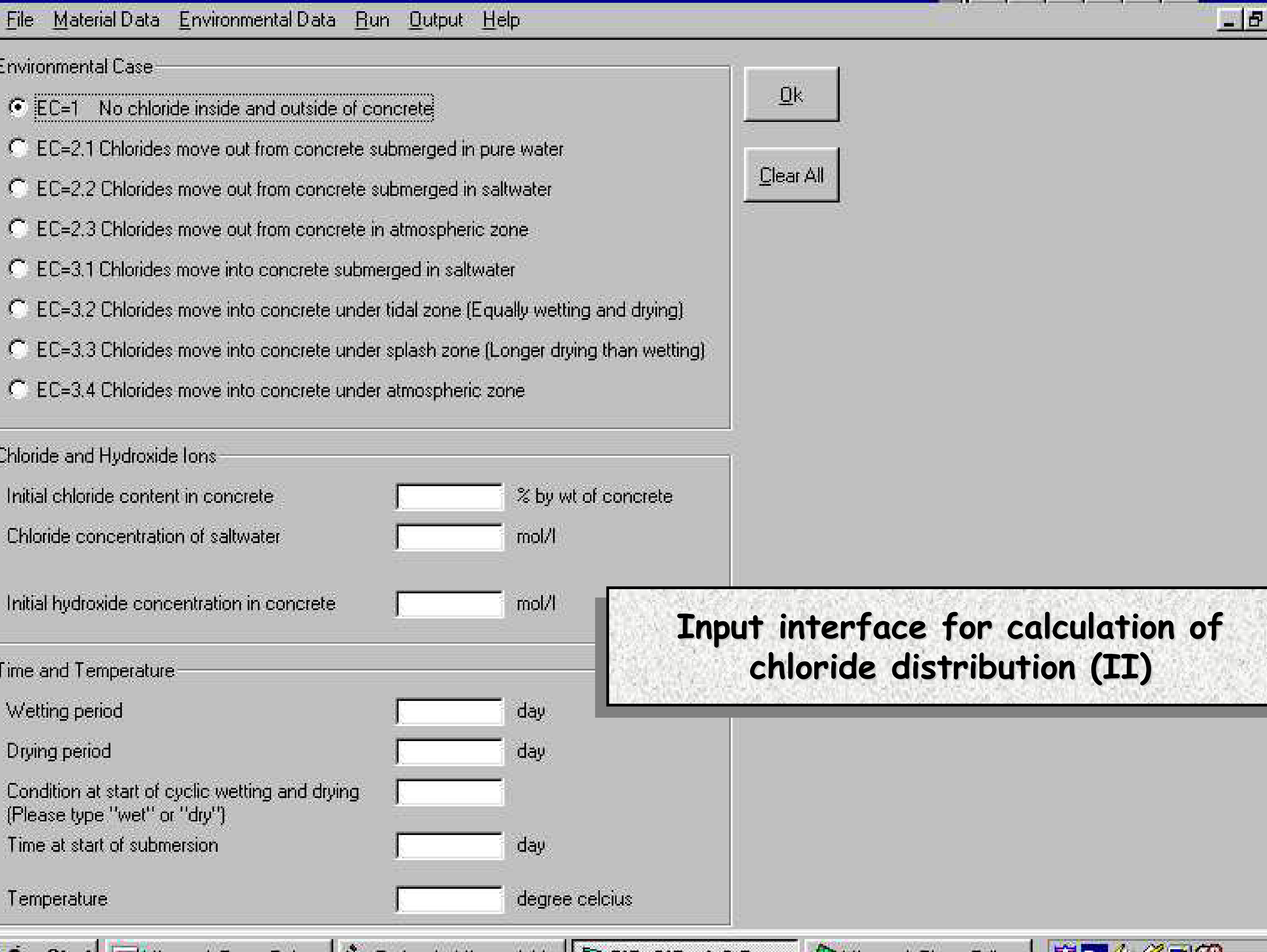
     $[OH^-]$ = hydroxyl concentration, mol/l



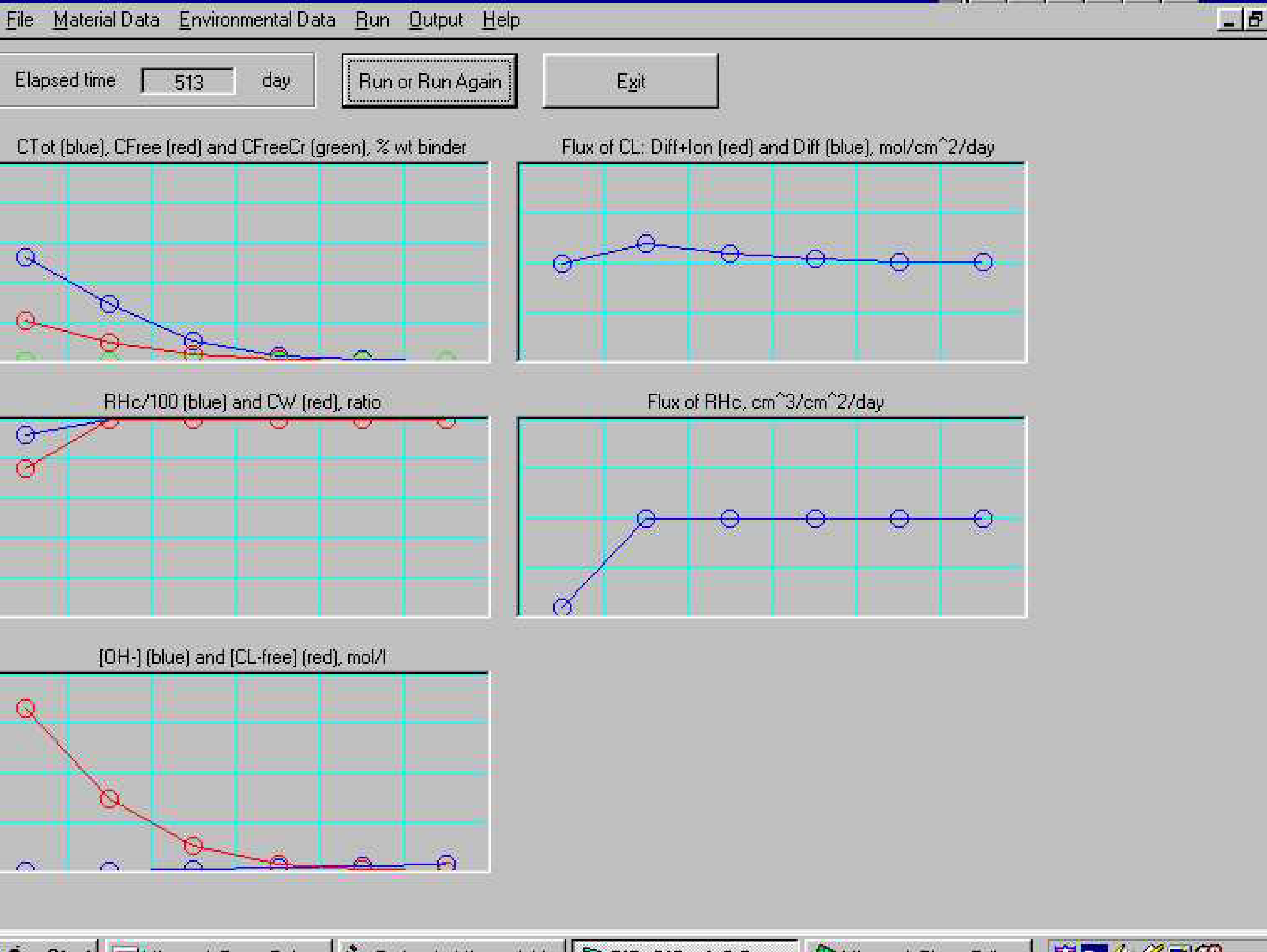
2. Adequate water supplied
   - Optimum relative humidity is 70-80%
3. Oxygen provided



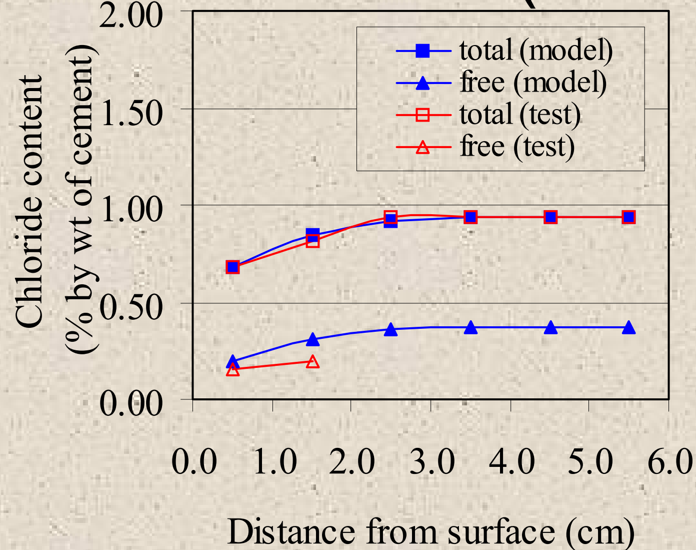
Input interface for calculation of chloride distribution (I)

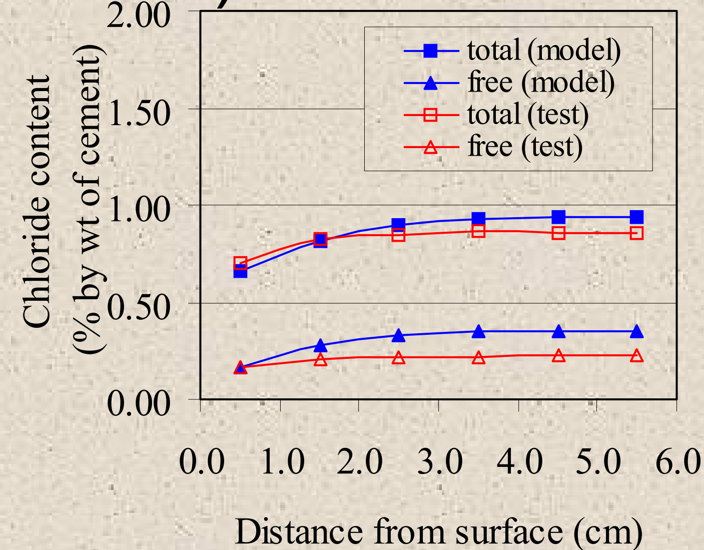


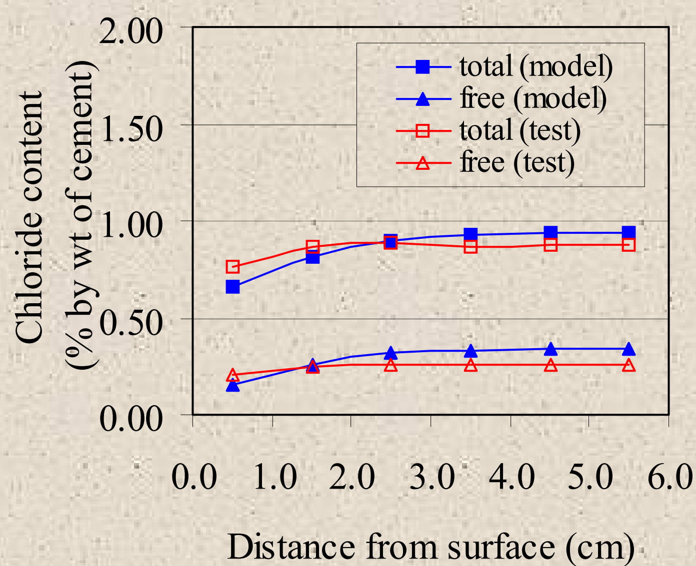
Input interface for calculation of chloride distribution (II)

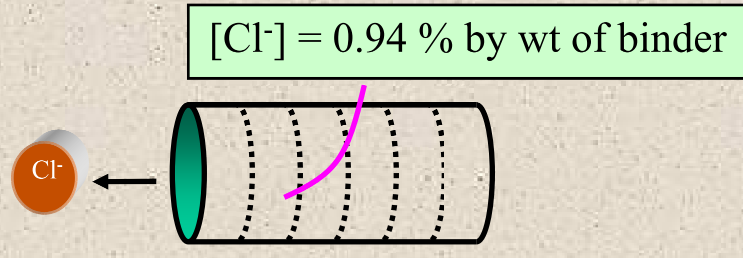

File
Material Data
Environmental Data
Run
Output
Help
Elapsed time
513
day
Run or Run Again
Exit
CTot (blue), CFree (red) and CFreeCr (green), % wt binder
Flux of CL: Diff+Ion (red) and Diff (blue), mol/cm^2/day
RHc/100 (blue) and CW (red), ratio
Flux of RHc, cm^3/cm^2/day
[OH-] (blue) and [CL-free] (red), mol/l

Simulation of Chloride Profile of Cement-Fly Ash Mortar (Internal chloride)









<u>*Maruya and Tangtermsirikul:*</u>

<u>(Dissolving Test)</u>

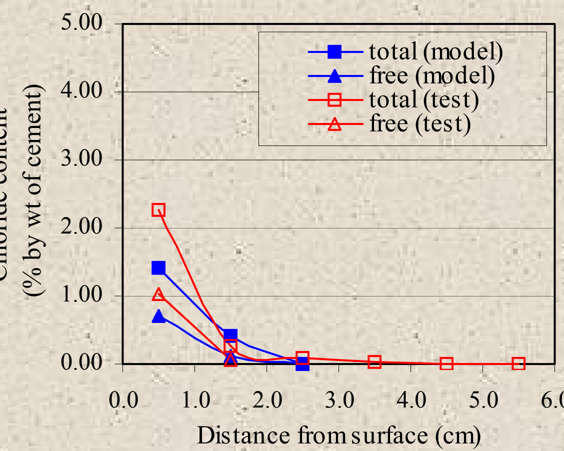
cement-fly ash mortar,

w/b = 0.50, f/b = 0.20

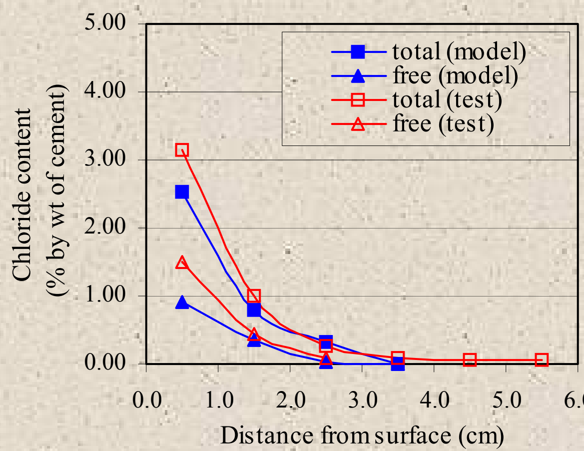
t_s = 28 days

Simulation of Chloride Penetration in Concrete (External chloride)

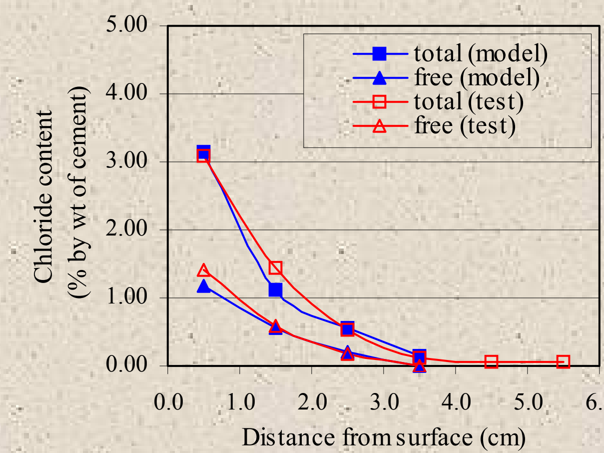
Submersion period = 28 days



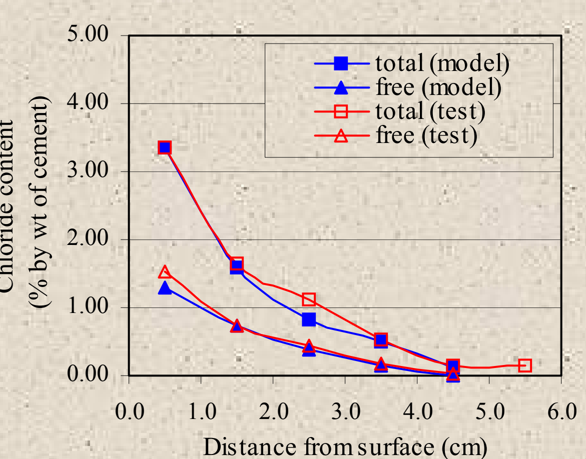
Submersion period = 91 days



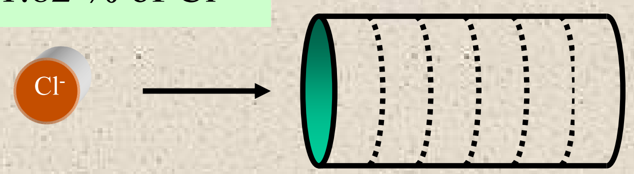
Submersion period = 182 days



Submersion period = 365 days



$[Cl^-]$ = 1.82 % of Cl^-

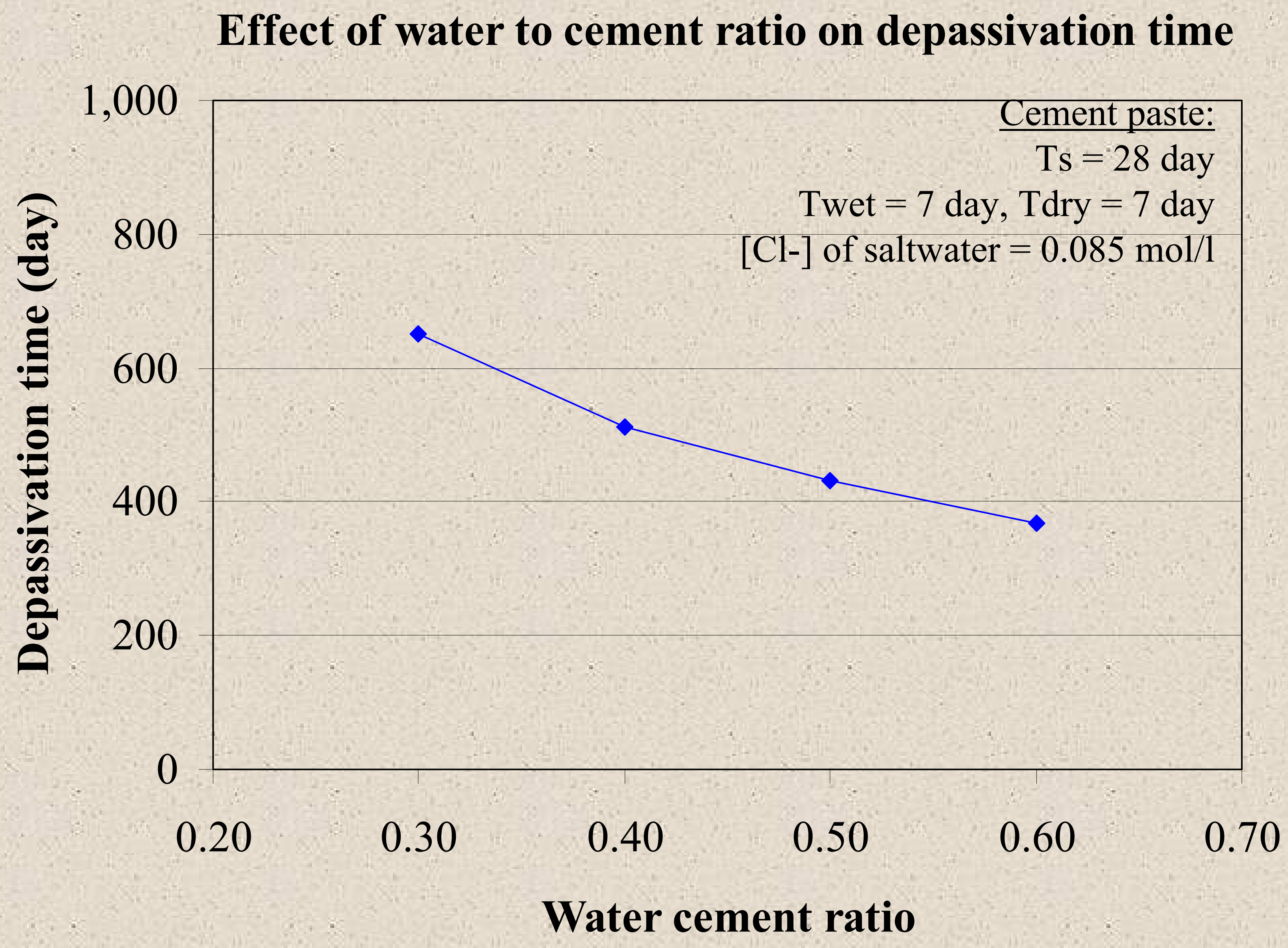


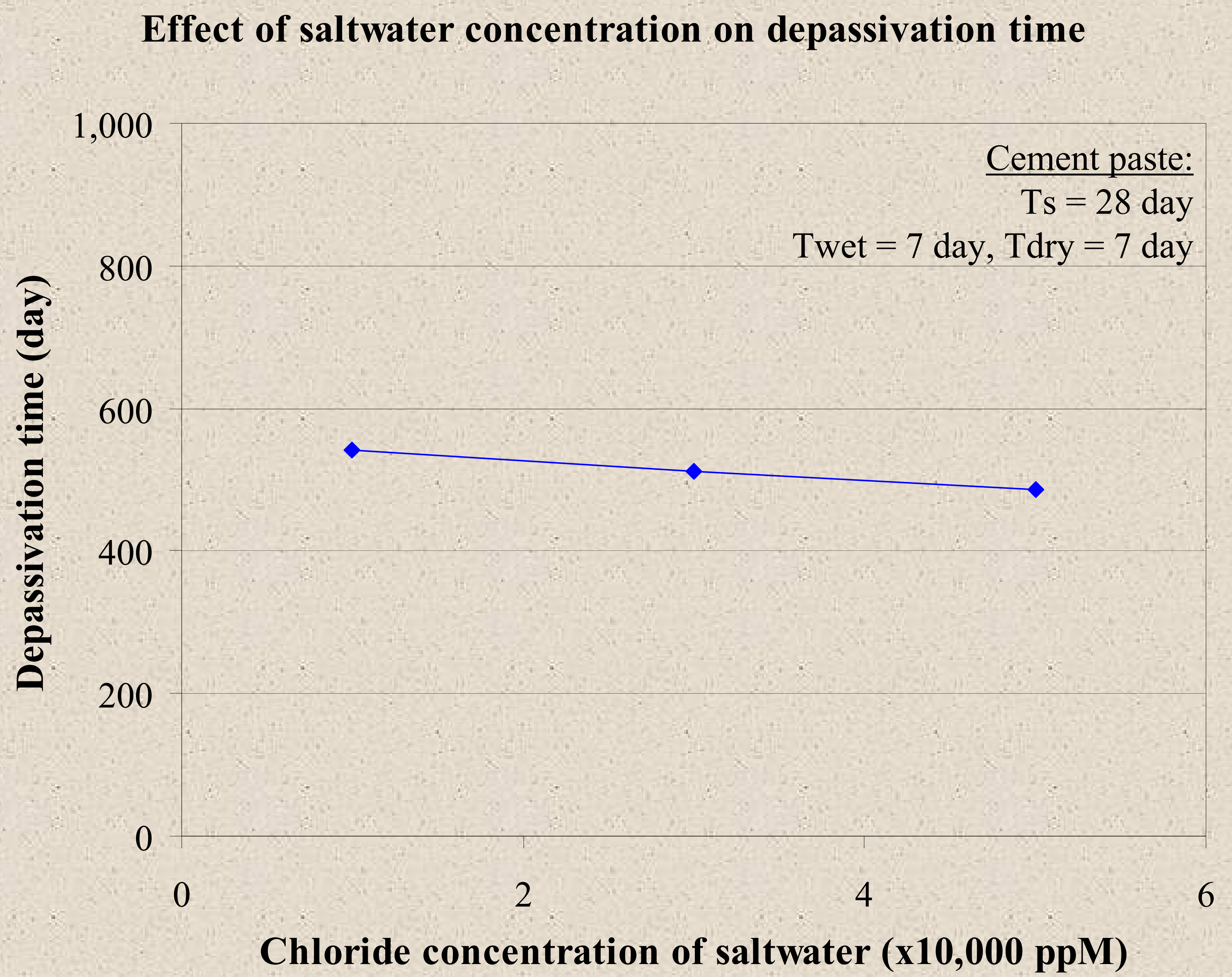
Maruya and Tangtermsirikul:

concrete,

w/c = 0.50

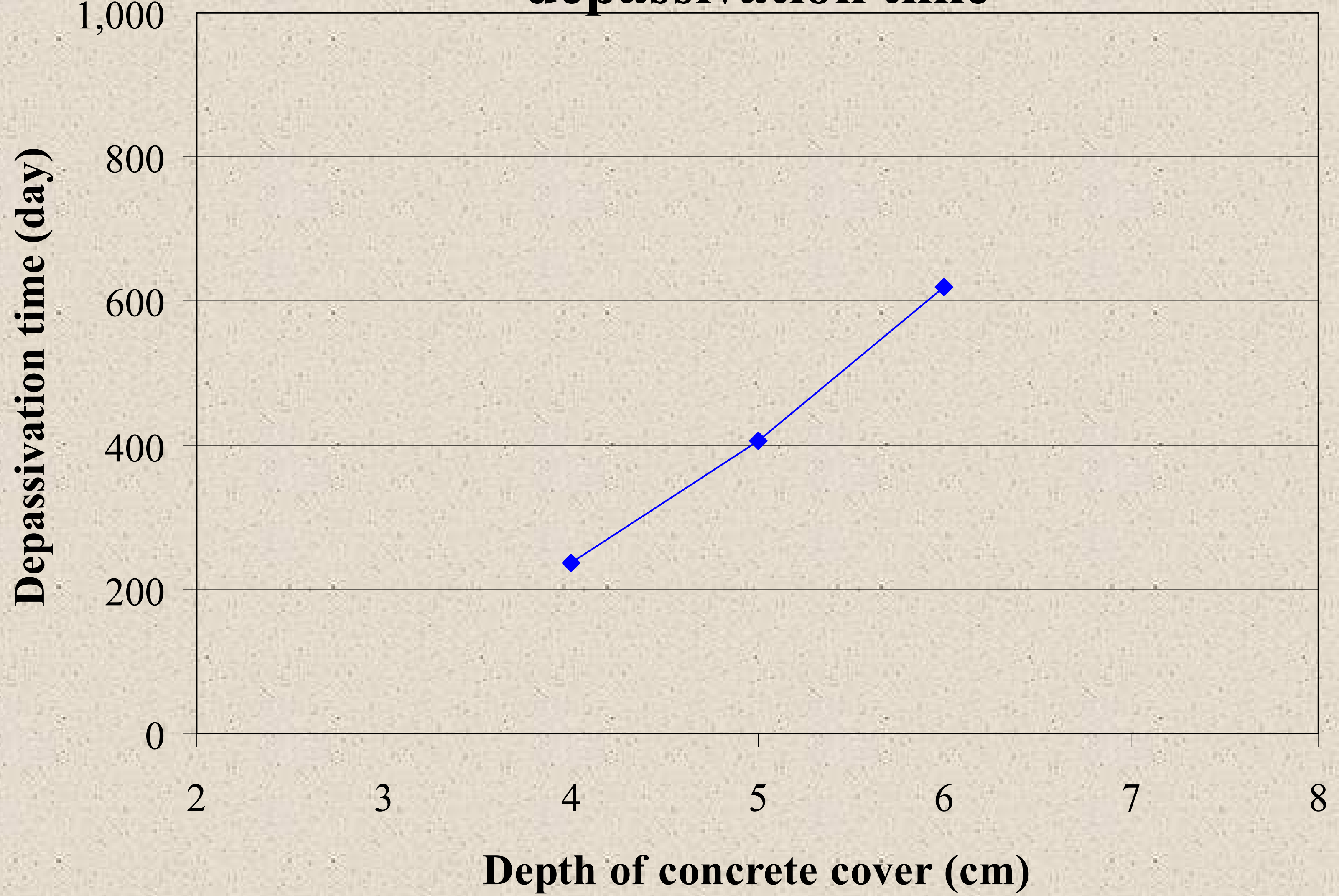
t_s = 28 days

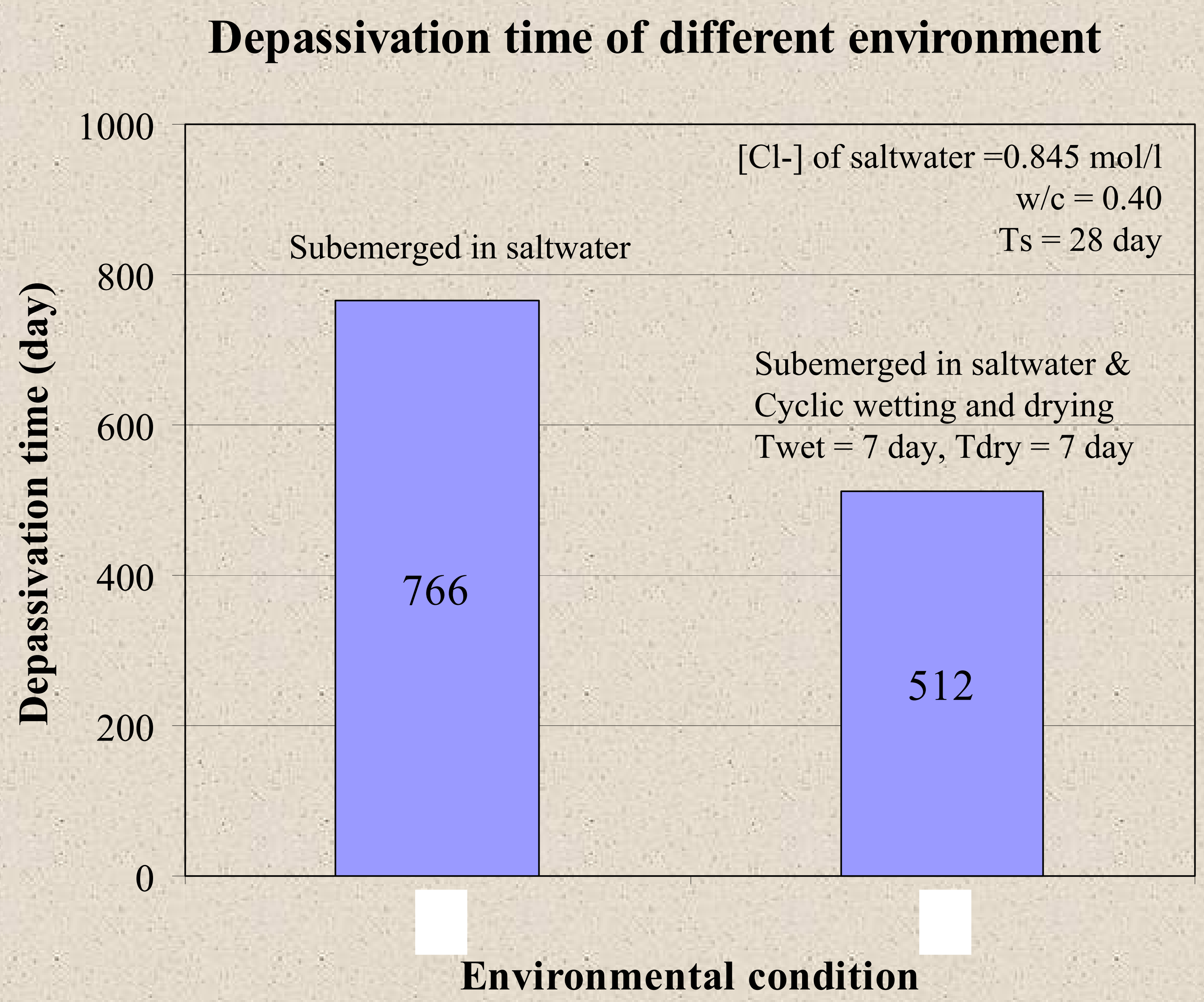

Effect of water to cement ratio on depassivation time
Cement paste:
Ts = 28 day
Twet = 7 day, Tdry = 7 day
[Cl-] of saltwater = 0.085 mol/l
Depassivation time (day)
1,000
800
600
400
200
0
0.20
0.30
0.40
0.50
0.60
0.70
Water cement ratio



Effect of saltwater concentration on depassivation time
Cement paste:
Ts = 28 day
Twet = 7 day, Tdry = 7 day
Depassivation time (day)
1,000
800
600
400
200
0
0
2
4
6
Chloride concentration of saltwater (x10,000 ppM)

Effect of depth of concrete cover on depassivation time




Depassivation time of different environment
1000
800
600
400
200
0
Depassivation time (day)
[Cl-] of saltwater =0.845 mol/l
w/c = 0.40
Ts = 28 day
Subemerged in saltwater
766
Subemerged in saltwater &
Cyclic wetting and drying
Twet = 7 day, Tdry = 7 day
512
Environmental condition

Durability of Fly Ash Concrete under Sulfate Attack

Sulfate Attack

1. Mechanisms of N$\underline{S}$ Attack

$$CH + N\underline{S} + 2H \longrightarrow C\underline{S}H_2 + NH \quad (1)$$

$$C_4AH_{13} + 3C\underline{S}H_2 + 14H \longrightarrow C_6A\underline{S}_3H_{32} + CH \quad (2)$$

$$C_4A\underline{S}H_{12} + 2C\underline{S}H_2 + 16H \longrightarrow C_6A\underline{S}_3H_{32} \quad (3)$$

$$C_3A + 3C\underline{S}H_2 + 26H \longrightarrow C_6A\underline{S}_3H_{32} \quad (4)$$

Sulfate Attack

2. Mechanisms of M$\underline{S}$ Attack

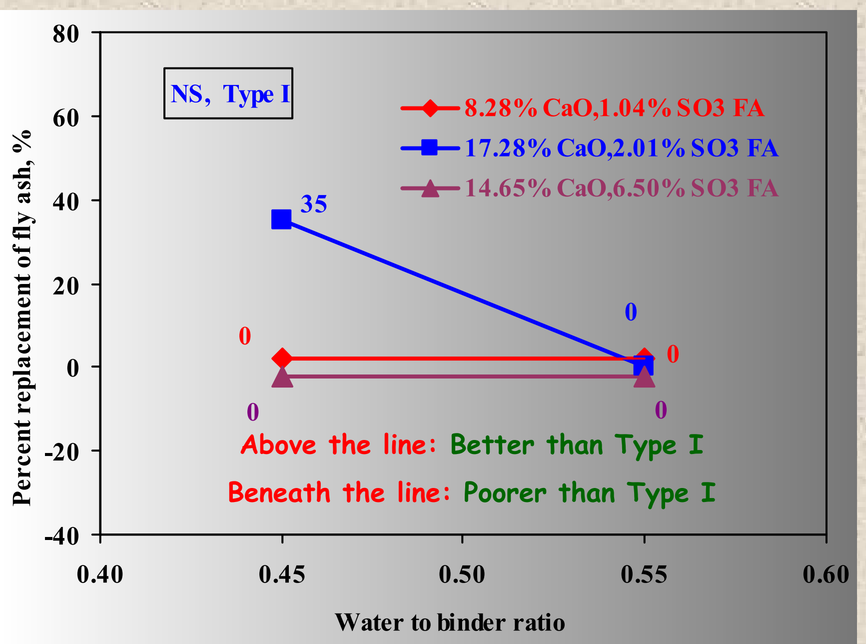
$$CH + M\underline{S} + 2H \longrightarrow C\underline{S}H_2 + MH \qquad (5)$$

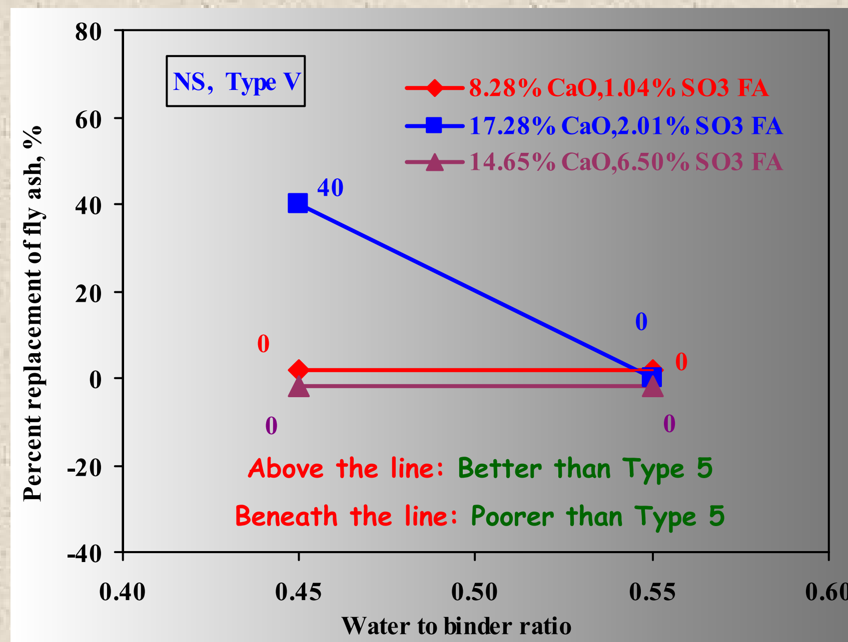
$$C_xS_yH_z + xM\underline{S} + (3x + 0.5y - z)H \longrightarrow xC\underline{S}H_2 + xMH + 0.5yS_2H \qquad (6)$$

$$4MH + SH_{11} \longrightarrow M_4SH_{8.5} + (n - 4.5)H \qquad (7)$$

Appropriate percent replacement of fly ash in sulfate environment

NS, Expansion





Conclusion

To obtain durable structures

- For New Construction
  - Good Analysis and Design (new PWCP design acts)
  - Good Materials (new TCA material spec.)
  - Good Construction (?)
  - Good Protection and Maintenance
- For Already Existing Structures*
  - Monitoring, Protection, Maintenance, Repair, Strengthening


The End
Thank you for your attention