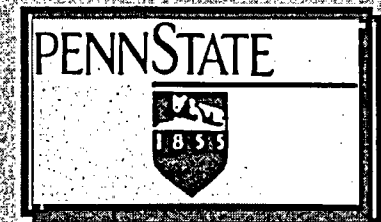


Causes of failure in cementitious materials Cracking

Barry E. Scheetz

Department of Civil and
Environmental Engineering
Pennsylvania State University



Disclaimer:

My observations are based upon the behavior of portland cement concretes used in civil infrastructure applications.

**A fundamental tenet when working
with portland cement concrete is:**

“all concrete cracks”

***That being said; not all cracks are
bad***

A more generalized description of the average permeability of a concrete body can be given by:

$$K_{\text{total}} = \rho g b^3 / 24 \mu s + K_{\text{matrix}}$$

Where:

s = crack spacing [cm/crack]

b/s = proportional area of crack = A_f

K = hydraulic conductivity [cm/sec]

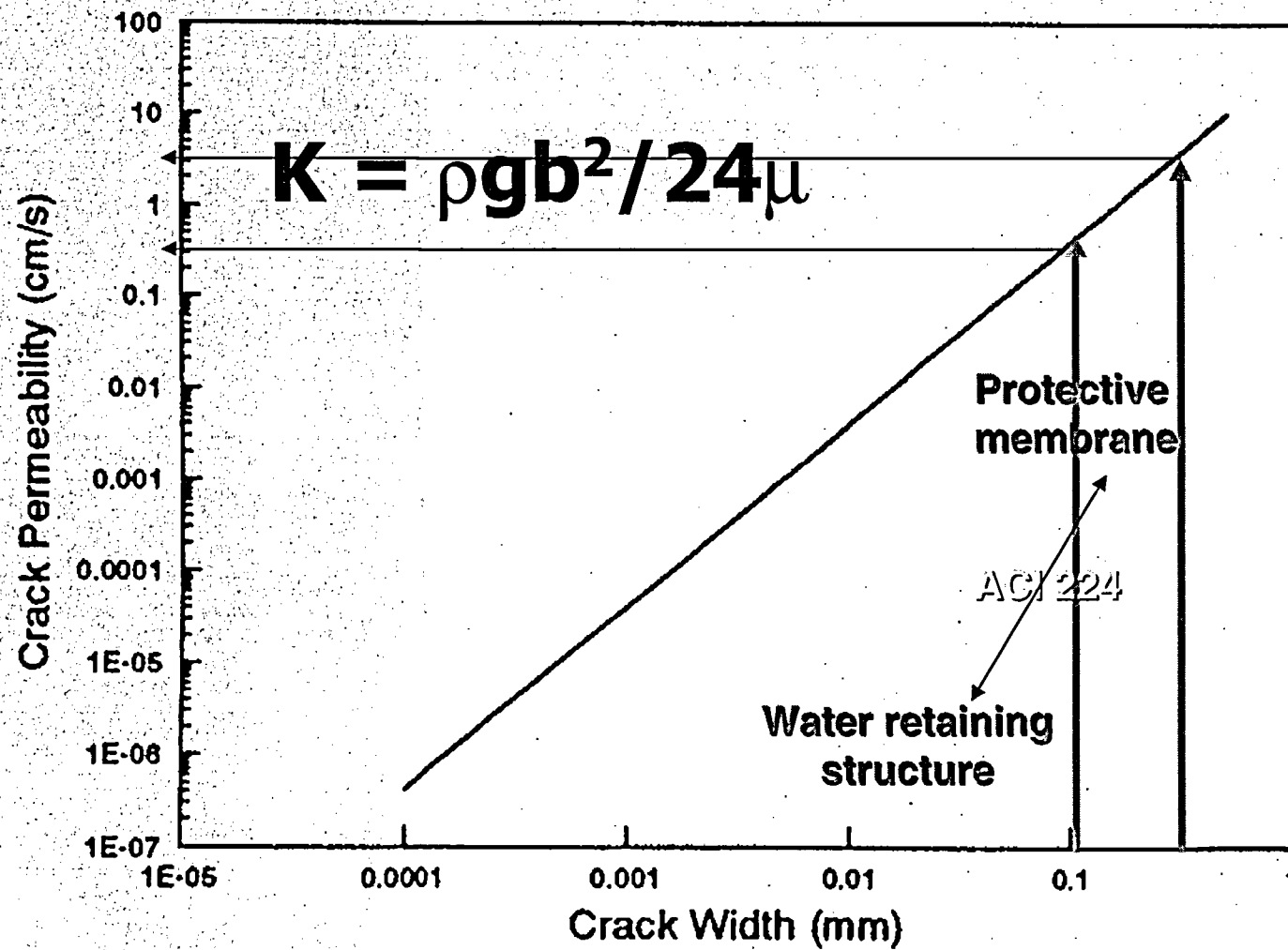
ρ = density of water [g/cm³]

g = acceleration of gravity [980 cm/s²]

b = fracture aperture [cm]

μ = viscosity of water [~.01 g/cm sec]

Crack permeability



Fluid flow in cracks in a partially saturated system takes the form:

$$h = -2\gamma\cos(\alpha)/b\rho g$$

Where:

γ = surface tension of water [72.7dyne/cm]

α = cement water contact angle [0]

h = pressure head [cm]

$$b_{maxflow} = -2\gamma\cos(\alpha)/h\rho g \approx -0.148/h$$

Max crack width that will not drain at a given pressure

It can be stated that most premature deterioration of concrete structures can be traced to cracking which has allowed ingress of deleterious agents to enter into the interiors of cementitious bodies.

Time frame for cracking processes

Sulfate attack

ASR

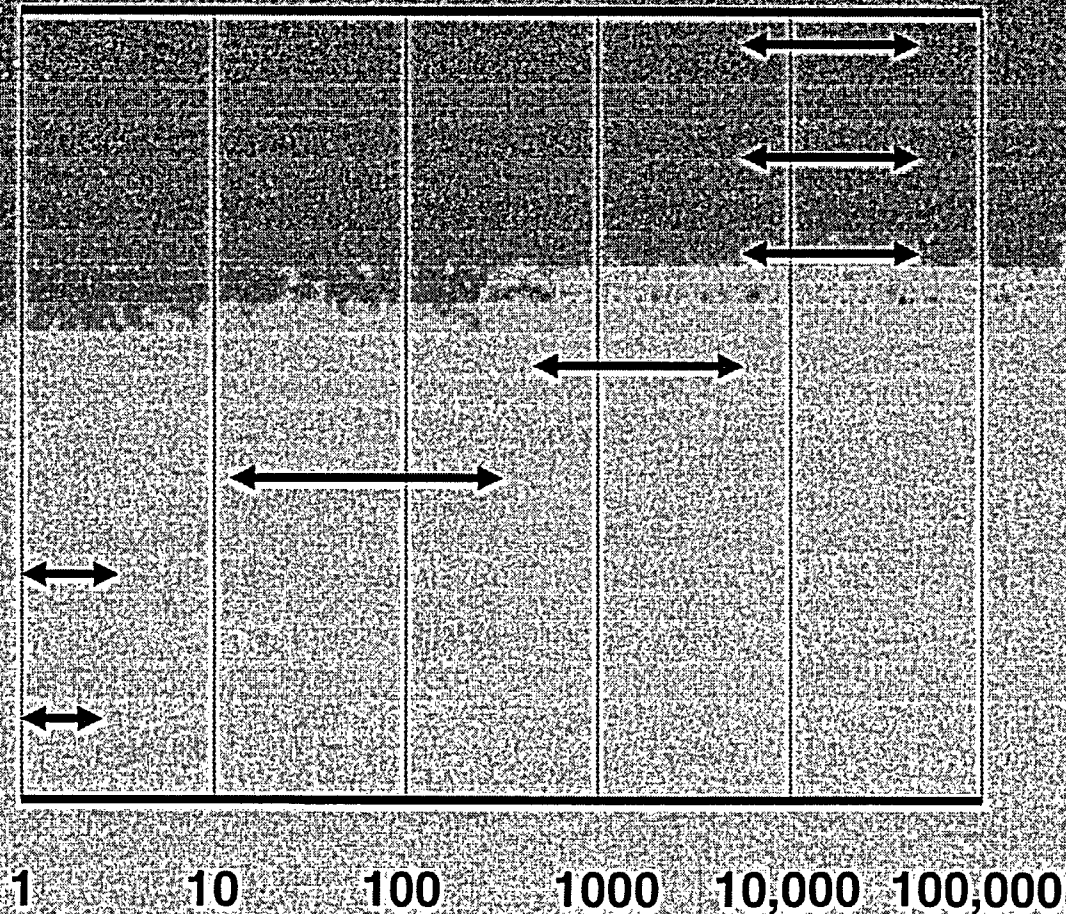
Freeze/thaw

Long-term thermal

Early thermal

Plastic shrinkage

Placement settling

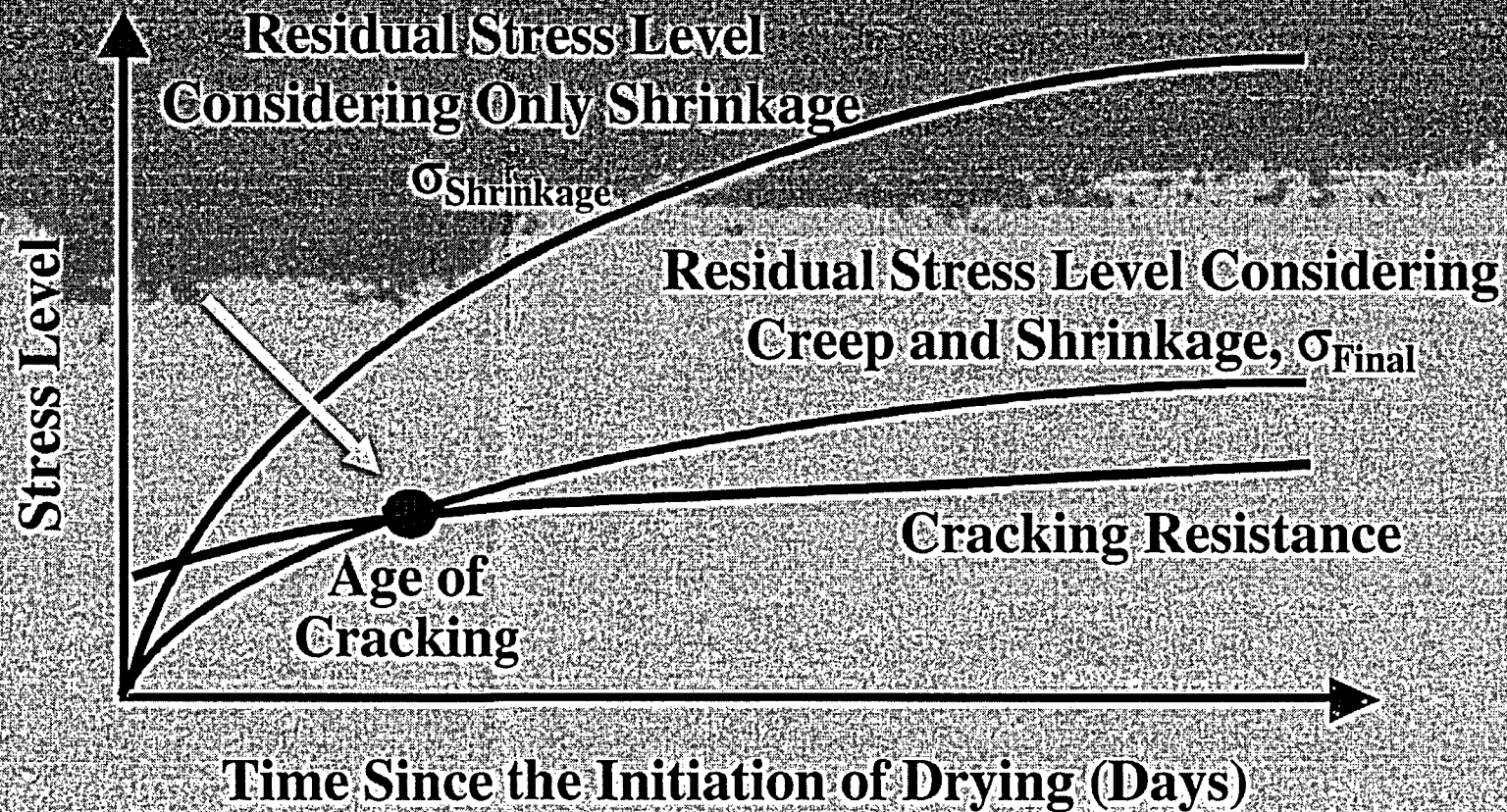


Log hours after casting

The underlying reasons for the development of cracking in portland cement concretes can be attributed to its low *tensile strength*.

Anytime the tensile stresses exceed the materials strengths – cracks develop.

On set of cracking



Creep in concrete is important in minimizing cracking because creep dissipates internal stress as concrete cures.

Creep is inversely related to strength of concrete.

Principal factors impacting cracking in cementitious bodies

- **Chemistry & physical properties
of cement**
- * **External exposure conditions**
 - **mechanical**
 - **environmental**

Properties of cement that impact cracking:

- High C_3S content [low C_2S]
- High C_3A
- High SO_3
- High fineness
- High alkali content

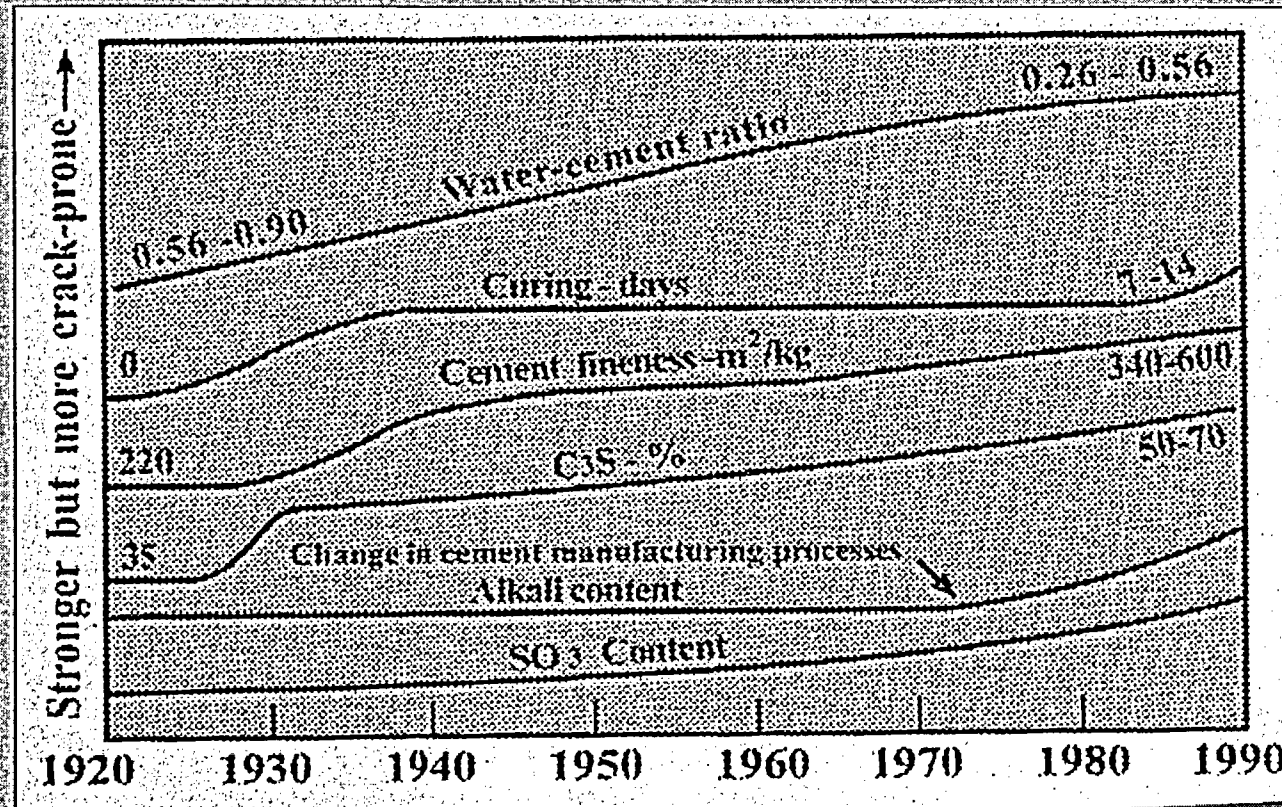
[Burrows, 1998]

Compared with early Blaine [1969] data:

- > SO_3 content is 40% higher
- > K_2O content is 45% higher
- > $\text{C}_3\text{S}/\text{C}_2\text{S}$ ratio is higher
- > $\text{Na}_2\text{O}_{\text{eq.}}$ is 8% higher
- > cements are finer [set faster]

Roy et al. [2003]

Many authors, including Burrows [1998], are convinced that modern cement manufacturing is leading to enhanced cracking [poorer quality]



Burrows [1993]

Change of cement properties with time

**Current cements are manufactured
for rapid hardening.**

**The consequence of these changes
A poorly developed microstructure.**

“slower hydration is better”

Practices that impact cracking:

- Low w/cs
- Accelerating admixtures
- Excessively long curing periods
 - Increases autogenous shrinkage
 - Rapid hydration results in poor quality microstructure
 - Consumes all of the anhydrous cement [eliminates autogenous healing]

External influences on cracking

Mechanical Loading

- * Static Loading

- * Cyclic Loading [fatigue]

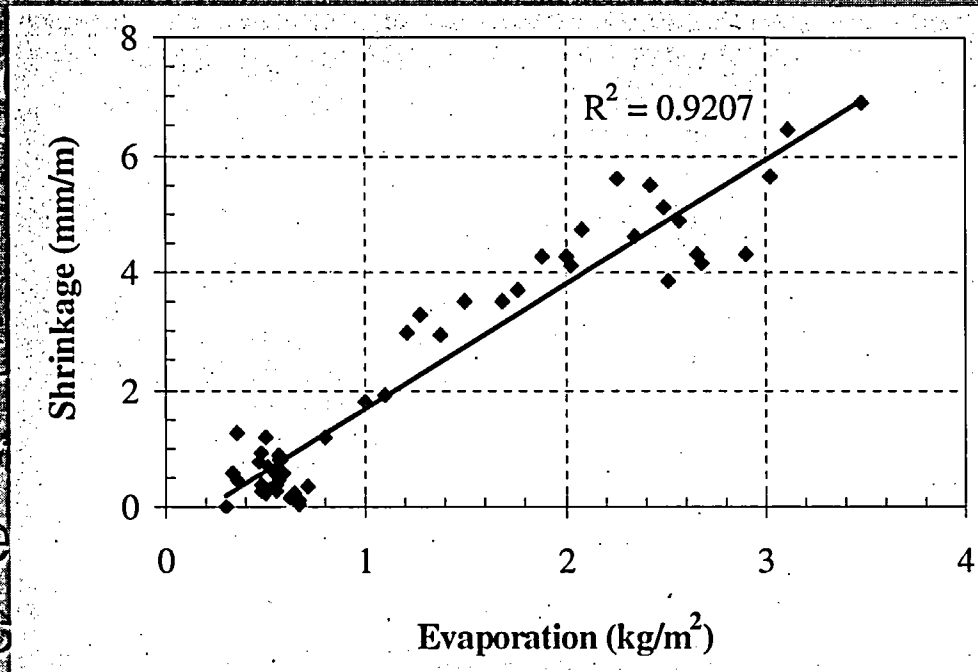
- In stress/strain space, concrete behaves as a nonlinear material
 - * microcracking begins at first loading and continues to failure

Environmental Effects:

* Shrinkage

> Plastic

A short term phenomenon
aggregate settling
of from high temperature
and/or wind. Tends



> Drying Shrinkage

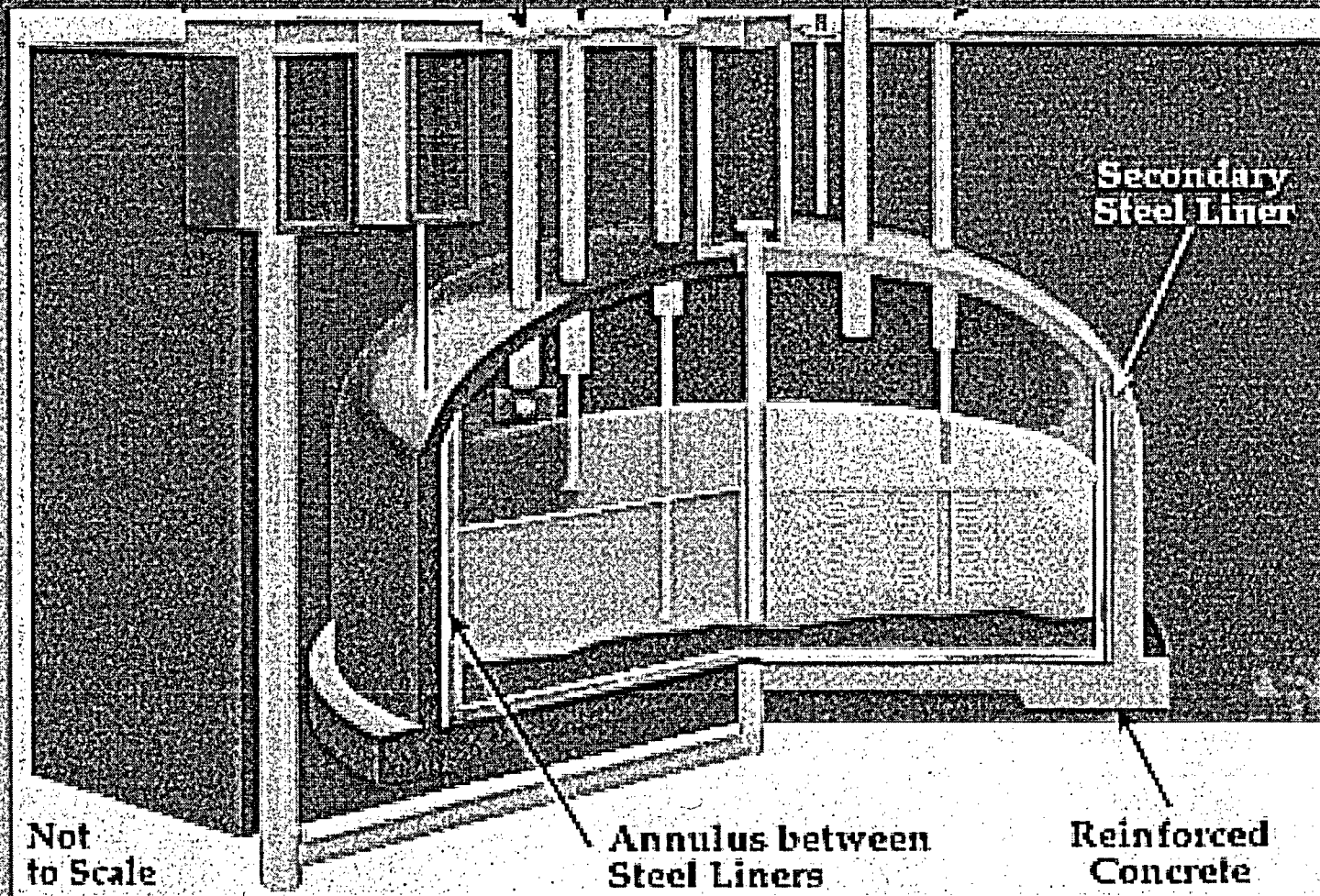
A longer term phenomena related to evaporation

➤ Autogenous shrinkage

Deleterious shrinkage from autogenous shrinkage normally occurs at very early ages and is incurred through the formation of hydration products notwithstanding any other external effects. This type of shrinkage is typically associated with concrete of that has a low w/cm (under 0.40) and includes silica fume.

Environmental Effects:

*Thermal behavior



Environmental Effects:

*Freezing and Thawing

Upon freezing, water expand 9% as it undergoes the liquid/solid phase transition.

The expansion places hydraulic pressure on the pore fluids. Microcracking will develop if the fluid has no where to flow .

Introduction of 5 – 9% air bubbles of 100µm

at a spacing of 20-2mm is used to

Environmental Effects:

*Corrosion

* For corrosion to initiate, moisture and oxygen must be present, in addition to the reduced pH or the presence of chloride ions.

* Corrosion is most deleterious in situations where the concrete is exposed to wetting and drying cycles because this allows for most efficient transport of oxygen and moisture into the concrete to the level of the reinforcing steel. [Leake, 2002]

Environmental Effects:

- * Alkali aggregate reaction

- > Alkali carbonate reaction

- > Alkali silica reaction

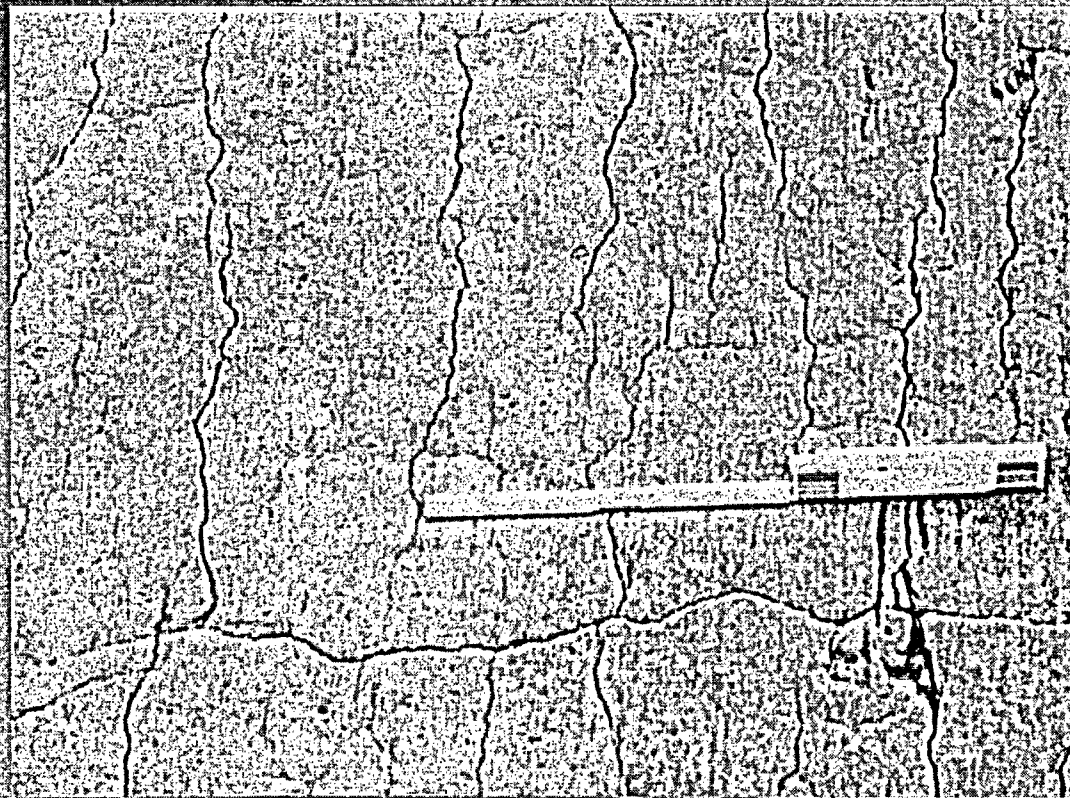
**Carbon dioxide reacts with portlandite
to form calcium carbonate**



*[none of the hydration products of portland cement
is thermodynamically stable with respect to water
and carbon dioxide.]*

**Carbonation is diffusion controlled
and is dependent on relative humidity.
between 50 and 100% RH there is a
maximum of CO_2 up take.**

**Alkali silicate reactions are recognized
by polygonal cracking in the concrete
surface**



The process is complex and no model has yet to be developed.

The evidence to date suggests that there is a 'pessimum' [an optimum] value in the silica to alkali ratio that favors deleterious expansion.

**Alkali silica reaction in concrete
can generally be minimized or
eliminated by the use of
blended cements, the size and
amount of offensive aggregate and
the use of lithium salts**

Alkali carbonate reaction



Dolomite

alkali
hydroxide

brucite

alkali
carbonate

calcite

Environmental Effects:

- * Sulfate attack

- > Alkali

- > Magnesium

- > DEF

- > Ettringite

Ingress of sulfate into the
concrete
reacts with the C_3A content to
form

Gypsum
Ettringite
Monosulphoaluminate

Gypsum:



Monosulphoaluminate:



Ettringite:



Literature data show that the rate of sulfate attack is roughly proportion to C_3A content of the cement

Magnesium attack:



Note the magnesium sulfate reacts with
C-S-H in the set cement

Delayed Ettringite Formation

Ettringite is an essential phase in the hydration of portland cement.

If the cement is allowed to set and temperatures exceed $\sim 65^{\circ}\text{C}$, ettringite becomes unstable with respect to:

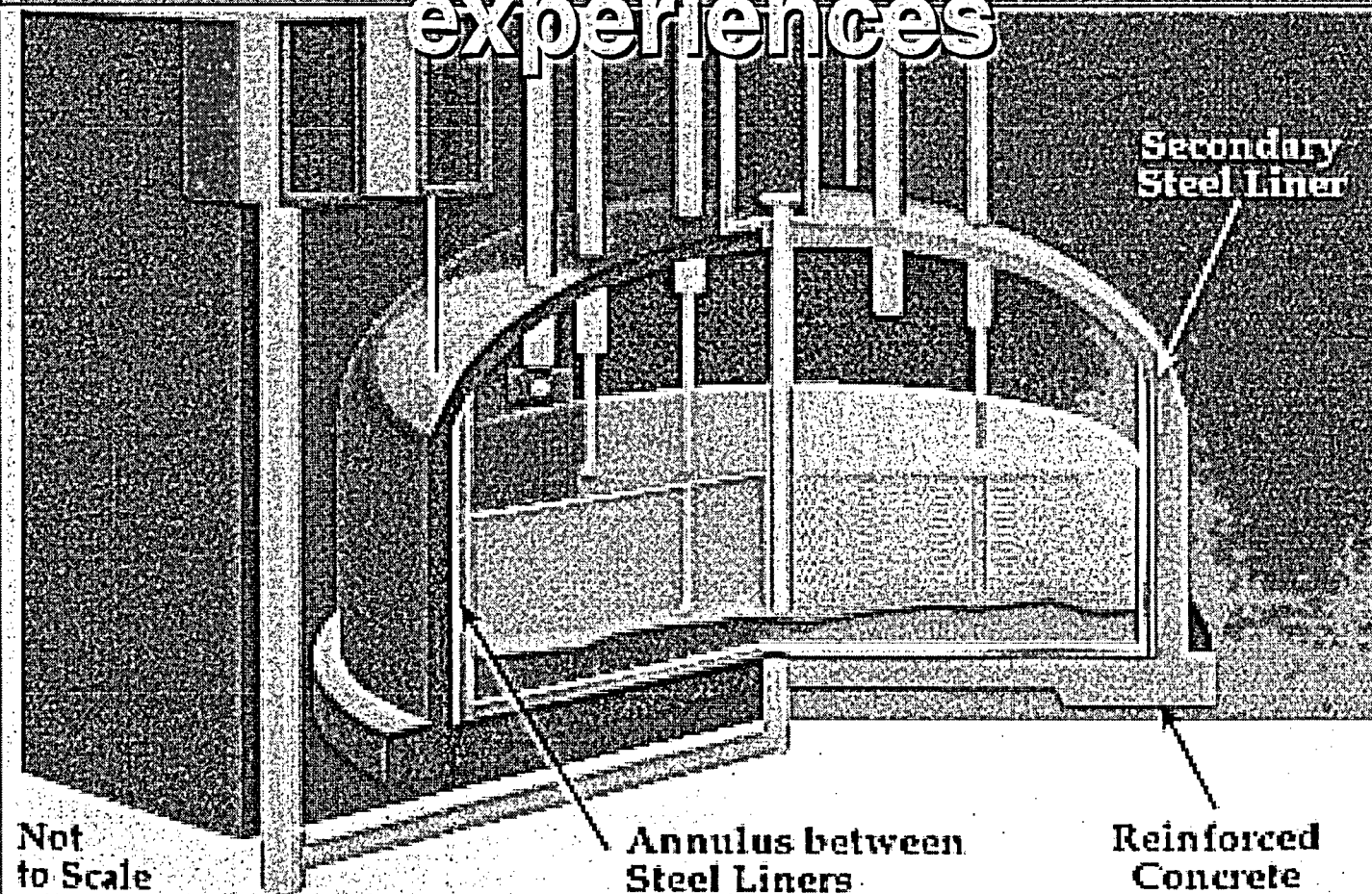
hydrogarnet

$\text{CaSO}_4 \cdot x\text{H}_2\text{O}$ [where $x = 0, 0.5, 1$ or 2]

H_2O

Rehydration will allow the decomposition products to reform ettringite with subsequent expansion.

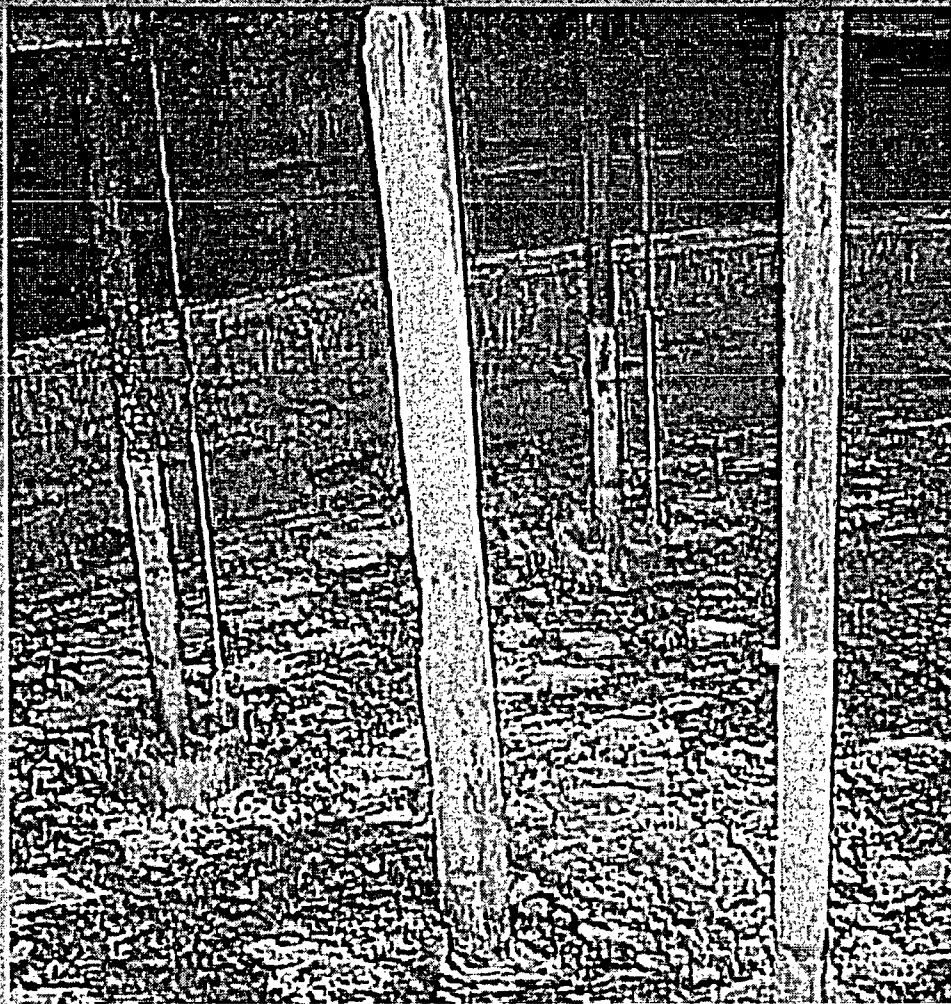
Closure of tanks is not unique to our experiences



C

C

C

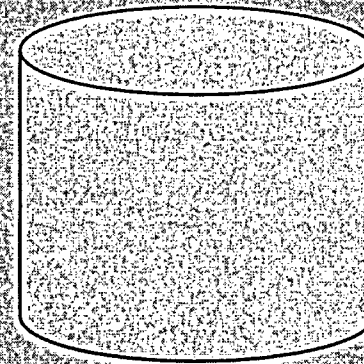


Size and geometry are important considerations:

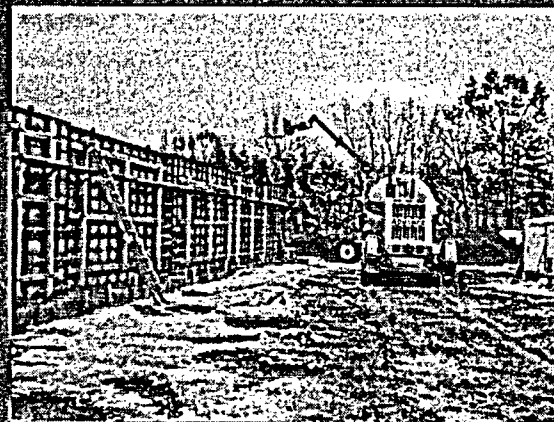
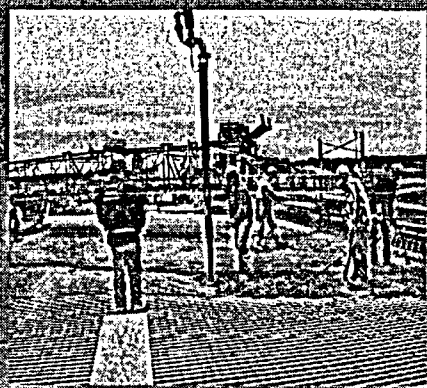
Lab vs. field



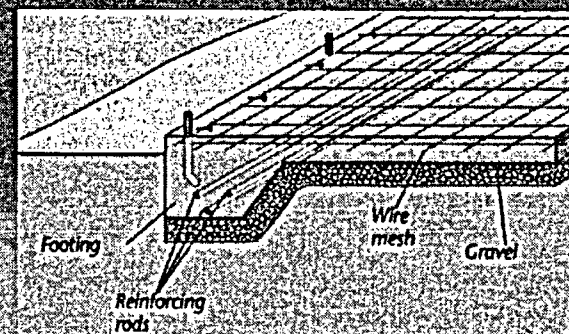
vs.



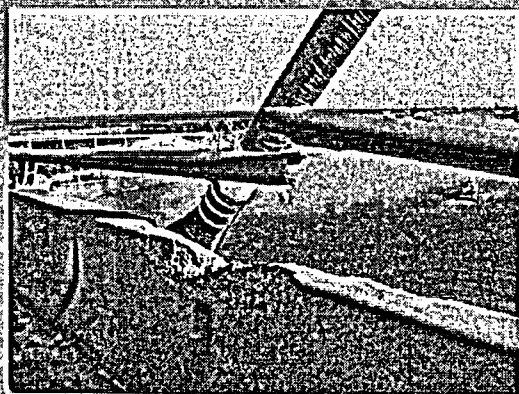
Bridge deck



Foot wall

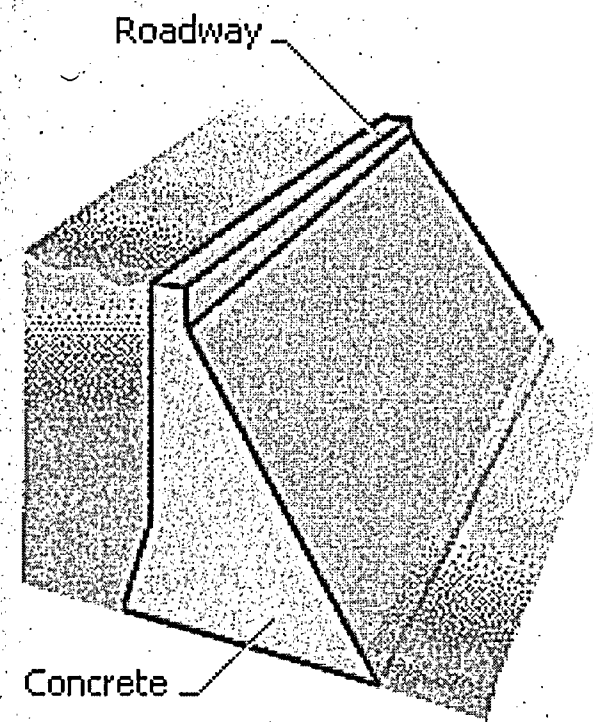


Slab on-grade



Parapet

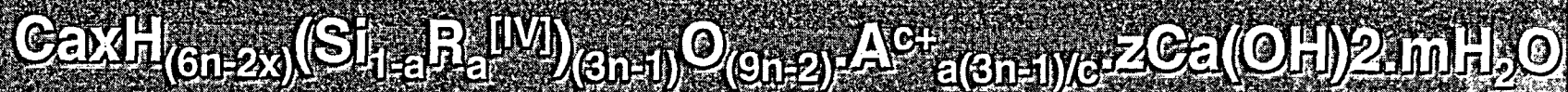
**Common applications
where most experience
in cracking is obtained**



Concrete gravity dam

**Unknowns associated with
the properties of waste substitute
phases such as tobermorite and
ettringite**

Crystal chemical substitution scheme for tobermorite



Where:

$$x=0.5(6n-w)$$

$$z=0.5[w+n(y-2)]$$

$$\text{and for } 0 < y < 2; n(2-y) < w < 2n$$

$$2 < y < 4; 0 < w < 2n$$

$$4 < y < 6; 0 < w < n(6-y)$$

$$\text{and } 0 < a < n-1/3n-1$$

R is a trivalent cation in tetrahedral coordination

A is an interlayer ion

Crystal chemical substitution scheme into ettringite



$(\text{Ca}^{2+})_{\text{VIII}}$

Sr

Ba

Pb

Cd

Co

Ni

Zn

$(\text{Al}^{3+})_{\text{VI}}$

Cr

Si

Fe

Mn

Ni

Co

Ti

(SO_4^{2-})

$\text{B}(\text{OH})_4\text{O}^-$

CO_3

Cl

CrO_4

AsO_4

SeO_4

VO_4

(OH^{1-})

BrO_3

NO_3

MoO_3

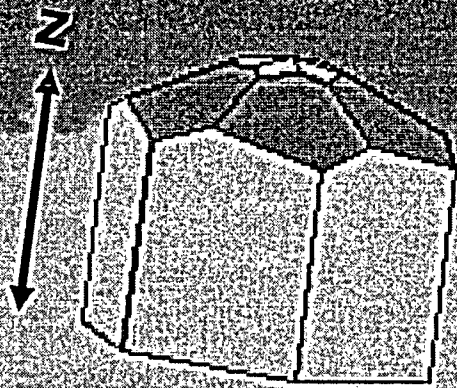
SO_3

IO_3

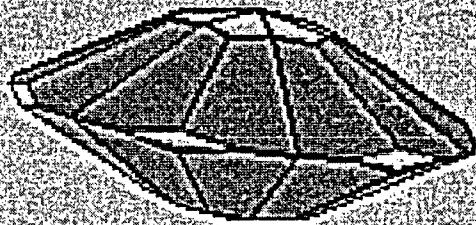
Ettringite has a crystal structure that is

Dihexagonal Dipyramidal ($6/m\ 2/m\ 2/m$)

Typically it is elongated along the z-axis



But when Fe^{3+} substitutes for Al^{3+} in the structure, growth in the z-axis direction is suppressed. Therefore normal problems with cracking from expansion are suppressed or do not occur.



Factors impacting cracking:

C_3S

SO_3

fineness

Alkali content

Low w/cs

Accelerating admixtures

Long curing time [unhydrated clinker]

ASR/ACR

Sulfate attack -- alkali

Sulfate attack -- magnesium

Sulfate attack -- ettringite

DEF

Drying shrinkage

Plastic shrinkage

Thermal contraction

Freeze/thaw

corrosion

Static loading

Cyclic loading

Internal/external restraint