Pull-Out Strength, Durability, Curing and Servíce Life

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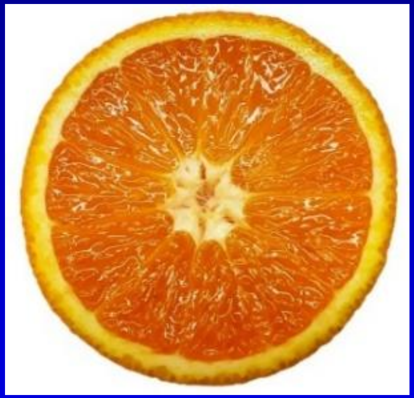
For durability, the cover layer protecting the reinforcement of a reinforced concrete structure is the important part,

Exactly as the PEEL of an orange protecting its enterior



In structures this PEEL has to have the right quality, be well compacted,, have sufficient thickness, be without cracking and be well cured during hydration

CURING

Enables more durable & stronger concrete

Proper hydration, requiring:

Suffient Moisture Content,

Temperatures 10^{o}C – 35^{o}C

Min. 7-Days Curing **And** for Time Necessary to attain 70% of the Specified Strength

Unhydrated and hydrated PC

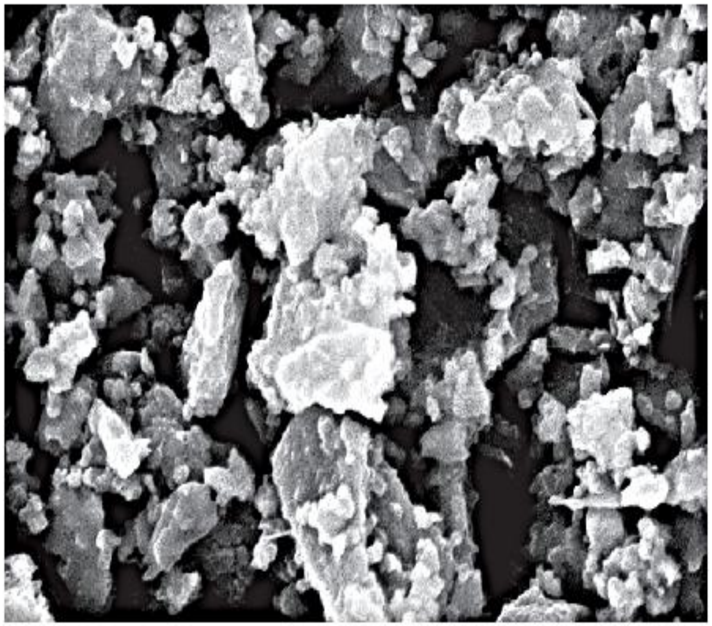


Fig. 1.3.1a—Unhydrated particles of portland cement—magnification 2000× (Soroos 1994).

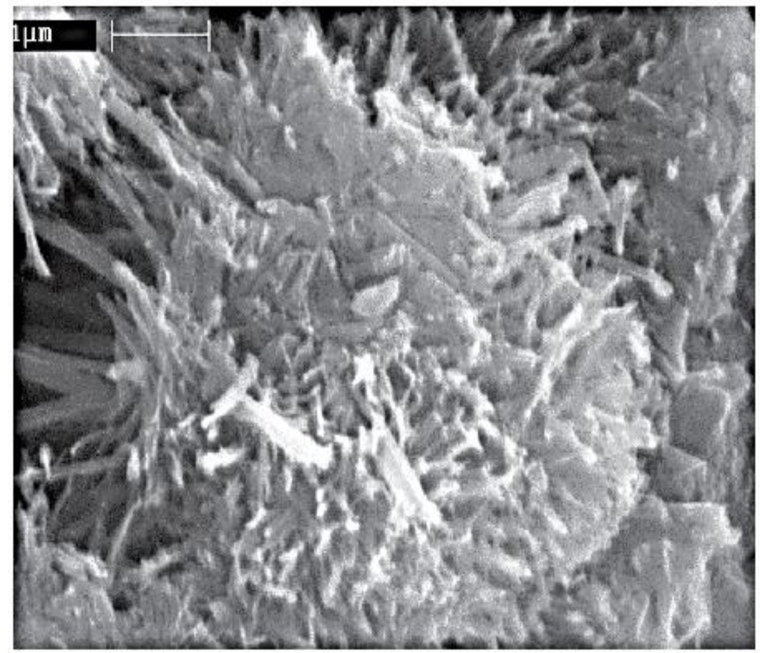
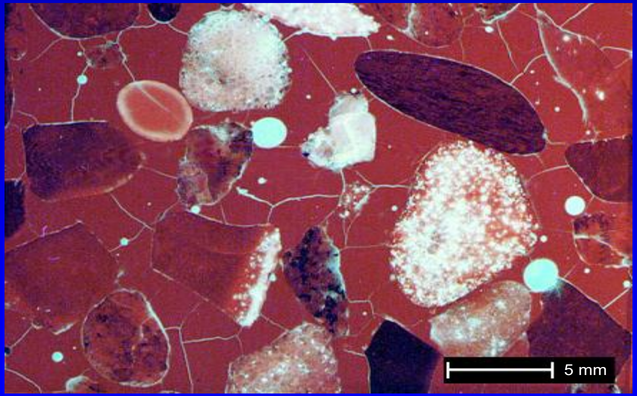


Fig 1.3.1c—Close-up of single particle of hydrated cement—magnification 11,000× (Soroos 1994).

Source: ACI 308R-16 Guide to External Curing of Concrete Reported by ACI Committee 308

Extreme examples of bad compaction,
no need for testing !



Example of cracking,
autogenous shrinkage

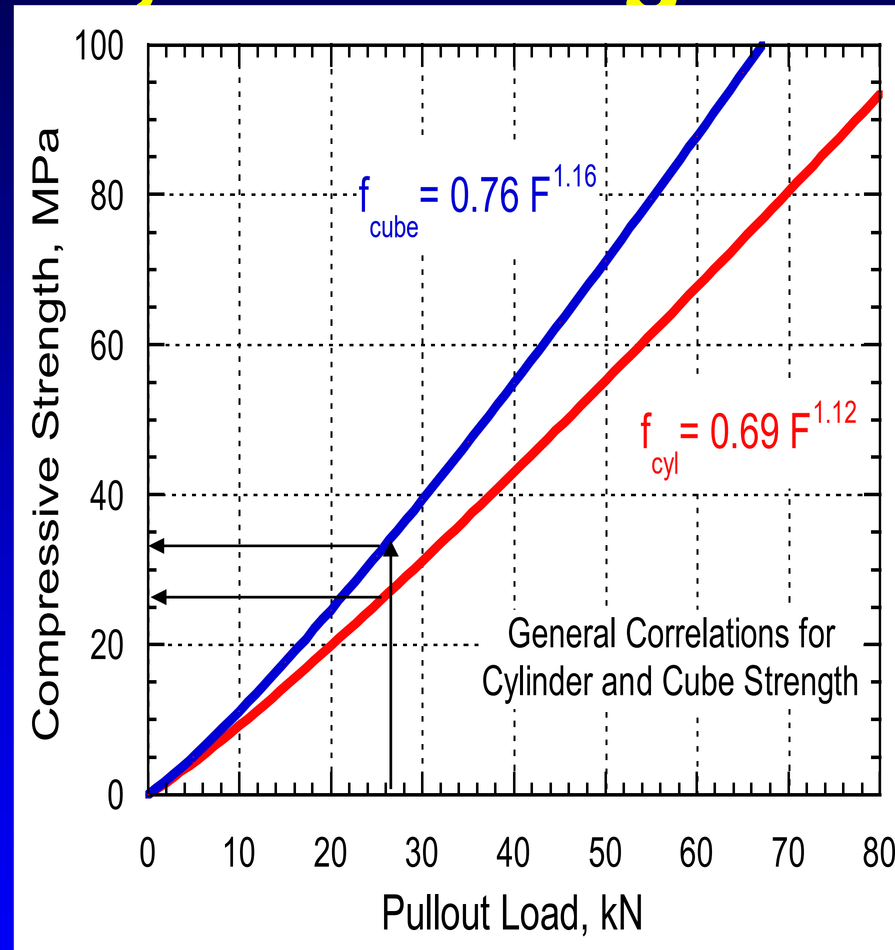
Curing methods, immediately after finishing

- Curing compounds
- Plastic sheets
- Apply wet materials
- Sprinkling or fog spraying
- Ponding with water
- Keep formwork on !

Alternative method: Internal curing using LW fine aggregates or water absorbent polymers

LOK-TEST

Pullout force F in kN, “H” for Highest



F = 27.4 kN ➔ f_{cyl}=28.1 MPa or f_{cube}=35.4 MPa

(Cubes 25% higher than cylinder strength)

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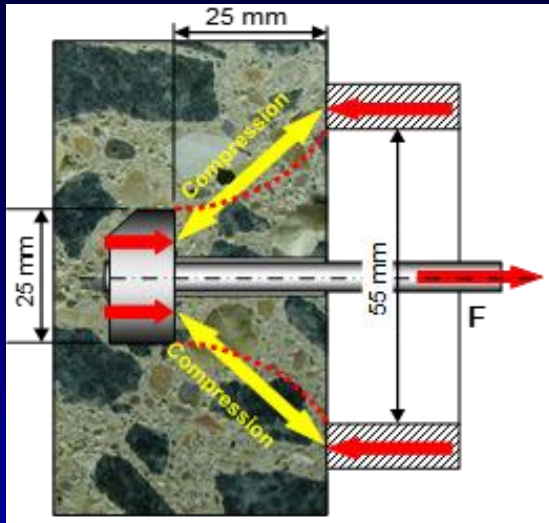
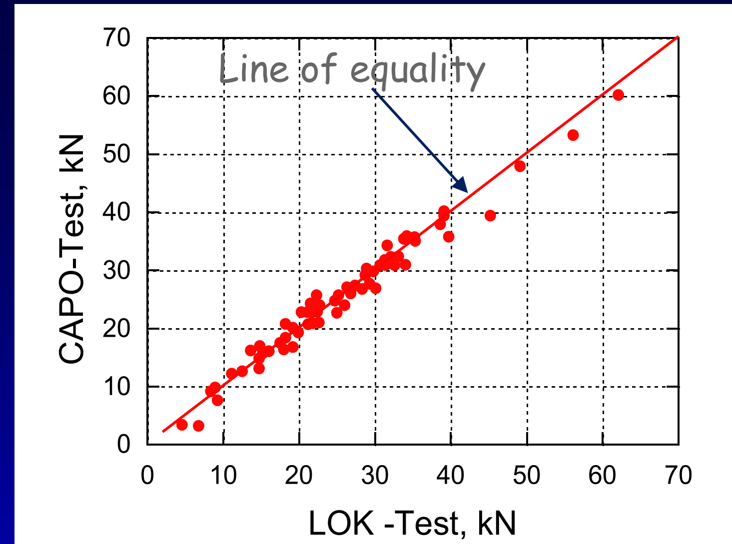
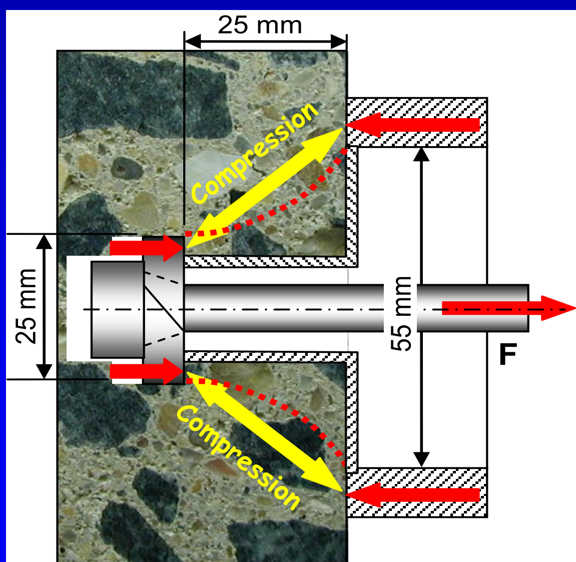


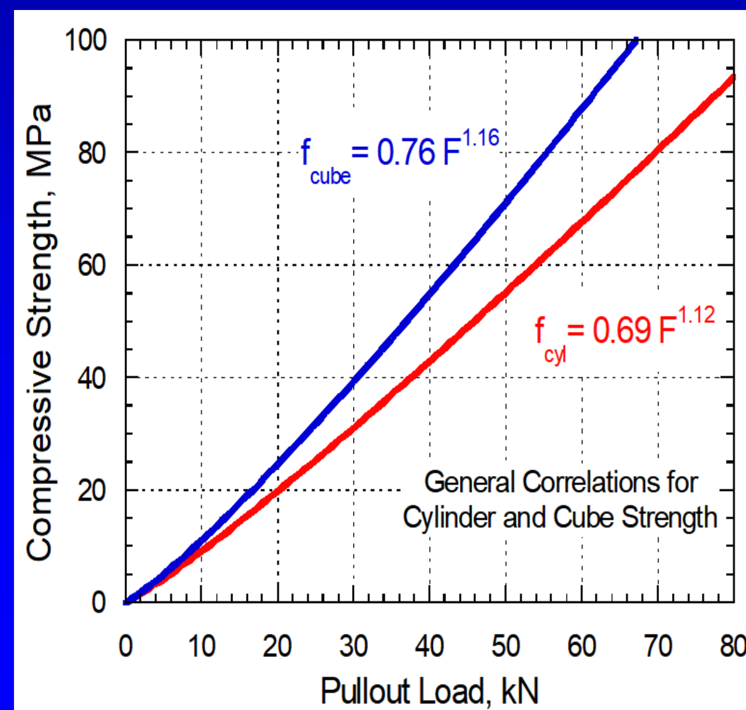
LOK-TEST



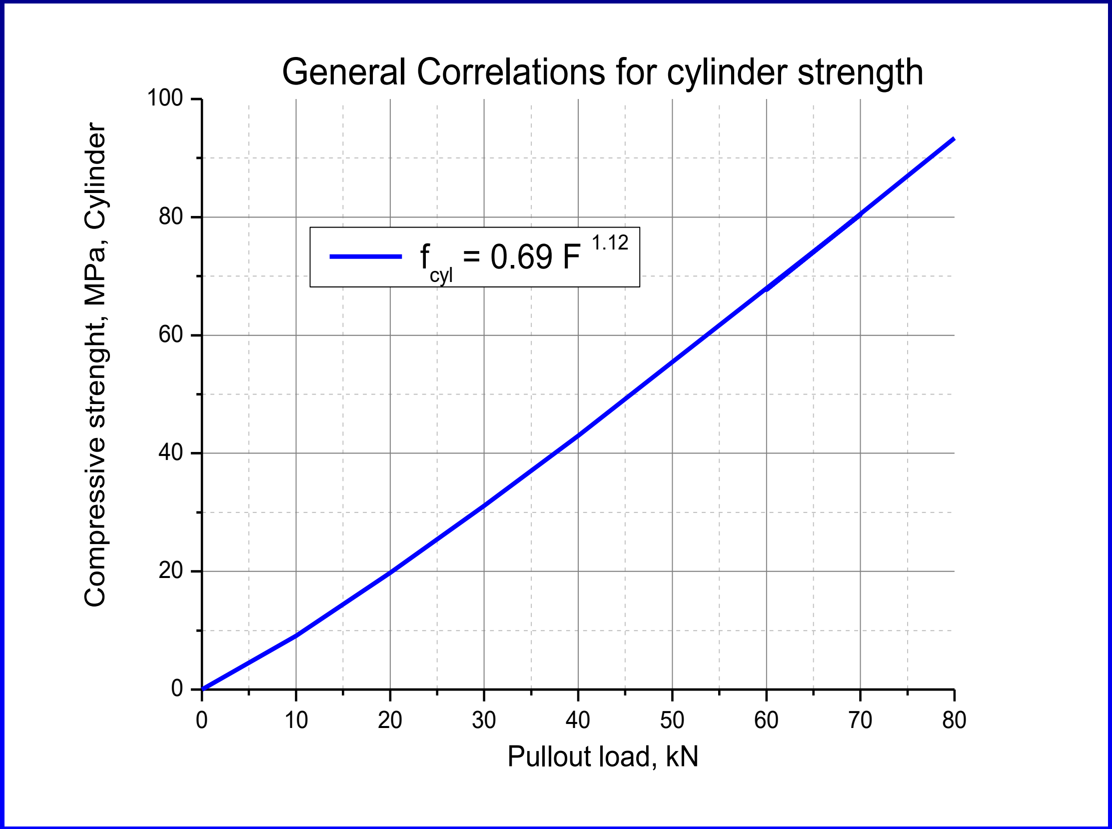
Robust, General Correlations



CAPO-TEST



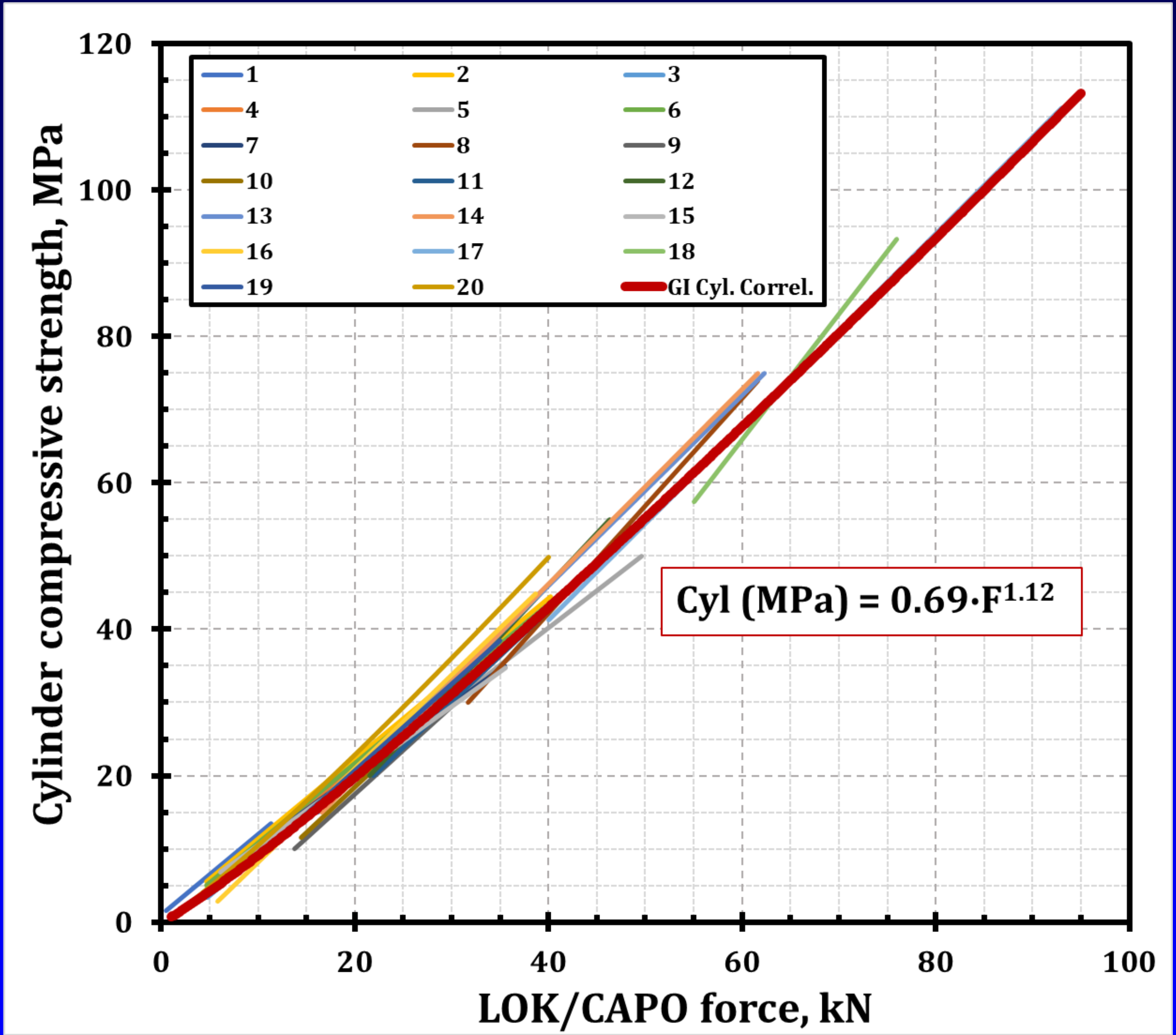
Correlation, pullout to uniaxial compressive strength also of the COVER LAYER



Parameters investigated

- Cementitious materials
- Water-cement ratio
- SCC mixtures
- Fibers
- Age
- Air entrainment
- Admixtures
- Curing conditions
- Age and depth of carbonation
- Stresses in the structure
- Shape, type or size of aggregate < 40 mm

Summary



Cylinder compressive strength, MPa
LOK/CAPO force, kN
0
20
40
60
80
100
120
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
GI Cyl. Correl.
Cyl (MPa) = 0.69·F1.12

Summary

Testing range: 1.5 MPa – 110 MPa
Nos of cylinders: 2642
Nos of LOK / CAPO-TEST: 3824

Average variations and correlation coefficient

LOK / CAPO-TEST		Cylinders		Rxy
S (kN)	V (%)	S (MPa)	V (%)	
2.6	8.8	2.1	5.3	0.95

Influence of curing on LOK-TEST

LOK- Testing after 28 days

Water cured "W"

W/C-ratio	No of cubes	Average of	LOK-Strength (kN)
0.50	5	10 LOK-TEST	49.4 [1)]
0.36	5	10 LOK-TEST	58.7 [2)]

1) Equiv. to 54.2 MPa Cylinder strength, 2) Equiv. to 66.0 MPa Cylinder strength

Combined curing "C" air

W/C-ratio	No of cubes	Average of	LOK-Strength (kN)
0.50	5	10 LOK-TEST	45.7
0.36	5	10 LOK-TEST	55.5

Mistreated "M" air and wind

W/C-ratio	No of cubes	Average of	LOK-Strength (kN)
0.50	5	10 LOK-TEST	29.8
0.36	5	10 LOK-TEST	40.3

Example, 45 large Columns cast horizontally outside, no curing, 181 CAPO tested with cores for comparison

Testing conducted by Eng. Jesper Stærke Clausen, CET

Trykstyrke CAPO Test	Trykstyrke kerner
MPa	MPa
70,4	97,5
66,1	99,1
59,6	100,4
69,9	98,0
81,3	99,6
60,8	95,6
58,8	95,2
53,2	96,8
66,8	93,4
74,3	97,6
77,0	91,2
75,9	99,9

Initial limited comparison:

12 Cores and 12 CAPO-TEST

CAPO average 67.8 MPa
CORE average 97.0 MPa

Reduction in cover strength 30% compared to the "interior"

NOTE: CAPO measures the compressive strength in the 25 mm cover layer, cores the compressive strength in ~100 mm depth, NOT THE COVER

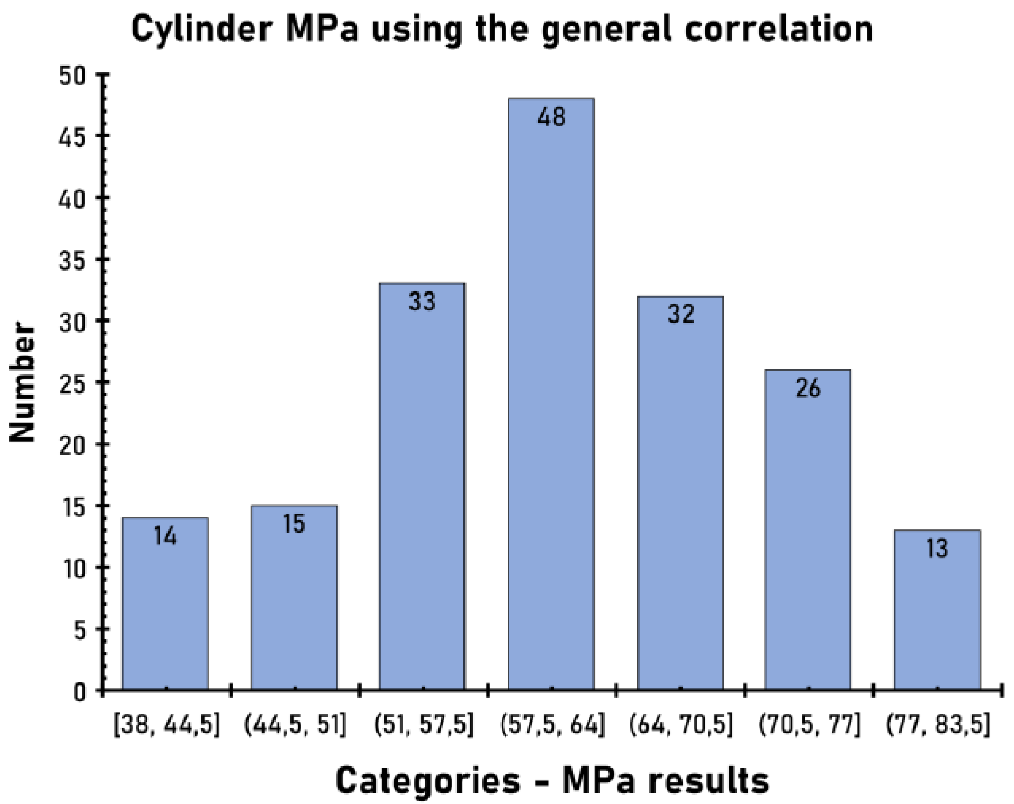
CAPO-TEST, 4 in each column

CAPO-TEST on high strength columns erected in a hotel

Columns tested in different heights

Columns 4 m long, 60 cm x 60 cm in square

181 CAPO-TEST´s



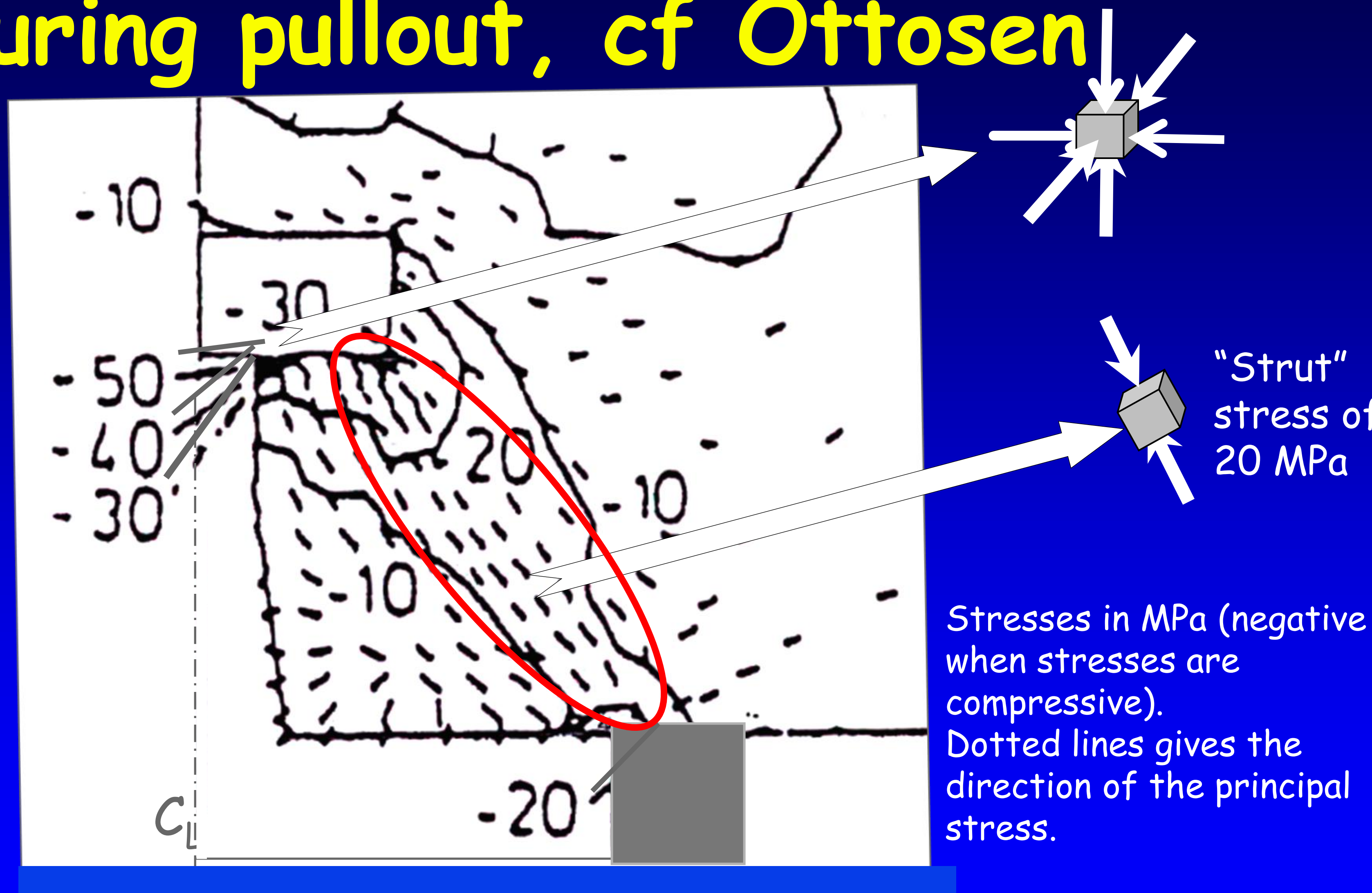
Compression Failures

110 mm
-140 mm

100 mm dia

Capo-Test failure above,
Core failure to the right,
compression zones in the ellipses

Stress curves at 65% loading during pullout, cf Ottosen

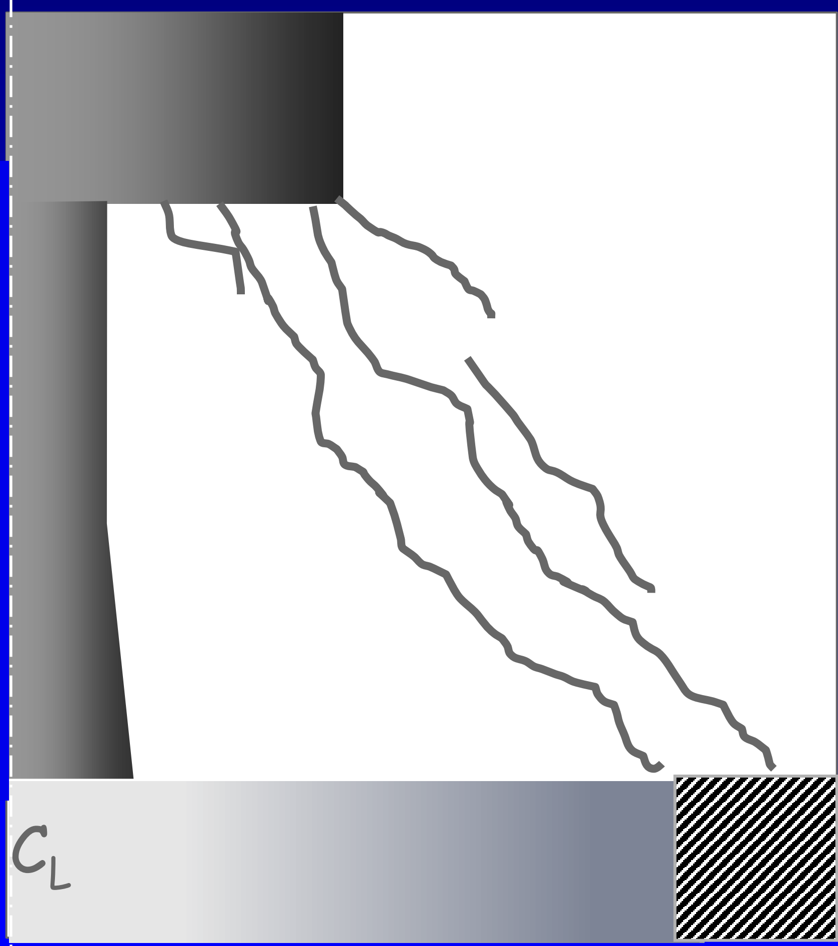


Stresses in MPa (negative when stresses are compressive).
Dotted lines gives the direction of the principal stress.

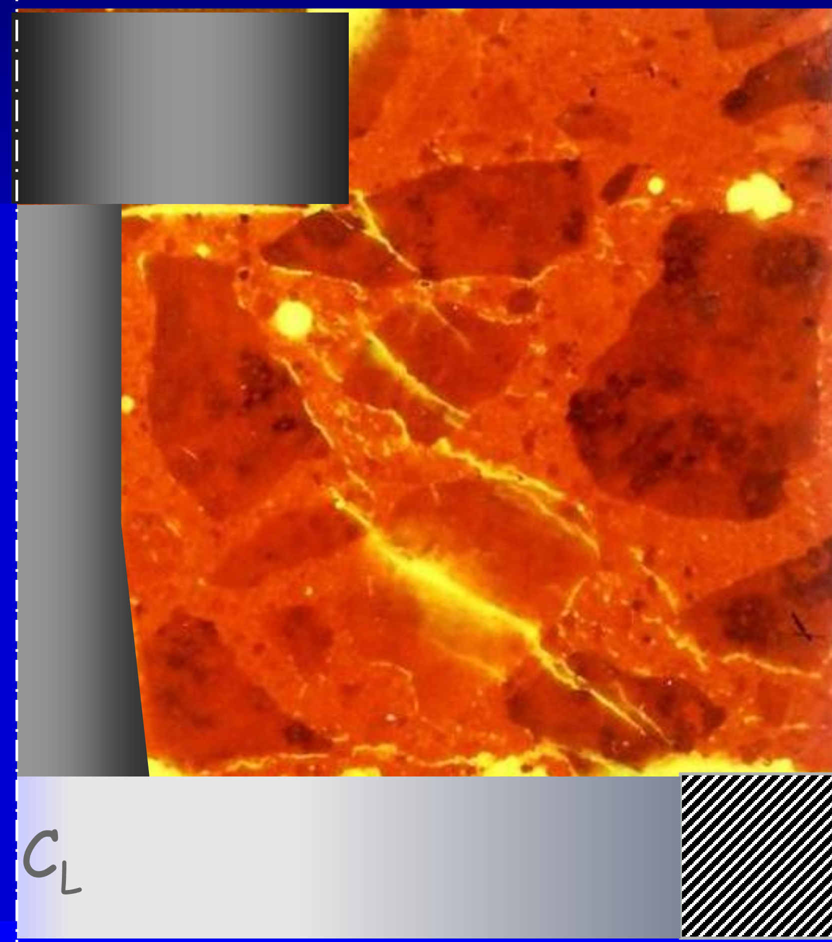
Calculations are made for a uniaxial compressive strength of 31.8 MPa. Note the much higher stresses (up to 50 MPa) are present right below the disc due to concentrated tri-axial loading in this area.

Compressive cracking, 98% loading, Finite element analysis and experimental analysis

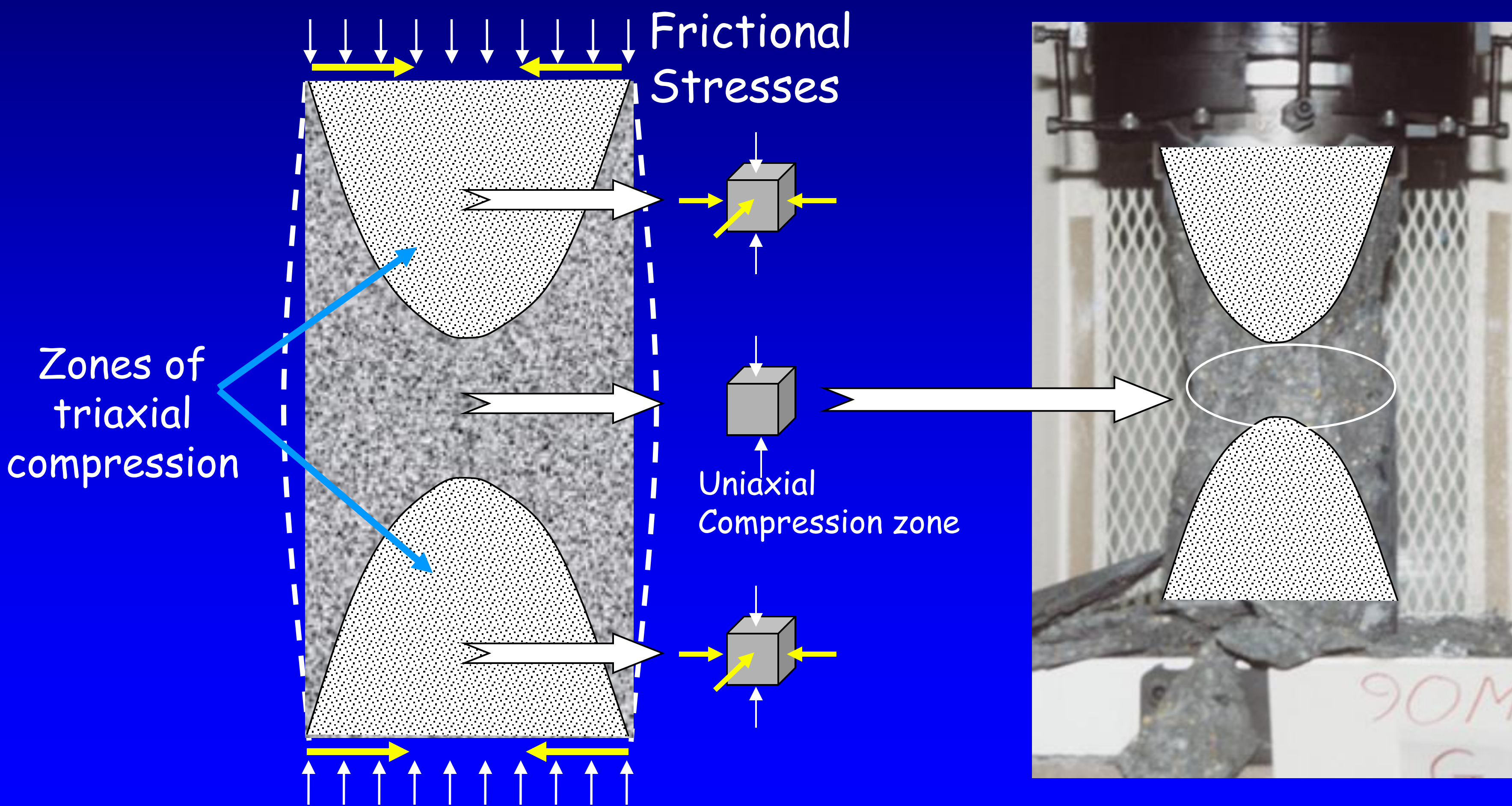
Ref.: Ottosen, N.S.: Nonlinear Finite ElelementAnalysis of Pull-Out Test, JSD, ASCE, Vol. 107, No ST4, April 1981



Krenchel, H. & Shah, S.P.: "Fracture analysis of the pullout test", Dept. of Structural Engineering, Technical University of Denmark, RILEM, Materials and Structures, Dunod, Nov-Dec. 1985 no 108



Cores or standard cylinders, Uniaxial compression in the middle Triaxial Compression at end faces



REMEMBER

- 1. For DURABILITY the critical part of a concrete structure is the cover layer protecting the reinforcement
- 2. The compressive strength of the cover layer is ALWAYS lower than the interior because of curing, mainly
- 3. Only pullout by LOK-TEST or CAPO-TEST measure the compressive strength directly of the cover layer based on one robust correlation covering all normal concrete mixes.
- 4. Cores are not measuring the compressive strength of the cover layer, strength estimation is half the depth of the core, for a 200 mm deep core, a depth of 100 mm – outside the cover

MERLIN
for Bulk Conductivty / Resistivity

Testing with pullout and bulk resistivity

Example: C40/C50 aggressive class concrete, 56 days old

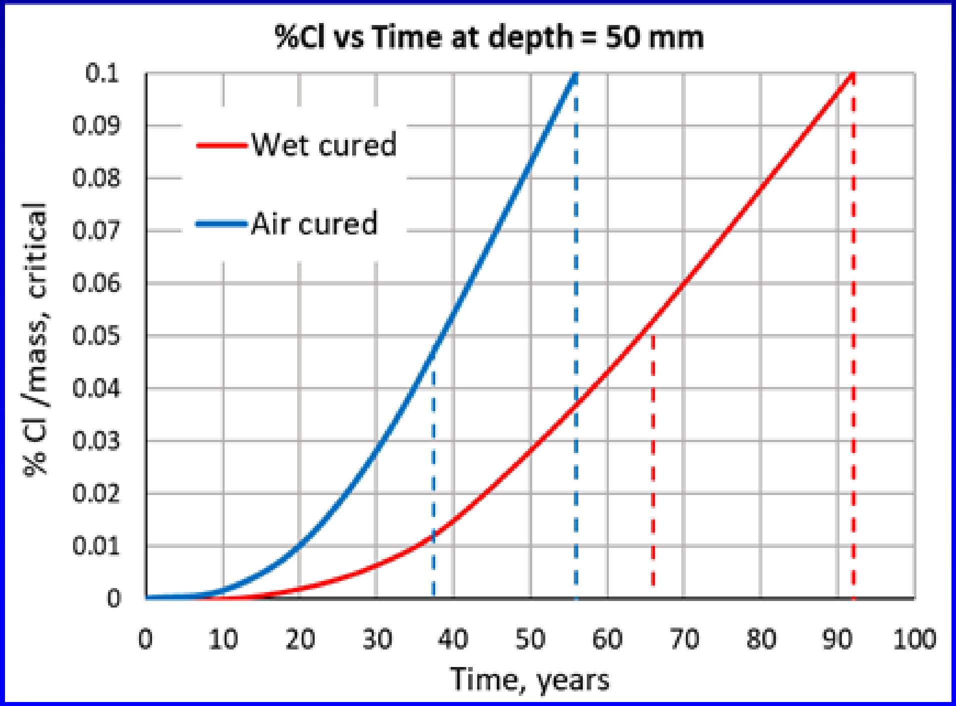
Pullout LOK-TEST

Curing	LOK-TEST
Wet cured	42.7 kN
Air cured	33.0 kN

Bulk Electr. Resistivy - MERLIN

Curing	Resistivity
Wet cured	**r = 166 Ωm**
Air cured	**r = 111 Ωm**

MERLIN resistivity testing of the 50 mm cover layer for two curing conditions resulted in 166 Ωm for wet curing and 111 Ωm for air curing. These resistivity values can be transformed to a chloride diffusion coefficient, D_a, using the ***Nernst-Einstein relation***. Wet curing corresponds to a chloride diffusion coefficient of 27.2 mm^2/y and air curing to 41.5 mm^2/y. By means of the ***Life 365TM Software***, based on Fick's second law of diffusion, the expected service life in years, t, can then be estimated:



Critical Chloride level	Service life	
	Wet curing	Air curing
0.050% Cl^-/mass	66 years	37 years
0.100% Cl^-/mass	92 years	56 years

For a 50 mm cover layer and sea water splash exposure condition, the estimation shows about a 40% reduction of the service life regardless of the critical limit for corrosion of the reinforcement is considered to be 0.050% Cl- or 0.100% Cl- by concrete mass. For miscured concrete (wind and higher temperature), the reduction would be much larger.

Final influence on service life

LOK-TEST showed a 23% strength reduction
MERLIN a 33% reduction in bulk resistivity
Service life reduced by 40% in a splash zone
of a sea structure

Wet cured – Air cured

LOK-TEST showed a 23% strength reduction
MERLIN a 33% reduction in bulk resistivity
Service life reduced by 40%

In this manner, a quick on-site strength test, the LOK-TEST, will immediately indicate the cover layer quality. If lower than expected, cores may be drilled and sliced for further testing of the cover layer with the MERLIN for bulk resistivity (or its inverse, conductivity) and estimating the remaining service life.

Examples

Great Belt Link, Denmark

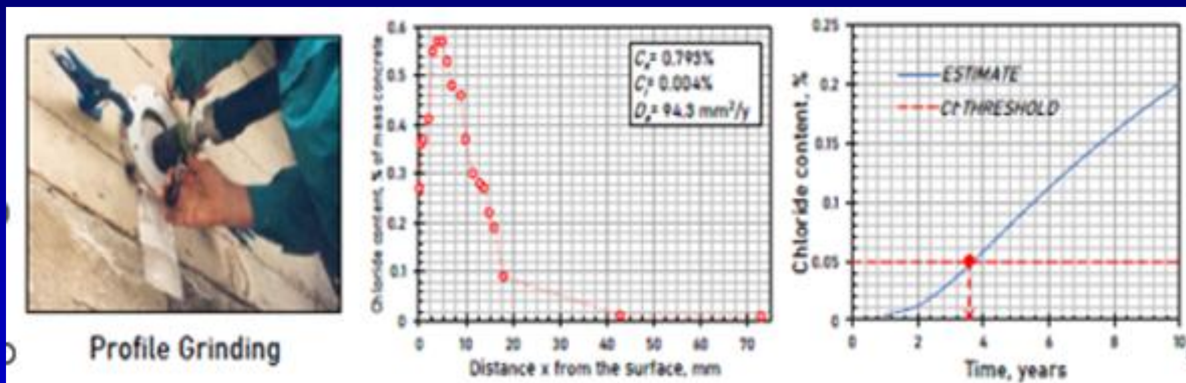
Strength by pullout accepted if the strength was 90% of the potential lab cyl. strength

Supporting sea wall, Copenhagen, Air cured. Pullout strength was 70% of lab strength

Tunnel lining segments, UK cured in a curing tunnel. Pullout strength matched lab cube strength

Garage parking slab, UK Pullout deeper matched the cyl. lab strength

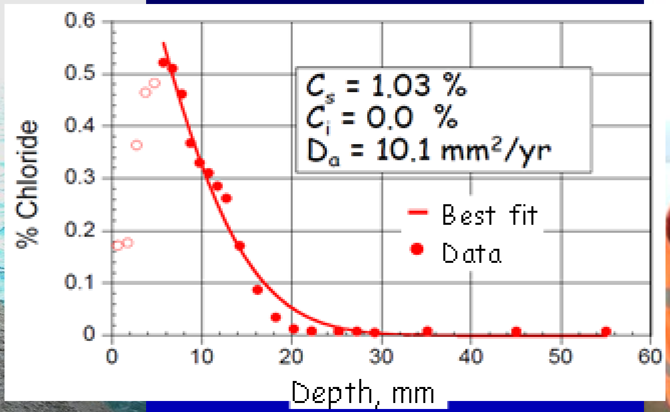
Examples of low service life SL due to very bad cover layers and presence of chlorides / carbonation



Remaining SL after profile grinding: 3.5 years of a Danish sea wall

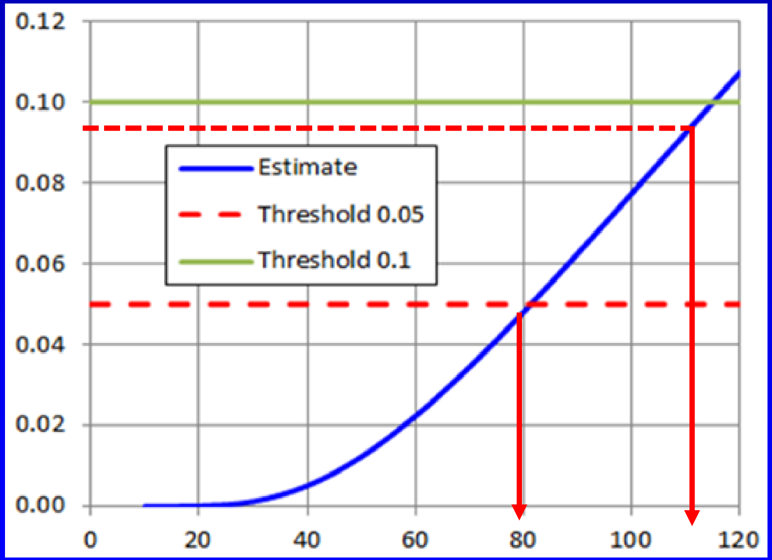
SL of Slab in KSA 11 years, Norwegian beam 14 years and 7 years for highway columns USA subjected to chlorides

Example of long Service Life SL



Mixes in the Mediterranean bridge were tested carefully during construction, e.g. with the PROOVE´it (< 300 Coulombs)

- 5 years later, testing by profiling and RCT.
- Reflects the average history of the exposure to chlorides
- Not affected by ambient conditions
- Fast to perform

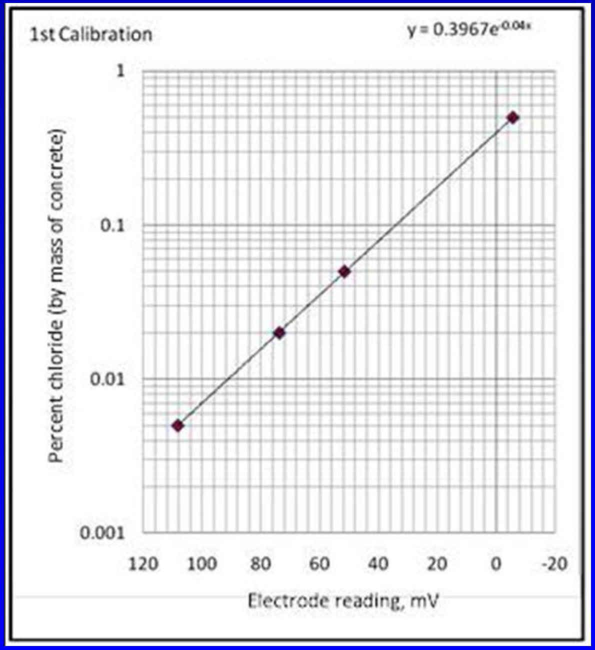


Profile Grinding, step 1

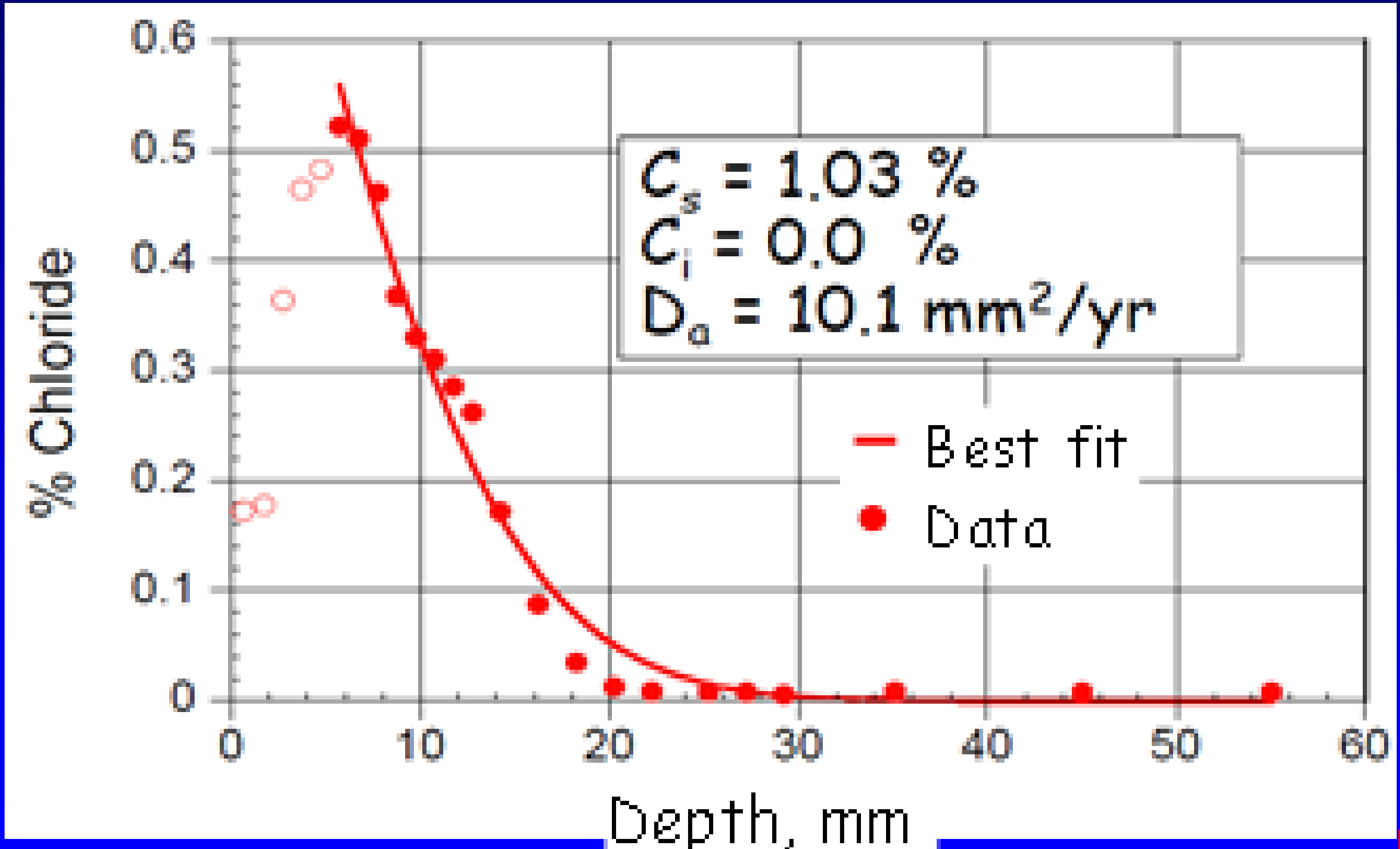
Powder samples obtained quickly at required depth, increments as required (usually 1 mm) tested right afterwards with RCT to establish the chloride profile

RCT measurement, step 2

- The chlorides are measured in each dust sample
- With a calibration curve, determine chloride ion content with a Chloride selective electrode by the RCT method.



Establish Cl^- profile, step 3



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Service life estimation, step 4

A simplified, conservative method for Service Life estimation is applied assuming:

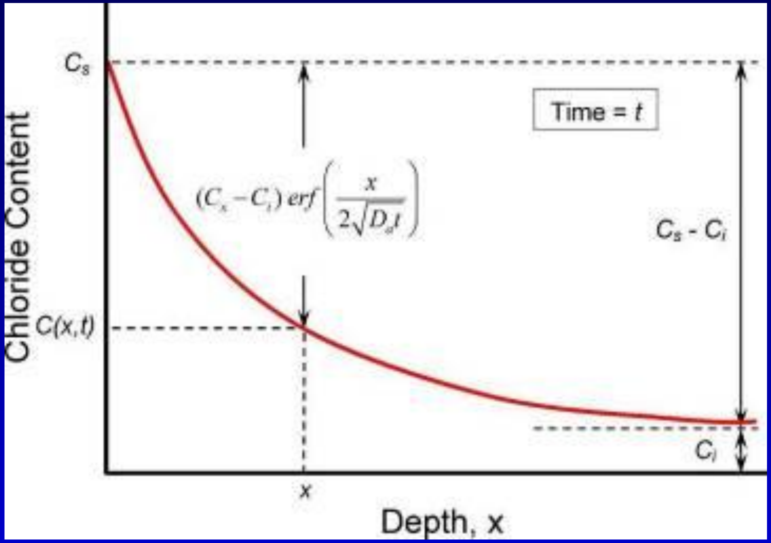
- Service life controlled by initiation of corrosion
  - Time to reach chloride threshold at depth of reinforcement
- Chloride penetration governed only by diffusion
- The diffusion coefficient remains constant
- The surface chloride ion content remains constant
- Concrete remains with similar saturation conditions
- No temperature effects are considered

Fick´s Second Law, step 5

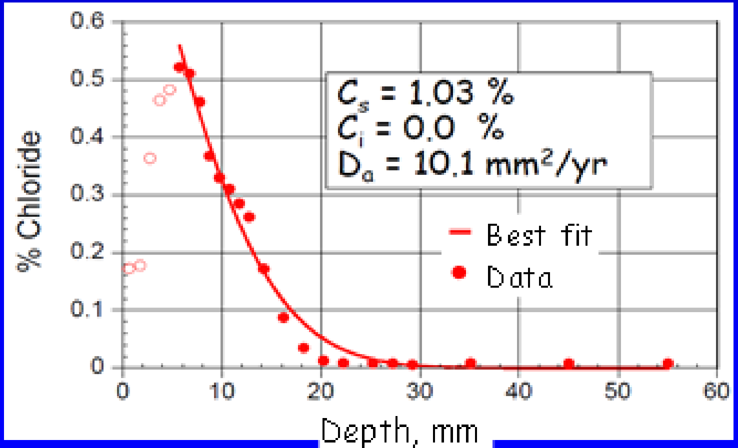
The solution to Fick's second law of diffusion is used:

$$\frac{\partial C(x,t)}{\partial t} = D_a \frac{\partial^2 C(x,t)}{\partial x^2}$$

$$C(x,t) = C_s - (C_s - C_i)\, erf\left(\frac{x}{2\sqrt{D_a t}}\right)$$



With the profile data, the values of Cs, Ci and Da are determined with the least squares method to best fit the equation of chloride content versus depth (x). E.g. with the Solver function of MS Excel.



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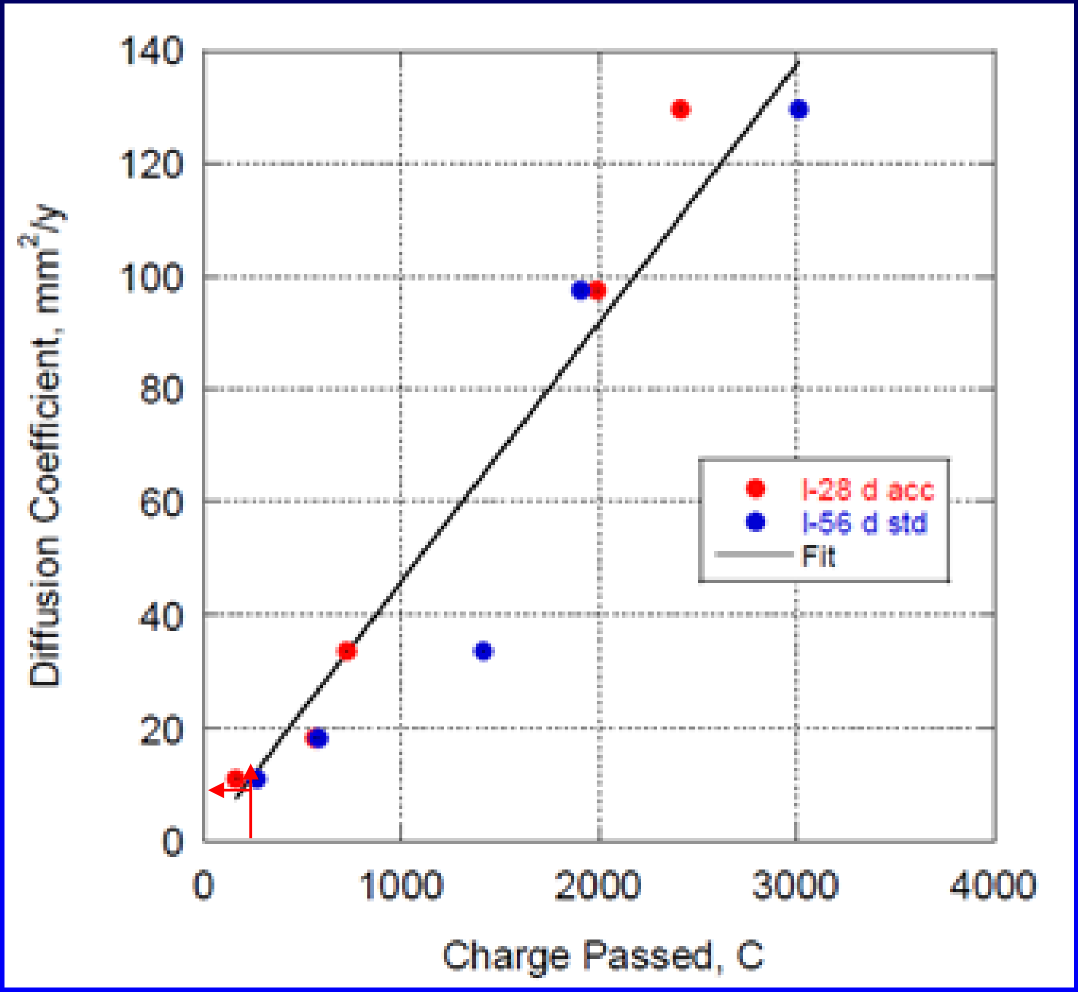
NOTE

The mixes used on the project were prior to start up tested by the PROOVE´it, and the value was measured to C=300 Coloumbs by the RCPT. This relates to an approx. diffusion coefficient of ~10.1 mm²/year, as was found by Profile Grinding / RCT / Figg´s Second Law, slide 32



Service life (SL) step 6

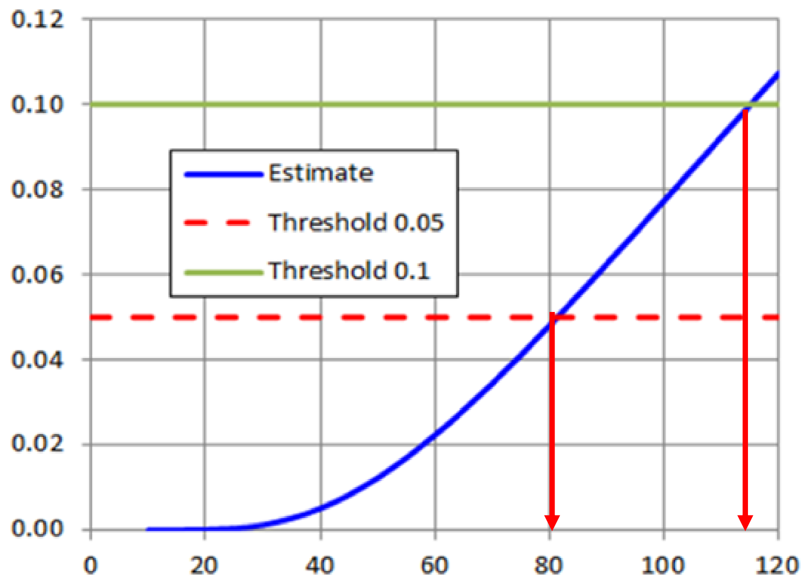
With the apparent coefficient of diffusion Da = 10.1 mm^2/yr,

the service life can be estimated for a given cover layer thickness and a certain assumed chloride threshold value:

Cover layer = 80 mm

For 0.05% by weight of concrete, SL ~ 80 years

For 0.1% by weight of concrete, SL ~ 115 years



Conclusions

1. For new structures the cover layer quality can be measured quickly and reliable by LOK-TEST / CAPO-TEST as the first step, and if too low compared to the potential strength supplemented by resistivity measurements by the MERLIN on cores (slide 22-26) transformed to chloride diffusion coefficient and service life (slide 36). Note that cores will not give the compressive strength at the surface layer, only LOK-TEST/CAPO-TEST will.
2. The mixes in a project - where chlorides are present in the environment- should be measured by the PROOVE´it, equally important as the compressive strength, if not more.
3. The PROOVE´it RCPT Colombs will give a good indication of the diffusion coefficient to be used for Service Life estimation if the in-place concrete quality is as when tested initially.
4. The actual Service Life of an existing structure can be estimated by Profile Grinding and RCT establishment of the chloride profile and using Fick´s Second Law of Diffusion (slide 29-36)

Thank you

Questions?

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