Saw-Cut Depth and Timing Model for Rigid Airfield Pavements

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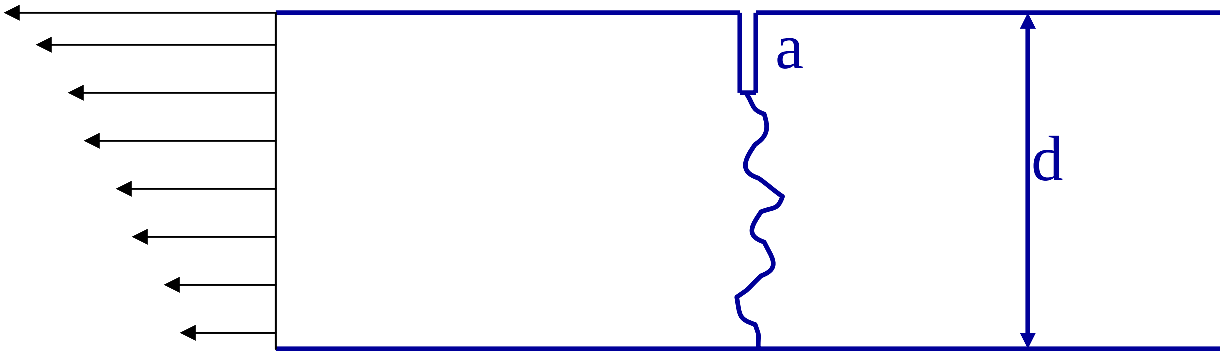
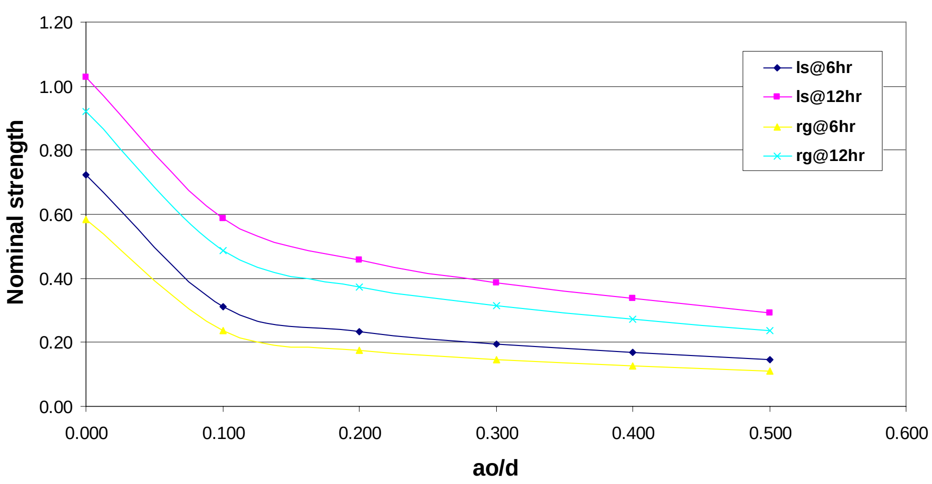
Saw-Cut Timing Model

- Concrete E and fracture properties(c_f ,K_{IC}) at early ages.
- Develop curves of nominal strength vs notch depth for timing.



Nominal strength vs ao/d for the 300mm slab

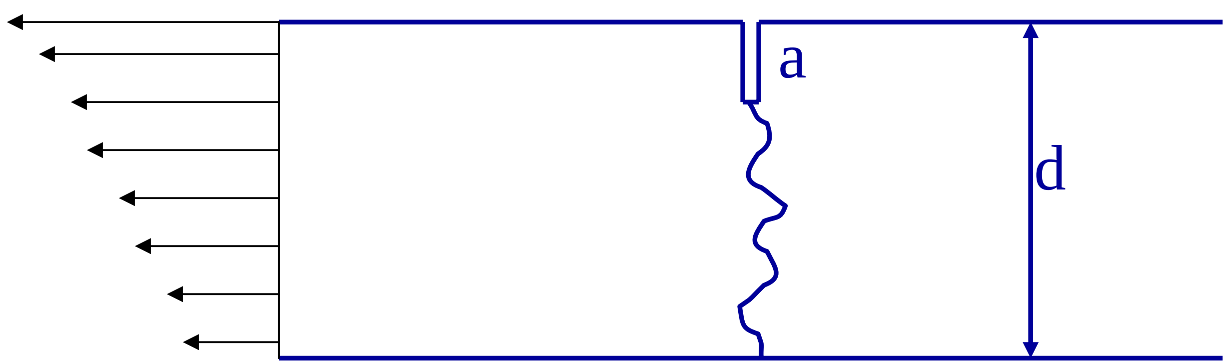


•Notch depth (a) depends on stress, strength, and slab thickness (d)

•Stress = f(coarse aggregate,ΔT,RH)

Saw-Cut Timing and Depth

- Saw cut depth / timing – EXPERIENCE
- Fracture properties at early ages
  - Critical Stress Intensity Factor (K_{IC})
  - Critical Crack Tip Opening Displacement ($CTOC_C$) form this type of specimen
  - Wedge Splitting Test (WST)
    - need geometric factors

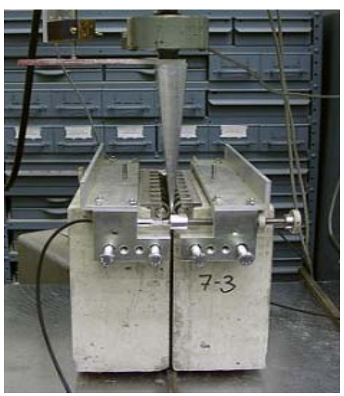


Saw-Cut Timing and Depth

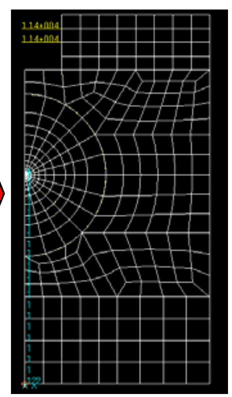
Process

Concrete Mix

- ***Aggregate size***
- ***Cementitious content***

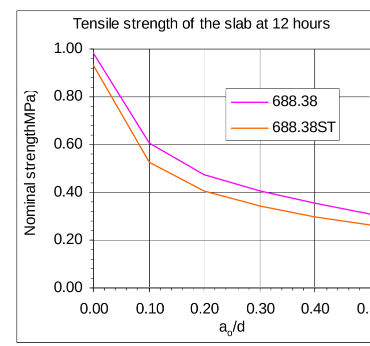


Wedge Split Test



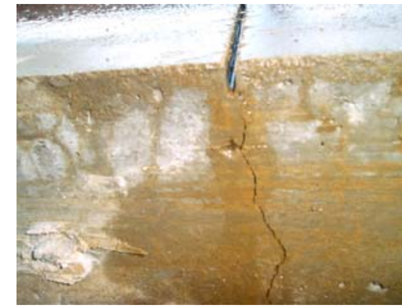
FEM Model

FRACTURE PROPERTIES



Saw Cut Depth Model

Crack Propagates



Saw-cut timing and Depth

Concrete

Mix proportions

ID	Units	555.44	555.44 st	688.38	688.38 st
w/cm		0.44		0.38	
Max aggregate size	mm (inch)	38 (1 1/2")	25 (1")	38 (1 1/2")	25 (1")
Water	kg/m^3	145	145	155	155
Cement	kg/m^3	270	270	349	349
Fly ash	kg/m^3	59	59	59	59
Coarse Aggregate (SSD)	kg/m^3	1152	1142	1093	1098
Fine Aggregate (SSD)	kg/m^3	678	672	643	654

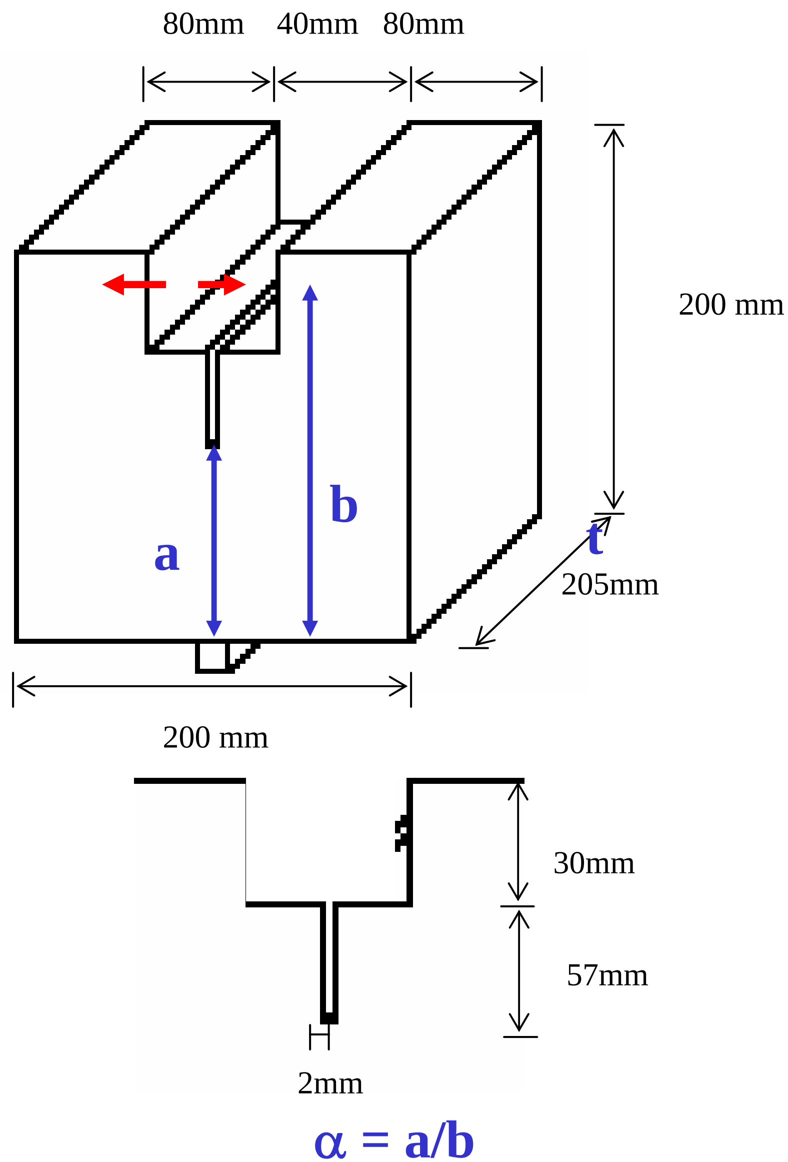
All mixtures were air entrained rangin from 4% to 8%

Aggregate gradations

Sieve Opening	Coarse Aggregate 38 mm(1 1/2") max. size BSG=2.71 AC= 1.27%			Coarse Aggregate 25 mm (1") max. size BSG=2.67 AC= 2.0%		
	Retained (%)	Cumulative retained (%)	Cumulative passing (%)	Retained (%)	Cumulative retained (%)	Cumulative passing (%)
1.5"	0	0	100	0	0	100
1"	59	59	41	0	0	100
3/4"	34	92	8	33	33	67
1/2"	7	99	1	56	88	12
3/8"	1	100	0	9	97	3
#4	0	100	0	3	100	0
Total	100			100		

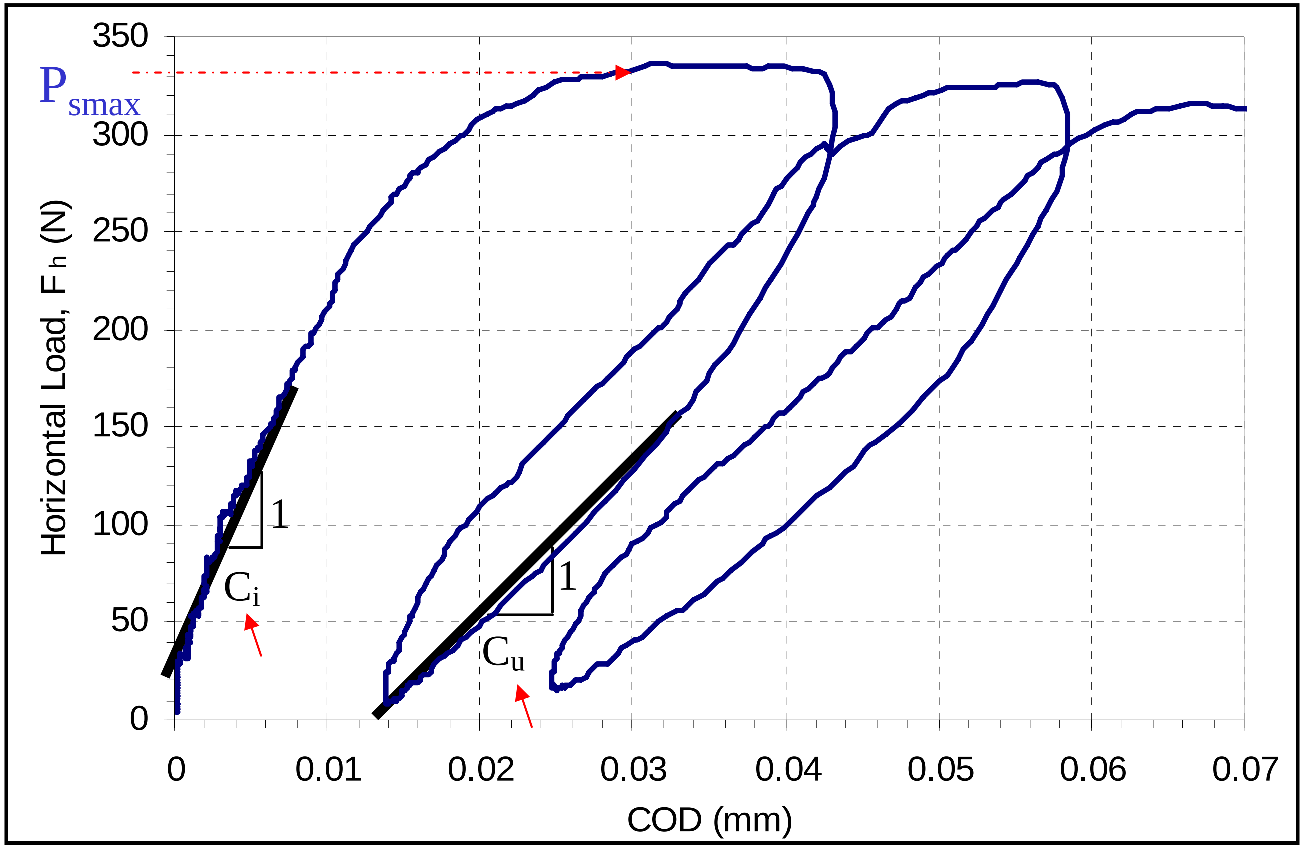
Wedge Split Testing

- WST setup and specimen



Wedge Split Testing

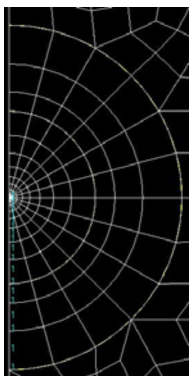
- Loading – unloading cycles
  - Measured Values:
    - P_{smax} (N)
    - C_i (mm/N)
    - C_u (mm/N)

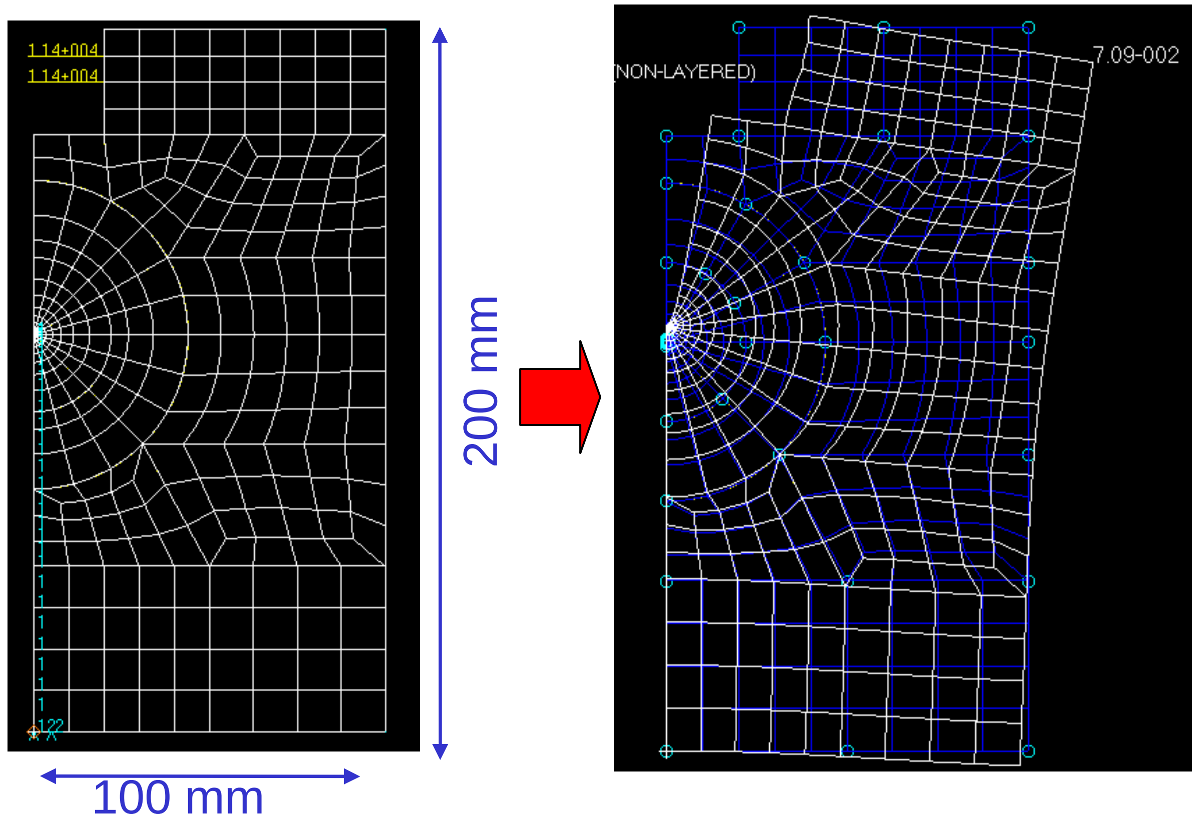


Saw-Cut Timing and Depth

FEM Model

- Special Mesh around crack tip





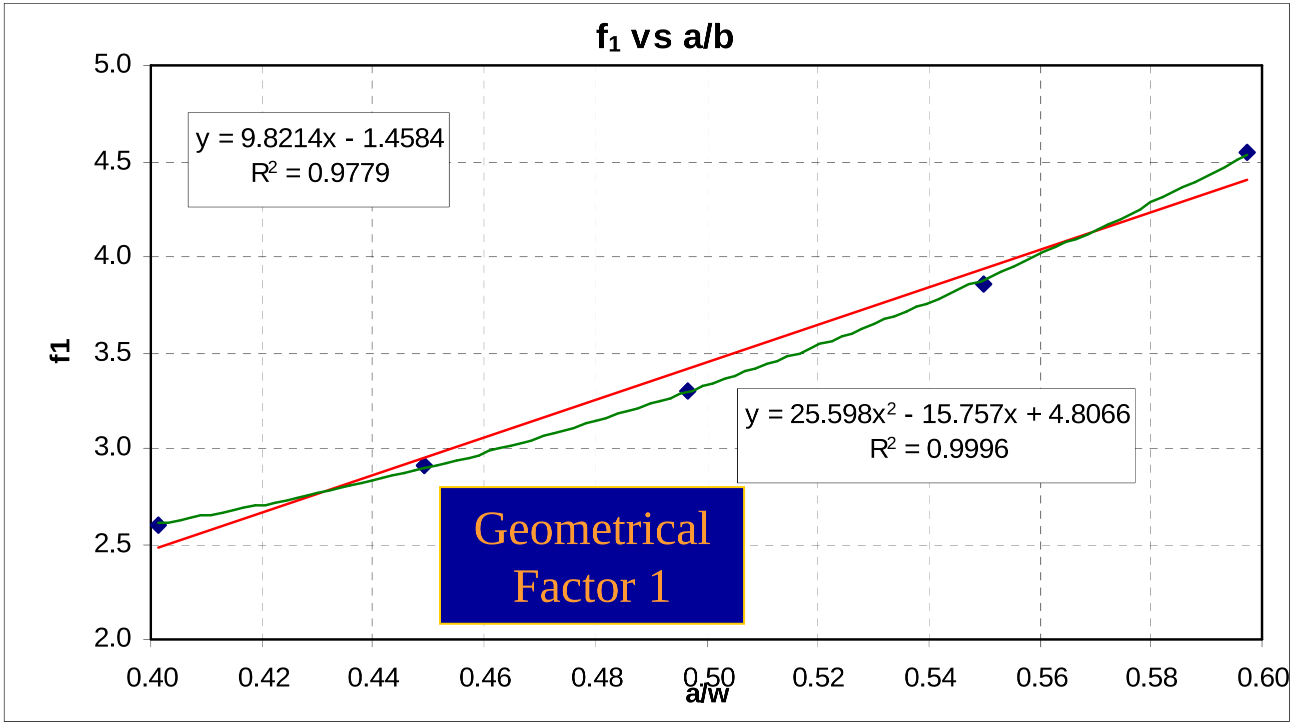
- Q8 elements
- Symmetry and BC considerations

Saw-cut timing and depth

FEM Model Results

- Determination of Fracture parameters

$$K_{IC} = P_{smax} * \frac{f_1(\alpha)}{t * b^{1/2}} \Rightarrow K_{IC} = \frac{P_{smax}}{t * b^{1/2}} * f_1(\alpha)$$



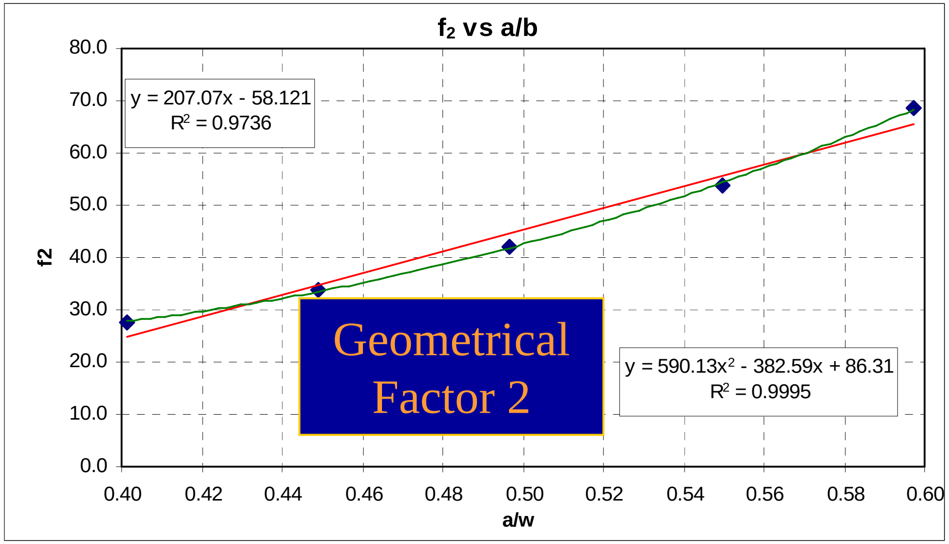
Saw-cut timing and depth

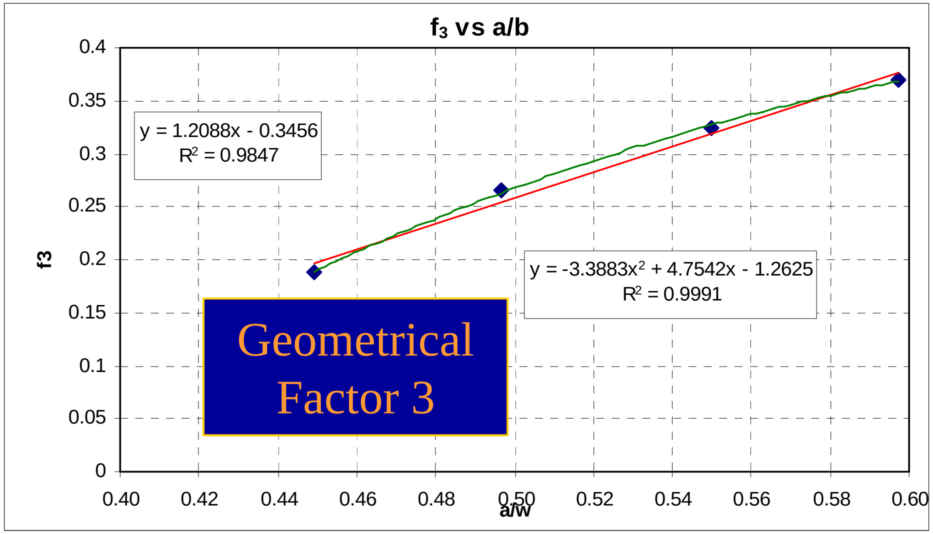
FEM Model Results

- Determination of Fracture parameters

$$CMOD = P_{sp} * \frac{f_2(\alpha)}{t * E} \quad \Rightarrow \quad CMOD = \frac{P_{sp}}{t * E} * f_2(\alpha)$$

$$CTOD = f_3(\alpha) * CMOD$$





Saw-cut timing and depth

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Methodology

- Based on Two Parameter Law
- Step 1 → Calculate splitting load

$$P_{smax} = P_{hmax} = P_{vmax}/(2\tan\beta)$$

- Step 2 → Calculate initial Modulus, E_i

$$E = \frac{P_{smax}}{CMOD} * \frac{f_2(\alpha)}{t}$$

($E \to E_i$, $\frac{P_{smax}}{CMOD} \to 1/C_i$, $\alpha \to \alpha_o$)

$$\Rightarrow \quad E_i = \frac{f_2(\alpha_0)}{C_i * t}$$

- Step 3 → Calculate unloading Modulus, E_u and critical crack length a_c

$$E_u = \frac{f_2(\alpha_c)}{C_u * t} \quad \text{and} \quad E_u = E_i \quad \Rightarrow \text{(solver)} \quad \alpha_c \quad \Rightarrow \quad a_c$$

β = angle of wedge

P_v = vertical load form test

$P_h = P_{sp}$ = splitting load

t = specimen width

C_i = loading compliance

C_u = unloading compliance

α_0 = initial depth (a_0/b)

α_c = critical depth (a_c/b)

$f_2(\alpha)$ = geometrical factor 2

Saw-cut timing and depth

Methodology

- Step 4 → Calculate K_{IC}

$$K_{IC} = P_{smax} * \frac{f_1(\alpha_c)}{t * b^{1/2}}$$

- Step 5 → Calculate critical $CTOD_c$

$$CMOD_c = P_{smax} * \frac{f_2(\alpha_c)}{t * E}$$

$$CTOD_c = f_3(\alpha_c) * CMOD_c$$

- Step 6 → Calculate G_f and c_f

$$G_f = \frac{K_{IC}^2}{E} \qquad c_f = \frac{CTOD_C * E}{K_{IC}^2}$$

P_{smax} = peak splitting load

K_{IC} = critical SIF

$CTOD_c$= critical CTOD

$CMOD_c$= critical CMOD

$f_1(\alpha)$ = geometrical factor 1

$f_2(\alpha)$ = geometrical factor 2

$f_3(\alpha)$ = geometrical factor 3

E = modulus of elasticity

G_f = initial fracture energy

Concrete Fracture Properties

- Critical Stress Intensity Factor (K_{IC}) and Critical Crack Extension (c_f)
  - Mixtures with lower cementitious content → lower K_{IC}
  - Larger coarse aggregate mixtures → higher K_{IC}
  - Increase in the critical crack extension (c_f) until 12 hours → less brittle (more quasi-brittle).
  - After 12 hours, c_f tends to plateau

AGE	MIXTURE			
	555.44	555.44st	688.38	688.38st
(hrs)	K_{IC}(MPam$^{1/2}$)			
0	0.0	0.0	0.0	0.0
6	0.01	0.01	0.02	0.02
8	0.05	0.03	0.07	0.06
10	0.08	0.14	0.14	0.11
12	0.19	0.15	0.32	0.25
24	0.31	0.28	0.51	0.45
(hrs)	c_f(m)			
6	0.001	0.003	0.002	0.001
8	0.005	0.008	0.007	0.004
10	0.006	0.008	0.012	0.006
12	0.006	0.023	0.024	0.018
24	0.007	0.017	0.021	0.017

Saw-Cut Depth Model

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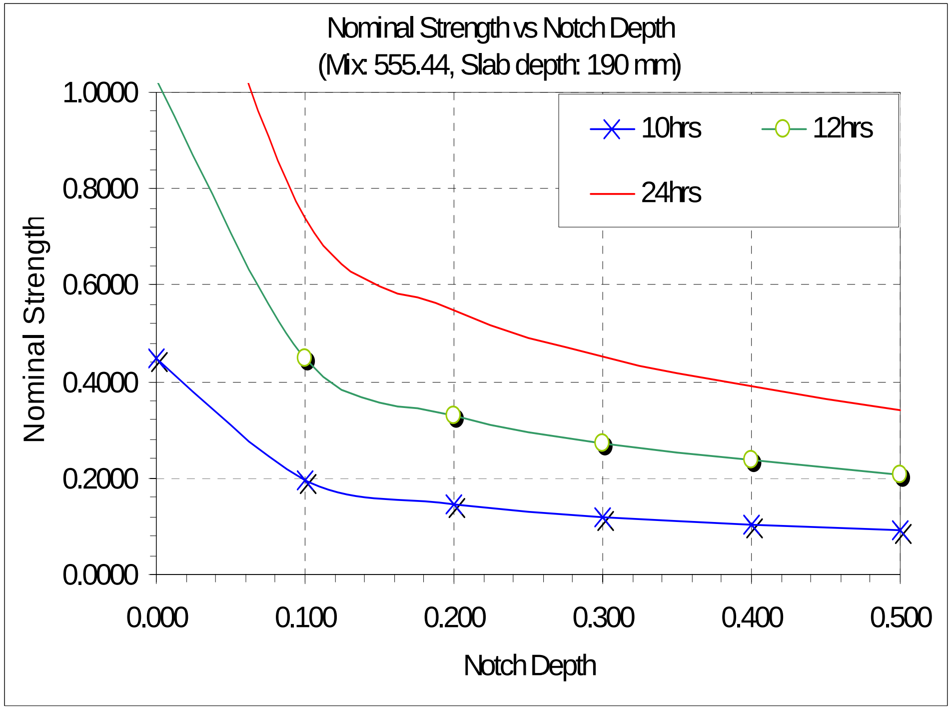
SEM Model (Bazant)

$$\sigma_t = \frac{c_n K_{IC}}{\sqrt{g'(a_o/d)c_f + g(a_o/d)d}}$$

$$c_f = \frac{CTOD_C * E}{K_{IC}^2}$$

$$K_{IC} = \frac{P_{smax}}{t * b^{1/2}} * f_1(\alpha)$$



Nominal Strength vs Notch Depth Chart

$$g(a_o/d) = \pi \alpha c_n f^2(a_o/d)$$

$$g'(a_o/d) = \pi f^2(a_o/d) + 2\pi \alpha c n^2 f(a_o/d) f'(a_o/d)$$

$$f(a_o/d) = 1.12 + 0.203\alpha - 1.197\alpha^2 + 1.93\alpha^3$$

$$f'(a_o/d) = 0.203 - 2.394\alpha + 5.79\alpha^2$$

Curling Stress in Concrete Slab

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ILLINOIS

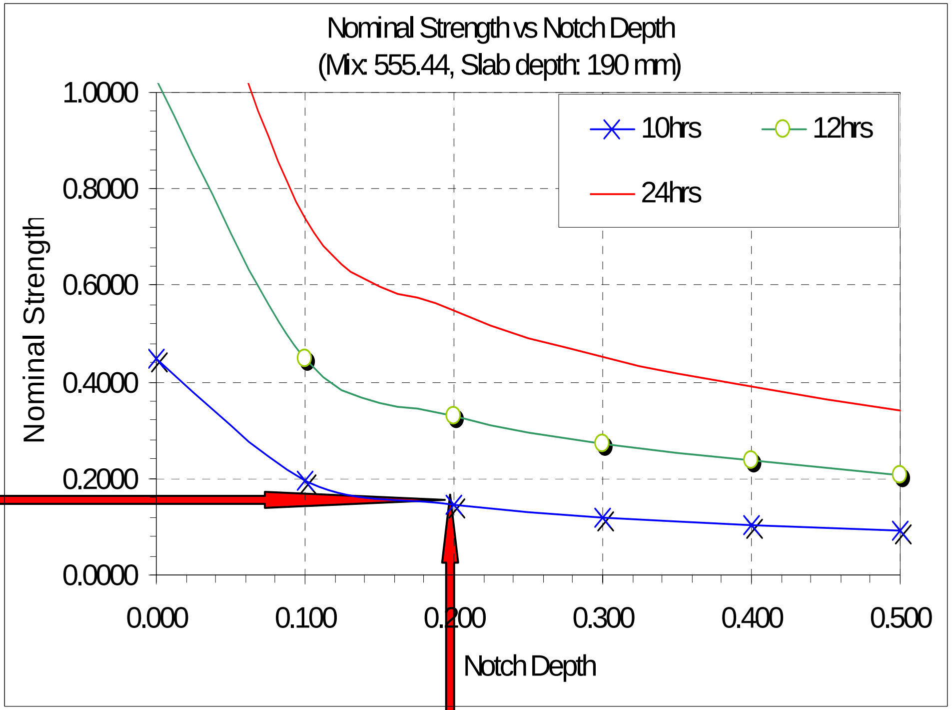
- Westergaard Slab Curling

$$C = 1 - \frac{2\cos\lambda\cosh\lambda(\tan\lambda - \tanh\lambda)}{\sin 2\lambda \sinh 2\lambda}$$

$$l = \sqrt[4]{\frac{Eh^3}{12(1-\nu^2)k}}$$

$$\lambda = \frac{L}{l\sqrt{8}}$$

$$\sigma = \frac{CE\alpha\Delta T}{2(1\text{-}\nu)}$$



Saw cut Depth at 10 hours

Case Study

- Two Pavement Sections : Highway and Airport
  - Case Information

	Highway	Airport
Pavement Depth mm (in)	190 / 7.5	380 / 15
k on subgrade Mpa/m (psi/in)	45.7 / 150	45.7 / 150
Modulus of Elasticty	see table	see table
Poissions Ratio	0.15	0.15
Coeff of Thermal Expansion 1/C'	9 x 10-6	9 x 10-6
Temperature Variation C` (F`)	8 /14.4	10 / 18

  - Early Age Modulus of Elasticity

AGE(hrs)	6	8	10	12
MIXTURE	Elastic Modulus(MPa)			
555.44	3,329	4,369	5,409	6,449
555.44st	2,917	3,961	5,005	6,050
688.38	3,188	4,184	5,180	6,176
688.38st	3,343	4,537	5,731	6,925

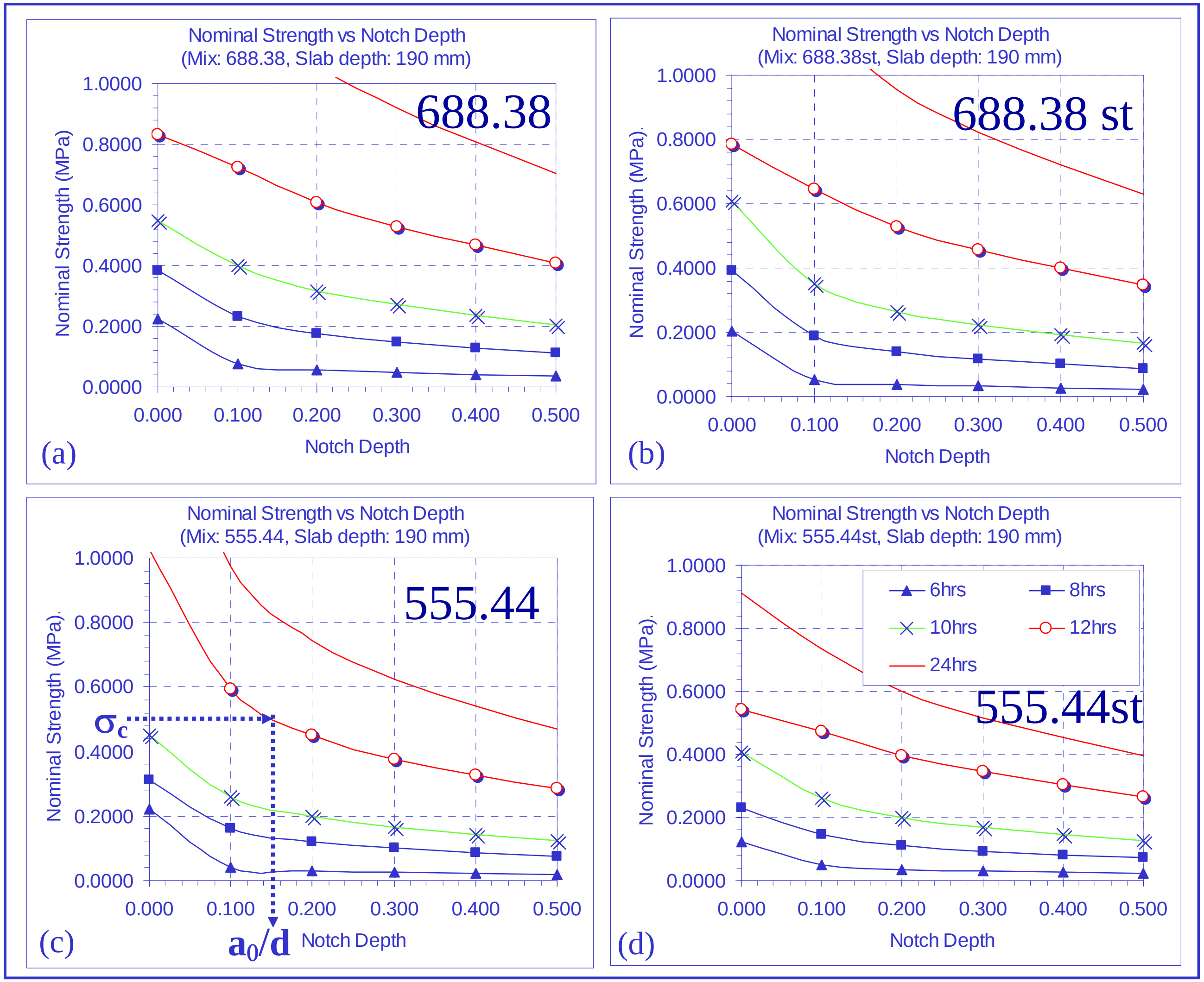
Case Study

- Two pavement Sections : Highway and Airport
  - Tensile Curling Stresses (Westergaard)
    - Effect of pavement depth
    - Effect of concrete mix
    - Effect of concrete age

Tensile Stress (MPa)								
AGE(hrs)	6		8		10		12	
Slab depth (m)	0.19	0.38	0.19	0.38	0.19	0.38	0.19	0.38
555.44	0.15	0.18	0.20	0.23	0.25	0.28	0.30	0.32
555.44st	0.13	0.16	0.18	0.21	0.23	0.26	0.28	0.30
688.38	0.15	0.18	0.19	0.23	0.24	0.27	0.28	0.31
688.38st	0.15	0.18	0.21	0.24	0.26	0.29	0.32	0.34

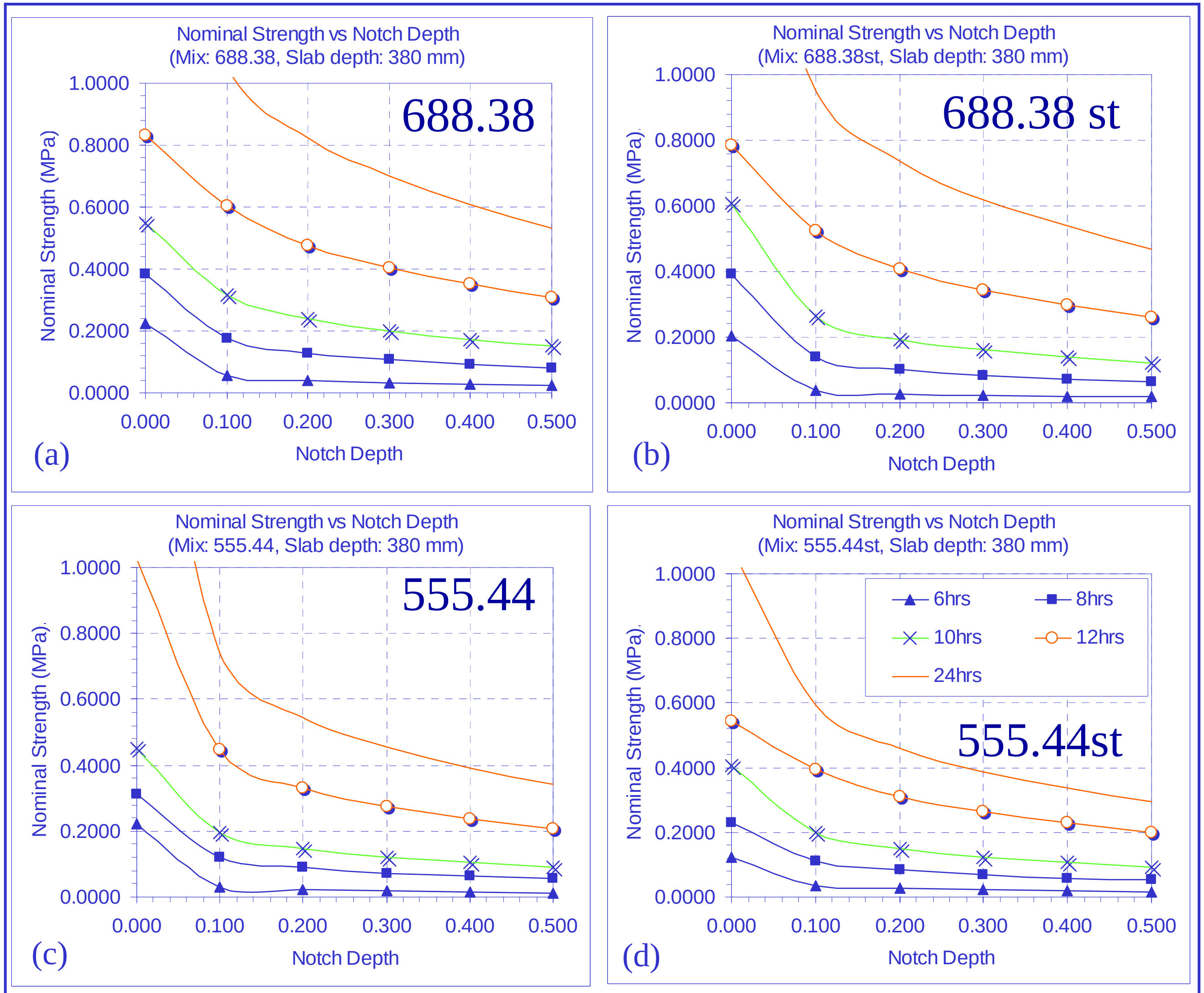
Case Study

Saw Cut Depth Charts → Highway



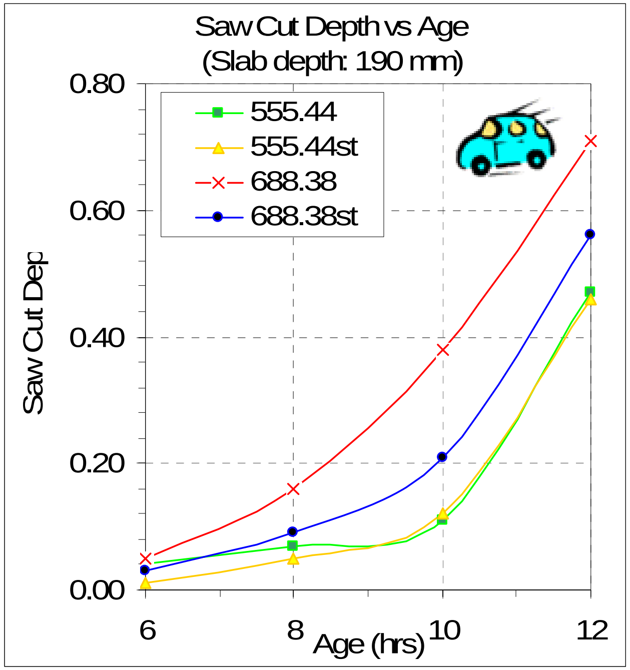
Case Study

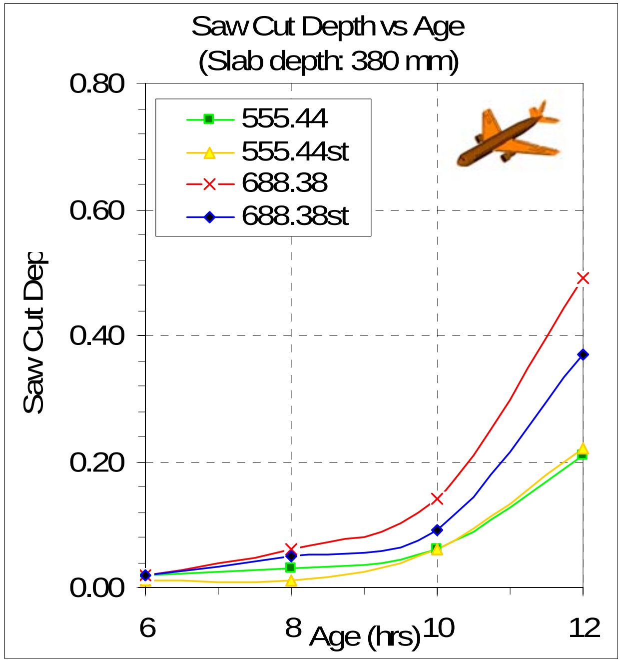
Saw Cut Depth Charts → Airport



Summary of Notch Depth Requirements

Saw Cut Depth (a_0/d)								
AGE(hrs)	6		8		10		12	
Slab depth (m)	0.19	0.38	0.19	0.38	0.19	0.38	0.19	0.38
555.44	0.04	0.02	0.07	0.03	0.11	0.06	0.47	0.21
555.44st	0.01	0.01	0.05	0.01	0.12	0.06	0.46	0.22
688.38	0.05	0.02	0.16	0.06	0.38	0.14	0.71	0.49
688.38st	0.03	0.02	0.09	0.05	0.21	0.09	0.56	0.37





Saw-cut timing and depth

Summary

- Saw-cut depth increases with concrete age
  - Dramatic increase after 10 to 12 hr.
- Larger maximum aggregate size increases saw cut depth
  - High cementitious materials especially
- Greater notch-depth ratio for thinner slabs