Maintenance-Free Service Life Design of Concrete subjecting to Carbonation

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Carbonation of concrete

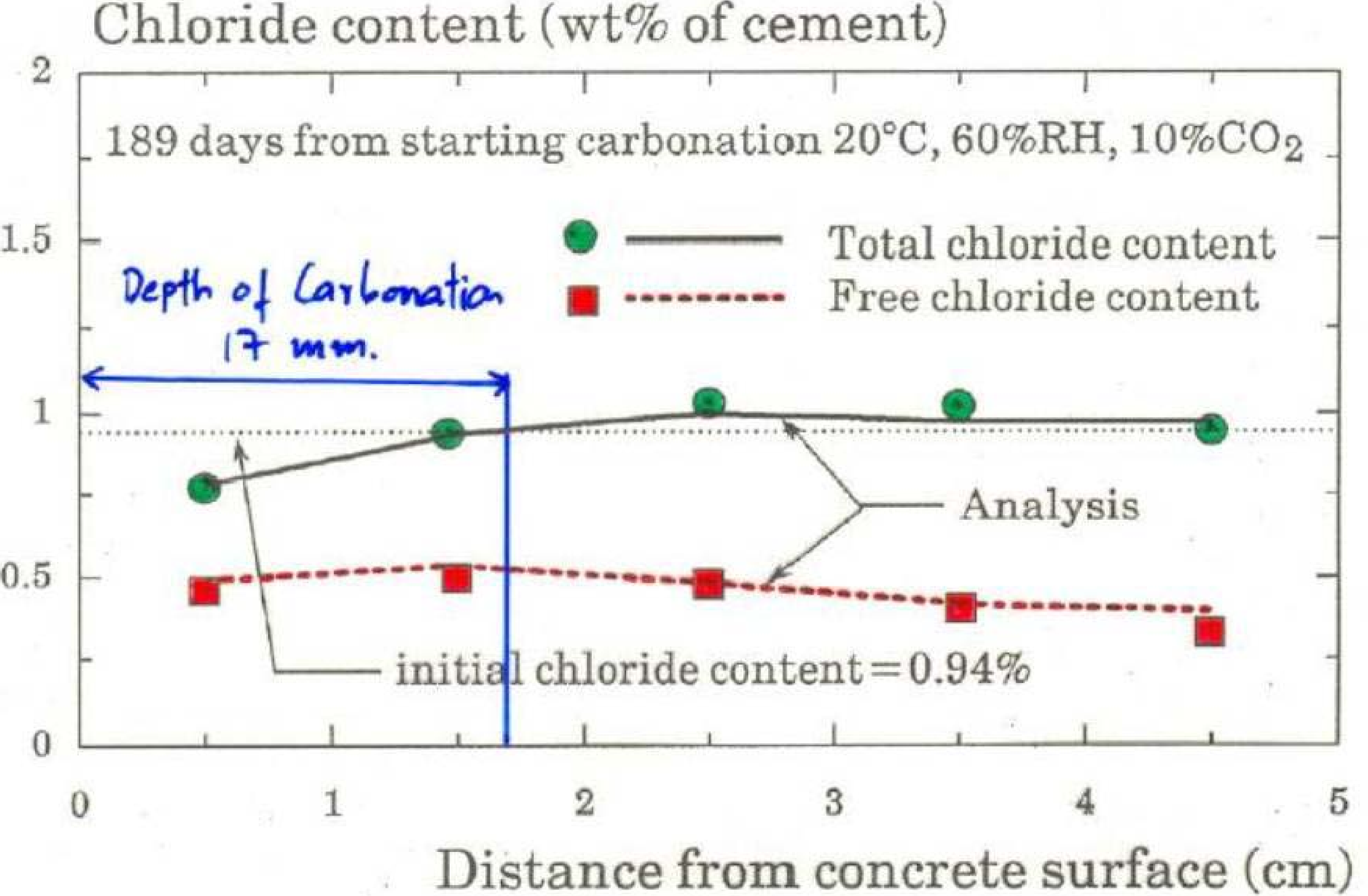
- CO_2 diffuses into concrete and react with $Ca(OH)_2$ in concrete.

$$Ca(OH)_2 + CO_2 \longrightarrow CaCO_3 + H_2O$$

- Reduces alkalinity of concrete, thus corrosion protection is destroyed.

↓

Problem in Reinforced Concrete



Effect of carbonation on chloride condensation in concrete

Situation of Carbonation Problem in Thailand

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

Thailand
Nakhon
Sawan
Sing Buri
Lop Buri
Ayutthaya
Pathum Thani
Ratchaburi
Samutprakarn
Samut
Songkhram
Bangkok
Cholburi
Gulf
of
Thailand
0
150 mi

In Bangkok

Carbonation induced steel corrosion


Carbonation induced steel corrosion



Carbonation induced steel corrosion


Steel Corrosion due to Carbonation

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

Effort toward durability design in Thailand

↓

A new Building Acts for Design of RC Structures by Department of Public Works & Urban Planning

(Enforced in 2005)

↓

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

Though, various design codes are available at present

↓

Different condition in Thailand

- Materials
- Environment
- Standard of practices

Urgently Require Tools for Durability Design

(Software/Design Charts)

To establish a suitable design to suit condition of Thailand

↓

Carbonation Model

↓

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

At SIIT, 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

Examples of Computer Software for Performance Based Analysis and Design

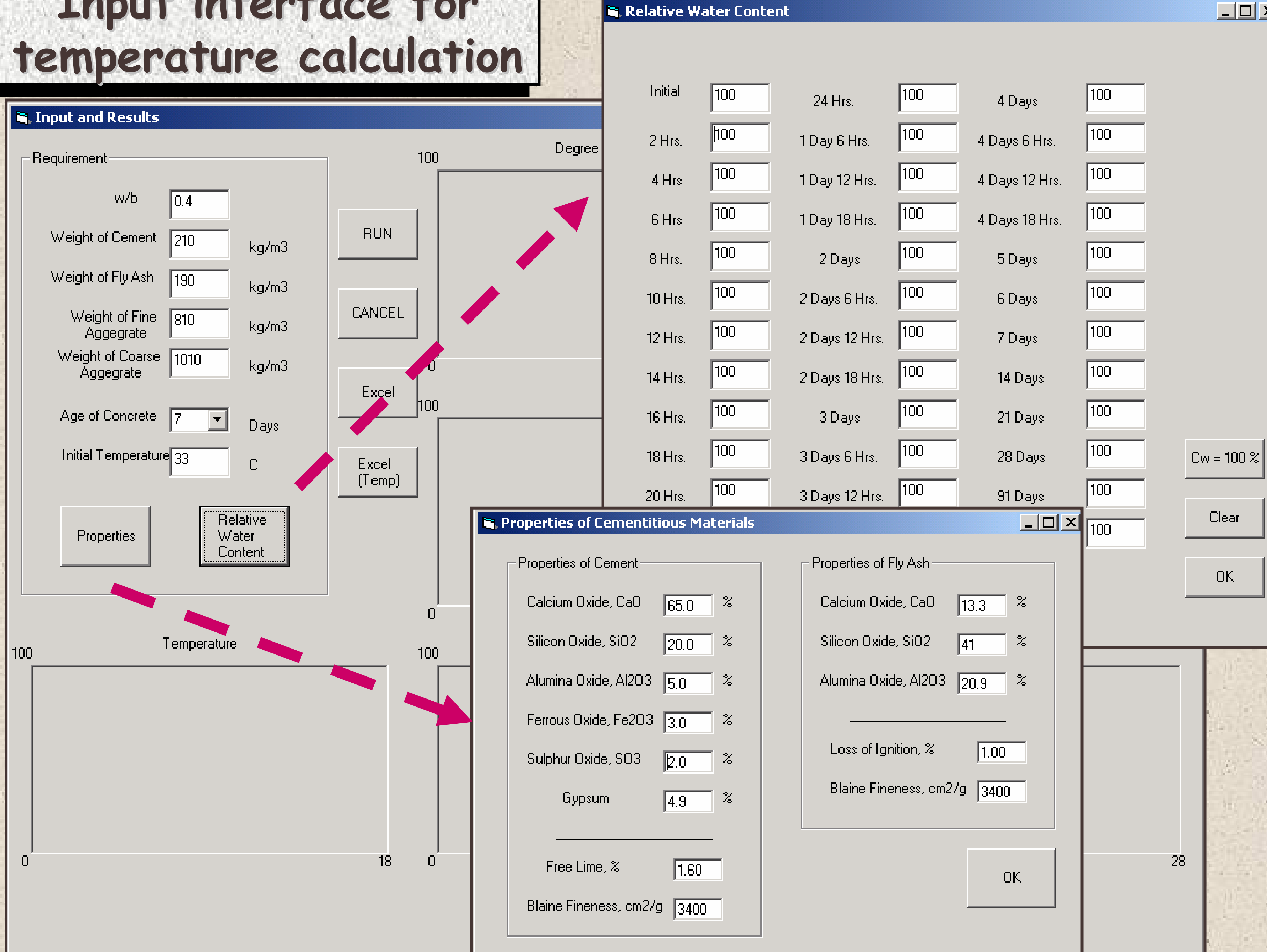
Edit Windows Help

2001

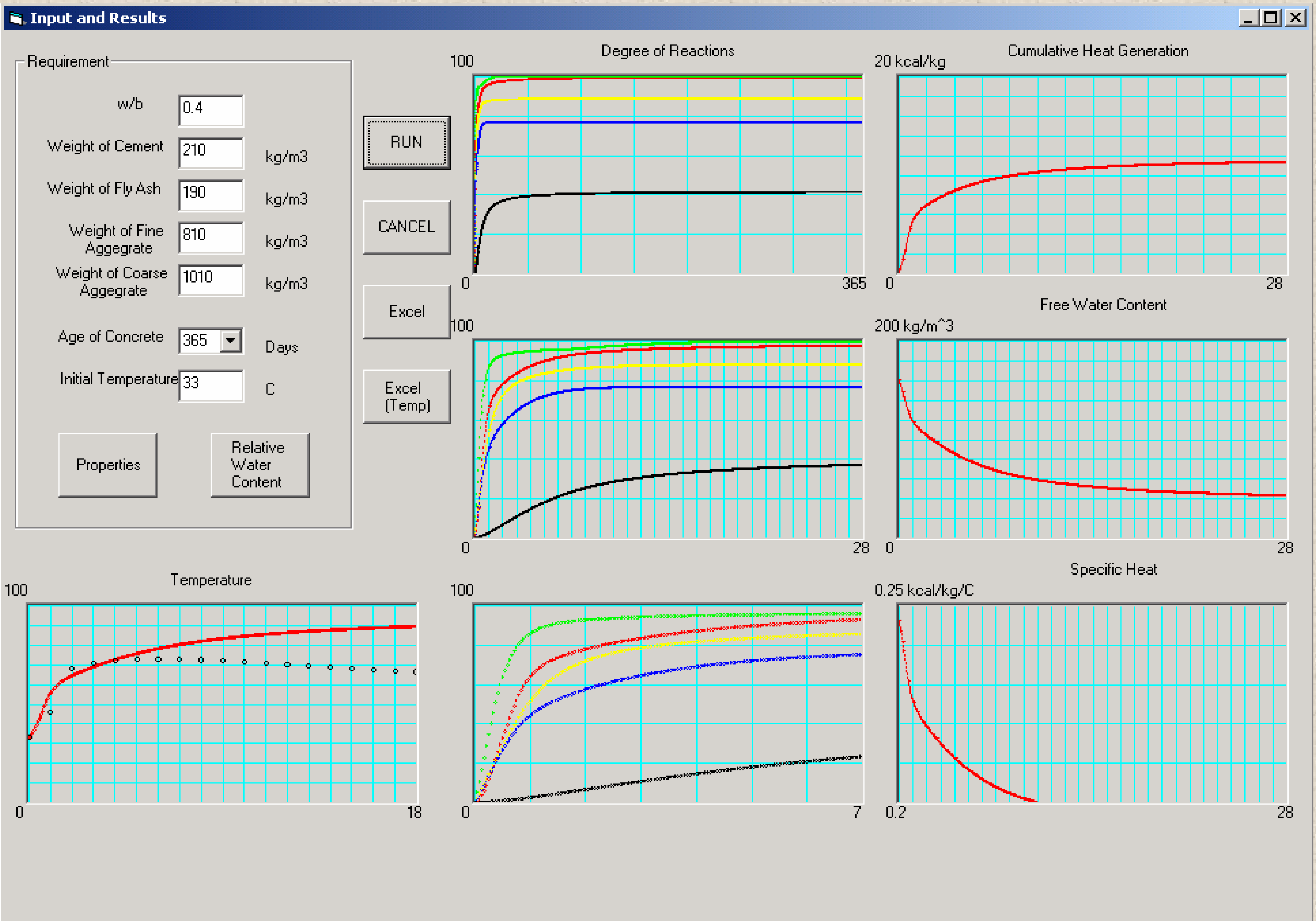
For workability and strength design

Software for Temperature Calculation in Mass Concrete

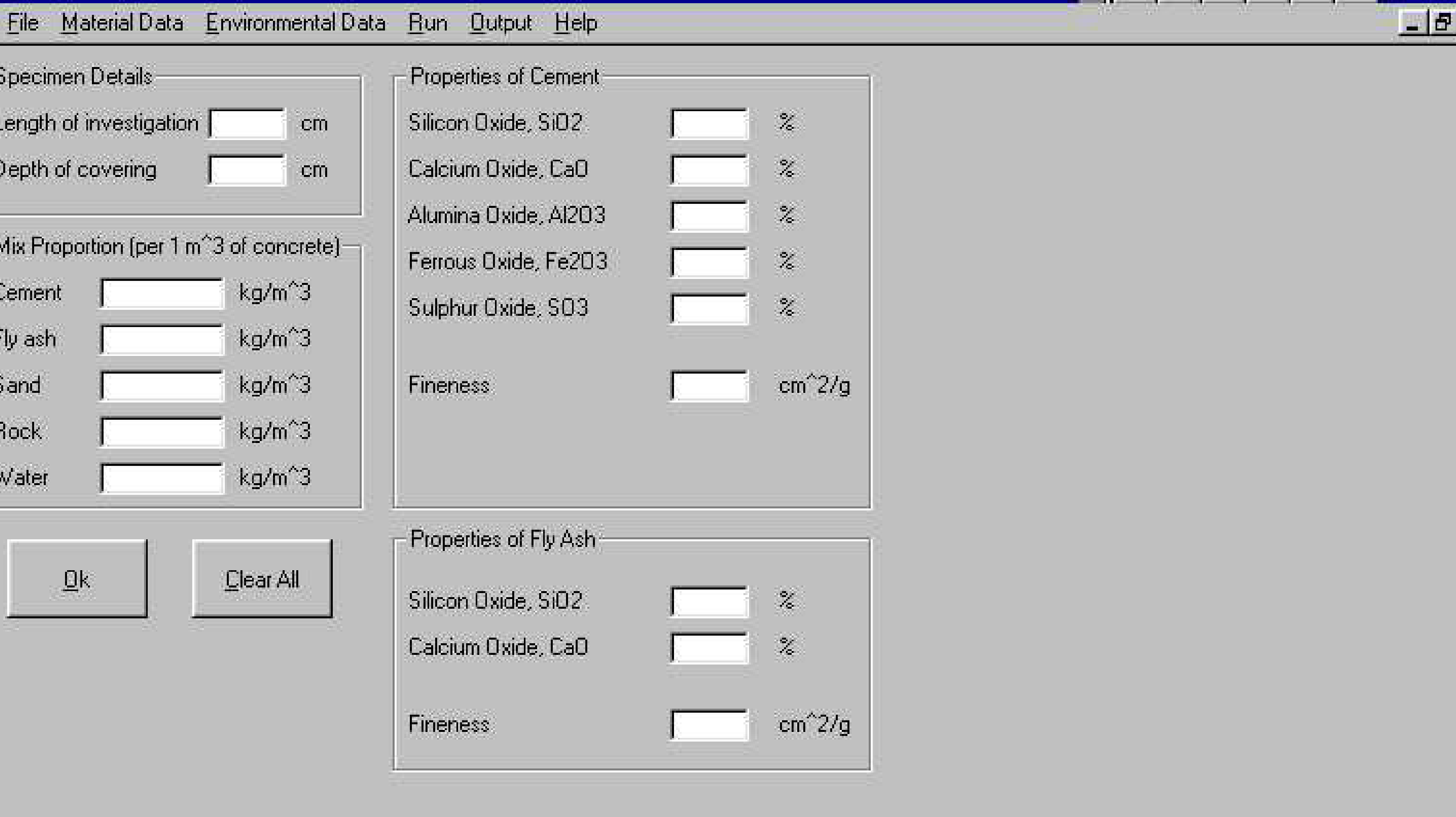
Input interface for temperature calculation



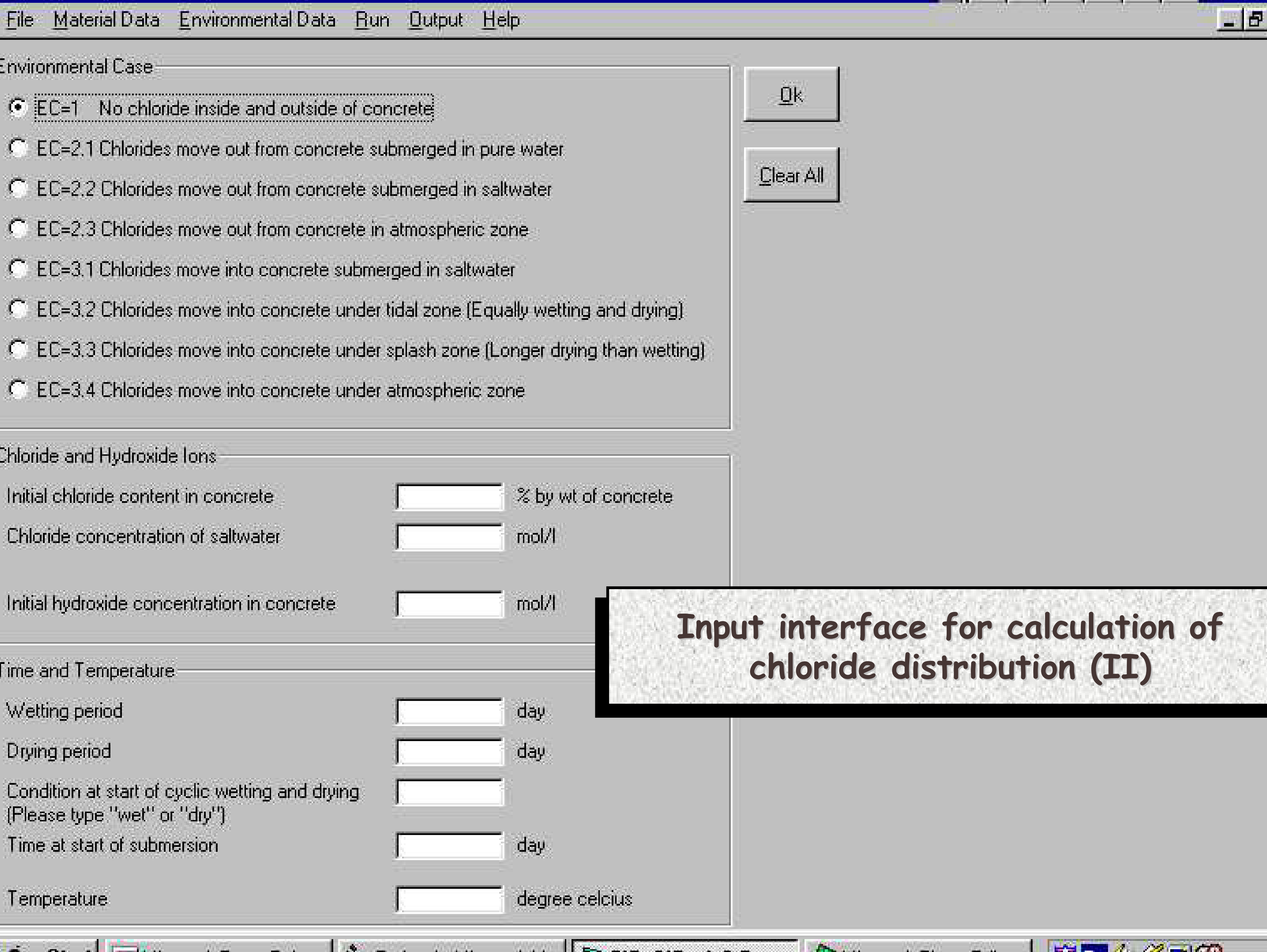
Output interface for temperature calculation



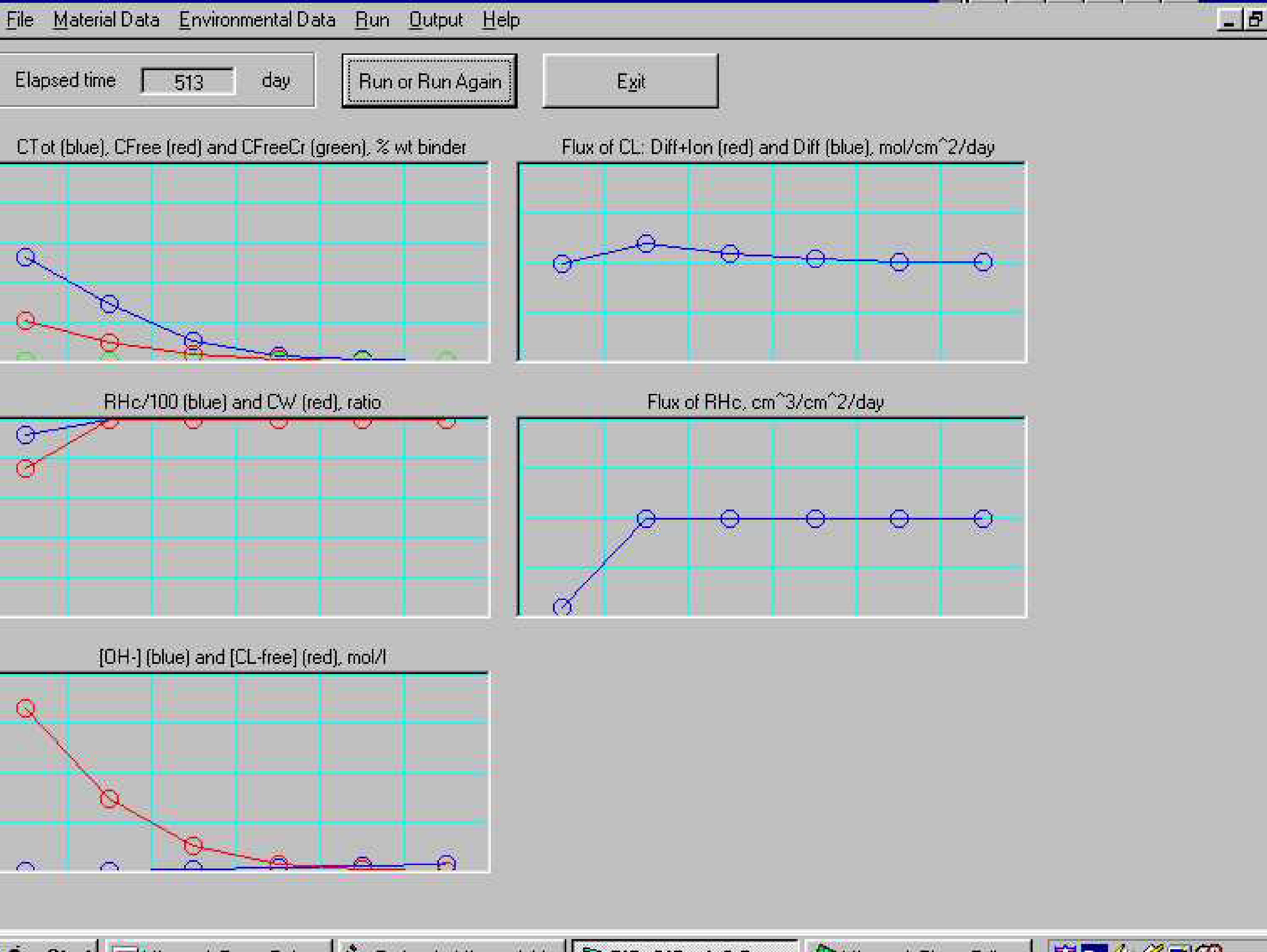
Software for Calculating Chloride Concentration in Concrete



Input interface for calculation of chloride distribution (I)

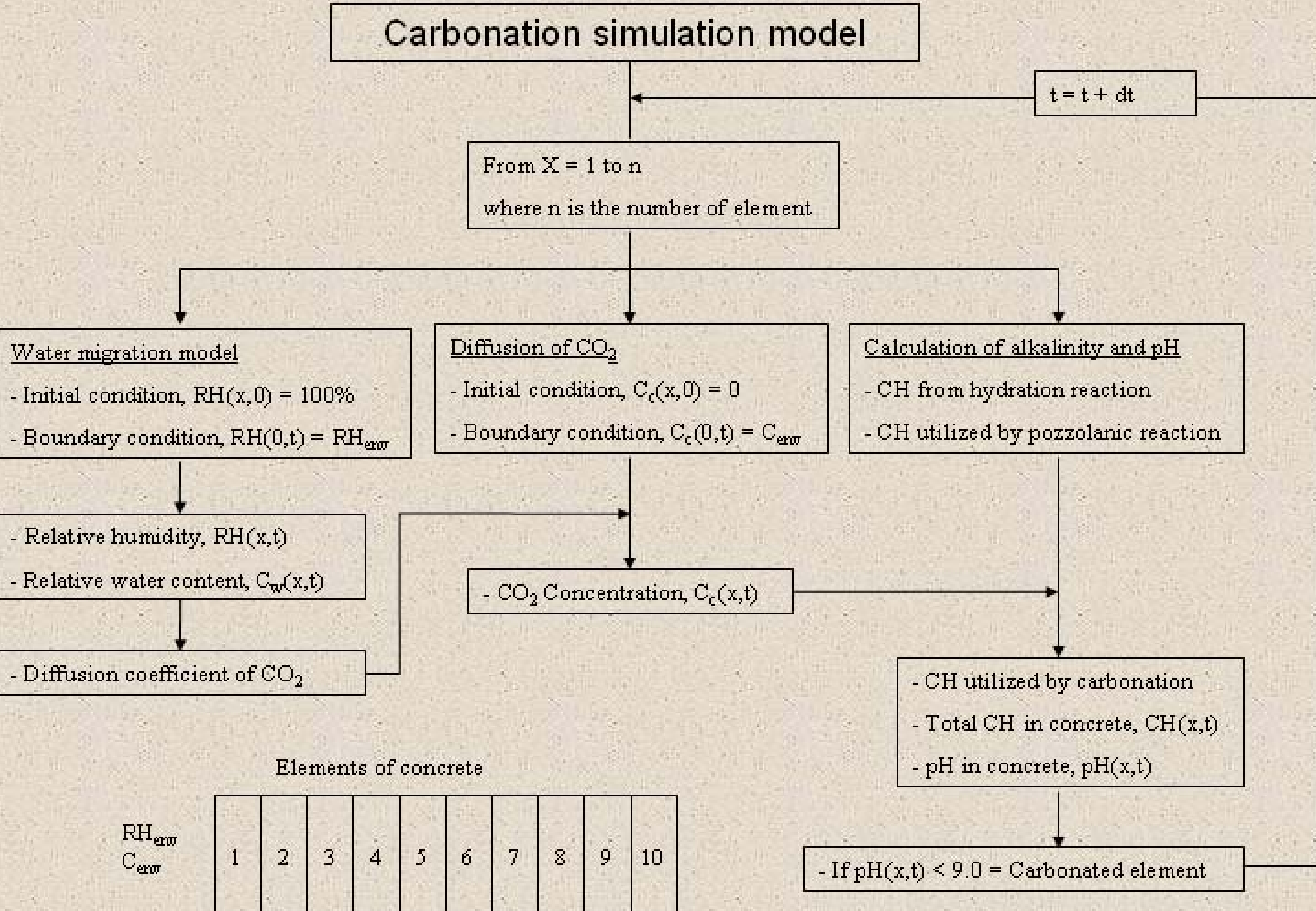


Input interface for calculation of chloride distribution (II)


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

Carbonation Simulation Model for Fly Ash Concrete

(ii) Flow chart of the model



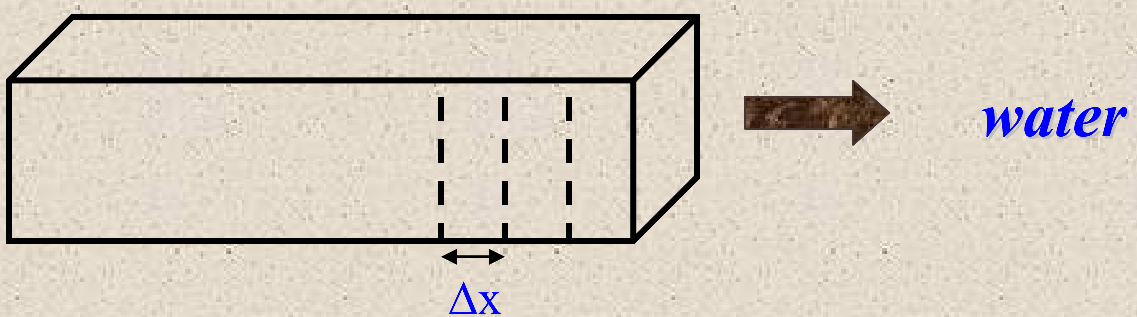
The model consists of 3 main parts

1. Water migration
2. CO_2 diffusion
3. Hydroxide generation/consumption and pH calculation

1) Water migration

(i) Model formulation

- Concrete is initially saturated with water. During drying, vapor migrates from concrete through the interconnect capillary pores, according to the gradient of vapor pressure (RH).



- **Fick's Law** →

$$\mathbf{FH(x,t) = -DH \cdot \frac{\partial RH_c(x,t)}{\partial x}}$$

(ii) Diffusion coefficient of water vapor

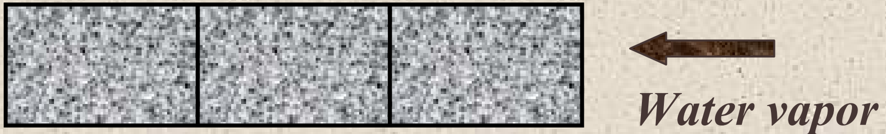
Parameter affecting DH

1. Pore characteristic of concrete
2. Water content in concrete
3. Aggregate content
4. Boundary condition

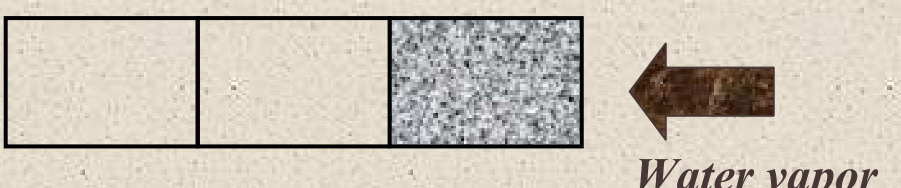
$$\mathbf{DH_0(t)} = 0.72\,\mathbf{d(t)\,n(t)}^{(1.6\mathbf{wb}-1.6)}\,\frac{\eta}{\mathbf{C_w^{0.11}(x,t)}}$$

$$\mathbf{DH_i(t)} = 0.70\,\mathbf{d(t)\,n(t)}^{(1.6\mathbf{wb}-1.6)}\,\frac{\eta}{\mathbf{C_w^{0.11}(x,t)}}$$

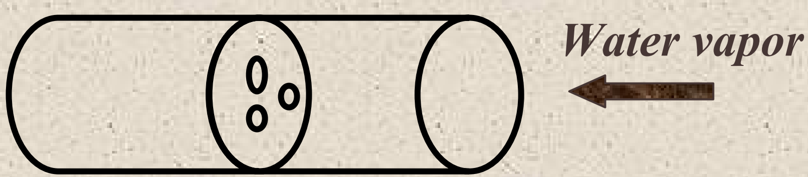
Concrete to concrete



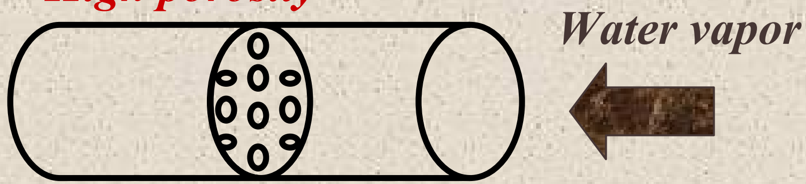
Concrete to environment



Low porosity

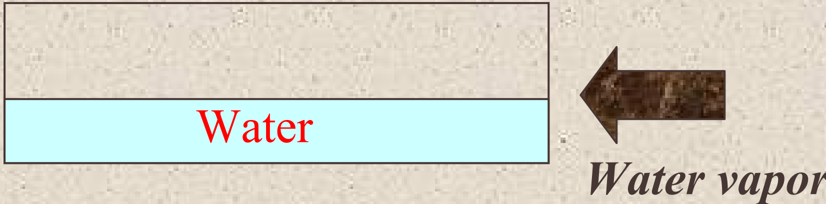


High porosity

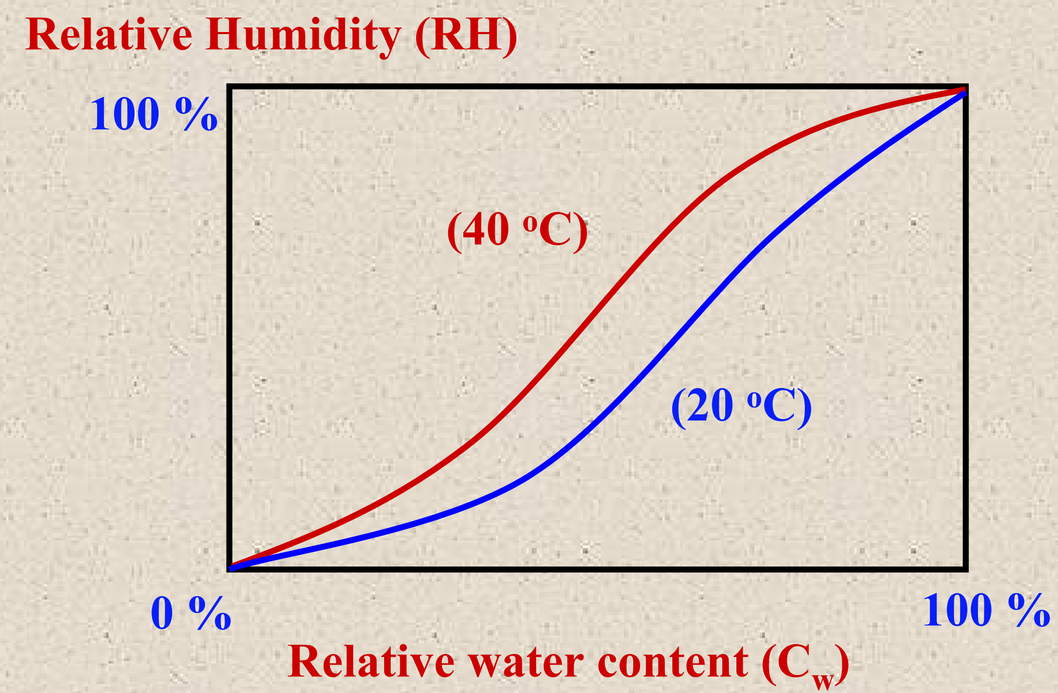


High degree of saturation in pore

Low degree of saturation in pore

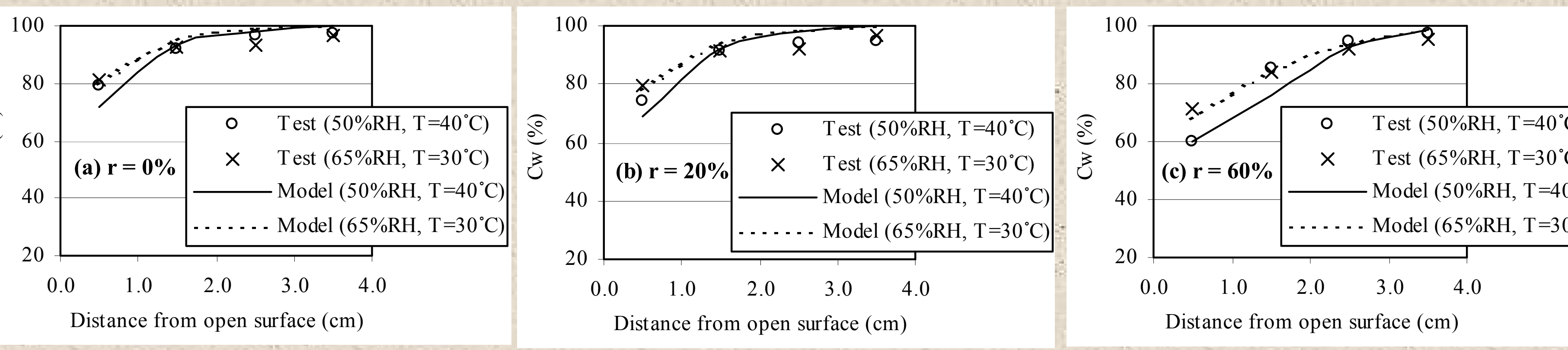


iii) State of equilibrium between liquid water and water vapor

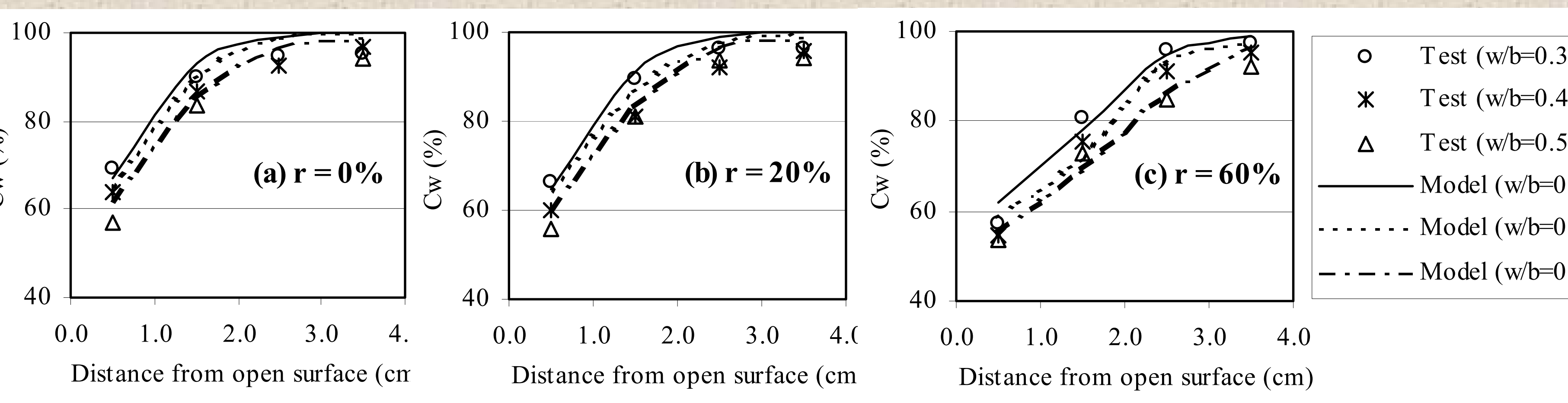


$$C_w = 100 \times \frac{W_e(x,t)}{W_{sat}(x,t)}$$

(iv) Verifications



Relative water content in pastes after drying for 28 days

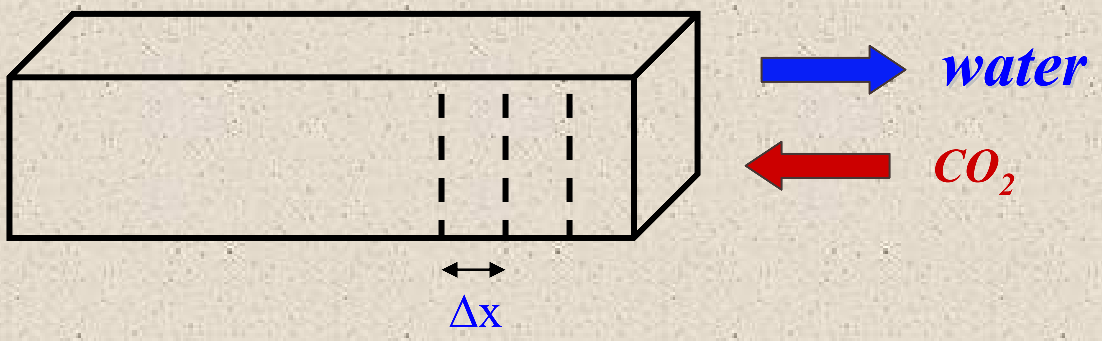


Relative water content in mortars after drying for 28 days

2) Diffusion of CO_2

(i) Model formulation

- After the migration of moisture out of concrete, CO_2 starts diffusing into concrete according to its concentration gradient.



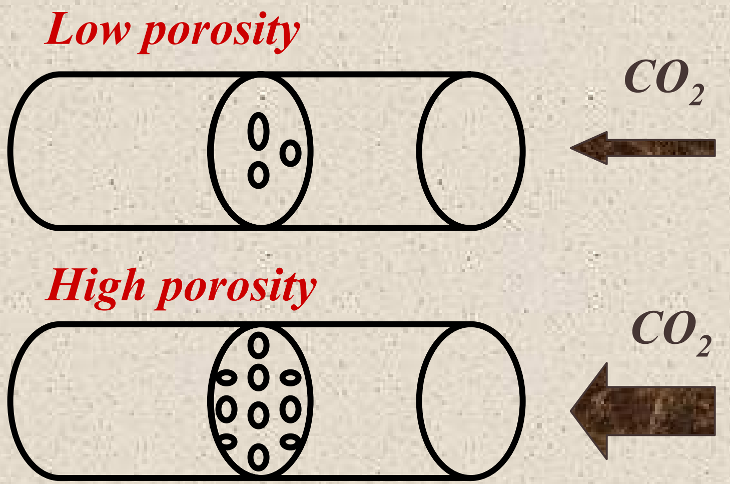
- **Fick's Law** →

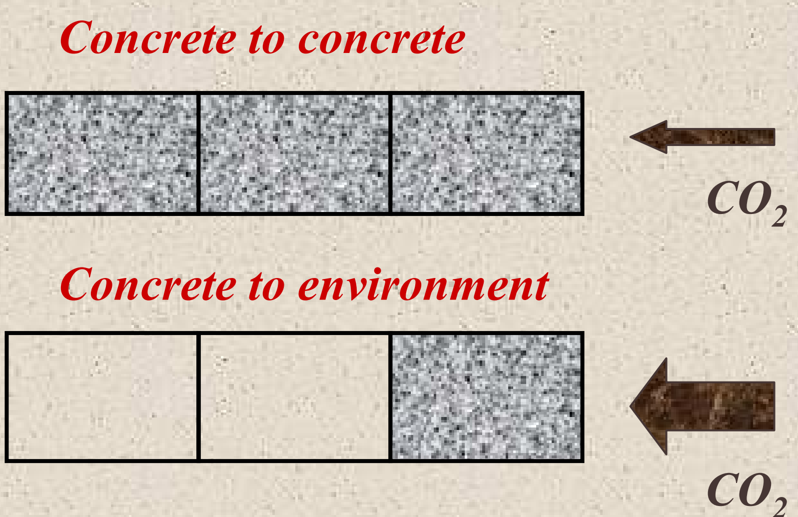
$$F_c(x,t) = -D_c \cdot \frac{\partial C(x,t)}{\partial x}$$

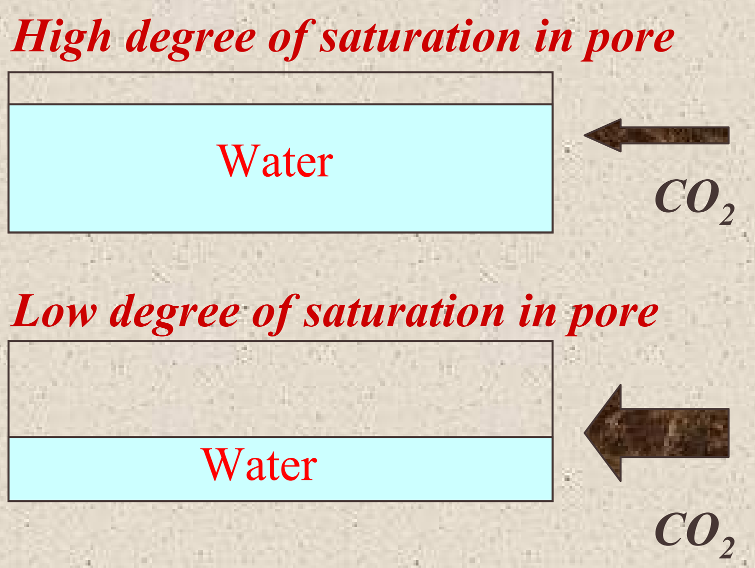
(ii) Diffusion coefficient of CO_2

<u>Parameters affecting Dc</u>

1. Pore characteristic of concrete
2. Water content in concrete
3. Aggregate content
4. Boundary condition
5. Relative humidity in pores







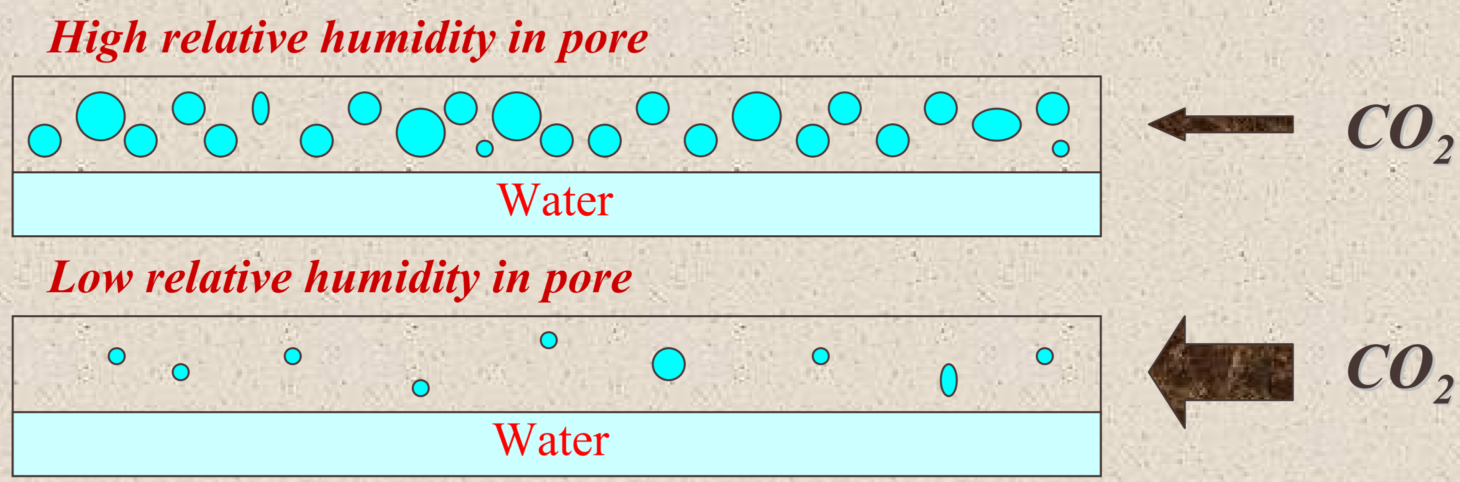
(ii) Diffusion coefficient of CO_2

<u>Parameters affecting DH</u>

1. Pore characteristic of concrete
2. Water content in concrete
3. Aggregate content
4. Boundary condition
5. **RH in pores of concrete**

$$D_{co}(1,t) = \frac{2\times10^{-7}\,\mathbf{d(t)\,n^{2}(t)}\,\eta}{\mathbf{RH(x,t)}}\left[1-\frac{\mathbf{C_{w}(x,t)}}{100}\right]$$

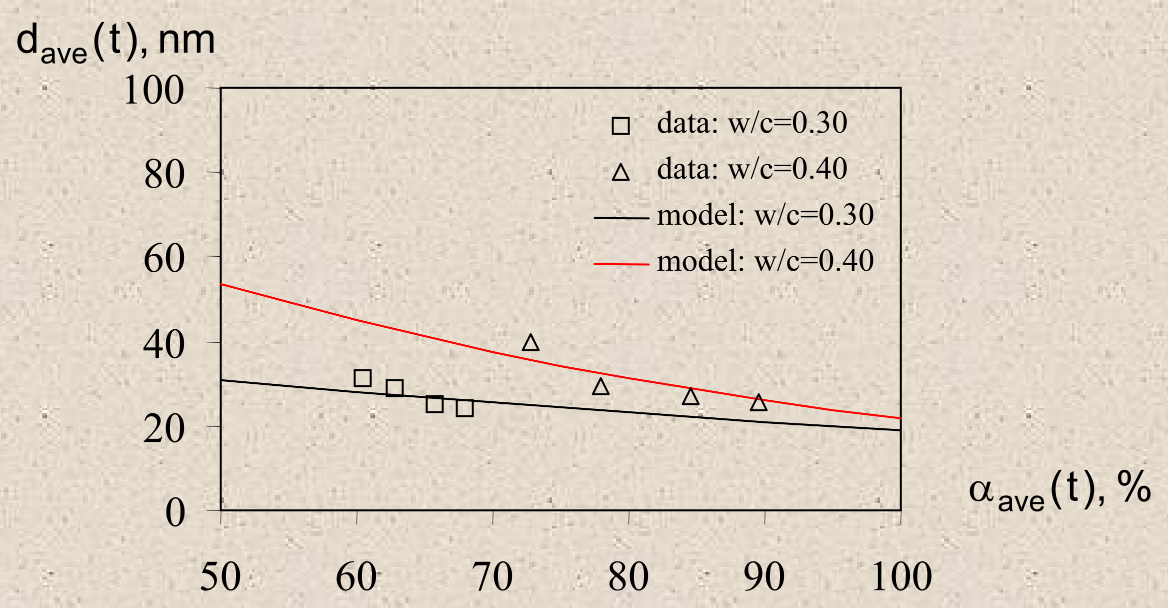
$$D_{ci}(x,t) = \frac{1\times10^{-7}\,\mathbf{d(t)\,n^{2}(t)}\,\eta}{\mathbf{RH(x,t)}}\left[1-\frac{\mathbf{C_{w}(x,t)}}{100}\right]$$



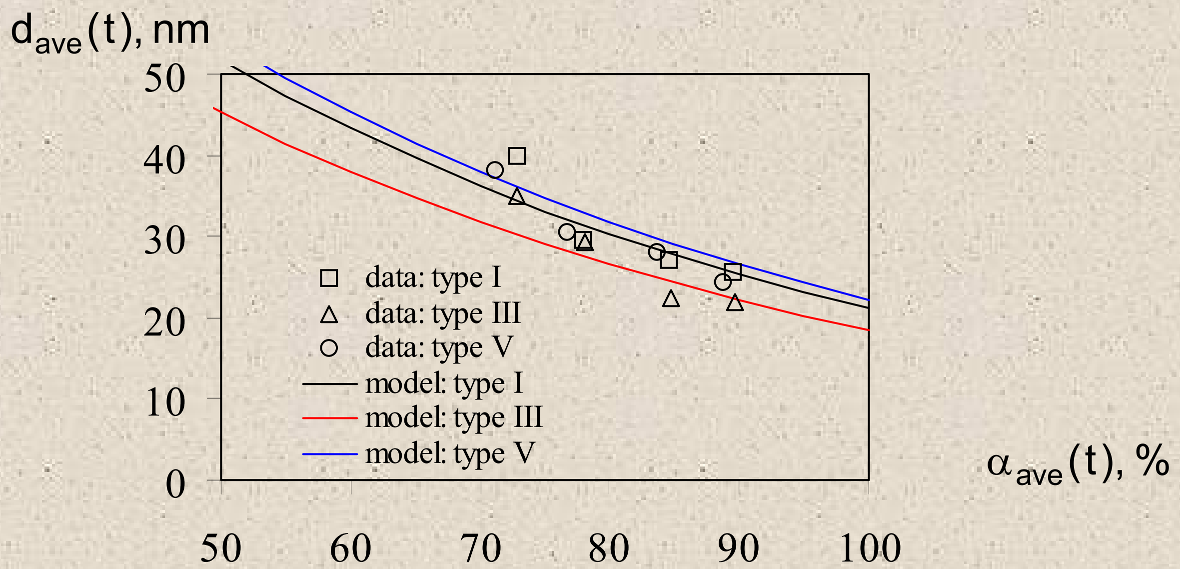
Pore Structures
(Average pore diameter and Total porosity)

Average Pore Diameter of Paste

Effect of water to cement ratio

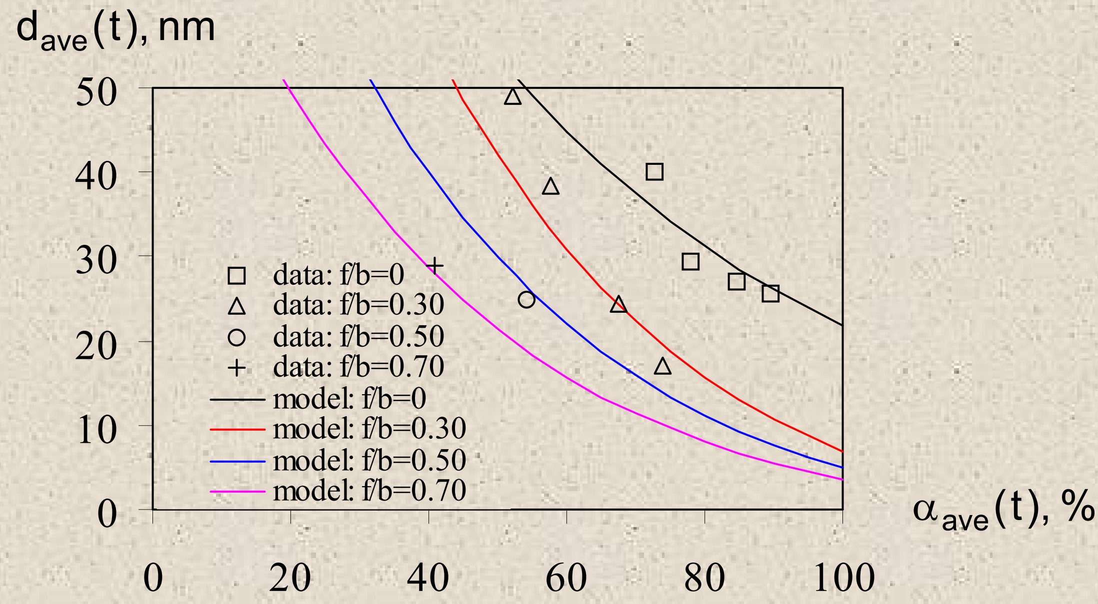


Effect of type of cement



Average Pore Diameter of Paste *(continued)*

Effect of fly ash



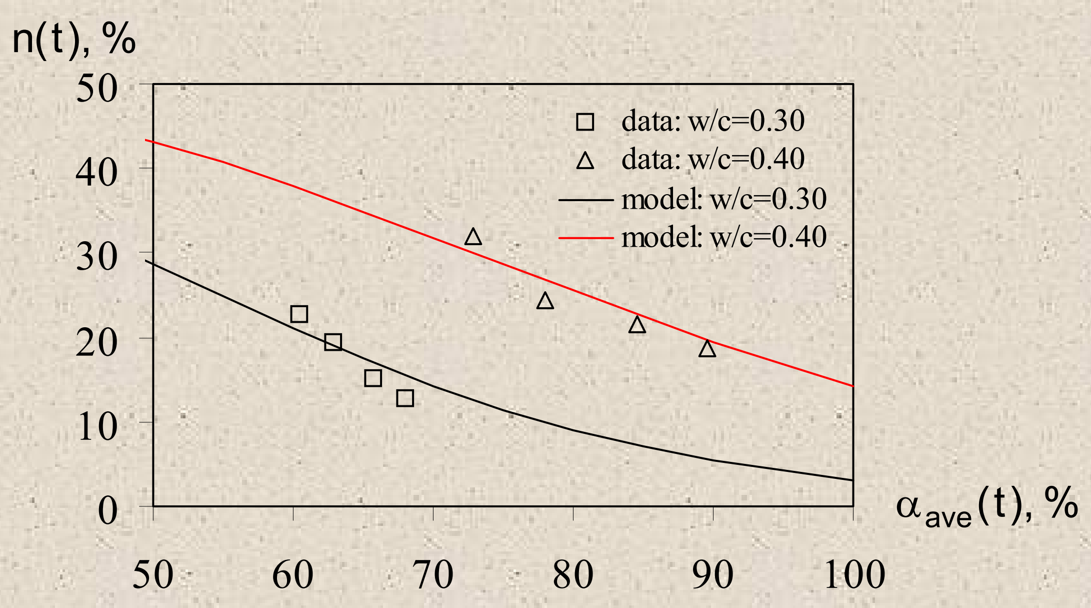
Model of average pore diameter, $d_{ave}(t)$

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

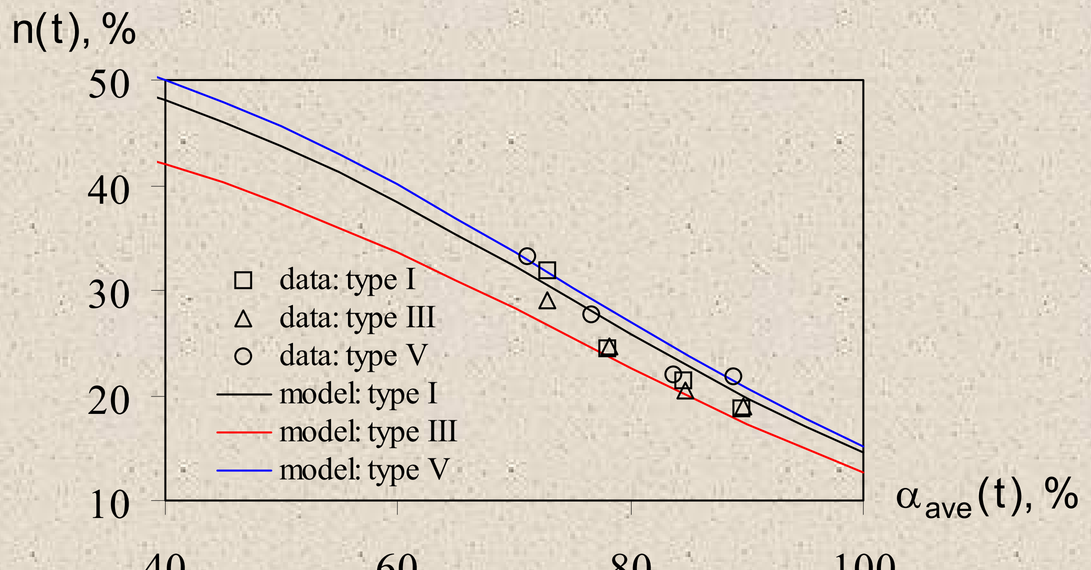
$$\times\left(1-\left(\frac{f}{b}\right)\times\left(-0.68\times\left(\frac{f}{b}\right)+1.45\right)\right)\times\left(-1.5\times\frac{\alpha_{ave}(t)}{100}+2\right)$$

Total Porosity of Paste

Effect of water to cement ratio

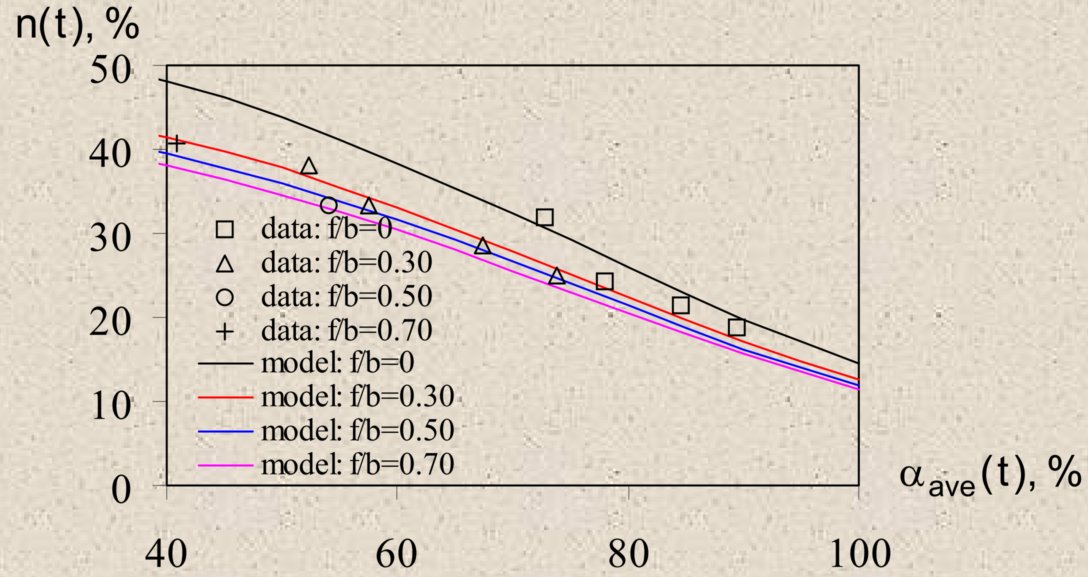


Effect of type of cement



Total Porosity of Paste *(continued)*

Effect of fly ash



Model of total porosity, n(t)

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

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

3) Calculation of CH content and pH

$$CH_t(x,t) = CH_{gh}(x,t) - CH_{cp}(x,t) - CH_{cc}(x,t)$$

Generated by hydration of cement

Consumed in pozzolanic reaction

Consumed in carbonation reaction

(i) CH generated by Hydration of Cement

- CH released from hydration reaction (C_2S and C_3S) is the main component generating alkalinity in concrete.

$$3C_3S + 6H \rightarrow CSH + 3CH$$

(100) (49)

$$2C_2S + 4H \rightarrow CSH + CH$$

(100) (22)

Amount of CH generated by hydration reaction (kg)

$$CH_{gh}(x,t) = \left[\alpha_{C3S}(t)\left(W_c\frac{\%C_3S}{100}\right)0.49 + \alpha_{C2S}(t)\left(W_c\frac{\%C_2S}{100}\right)0.22\right]A\Delta x$$

Reacted mass of C_3S

Reacted mass of C_2S

Degree of hydration of C_3S

Degree of hydration of C_2S

(ii) CH consumed by Pozzolanic Reaction of Fly Ash

- CH liberated from the hydration reaction becomes available for pozzolanic reaction.

$$3CH + 2SiO_2 \rightarrow CSH \qquad (252\text{-}100)$$

(252) (100)

- Amount of siliceous component in FA

$$CH_{cp}(x,t) = \left[\alpha_{poz}(t)\left(\phi_f W_f \frac{\%SiO_2}{100}\right)2.52\right] A\,\Delta x$$

ϕ_f: Effectiveness ratio, which is the weight fraction of the amorphous phase of SiO_2 to the total weight of SiO_2 in fly ash

* Amount of CH in non-carbonated concrete

$$CH_t(x,t) = CH_{gh}(x,t) - CH_{cp}(x,t)$$

(iii) Carbonation reaction and its reaction rate

- CO_2 and CH dissolve and enter the reaction process.

- Concentration of CH in pore water (solubility of CH)

$$[CH](x,t) = \frac{CH_t(x,t)}{V_w(x,t)} \cdot \frac{1000}{74} \quad ; \quad V_w(x,t) = \left[\frac{C_w(x,t)}{100} \cdot \frac{n(t)}{100} \right] A \Delta x$$

Volume of pore water (V_w)

Molecular weight of CH (74)

However, the solubility of CH in water is very low. The saturated molar concentration of CH in water is 25 and 10 mol/m^3 at 0°C and 100°C, respectively. Therefore, [CH] is limited by its concentration at saturated state.

Concentration of CO_2 in pore water

Assumption : Rate of dissolution of gas in the pore water follows the Henry's law and ideal gas law.

Henry's constant

Gas pressure in pores

$$[CO_2] = H \cdot P_x$$

$$P_x = \frac{n}{V} RT = CRT$$

$$[CO_2](x,t) = HRTC(x,t)$$

* Rate of CH reduction

Rate of carbonation reaction

$$r_c(x,t) = k_c \cdot [CH](x,t) \cdot [CO_2](x,t)$$

Rate of reduction of dissolved CH in the considered element x

- Rate of Carbonation Reaction

Rate of reaction was formulated based on Arrhenious' law.

$$k_c = \beta \exp\left[\frac{E_0}{RT}\right]$$

$\beta = 1.2\times10^8$ mol/m^3/day, E_0 = 40000 j/mol

* Amount of dissolved CH in pores of carbonated concrete

$$CH_t'(x,t) = CH_t(x,t) - 74\, W_e(x,t) \times \int_0^t r_c(x,t)\,dt$$

(iv) pH in pore solution

- The soluble part of CH in water is completely ionized because CH is categorized as a strong base.

$$CH \rightarrow Ca_2^{2+} + 2OH^-$$

- Concentration of OH^- in pore solution

$$[OH](x,t) = 2 \times [CH'](x,t)$$

* pH in pore solution of concrete

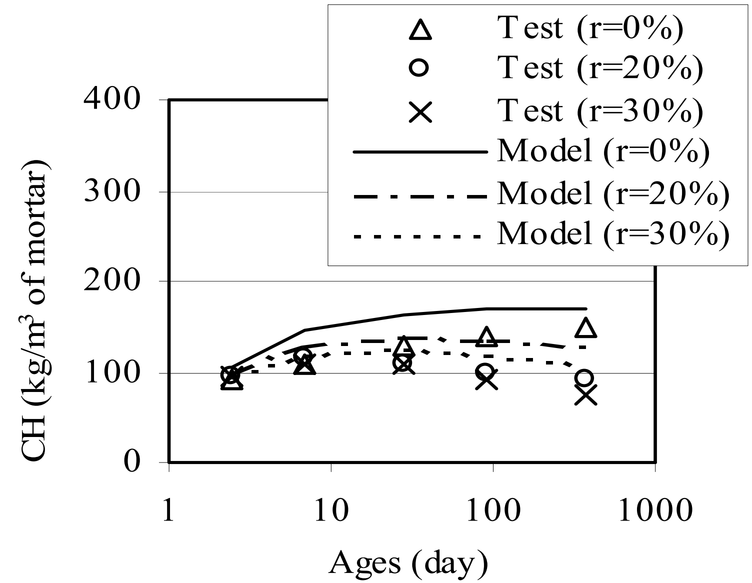
$$pH(x,t) = 14 + \log\left([OH](x,t)\right)$$

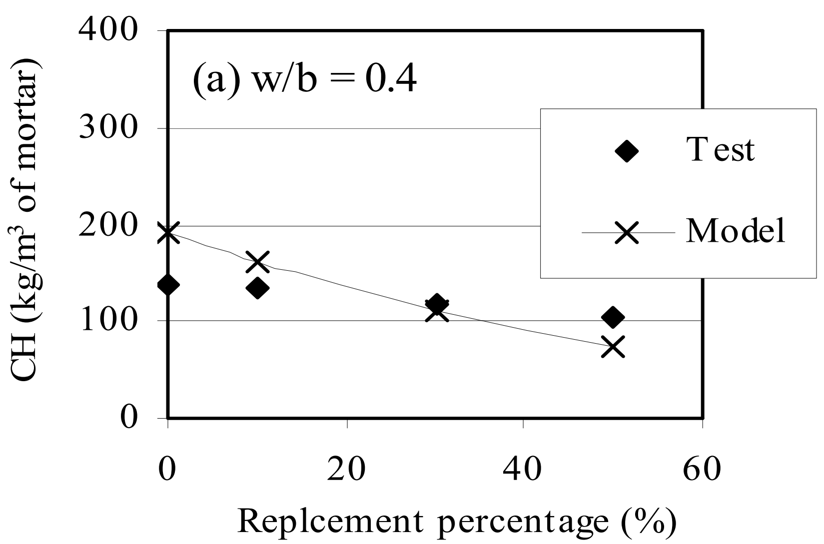
4) Verifications

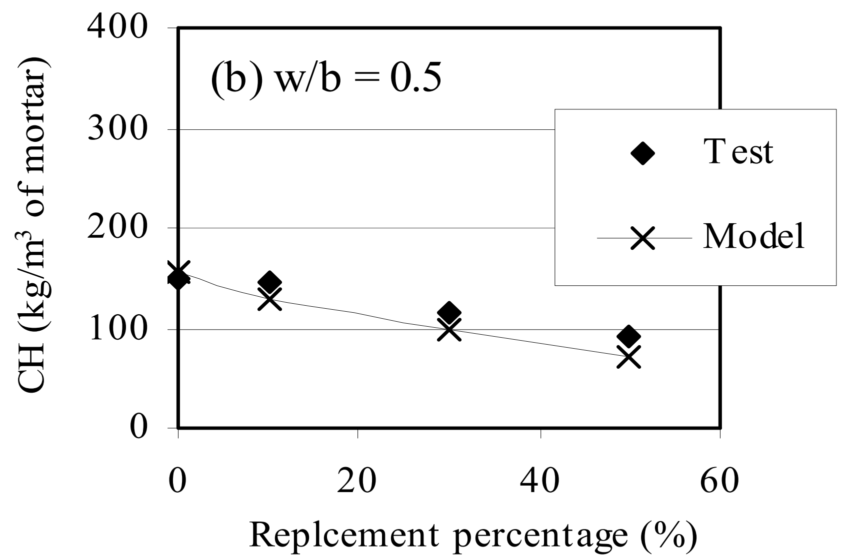
(i) Verification of CH

CH in mortar specimens (Papadakis's data)

: w/b = 0.5 and A/B = 3.0







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

γ	w/b	%r	K
Concrete with FA1 in city indoor condition			
1.2	0.50	0	0.62
1.2	0.50	10	0.69
1.2	0.50	30	1.27
1.2	0.50	50	1.69
1.2	0.60	0	1.17
1.2	0.60	10	1.13
1.2	0.60	30	1.64
1.2	0.60	50	2.72
1.4	0.40	0	0.29
1.4	0.40	10	0.32
1.4	0.40	30	0.66
1.4	0.40	50	1.07
1.4	0.50	0	0.63
1.4	0.50	10	0.78
1.4	0.50	30	1.23
1.4	0.5	50	1.83
1.4	0.50	0	1.01
1.4	0.50	10	1.22
1.4	0.50	30	1.64
1.4	0.50	50	2.54
1.4	0.60	0	0.62
1.4	0.60	10	0.69
1.4	0.60	30	1.27
1.4	0.60	50	1.69

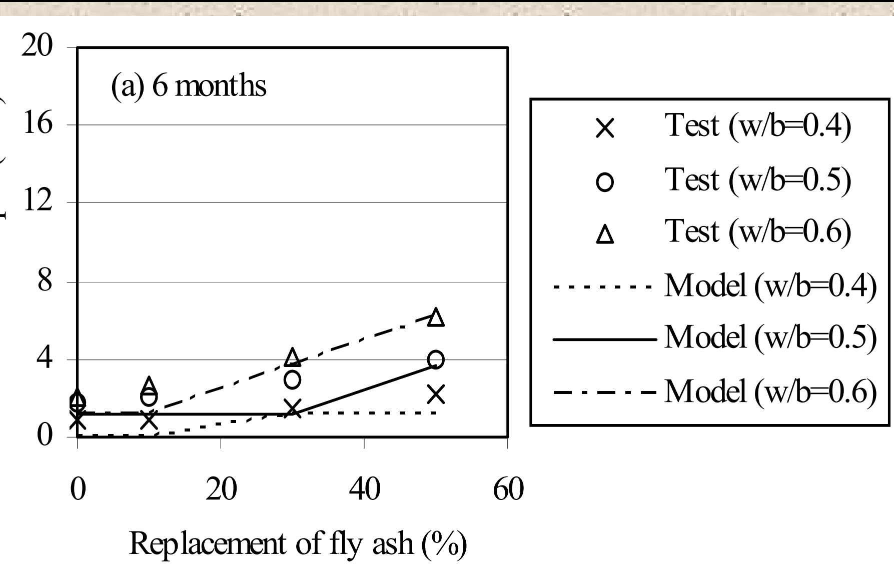
γ	w/b	%r	K
Concrete with FA2 in city indoor condition			
1.2	0.50	0	0.62
1.2	0.50	10	0.64
1.2	0.50	30	1.08
1.2	0.50	50	1.51
1.2	0.60	0	1.17
1.2	0.60	10	1.26
1.2	0.60	30	1.67
1.2	0.60	50	2.26
1.4	0.40	0	0.29
1.4	0.40	10	0.31
1.4	0.40	30	0.58
1.4	0.40	50	0.80
1.4	0.50	0	0.63
1.4	0.50	10	0.71
1.4	0.50	30	0.92
1.4	0.5	50	1.62
1.4	0.50	0	1.01
1.4	0.50	10	1.18
1.4	0.50	30	1.49
1.4	0.50	50	2.15
1.4	0.60	0	0.62
1.4	0.60	10	0.64
1.4	0.60	30	1.08
1.4	0.60	50	1.51

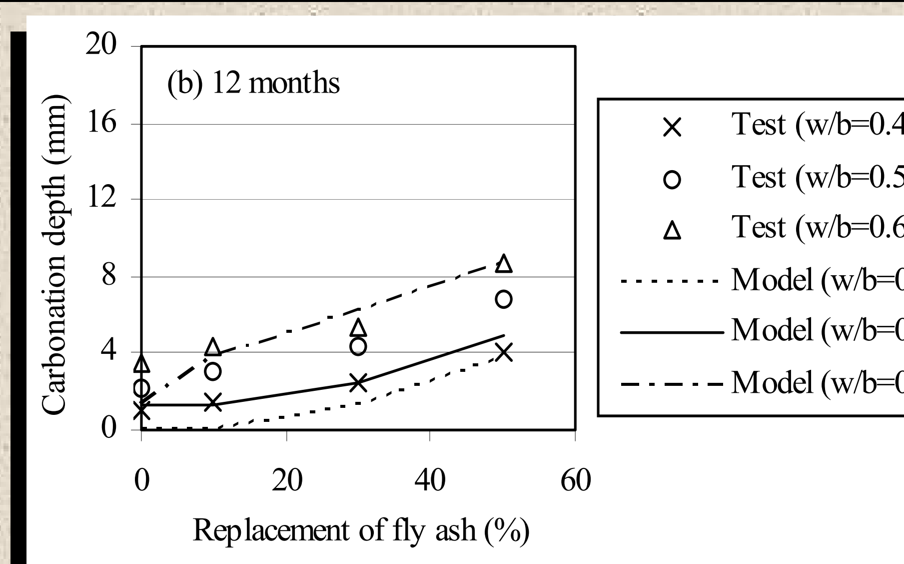
γ	w/b	%r	K
City outdoor condition (FA1)			
1.2	0.50	0	0.49
1.2	0.50	10	0.65
1.2	0.50	30	1.13
1.2	0.50	50	1.50
1.4	0.50	0	0.50
1.4	0.50	10	0.68
1.4	0.50	30	1.13
1.4	0.50	50	1.56
Rural condition (FA1)			
1.2	0.50	0	0.38
1.2	0.50	10	0.48
1.2	0.50	30	0.86
1.2	0.50	50	1.21
1.2	0.60	0	0.66
1.2	0.60	10	0.69
1.2	0.60	30	1.06
1.2	0.60	50	2.15
Seaside condition (FA1)			
1.2	0.50	0	0.30
1.2	0.50	10	0.36
1.2	0.50	30	0.82
1.2	0.50	50	1.08
1.2	0.60	0	0.57
1.2	0.60	10	0.70
1.2	0.60	30	1.05
1.2	0.60	50	2.18

No.	Carbonation depth (mm) of mortar exposed for						K
	1 month	3 months	6 months	12 months	18 months	24 months	
Mortar made with FA1							
M1	0.40	0.83	1.20	2.00	2.58	3.08	0.59
M2	0.50	1.17	1.40	2.00	2.60	3.17	0.62
M3	0.83	2.07	2.83	3.17	4.33	4.50	1.00
M4	1.60	3.93	5.67	7.50	10.00	11.50	2.31
M5	0.17	0.30	0.70	0.92	1.08	1.25	0.25
M6	0.30	0.73	1.00	1.50	1.67	1.67	0.38
M7	0.37	1.27	1.47	2.00	2.50	3.00	0.61
M8	0.60	2.07	3.17	4.50	6.00	6.50	1.35
M9	0.38	0.88	1.40	1.83	2.75	2.92	0.59
M10	0.73	1.43	1.77	2.67	3.33	3.50	0.76
M11	0.97	2.23	2.80	3.67	4.83	5.67	1.15
M12	1.87	3.93	5.40	6.83	8.83	10.67	2.13
Mortar made with FA2							
M13	0.40	0.83	1.20	2.00	2.58	3.08	0.59
M14	0.27	1.17	1.30	2.17	2.50	2.83	0.59
M15	0.73	2.17	2.53	3.17	5.17	5.00	1.04
M16	1.50	3.50	5.13	6.33	9.67	11.17	2.14
M17	0.17	0.30	0.70	0.92	1.08	1.25	0.25
M18	0.27	0.50	1.00	1.33	1.33	2.00	0.37
M19	0.33	1.17	1.40	1.83	2.57	2.50	0.55
M20	0.93	2.00	3.17	4.33	5.73	6.50	1.30
M21	0.38	0.88	1.40	1.83	2.75	2.92	0.59
M22	0.53	1.40	1.70	2.50	3.17	3.33	0.70
M23	0.90	1.83	2.77	3.33	4.83	5.33	1.07
M24	1.17	3.67	5.10	6.67	8.67	11.00	2.08

(ii) Verification of carbonation depth (natural environment)

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



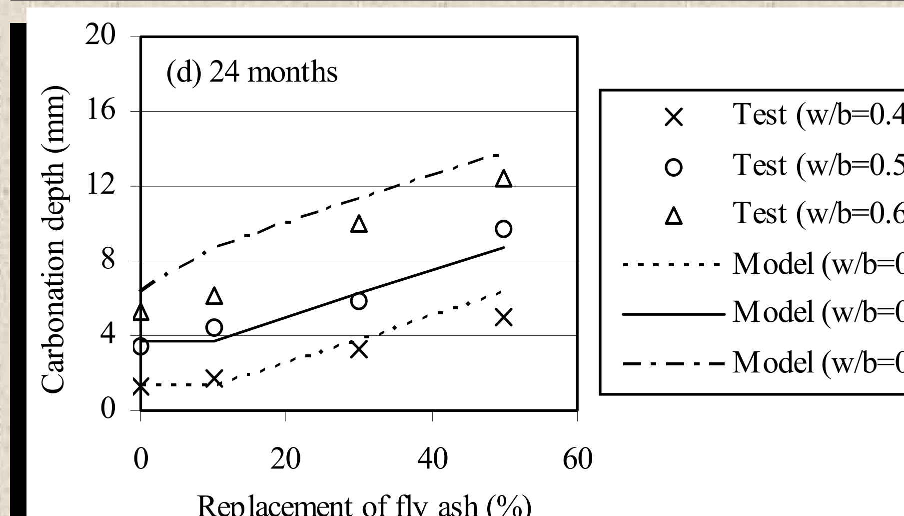


City-sheltered

Average CO_2 concentration = 650 ppm.

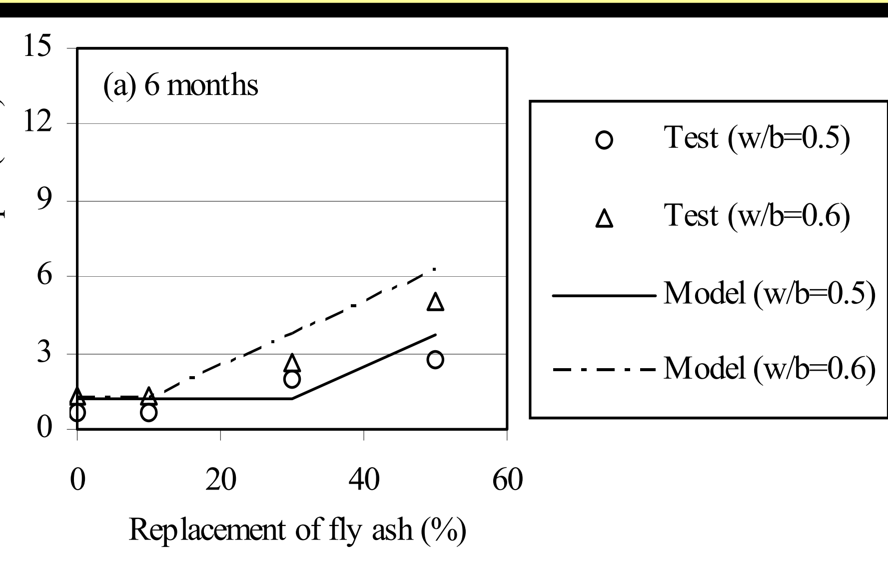
Average relative humidity = 72.5%

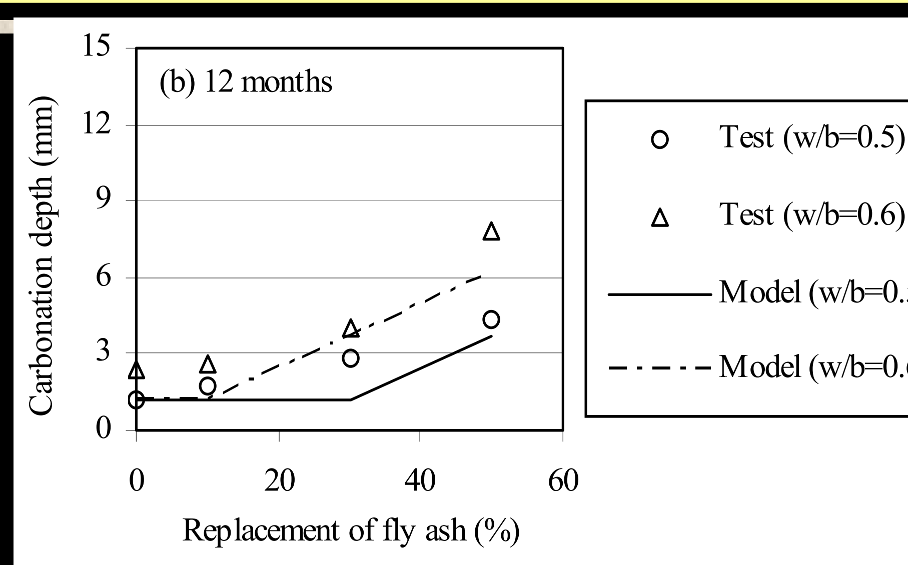
Average temperature = 28.9 °C



(ii) Verification of carbonation depth (natural environment)

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



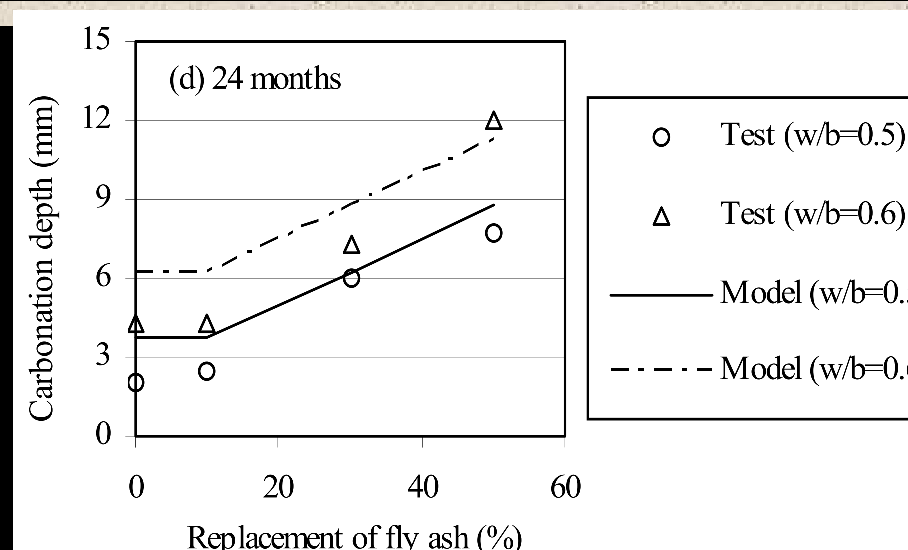


City-non-sheltered

Average CO_2 concentration = 650 ppm.

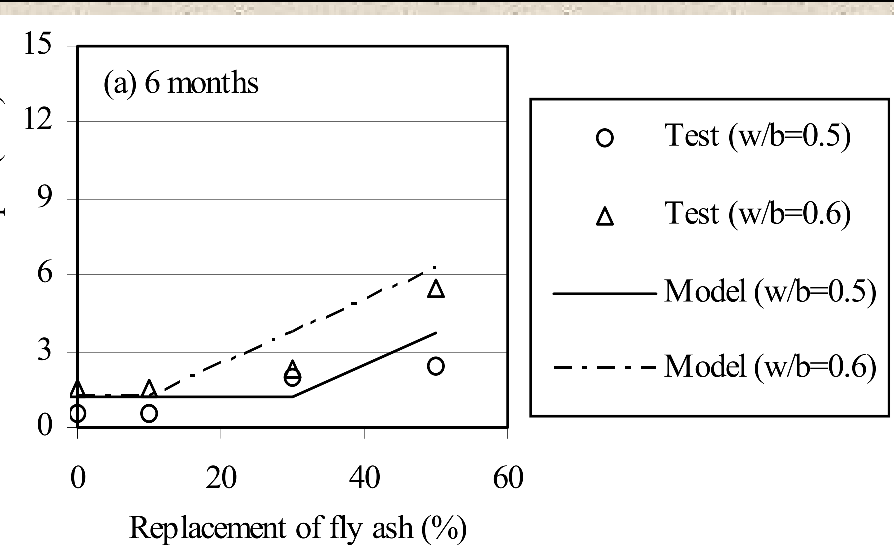
Average relative humidity = 83%

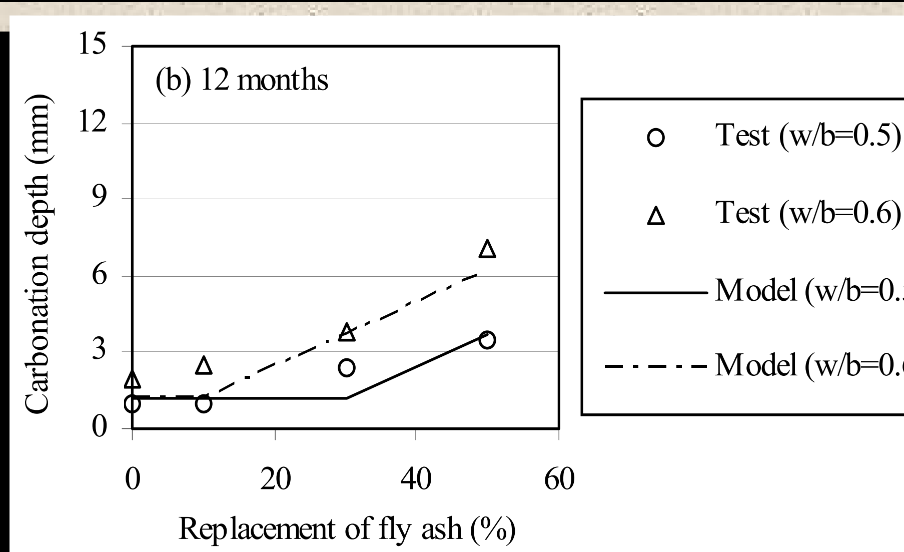
Average temperature = 28.9 °C



(ii) Verification of carbonation depth (natural environment)

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



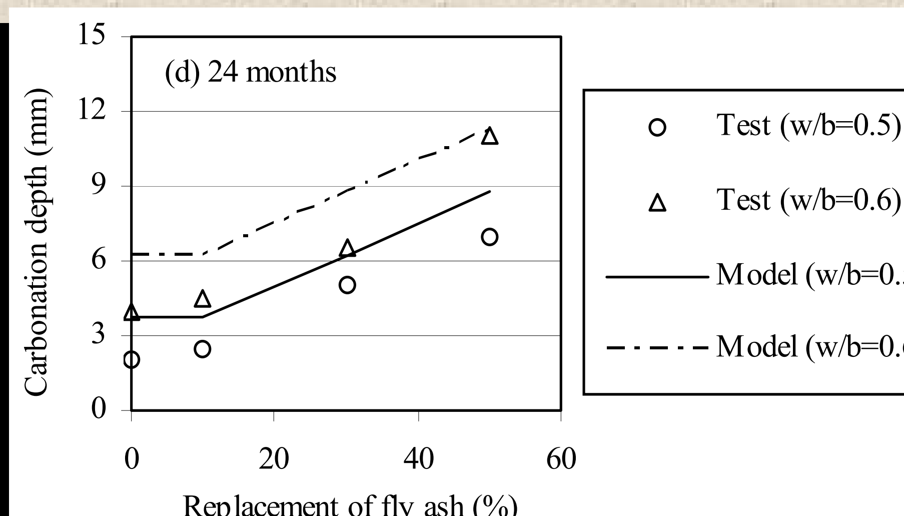


ural-sheltered

verage CO_2 concentration = 300 ppm.

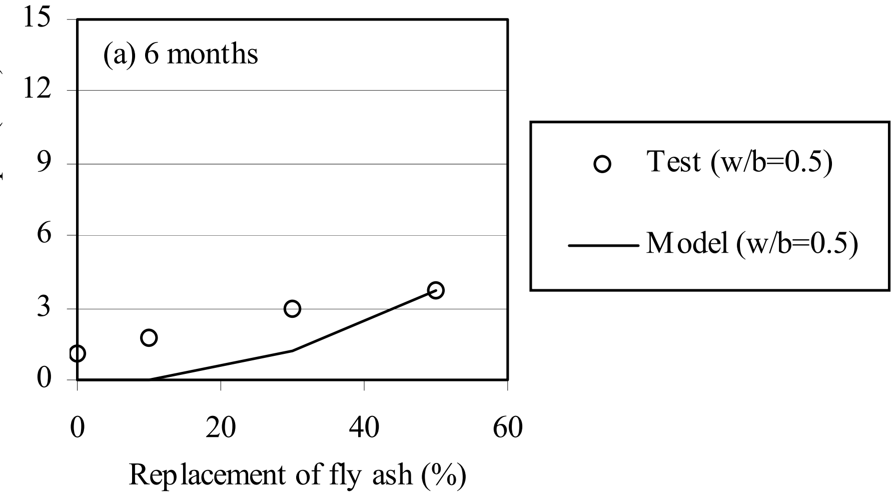
verage relative humidity = 80%

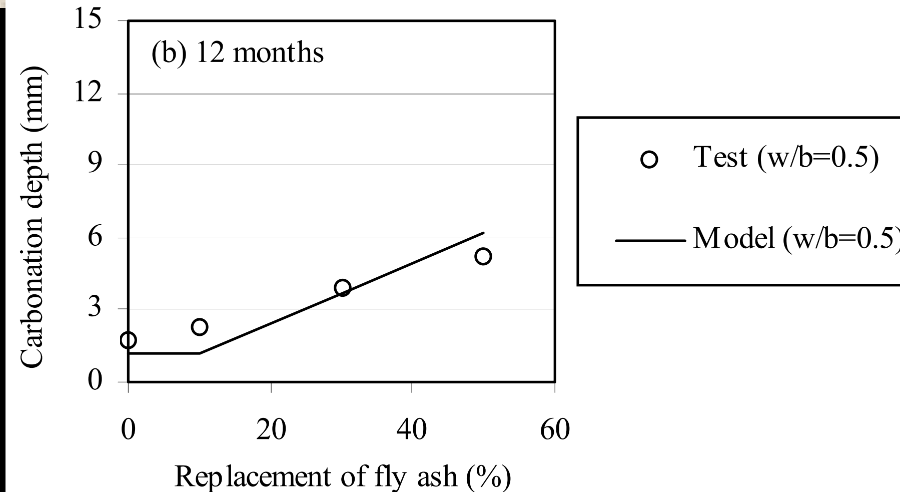
verage temperature = 28.1 °C



(ii) Verification of carbonation depth (natural environment)

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



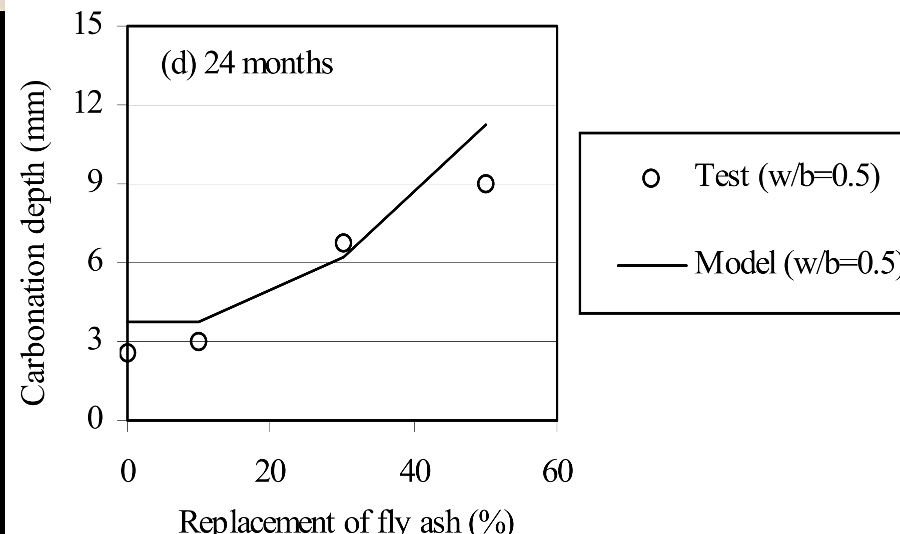


Seaside-sheltered

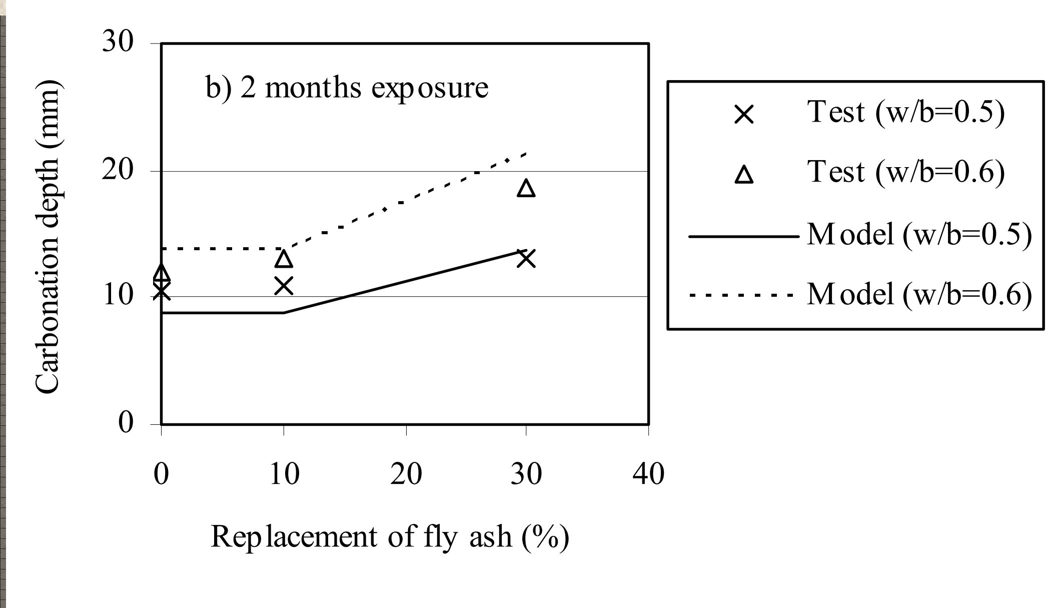
Average CO_2 concentration = 225 ppm.

Average relative humidity = 72%

Average temperature = 28.7 °C

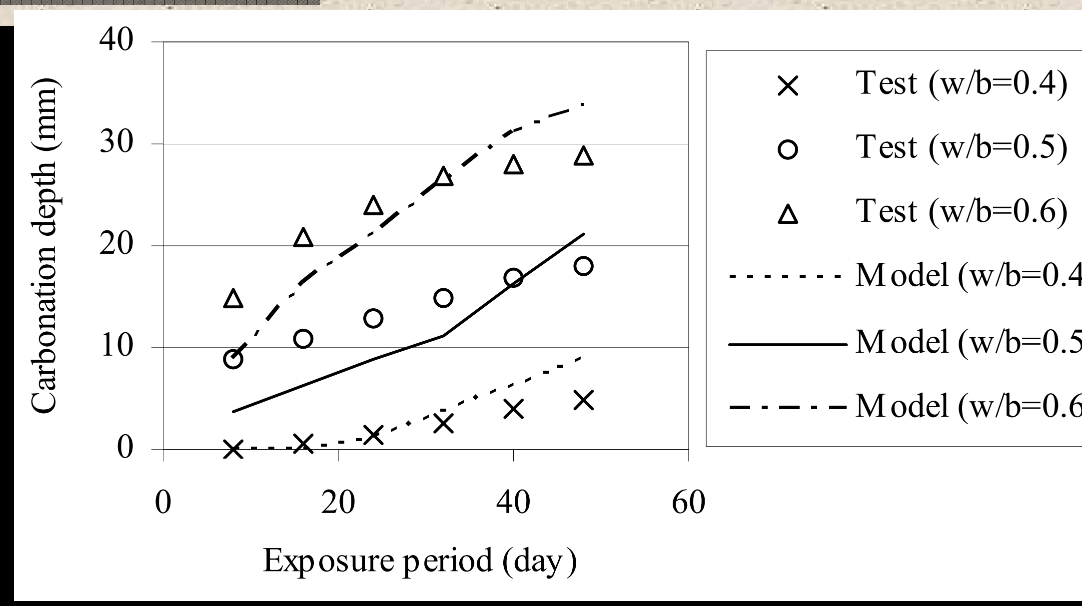


iii) Verification of carbonation depth (accelerated environment)



CO_2 concentration = 4%
Relative humidity = 55%
Temperature = 40 °C

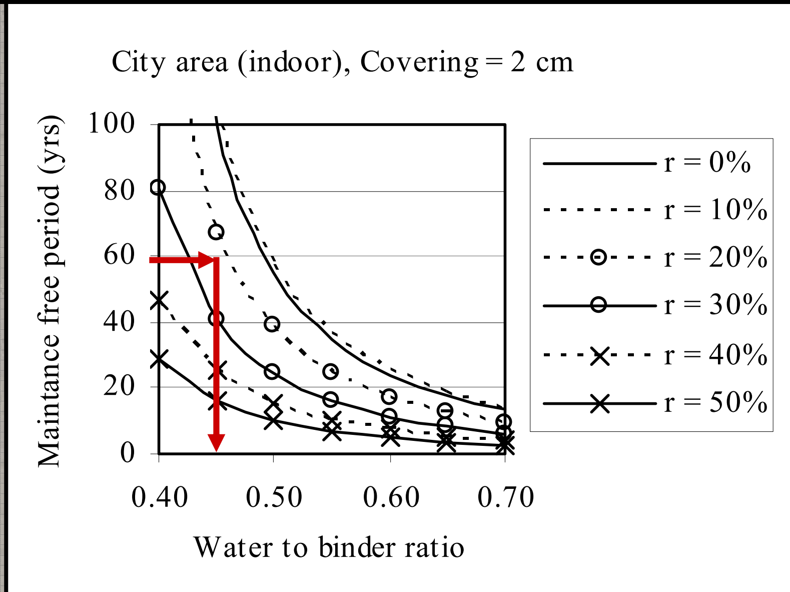
CO_2 concentration = 6.5%
Relative humidity = 65%
Temperature = 30 °C

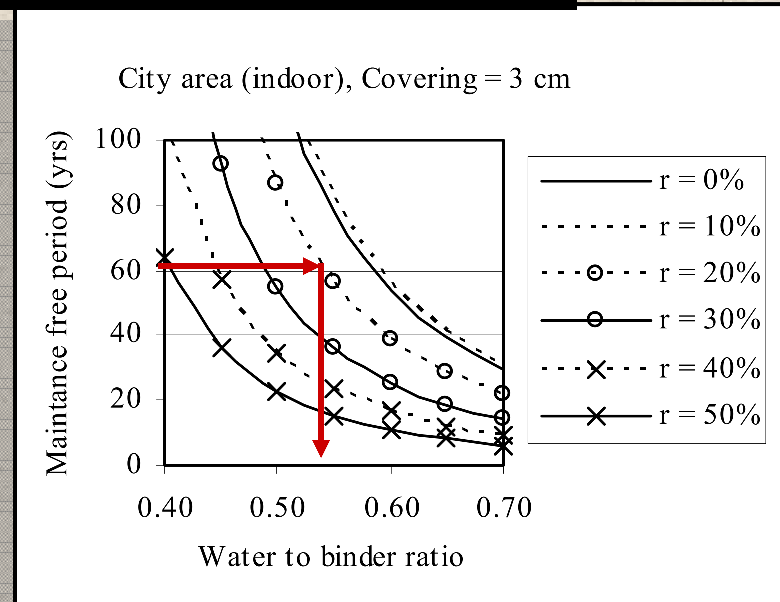


Mix Design of Concrete Subjecting to Carbonation

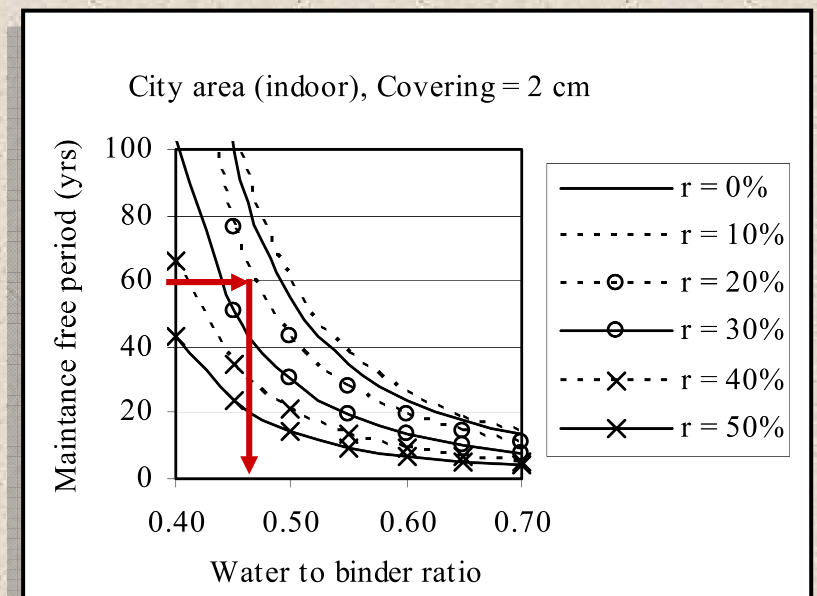
(iii) Design charts for depassivation time

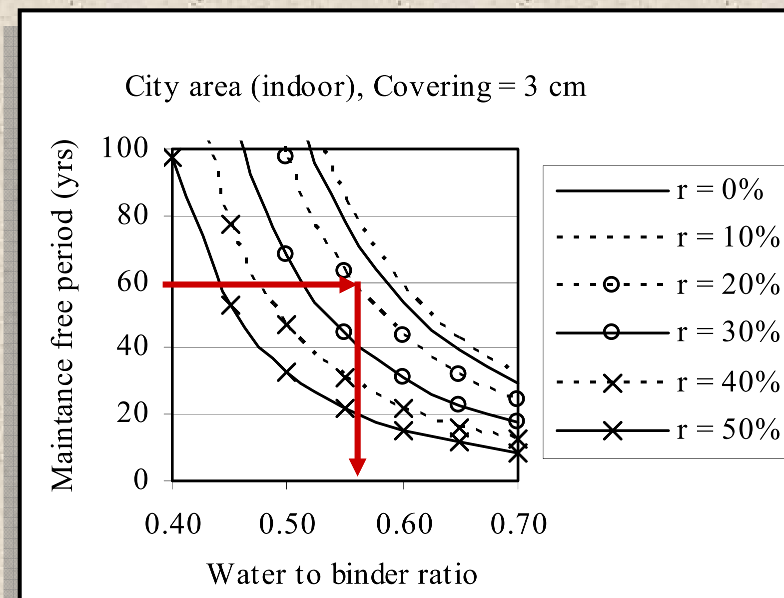
FA 2ก





FA 2ข

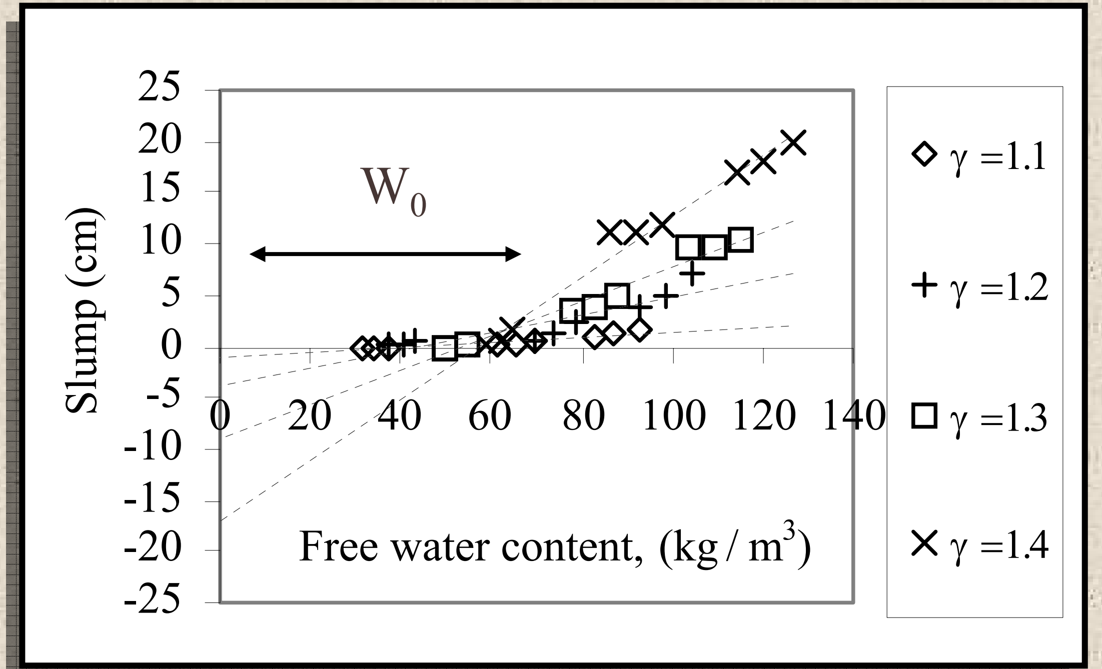




(ii) Workability prediction model

(Khunhongkeaw 2002, Wangchuk 2003)

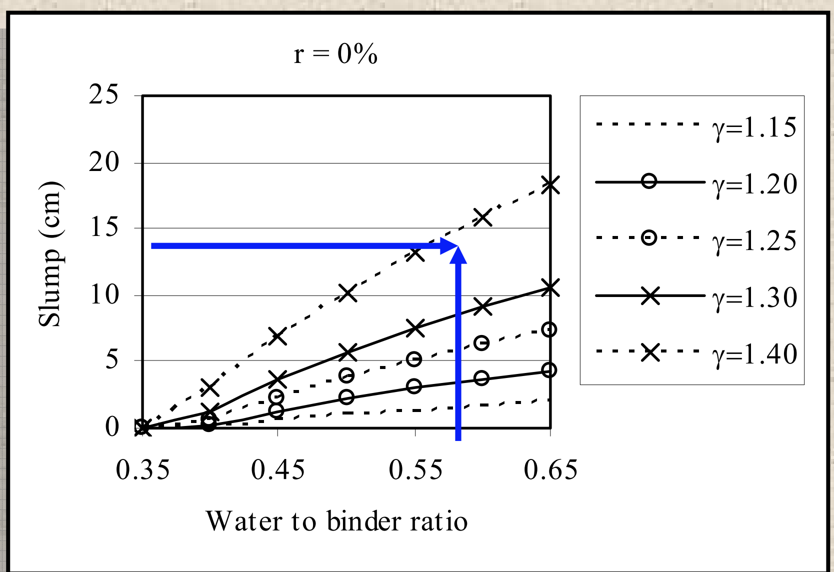
- It was verified that free water content has linear relationship with deformability of ordinary concrete

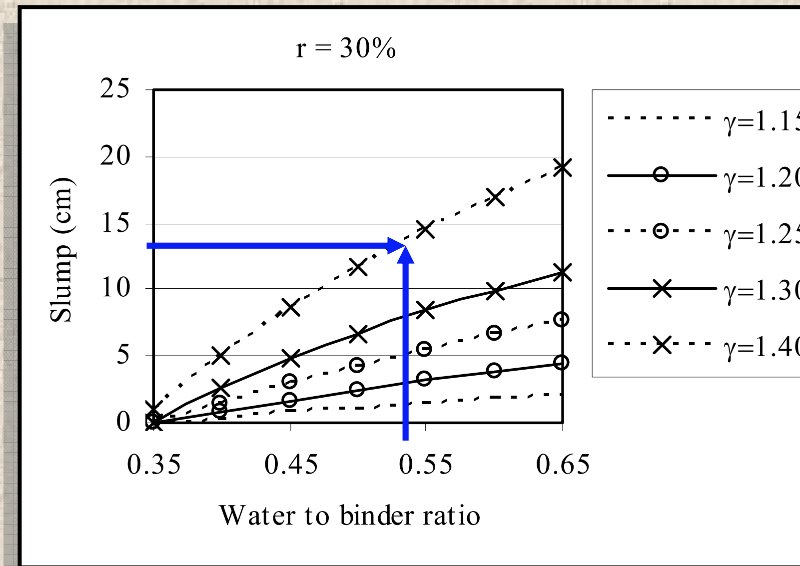


$$SL = \alpha (W_{fr} - W_0)$$

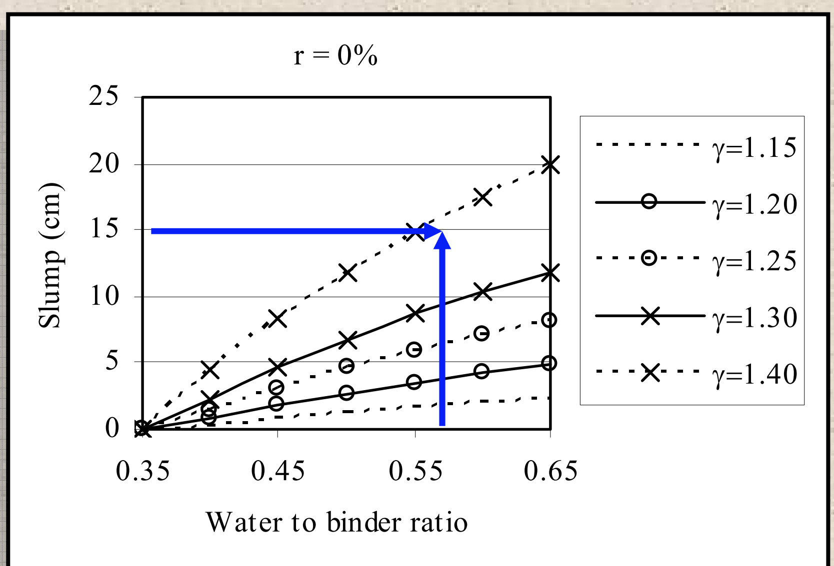
(iv) Design charts for slump

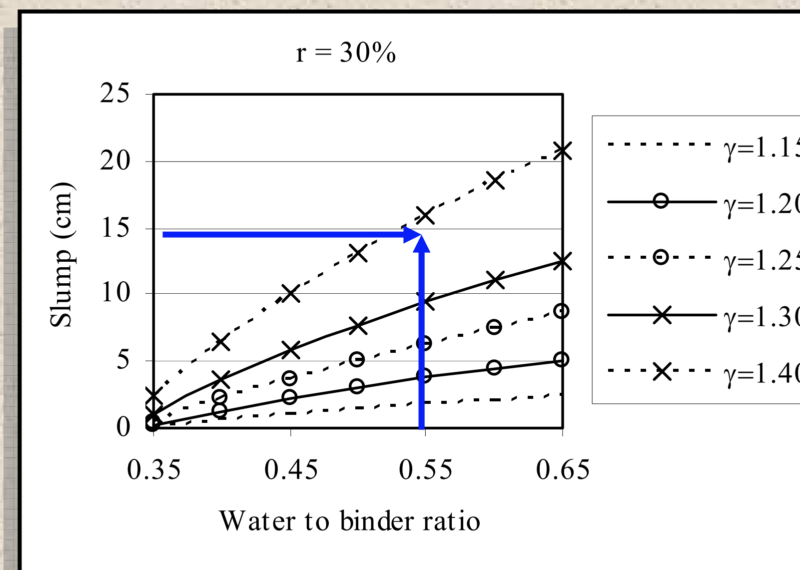
FM 2.75





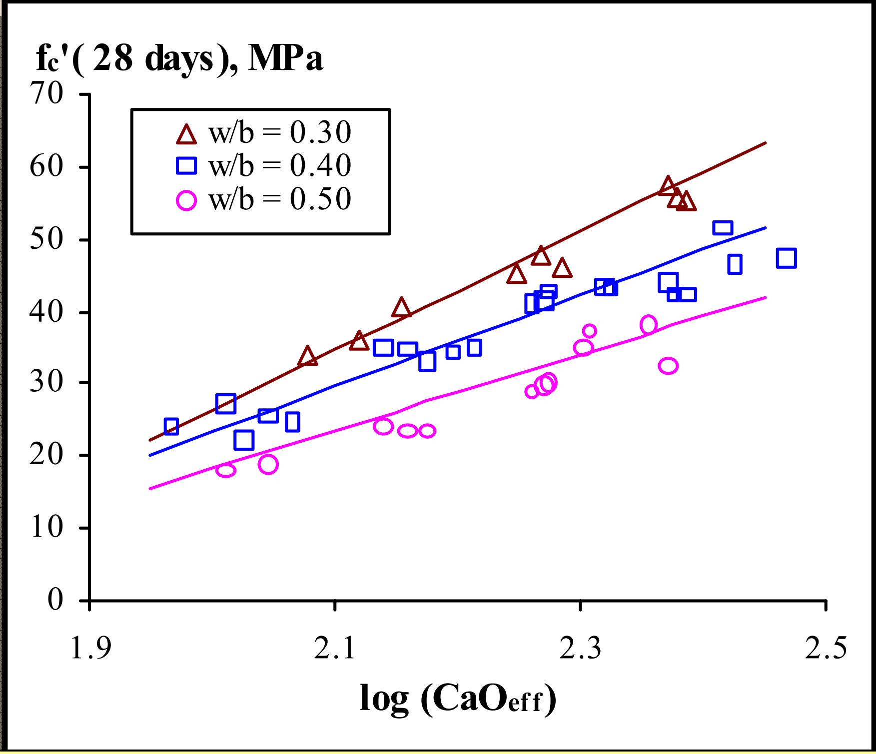
FM 3.25





(i) Strength prediction model (Kaewklurb 2002)

- It was empirically formulated to have relationship mainly with CaO content in concrete.

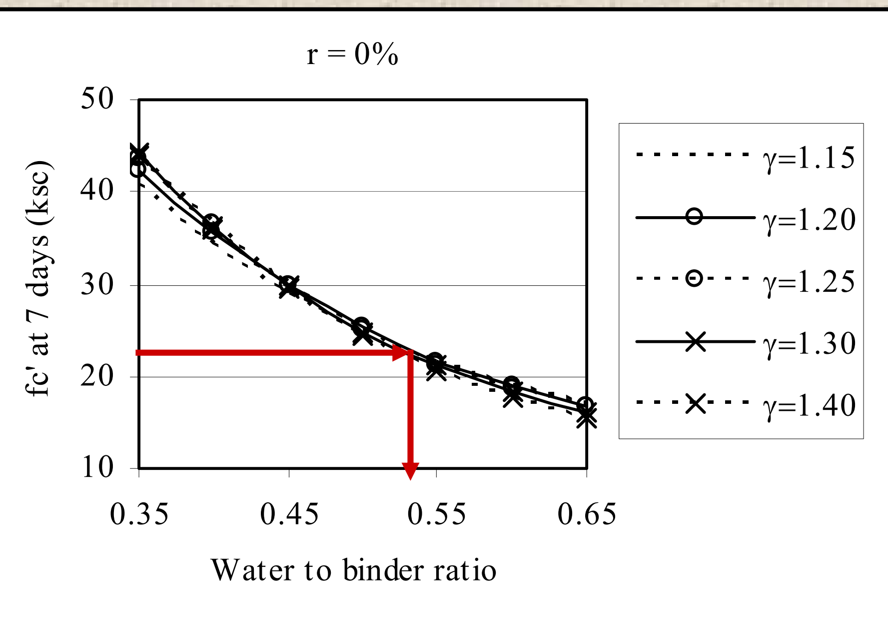


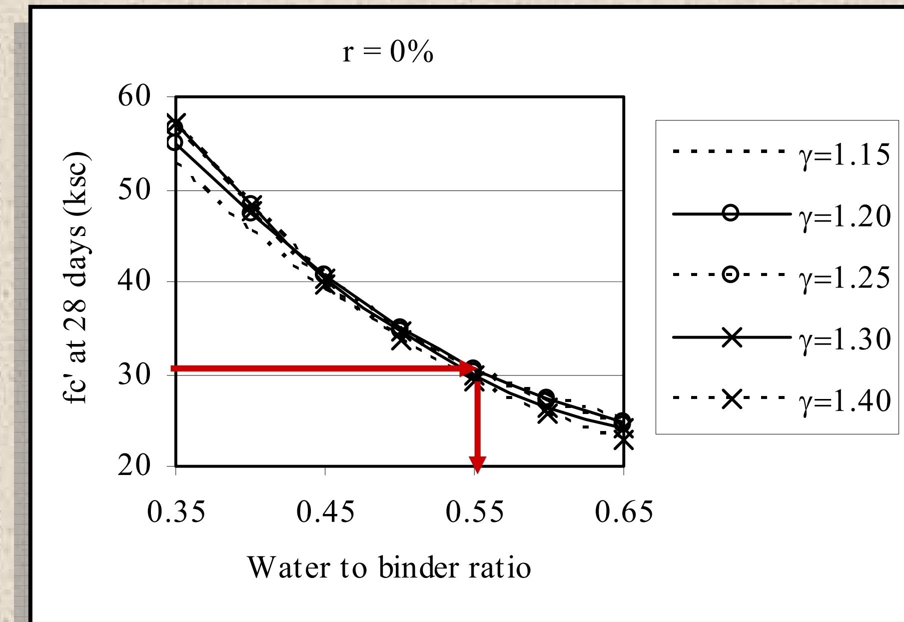
- The 28-day compressive strength is given by,

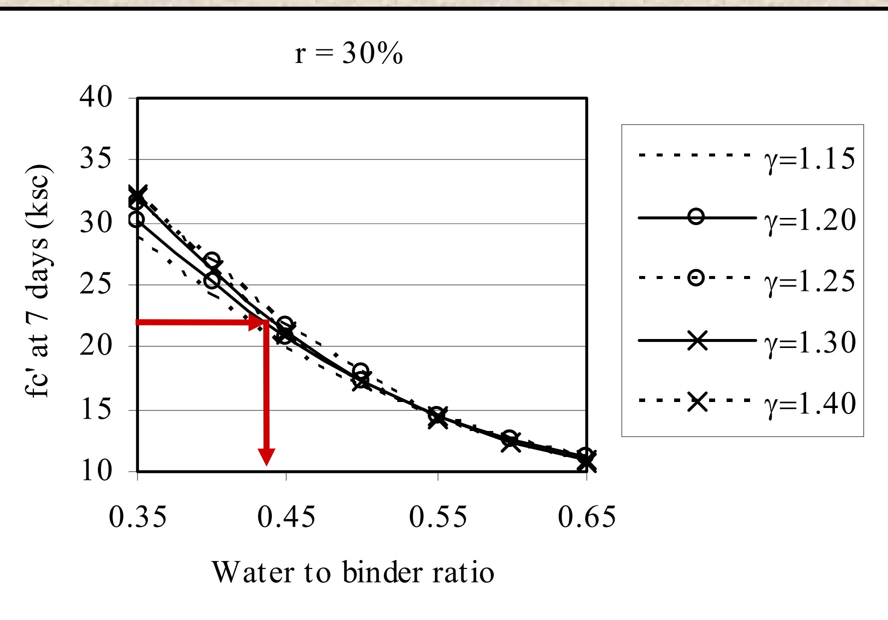
$$f_c'(28) = [\, \alpha_1 \log(C) + \lambda_f \alpha_2 \,]\, \chi_\gamma \chi_l \chi_w \chi_a$$

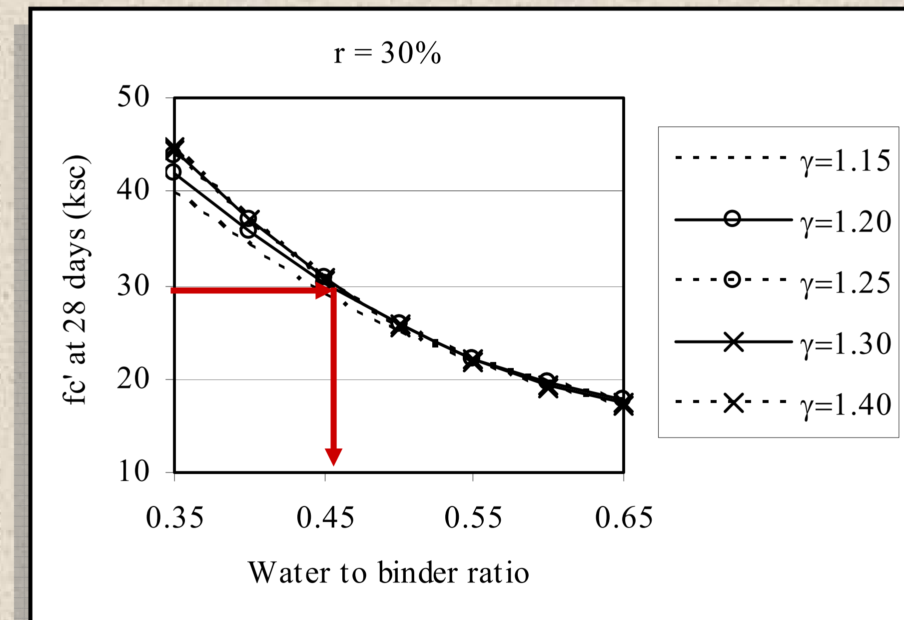
FA 2a, 7 days

FA 2b, 28 days



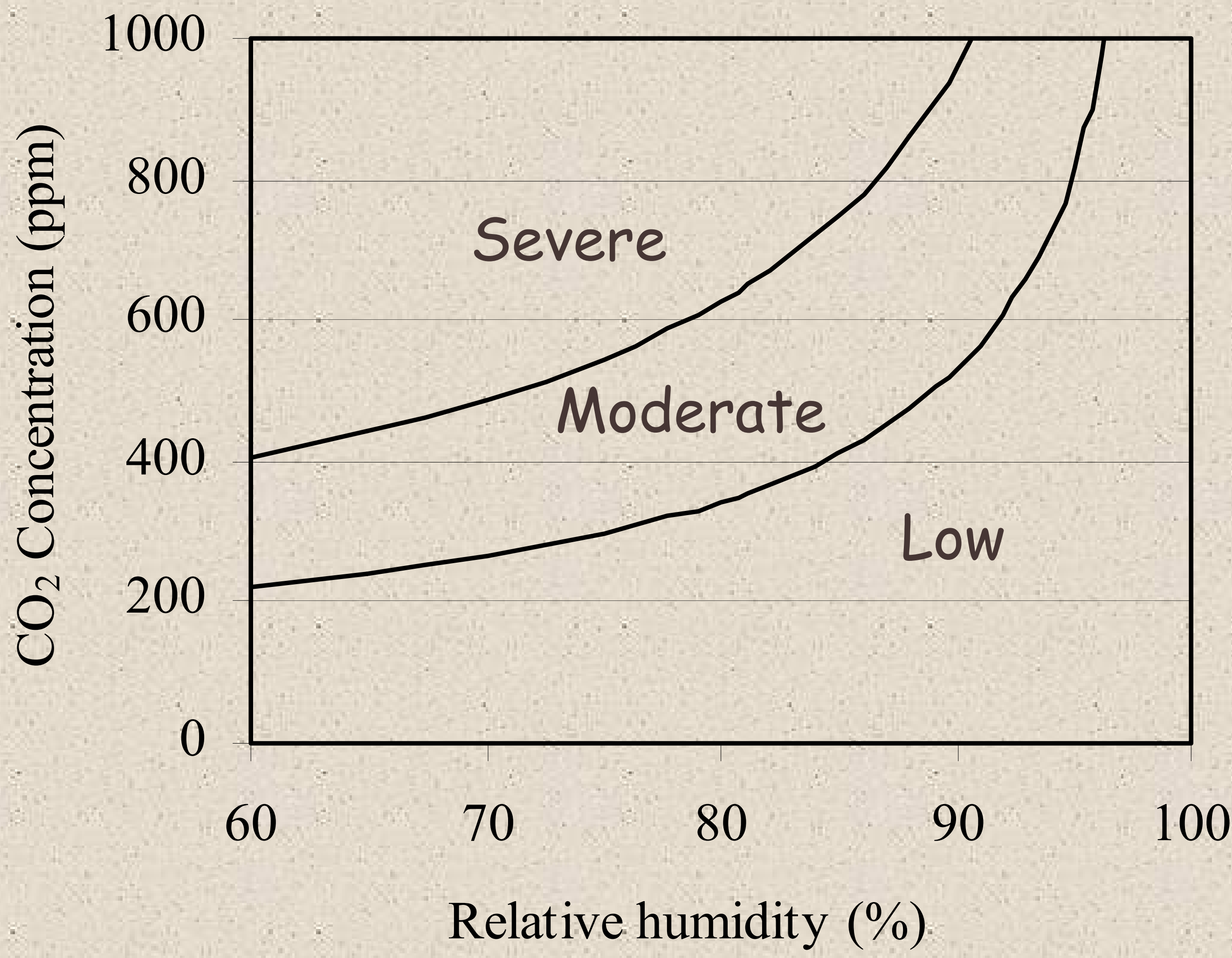




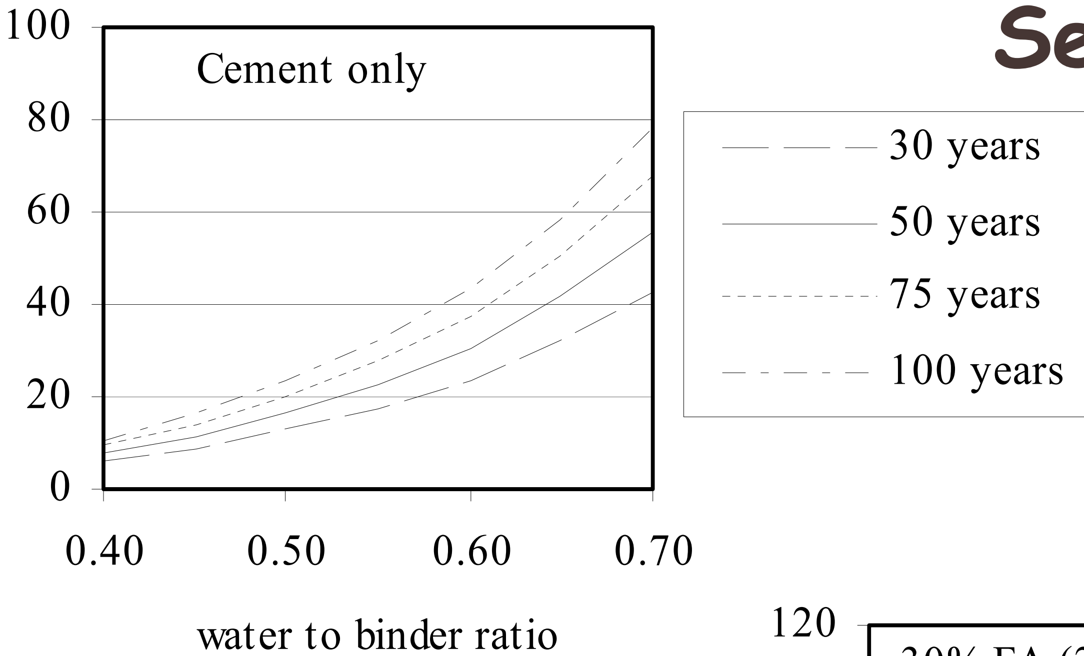


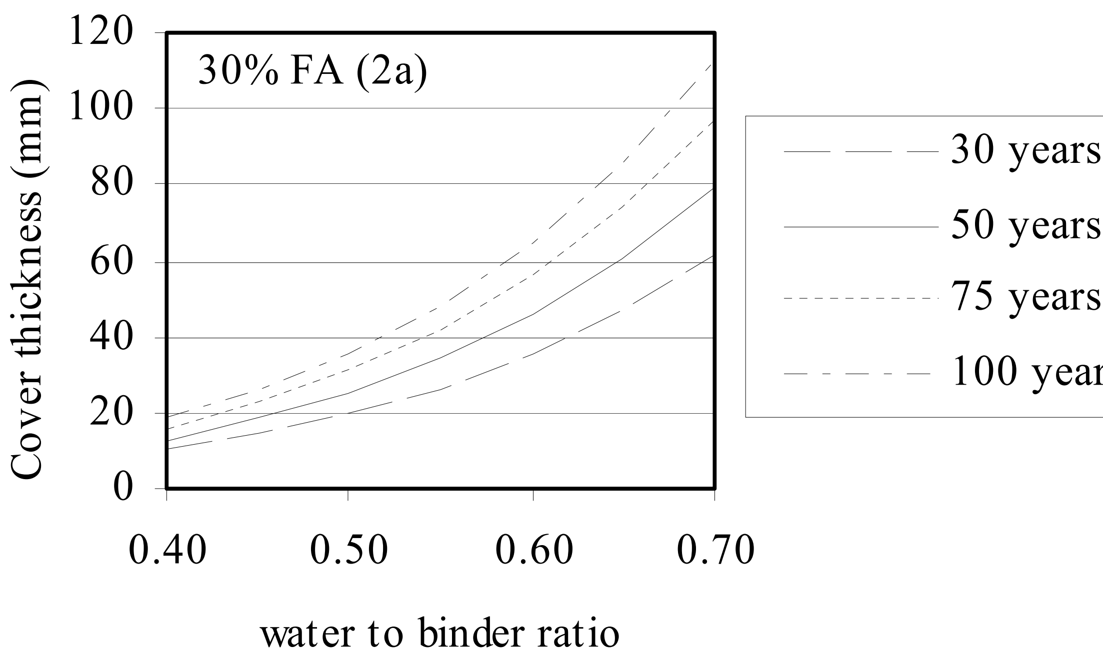
Proposed Design Guideline for Thailand

Proposed Three Zones based on Severity of Environment



Design Chart for Severe Environment





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For workability and strength design

The END

3.2 Design charts

(i) Limitations

- This method is appropriate for conventional fly ash concrete that has $f_c'(28)$ not over 60 Mpa and slump between 1 to 25 cm.

-The standard Portland cement type I complied with the requirement of TIS-15 is recommended.

- The method is suitable for unprocessed FA that are classified as type 2a and 2b by EIT-1014 and have fineness not over than 320 m^2/kg and water requirement between 90 – 105 %.

- Fine and coarse aggregates must be river sand and limestone, respectively. The aggregates must satisfy the industrial standard (TIS-566).

(ii) Design charts for compressive strength

- The design charts for compressive strength are constructed at age of concrete of 7, 28, 91 days and separated into two sets for fly ash type 2a and 2b.

- Compressive strength is designed by assuming the value of γ equal to 1.2. Then the value of water to binder ratio is selected from the design charts from the required compressive strength.

- It is noted that if the compressive strengths at more than one specific age is required, the minimum water to binder ratio that satisfies all strength requirements is selected.