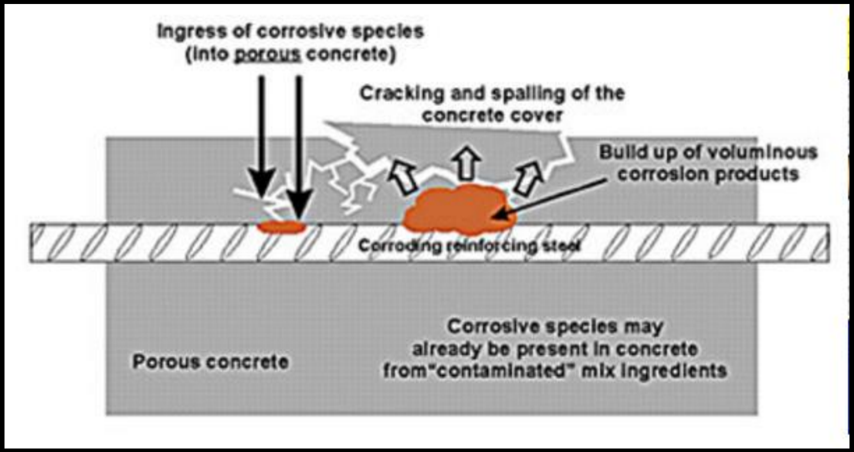
THE HIDDEN WEAK LINKS LEADING TO REINFORCED CONCRETE CORROSION

CHRISTINE COURTEL

18 November 2016

What is nowadays WELL UNDERSTOOD is : How to act on concrete & reinforcement bars to avoid this :



Source: Shyamsteel

Sea Wall in Casablanca (October 2016)

Hong Kong GS 2006
Section 21 - Marine works

specify :

“ Concrete for Marine structures shall comply with Appendix 21.2 entitled :

“*Specification for Reinforced Concrete in Marine Environment*”

to address the corrosion of reinforced concrete for marine structures.

Criteria on concrete mix design specified in GS 2006 (Appendix 21.2) For reinforced concrete in marine environment

- **W/C shall not exceed 0.38.**
- **Maximum cementitious content = 450 kg/m3.**
- **CSF replacement within 5-10% by mass of the cementitious content.**
- **PFA replacement shall be within 25-40% by mass of the cementitious content or, if GGBS is used instead of PFA, it shall be within 60-75%.**

What is LESS WELL UNDERSTOOD is that :

SOME MEASURES KNOWN AS BENEFICIAL TO REDUCE THE RISK OF REINFORCED CONCRETE CORROSION

MAY HAVE EFFECTS,

PARADOXICALLY,

LEADING

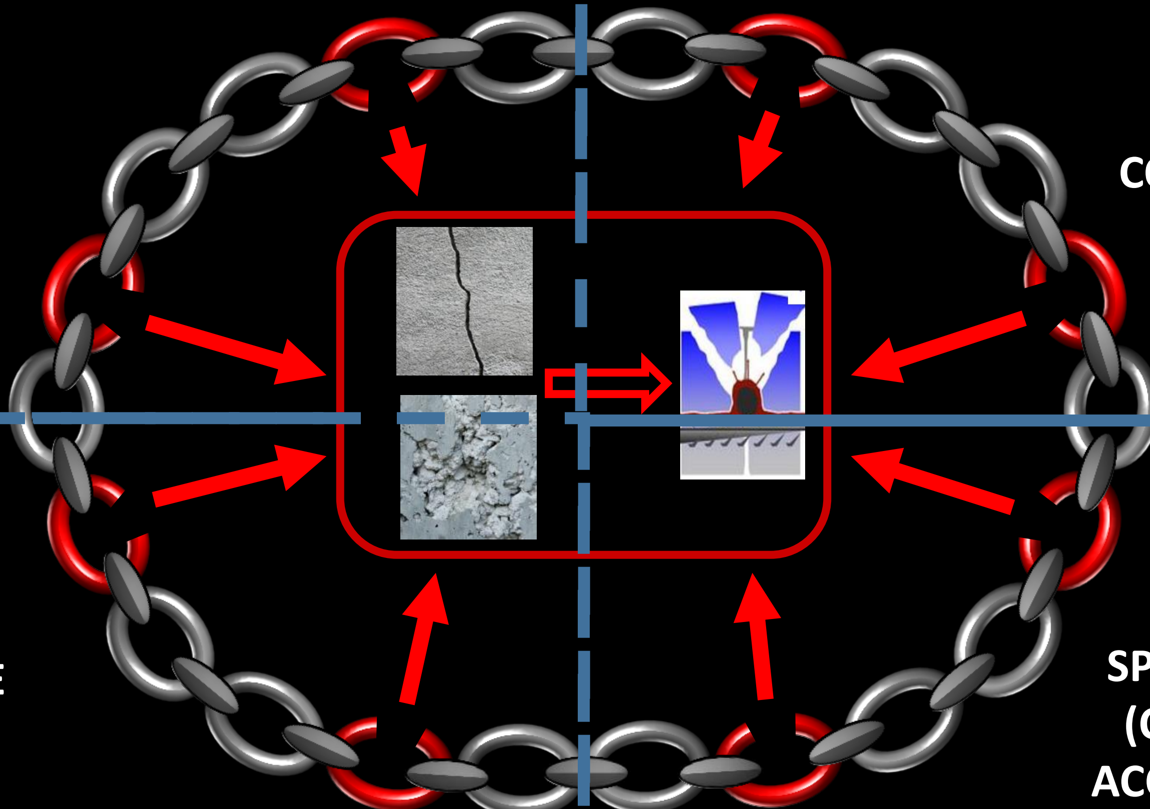
TO CONCRETE DEFECTS AND CORROSION

Despite the use of a concrete mix design complying with marine concrete specification

WEAK LINKS LEADING TO POTENTIAL CORROSION

CONCRETE
MIX
DESIGN

DESIGN &
CONSTRUCTION



CONCRETE
SUPPLY

CONCRETE
SPECIFICATION
(CRITERIA OF
ACCEPTABILIITY)

OUTLINE

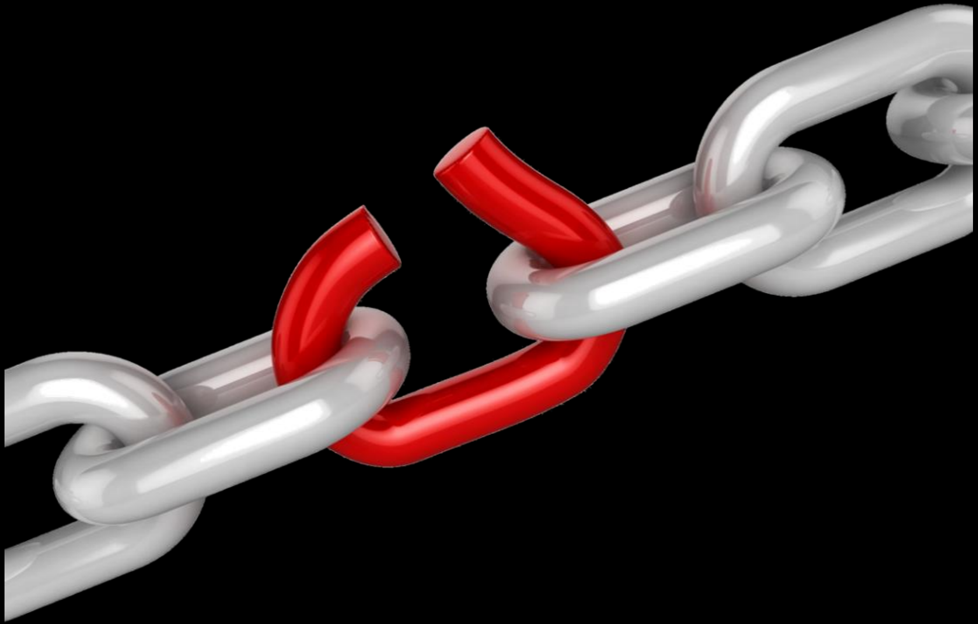
Highlights of some of the existing weak links at following levels :

- **Concrete Mix Design**
- **Concrete Supply**
- **Specification**
- **Design and Construction**

Examples of existing weak links

(although with concrete complying with marine concrete criteria)

at Mix design level



Low water on cement ratio

Is limitation of maximum W/C ratio justified ?

YES

Because of the need of low porosity to limit carbonatation and chloride penetration

Low water on cement ratio

is a very effective measure against corrosion

BUT

it can become, paradoxically, THE cause of concrete defects (cracking/segregation) that could lead to reinforced concrete corrosion

Low water on cement ratio

If specific measures are not implemented, will lead to high risk of :

→ Segregation or bleeding (the lowest the W/C ratio, the more sensitive the concrete is to the variations of the water dosage and of the fines content of the sand)

→ Autogeneous shrinkage cracks (lower water on cement => higher autogeneous shrinkage)

→ Early drying plastic shrinkage cracks

Use of Slag (60 to 75%)

Is the use of slag or PFA justified to improve reinforced concrete resistance to corrosion ?

YES

Because

less thermal shrinkage

& better resistance to

chemical attack

Using 60% to 75% slag

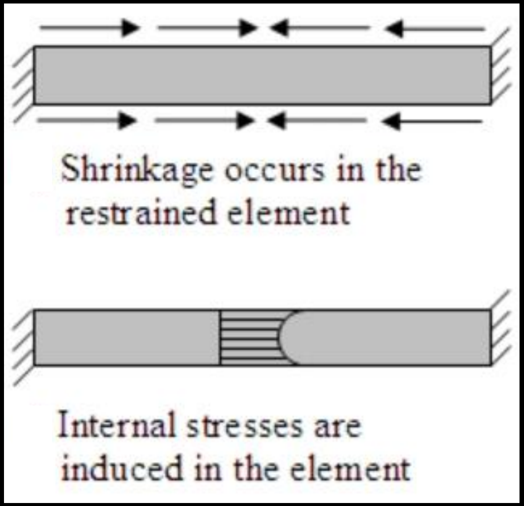
Is it beneficial ?

NOT always

because it can be the cause of concrete defects leading to possible corrosion

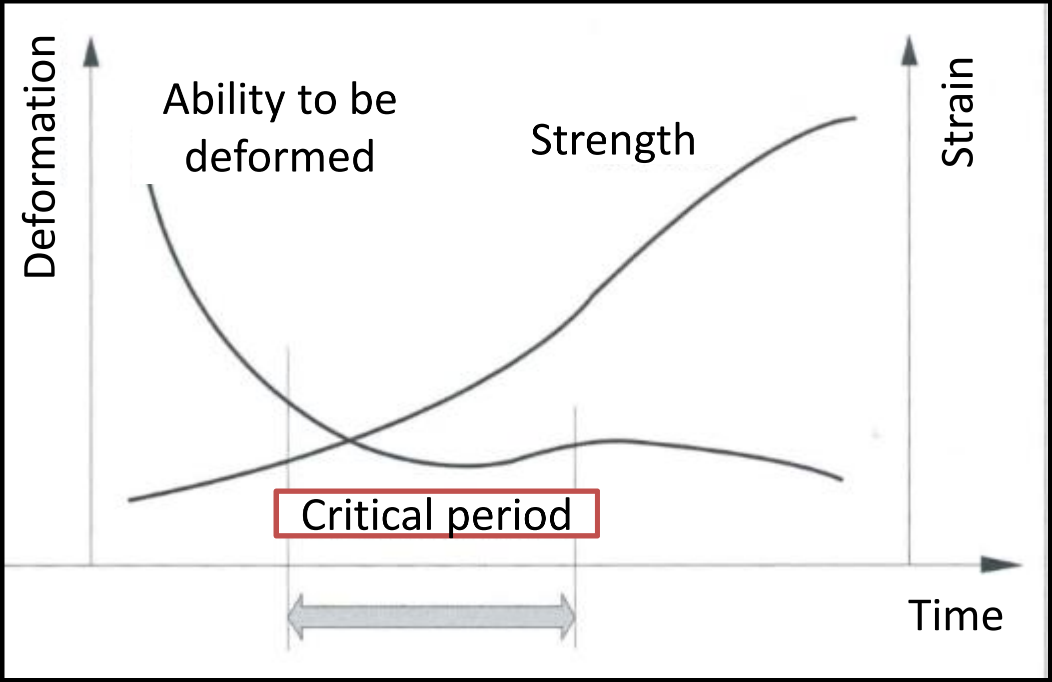
The risk of concrete <u>early shrinkage cracking is not only a function of the thermal differential</u> shrinkage like employer's requirements usually focus on.

Early shrinkage cracks is depending on the capacity of the young concrete to sustain the internal stresses induced by the early shrinkage (thermal and autogeneous)



Shrinkage versus strength

The early tensile strength of the concrete made with slag cement is lower



Use of 60% to 75 % of Slag

Therefore, despite a lower thermal shrinkage, the structure cast with a concrete mix with slag may crack more at early age compared to other concrete mixes

Use of 60% to 75 % of Slag

The use of high percentage of slag may cause the concrete to bleed with consequent difficulties of finishing and weak concrete surface.

BS 8500-1: 2015 Table A.9 states that :

"Cements or combinations containing more than a mass fraction of 55% GGBS might not be suitable for the wearing surfaces of pavement concrete due to the possibility of surface scaling in the top few millimetres."

Use of 60% to 75 % of Slag

is an effective measure against corrosion

BUT

it can be also, paradoxically, THE cause of defects including early shrinkage cracks that can lead to reinforced concrete corrosion

Use of Silica Fume (5 to 10%)

Is the use of Silica Fume (5 to 10%) justified to improve reinforced concrete resistance to corrosion ?

YES

Because of the very low permeability and chloride penetration / diffusion of the concrete mix with silica fume

Extremely low chloride penetration (RCPT - CS1 Section 19) (Example of Tuen Mun Chek Lap Kok Tunnel precast segment concrete mix with silica fume)

Total Charge Passed (Adjusted to 95mm Diameter Specimen) = **98** Coulombs
The Qualitative Chloride Ion Penetrability Based on Charge Passed (from CS1 2010 Section 19 : table 1) : **Negligible**

RCPT test (CS1 Section 19)

Tuen Mun Chek Lap Kok
Tunnel Project
Precast segment (July 2016)
(curing in water) -

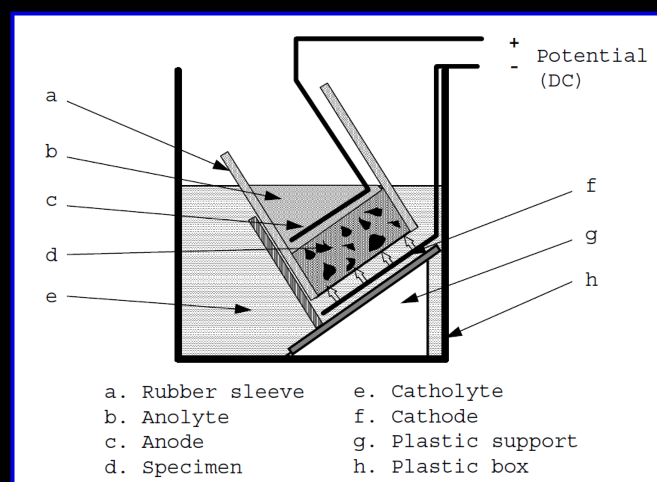
Very low Chloride migration coefficient (NT Build 492)

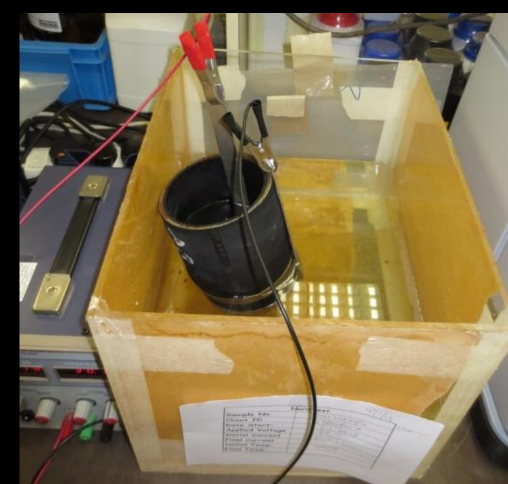
(< 0.5 x 10^{-12} m2/s (TMCLK project precast segment)

Individual penetration depth of chloride migration							
Location	1	2	3	4	5	6	7
Depth, mm	0.0	0.8	1.5	1.4	0.8	0.0	1.0

Average penetration depth of chloride migration .... 0.8 mm

∴ Non-Steady-State Migration Coefficient (D_{nssm}).. 0.2 x 10^{-12} m^2/s





Thanks to the use of silica fume (and proper admixtures), concrete mix with extremely high workability and very high cohesion of the fresh concrete, despite low water on cement ratio can be designed

Example of Grade 75 Self - compacting concrete
with slump flow value: 780 mm and L- box value: 0.93 (SF3, PL2, SR2 EN 206:2013)
Plant trials dated 11 October 2016 (Casablanca Financial Center Project (Morocco)

EN 12350-8:2010 : Self -compacting concrete Slump-flow test

EN 12350-10:2010: Self Compacting concrete L-Box

Using silica fume

is a very effective measure against corrosion

BUT

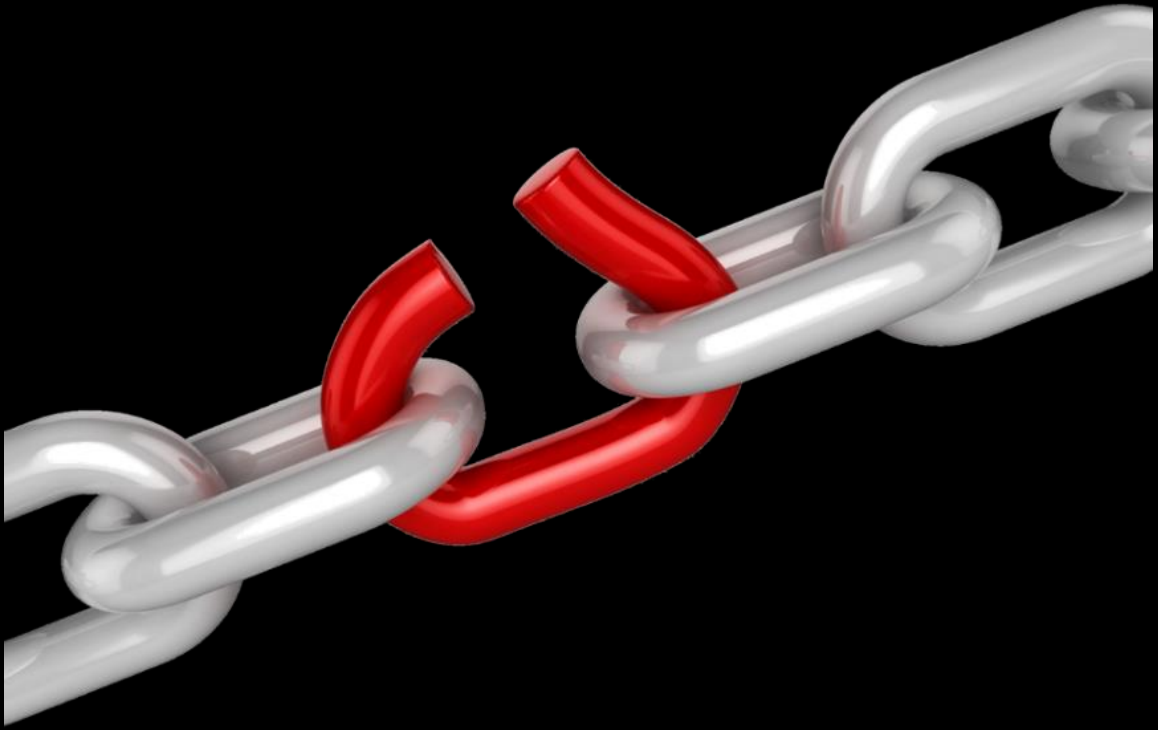
it can be, paradoxically, the cause of cracking that could lead to reinforced concrete corrosion.

As using silica fume is generating :

- **higher early drying shrinkage**
  that, if not properly addressed through appropriate curing, may cause cracks

- **higher autogeneous shrinkage**
  that , if not properly repaired through appropriate method, may cause corrosion

Examples of existing weak links at CONCRETE SUPPLY level



Thanks to Hong Kong concrete suppliers efforts for complying GS, ER and QSPSC, the quality of the produced concrete in Hong Kong is among the best I have experienced in the 28 countries I have been working as Concrete Technologist

Having said that, I like to highlight some of the existing  at concrete supply level that require specific care to prevent Reinforced Concrete structures from corrosion

Concrete mixes with low water on cement ratio, materials such as silica fume, PFA and superplasticisers can be effective solutions to prevent from concrete corrosion

ONLY if the concrete suppliers design and produce <u>ROBUST MIXES</u> that can fully comply with the site needs

It means workable and cohesive mixes with sufficient fines and proper admixtures that do not present tendency of :

- **Bleeding**
- **Segregation**
- **Rapid loss of slump**

with the integration of the existing variations in quality of the raw materials and weather conditions

For this, three major existing weak links (among others) to keep focused at concrete supply level:

1. **Value and consistency of the fines content of the crushed rock fines**
2. **Accuracy in the determination of actual moisture contents of the fine and coarse aggregates**
3. **Proper selection of the superplasticizers**

These aspects are not specification requirements as such.

Nevertheless they are of

UTMOST IMPORTANCE

for the concrete suppliers to supply

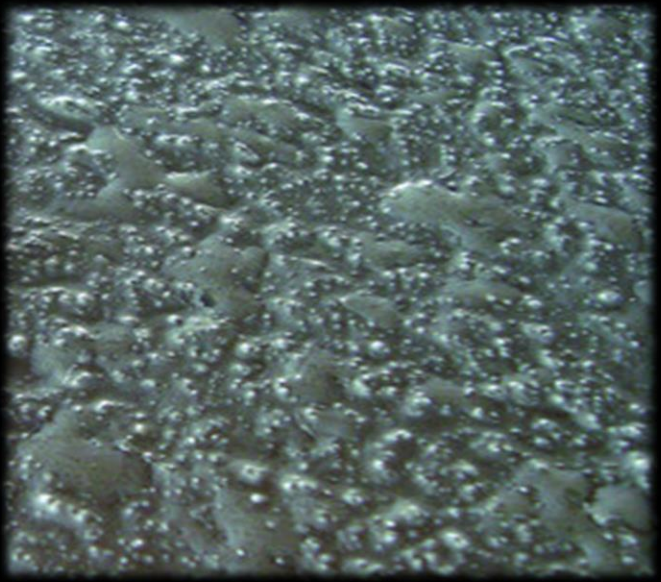
fresh concrete preventing from

reinforced concrete corrosion risk

Concrete bleeding leads to:

- PLASTIC SETTLEMENT CRACKS
- CONCRETE SURFACE WEAKNESS
- CONCRETE SEGREGATION

=> POTENTIAL CORROSION



Extract of Code Of Practice For Structural Use of Concrete 2013

« **4.2.6 Mix proportions**

4.2.6.1 *General*

The free water/cement ratio is an important factor in the durability of concrete and should always be the lowest value compatible with **producing** fully compacted **concrete without segregation and bleeding** »

Extract of CS1:2010 - Section 2 Part IV - Flow table test

Normal

Segregation

YES

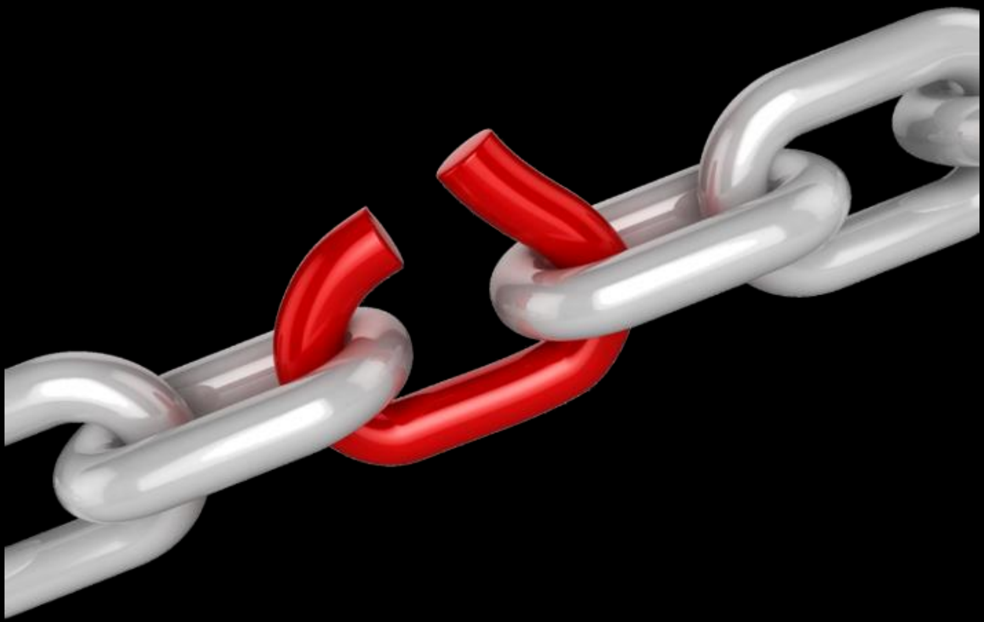
NO

YES **NO**

Concrete suppliers shall focus on producing and supplying ROBUST CONCRETE MIXES, using low W/C ratio and limitation in maximum cement content which DO NOT BLEED or SEGREGATE or loose quickly workability

Examples of weak links at

Specification (criteria of acceptability) level

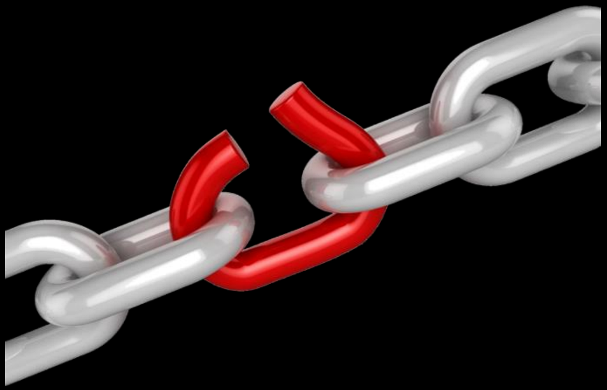


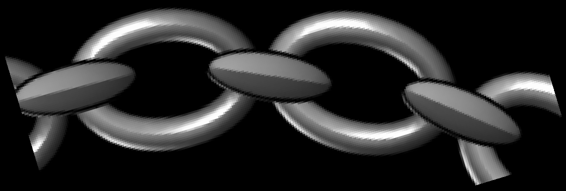
Concrete Project Specification consists mainly in :

- **General Specification / Code of practice**
- **Particular specifications**
- **Testing Standards**

Criteria of acceptability

There is presently no criteria of acceptability in the GS to prevent the supply of bleeding / segregating concrete



To fix this weak link, 

General Specification should specify

a criteria of acceptability at plant trial stage

but also at QC stage during production :

A « NO BLEEDING / NO SEGREGATION » Criteria

Criteria of thermal differencial of maximum 20C

Is a limitation of maximum temperature differential justified ?

YES

Because

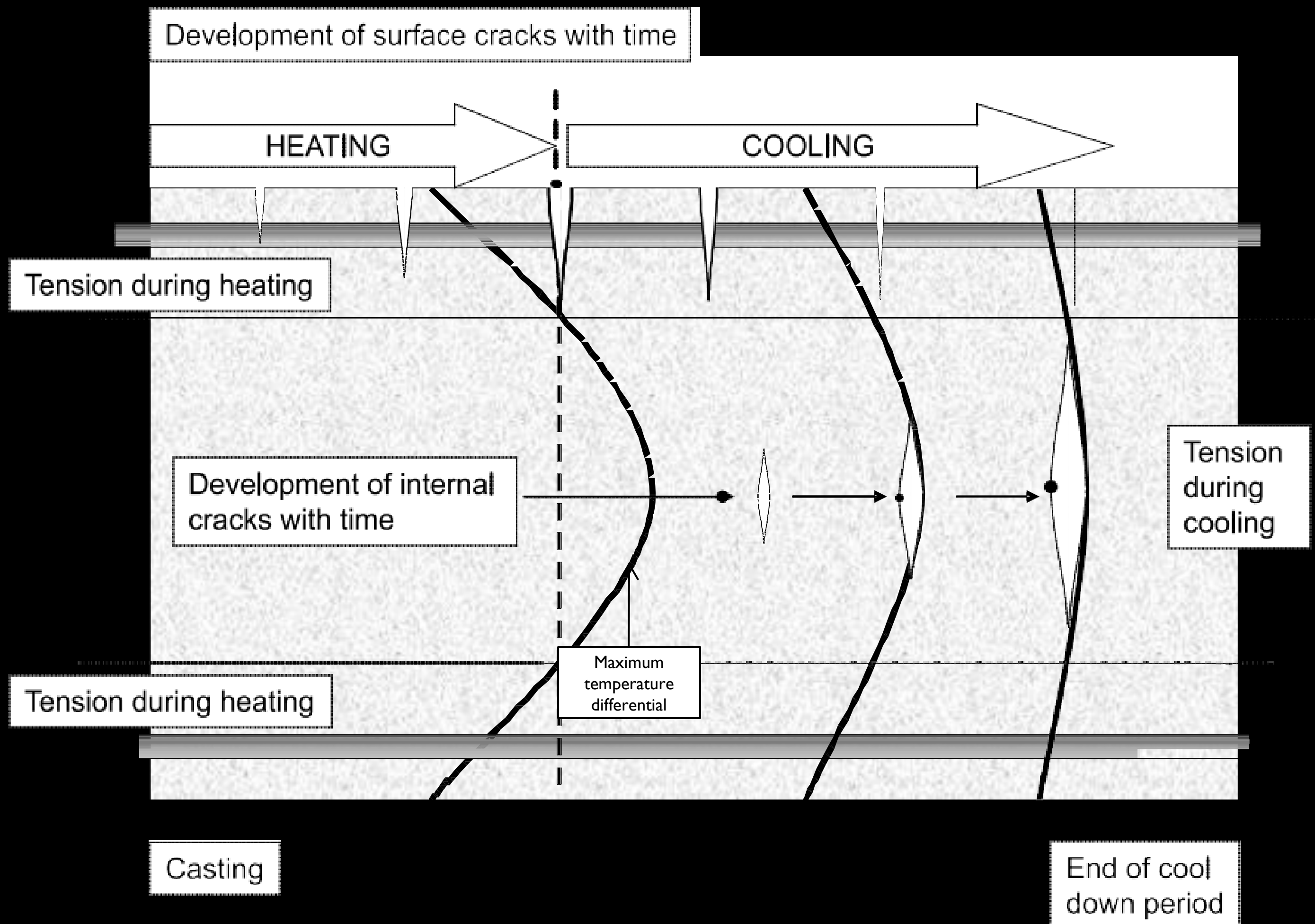
of the risk of cracking

due to

Internal restraint thermal

shrinkage

Cracking due to temperature differential



Development of crack in a massive element due to temperature differentials assuming no external restraint (CIRIA C660)

Prescribed values in many particular specifications :

Maximum 20ºC temperature differential

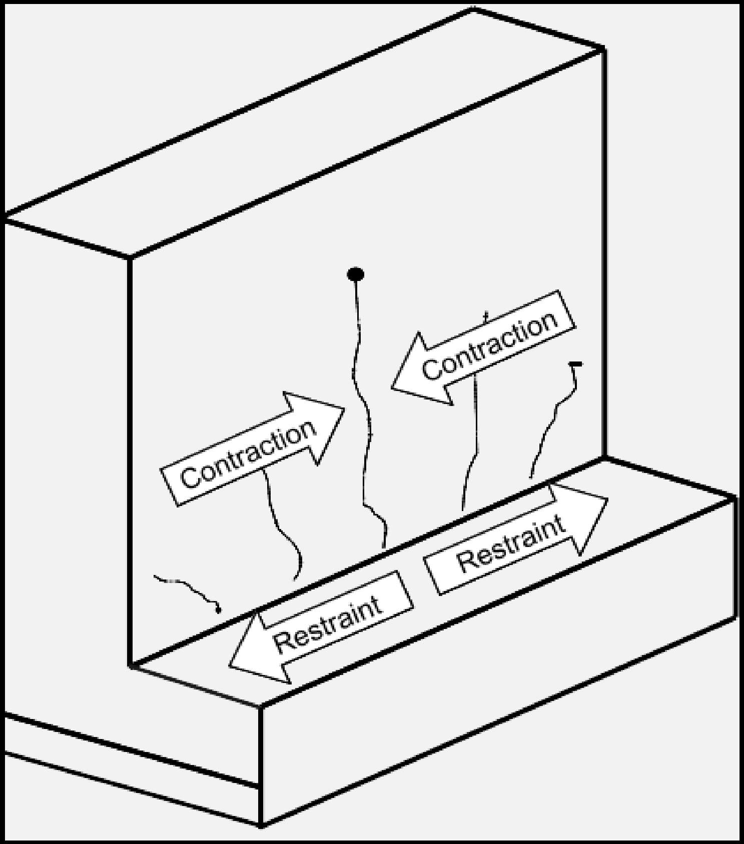
Criteria of maximum temperature differential

Value of 20^{o}C justified ?

NO because it depends on:

- **The restraint factor**
- **The type of aggregates used (CTE)**

If the shrinkage is restrained, then cracking does occur (despite Δ Tp << 20ºC)



Figures from CIRIA C660: early thermal cracking in a wall

Effect of the aggregates type on the concrete thermal shrinkage

Thermal shrinkage = $C_d \times \Delta T$

With :

- C_{d} **:** **= Coefficient of thermal expansion of the concrete**
- **ΔT = Thermal differential**

$C_d = 13.10^{-4}$
if quartzite

$C_d = 8.10^{-4}$
if limestone

→Possible reduction of more than 60% of the concrete thermal shrinkage by selecting limestone aggregates

Allowed temperature differential (CIRIA C660, 2007) = function of aggregate type & restraint factor

Aggregate type		Gravel	Granite	Limestone
Thermal expansion coefficient (με/°C)		13	10	9
Tensile strain capacity (με) under sustained loading		65	75	85
Limiting temperature change in °C for different external restraint factors :				
	1.00	6	9	12
	0.80	8	12	16
	0.70	9	14	18
	0.60	11	17	22
	0.50	14	21	27
	0.40	18	27	34
	0.30	24	36	46
Limiting temperature differential (°C) for for internal restraint R = 0.42		**20**	28	**35**

Limiting temperature differentials Δt max, to avoid early-age cracking as affected by aggregate type (TEC)

IN ORDER TO REDUCE RISK OF THERMAL CRACKING IN MASS CONCRETE

SPECIFICATIONS

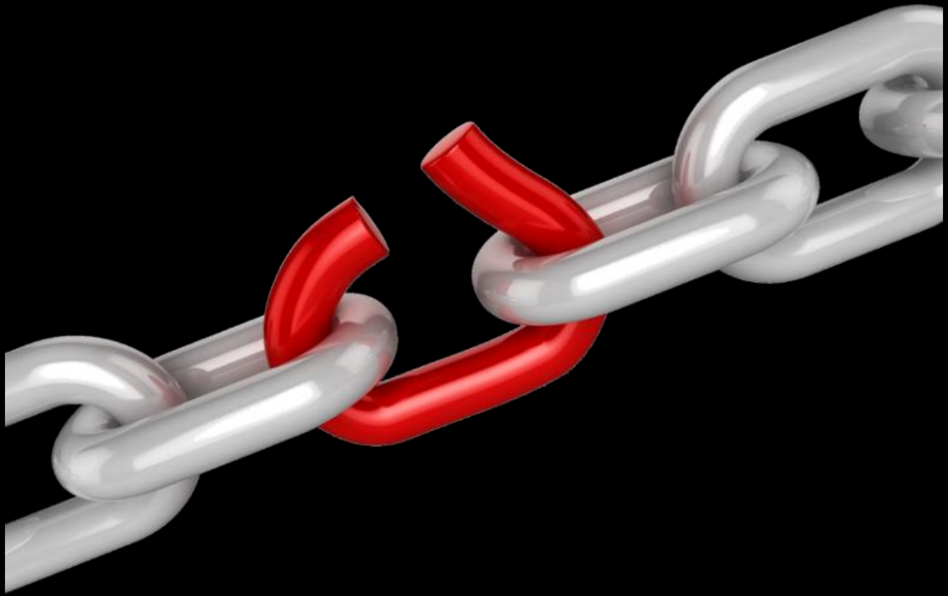
shall take an engineering approach when specifying the criteria of maximum thermal differential :

- ✓ **by taking into consideration the type of aggregates used (CTE)**
- ✓ **by taking into consideration the restrained factor of the structural element**

Weak links

are also existing

<u>at design and Construction site level (Contractor and Engineer)</u>



At design level

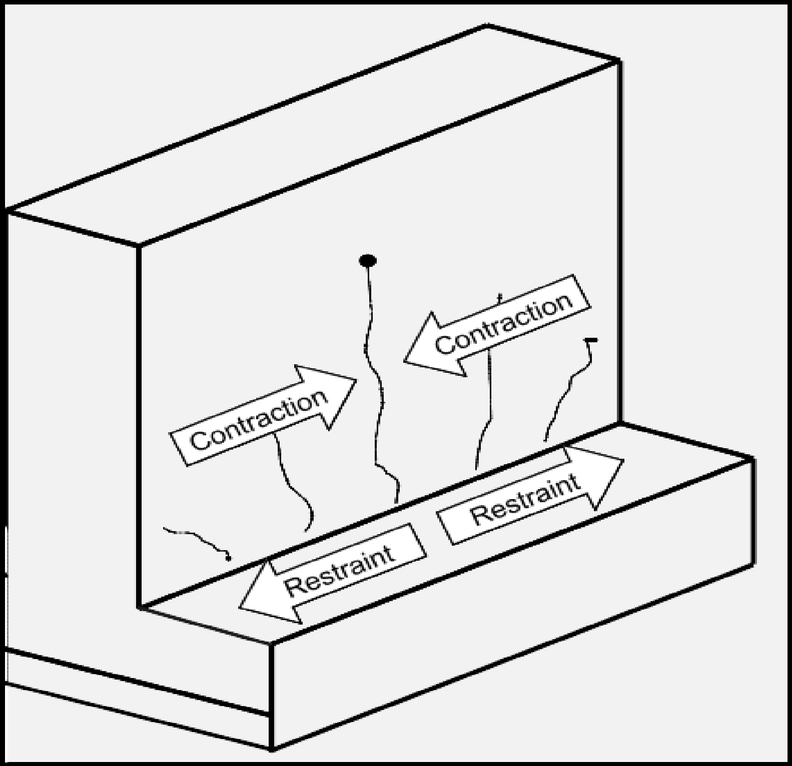
Among the most common weak links, there are:

- **A design with too many rebars in a confined space. In this instance, the arrangement of congested rebars prevent the concrete to be properly placed and compacted**

- **Location and number of construction joints not properly forecast**

Wrong placement of reinforcement / too congested reinforcement bars (not complying cover)

Wrong forecast of construction joints



Efficient measures and control shall not only apply to the concrete mix and the design but also on the workmanship.

Poor workmanship

In term of reinforced concrete corrosion, the whole construction industry knows the risk of honeycombs and cracks generated by poor workmanship such as:

- **Defective formworks**
- **Defective steel fixing**
- **Defecting casting and compaction**
- **Defective curing**
- **Unproper finishing methods**
- **Use of porous spacers**

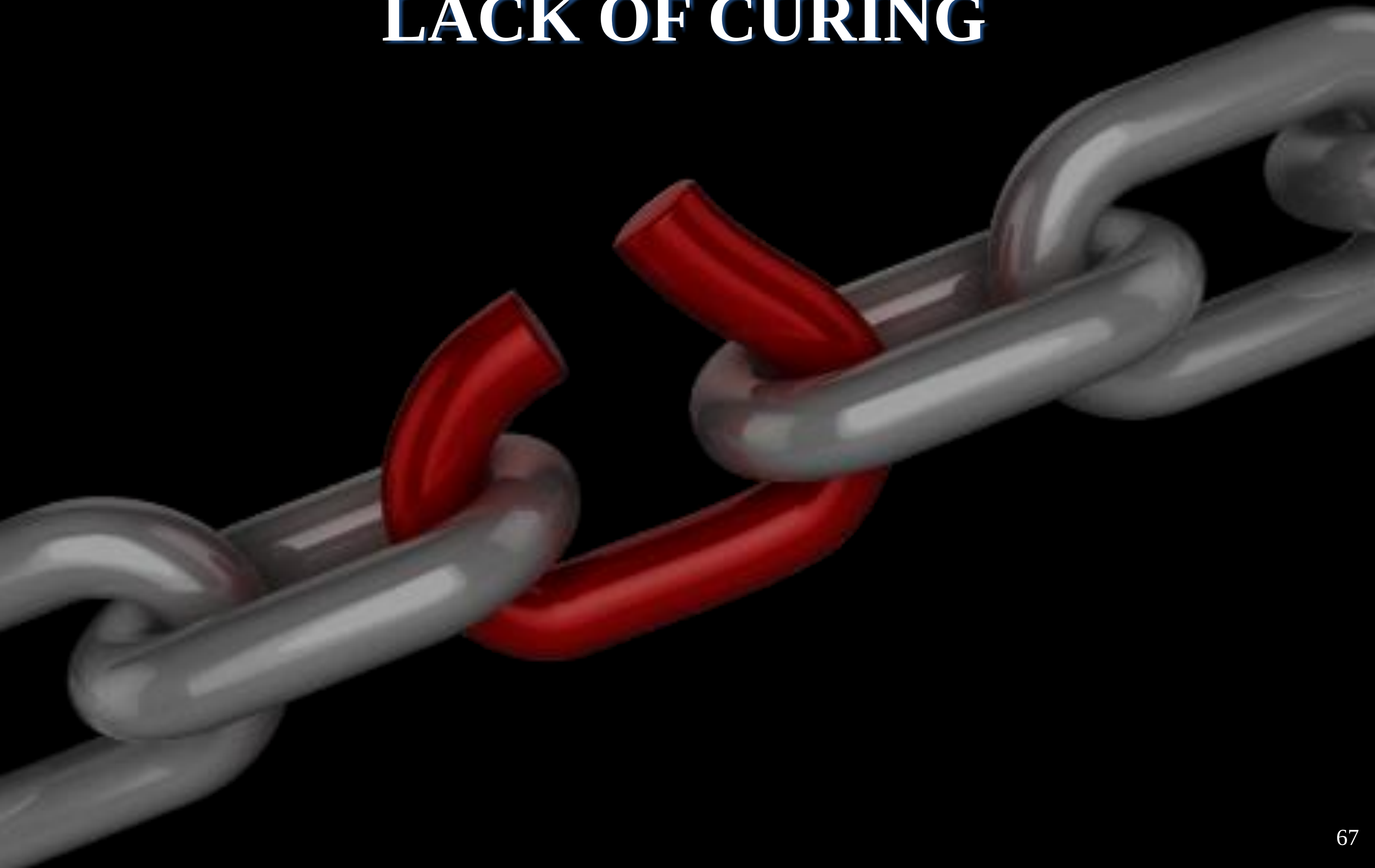
Each of these may contribute to corrosion of the concrete through voids or cracks.

= HONEYCOMBS

DUE (and not limited) TO :

1. **FORMWORK LEAKAGE**
2. **DEFECTIVE STEEL FIXING**
3. **UNPROPER VIBRATION**
4. **NOT SUITABLE CONCRETE MIX**
5. **WRONG CONCRETE PLACING METHOD**
6. **TOO LONG WAITING TIME PRIOR PLACING AND/OR TOO FAST LOSS OF WORKABILITY**

LACK OF CURING



Evaluating of the risk of plastic shrinkage

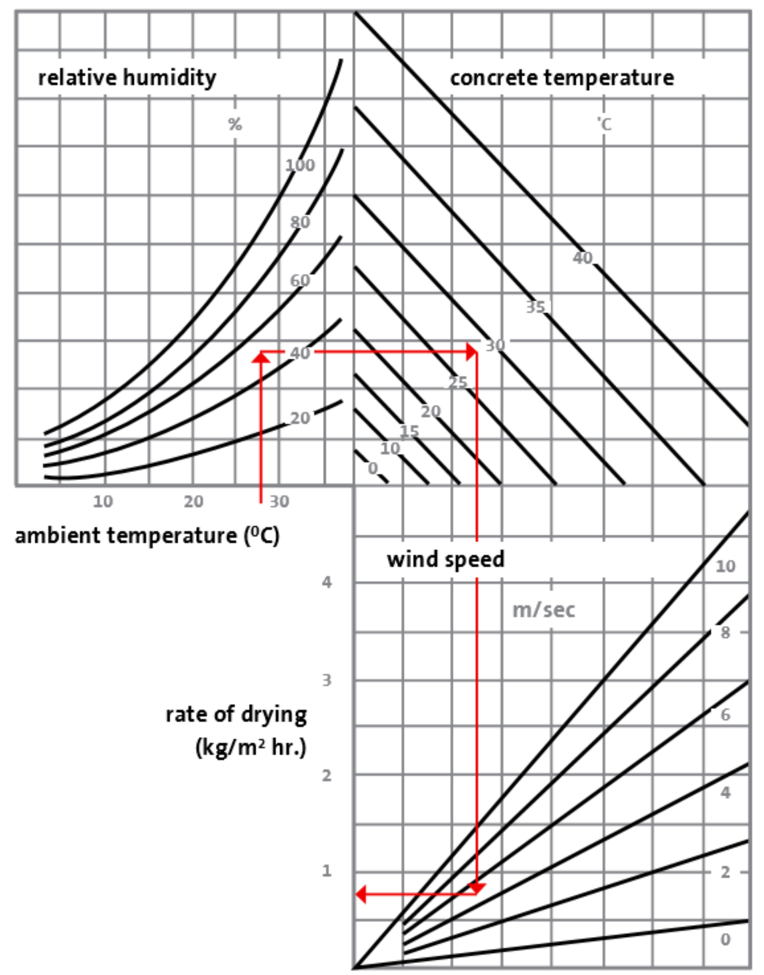
Chart of the ACI

Estimation of evaporation rate on the surface of concrete depending on air temperature relative humidity, concrete temperature and wind speed

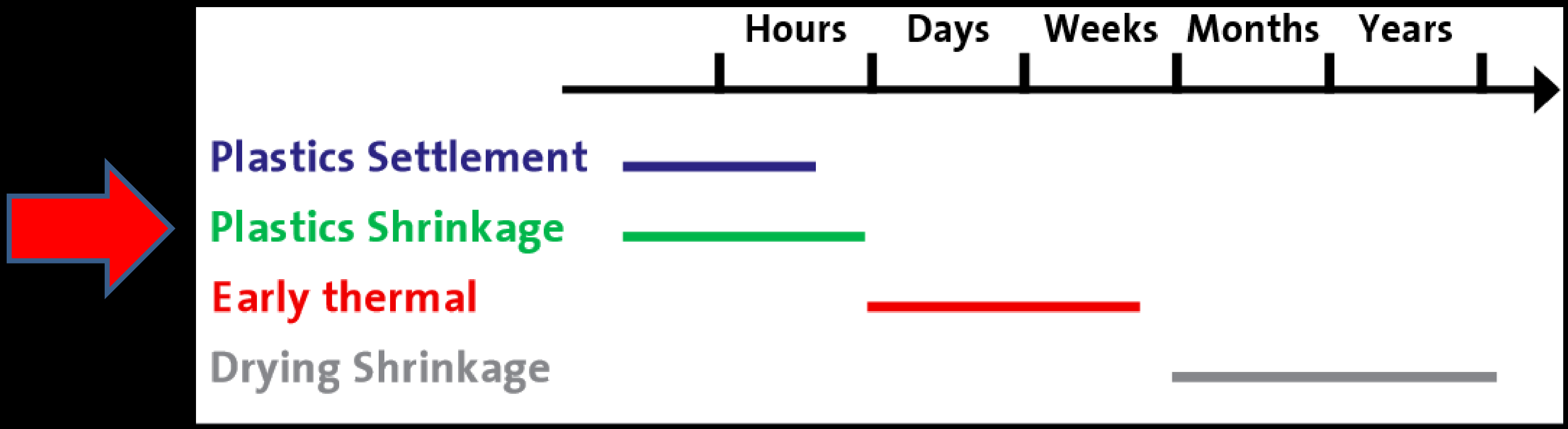
If E > 1 kg/m²/h, plastic shrinkage is certain (ACI 305).

NOTING that values less than 0.5 kg/m²/h for high durable concrete with low water on cement ratio and cementitous products as silica fume, PFA or Slag could be at risk

Fig I.68 - Chart for calculating the rate of drying of exposed concrete surfaces. Example illustrated: air temperature: 28°C relative humidity: 50% concrete temperature: 28°C wind speed: 5m/sec. result: rate of drying = 0.8 kg/m² hr.



Plastic shrinkage appears in the very first moments of the concrete life

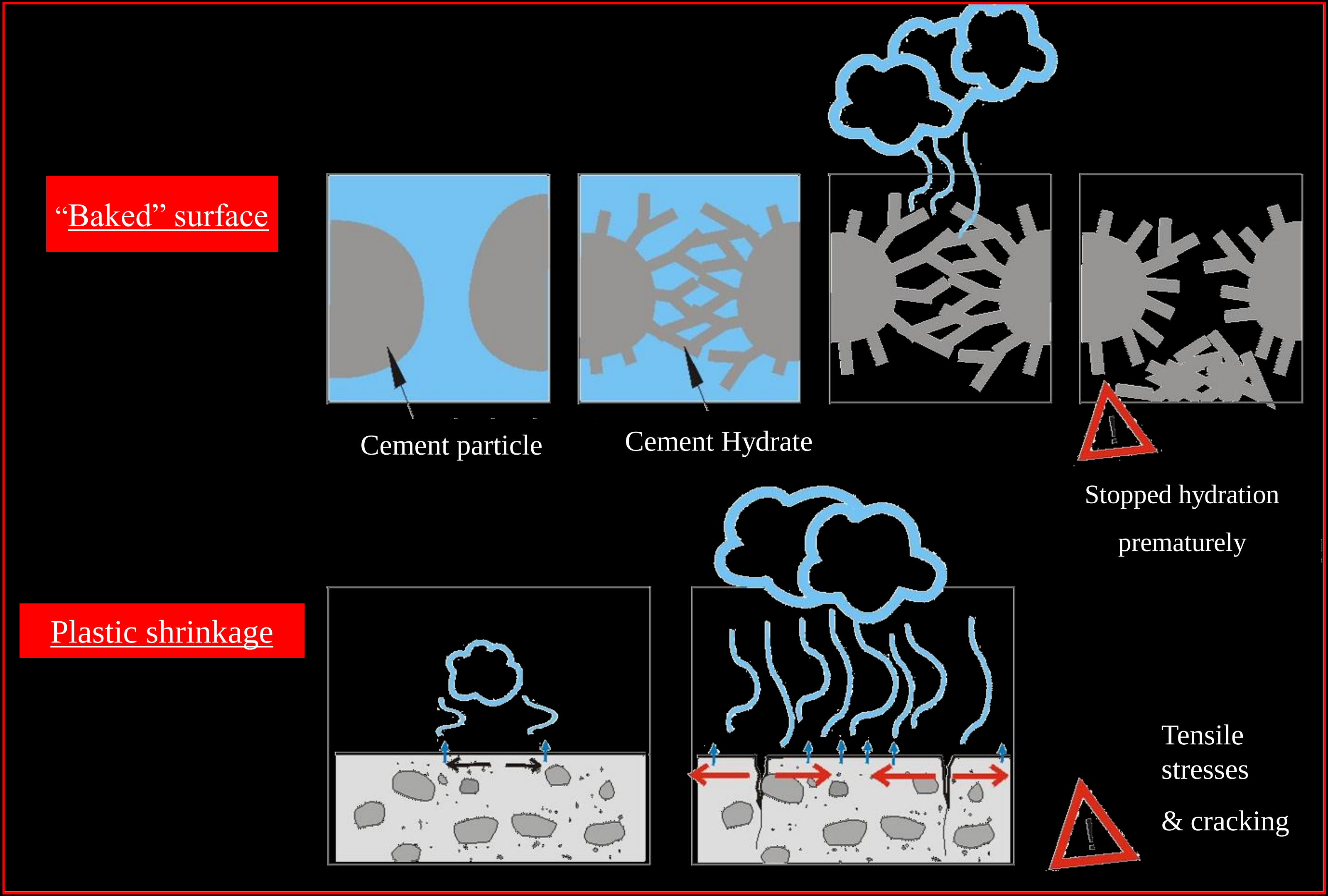


Time period of cracking occurence

Lack of curing and/or unproper finishing

Extensive plastic shrinkage cracks

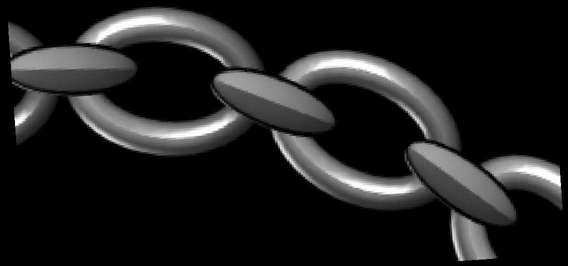
Pathology linked to the absence of cure



Source: DTP Sing.

USE OF POROUS SPACERS

Weak links



To prevent the weak links and to achieve good concrete construction at site, it is necessary that **manpower from the Consultant and from the Contractor MUST BE properly trained and certified in relevant type of works**

The corrosion of the reinforced structures, despite using concrete mix with very low permeability, can still occur if there are concrete cracks / defects not properly repaired.

→ Recommendations of improved control on site :

- **To ENSURE through ACTUAL professional inspection that efficient curing procedure is implemented for each and every pour**
- **To PERFORM a SYSTEMATICAL inspection of all the concrete surface after casting / striking the forms**
- **In case of cracks, to MAKE ACTION to avoid recurrence**
- **TO ENSURE that cracks are never repaired prior to any survey and reporting.**
- **To ENSURE the use of repair method and material with justified durability properties.**
- **To PERFORM actual inspection during the whole repair operation**

AND what seems to be an evidence but in the real life is not ensured while it is A MUST :

- To ensure that never any water can be added in the fresh concrete for any reason after leaving the batching plant (with the application of an actual procedure of verification)

AND what seems to be an evidence but in the real life is not ensured while it is A MUST :

- To ensure that the batching plants will identify any produced concrete which could exhibit bleeding and segregation at arrival on site and in this case:

  1. Will not deliver such concrete to a construction site
  2. Will make corrective action to produce cohesive concrete without risk of bleeding and segregation for the following batches

AND what seems to be an evidence but in the real life is not ensured while it is A MUST :

- To ensure that any supplied fresh concrete exhibing bleeding and segregation will be systematically rejected by the site (with full coordination between the supplier and contractor)

AND what seems to be an evidence but in the real life is not ensured while it is A MUST :

- To ensure that never any defect / crack in marine structure can be patched after striking without any reporting and proper repairing

AND what seems to be an evidence but in the real life is not ensured while it is A MUST :

- To ensure proper casting, compacting and curing of the concrete

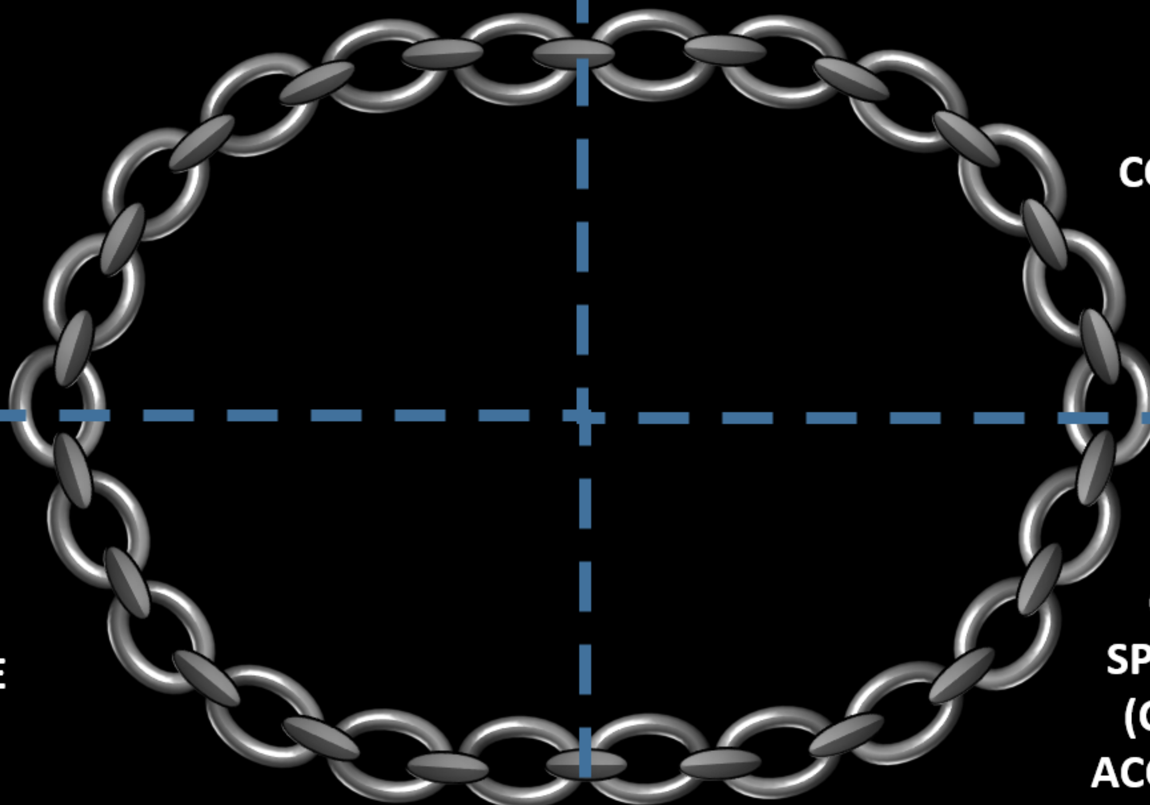
Conclusion

- **Numerous weak links are existing on the way of prevention RC from corrosion**
- **Some are hidden and linked to the implemented measures themselves to fight against *corrosion***
- **Some are known but still not sufficiently addressed**
- **Concrete corrosion protection will be really effective when the existing weak links will be tracked and addressed in a PROFESSIONAL way by the Concrete Producer, the Contractor and the Engineer with the Clerks of Works.**

NO MORE WEAK LINKS

CONCRETE MIX DESIGN

DESIGN & CONSTRUCTION



CONCRETE SUPPLY

CONCRETE SPECIFICATION (CRITERIA OF ACCEPTABILIITY)

Thank you for your attention