Why and how to repair concrete? Compatibility assessment

COURARD Luc

University of LIEGE, BELGIUM
Department of Architecture, Environment, Civil Engineering and Geology
GeMMe - Building Materials

Université de Liège

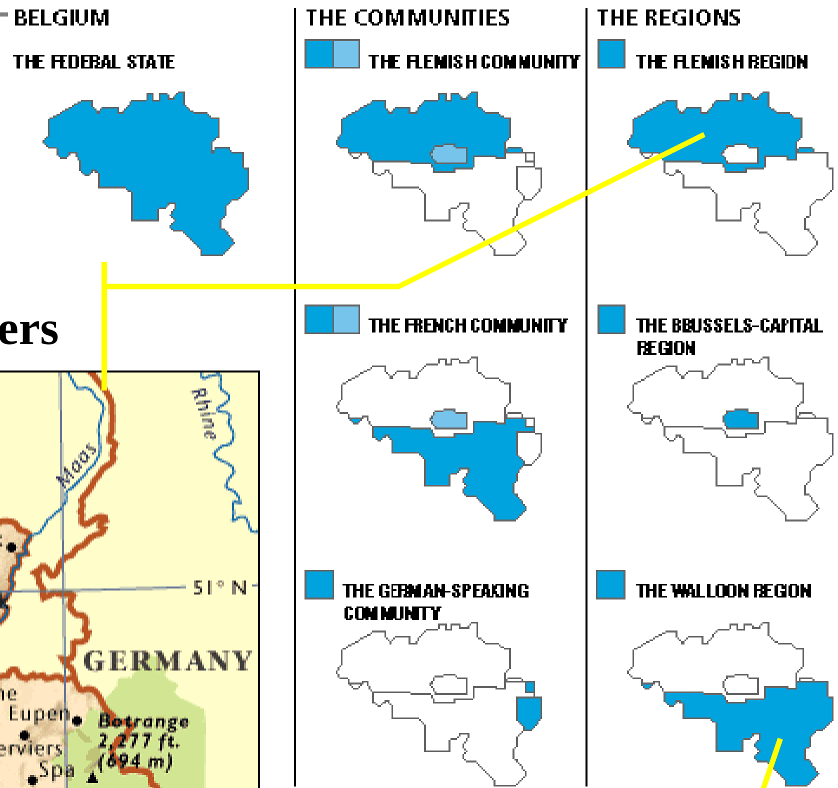
Warsaw Lecture, Oct 27th, 2014

Génie Minéral
Matériaux & Environnement

Population : 11,000,000

Surface area : 32,545 km²

Federal capital : Brussels



Flanders

Wallonia

- 22.000 students
- 2.050 foreign students (1200 from E.U.)
- 78 nationalities and 5 continents
- 3.300 graduated per year
- 350 doctors *Honoris Causa*
- 10 faculties
- 450 professors
- 1800 researchers

UNIVERSITÉ de Liège

http//www.ulg.ac.be

Programu Polsko-Walońskie

Deux partenaires encore plus proches.
Signature à Varsovie du programme de travail Wallonie-Bruxelles-Pologne 2005-2007.

Dwaj, jeszcze bliższi sobie, partnerzy
Podpisanie Programu pracy na lata 2005 - 2007 między Walonią – Brukselą i Polską, Warszawa

Przystąpienie Polski do Unii Europejskiej pozwoli zoptymalizować podejmowane wysiłki przy współpracy dwustronnej oraz programach wielostronnych funkcjonujących w ramach Unii Europejskiej, przede wszystkim w dziedzinie wspierania rozwoju regionalnego. Wybrano ponad 40 projektów, które zostaną zrealizowane w latach 2005-2007.

Research projects on surface preparation of concrete, NDT, development of SCRM and may be …

Sylwia Perkowicz

Micha Gorka

Tomasz Piotrowski

Xavier Willems

Grjegorz Moczulski

Damien Schwall

Piotr Harassek

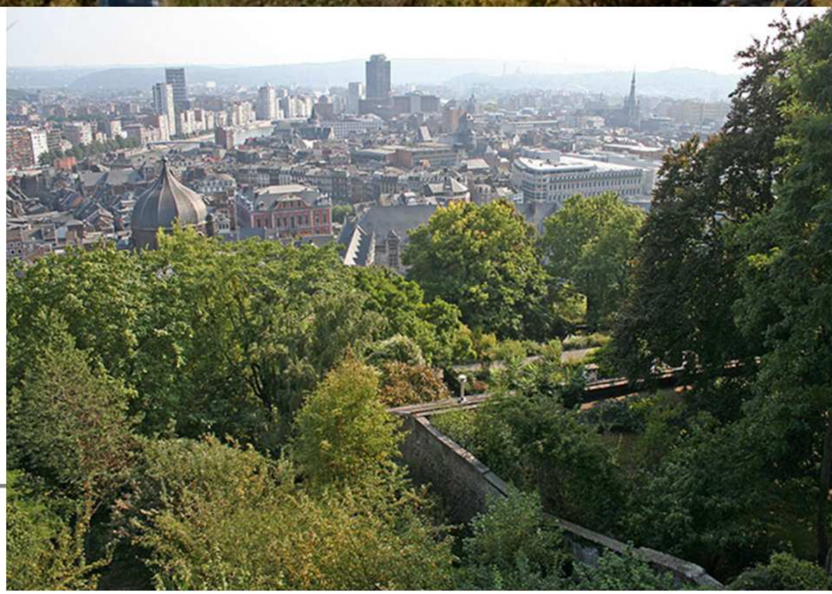
Audrey van der Wielen

…

Dwaj, jeszcze bliźsi sobie, partnerzy

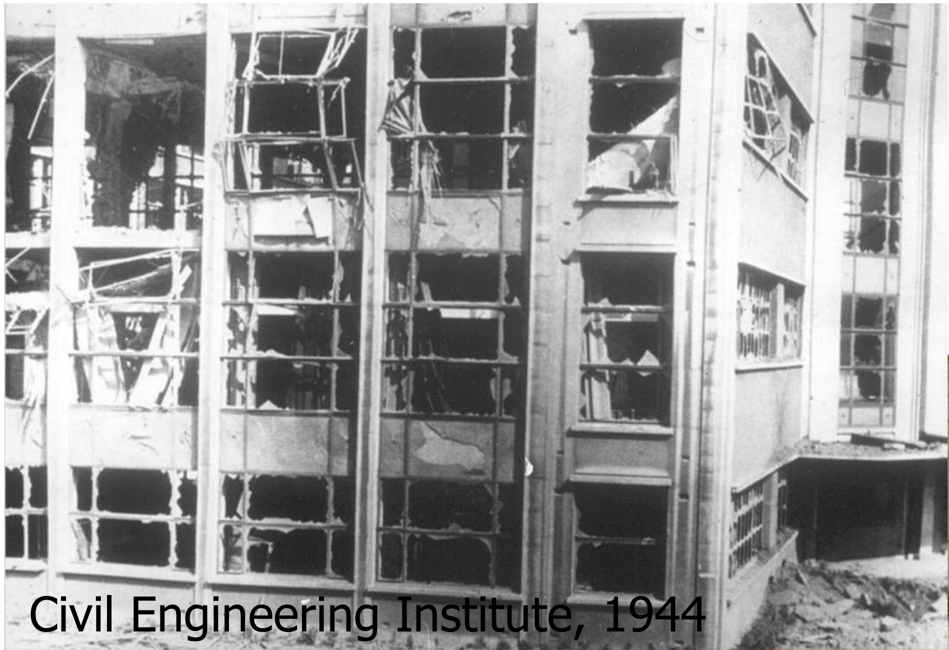
Deux partenaires encore plus proches

Université de Liège



The question is: what is the problem?

Degradations of concrete



Civil Engineering Institute, 1944

Upper layer of concrete slab

Under face of the bridge deck

Degradations of concrete

Agricultural infrastructures, Tintigny, Belgium (A. Vandenbussche)

Balcony, Liège, Belgium

Degradations of concrete

Degradations of concrete

Degradations of concrete

Québec, Canada

Building, Liège, Belgium

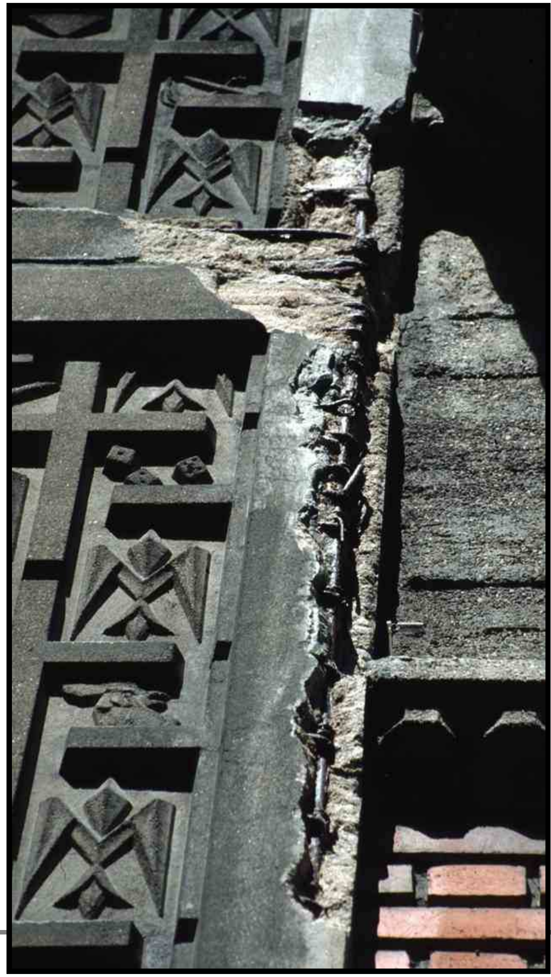
Degradations of concrete

Montréal, Canada

Military infrastructures, Loncin, Belgium

Degradations of concrete

*Industrial infrastructures,
Meudon, France*



*Saint-Eloi Church,
Roscanvel, France*

Steel corrosion

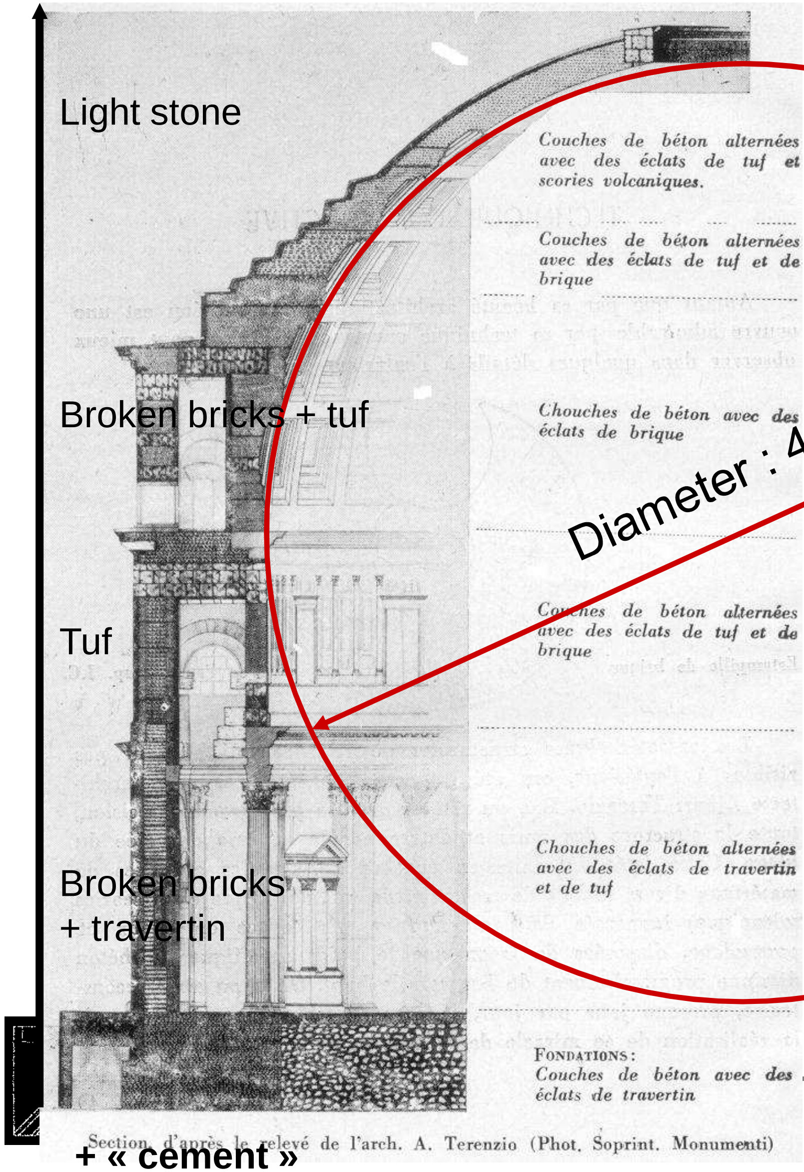
Awans Bridge deck, E40, Belgium

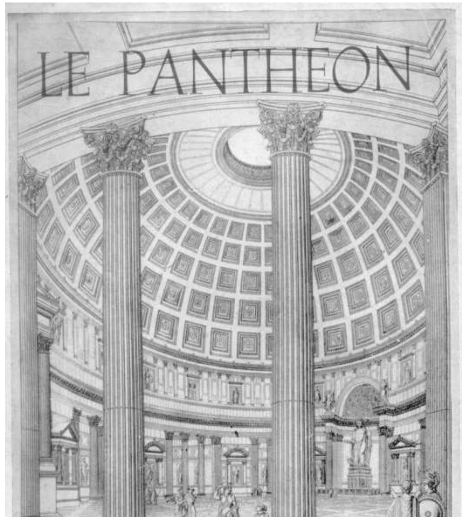
Degradations of concrete

- **Belgium**
  - 3684 bridges → 3.3 milliards Euros
  - 1400km highways→ 8.75 milliards Euros
  - 12000km roads → 12 milliards Euros
  - Needed for maintenance: 0.5 à 2% of rebuild costs
- **USA**: costs to repair concrete damaged due to freeze-thaw cycles or corrosion: 24 milliards USD
- **Québec:** 1/2 budget of MTQ needed for repair works
- **Canada:** 5 milliards CAD for parkings multi-stored repair (corrosion)

The question is: what are the causes?

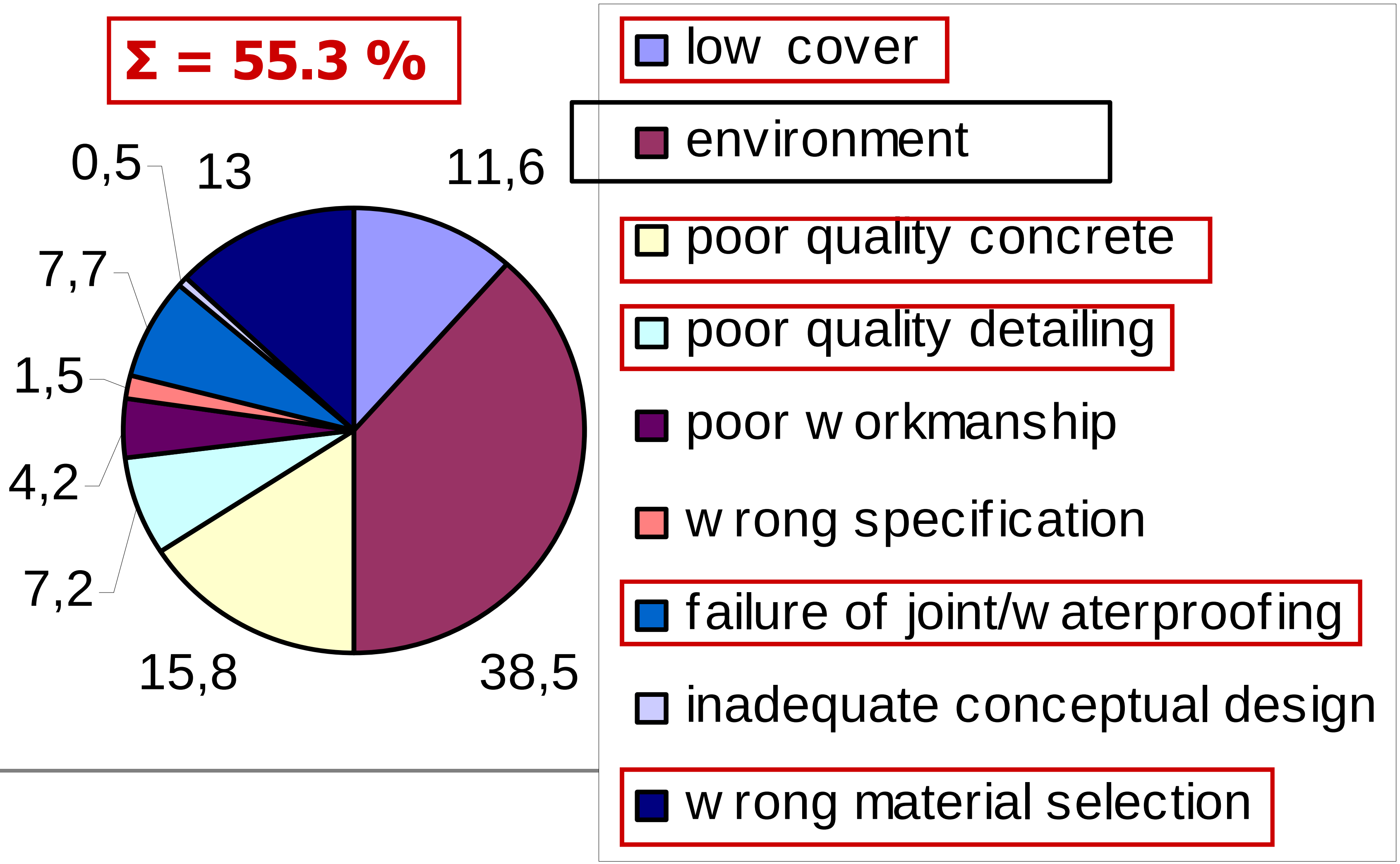
Why not?





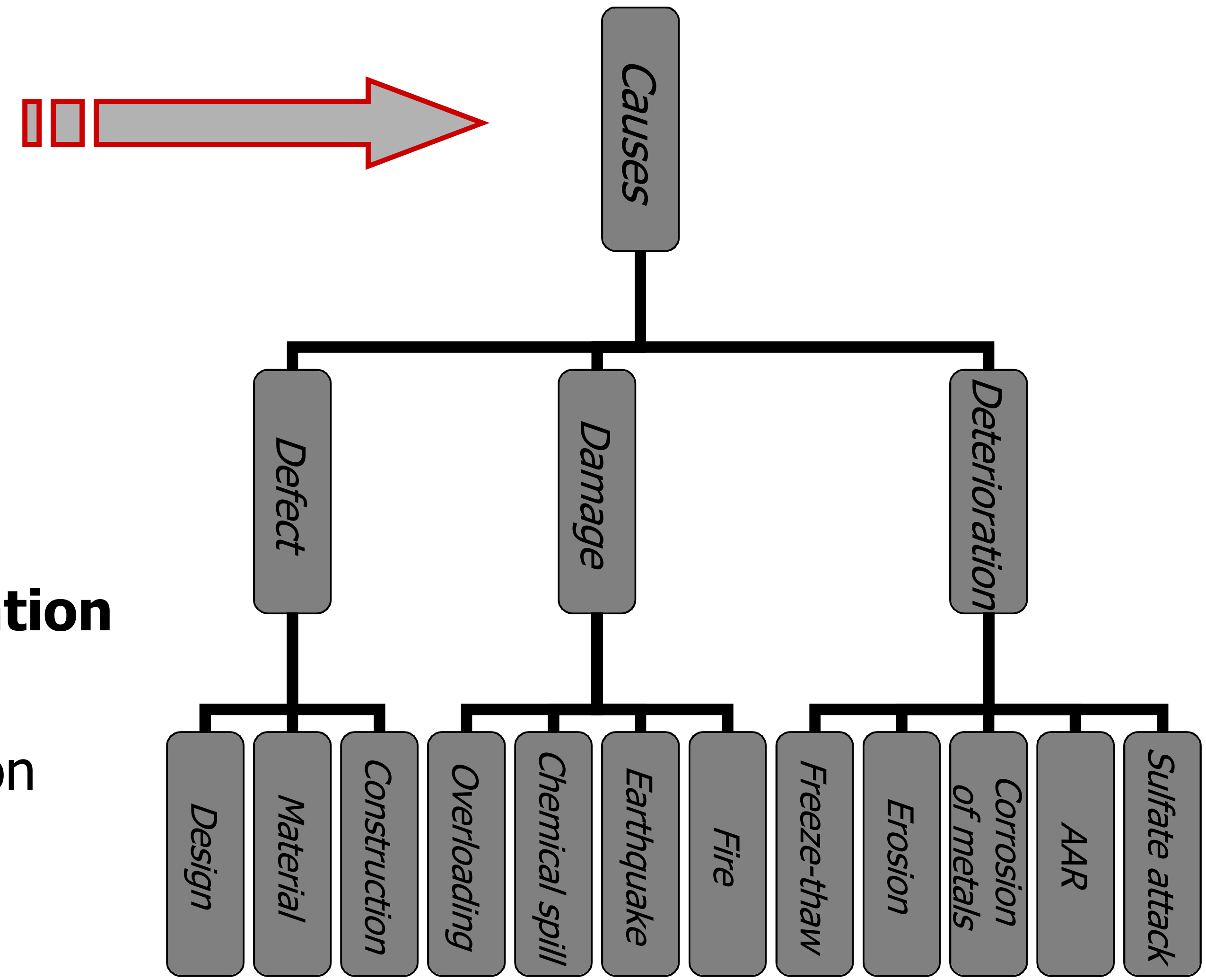
Pantheon, Roma (118-125 after J.C.)

Main factors contributing to the failure of structures *(BCA, 1997)*



Pathology of concrete elements

- EFFECTS
  - Leakage
  - Settlement
  - Deflection
  - Wear
  - **Spalling**
  - **Disintegration**
  - **Cracking**
  - Delamination
  - Scaling

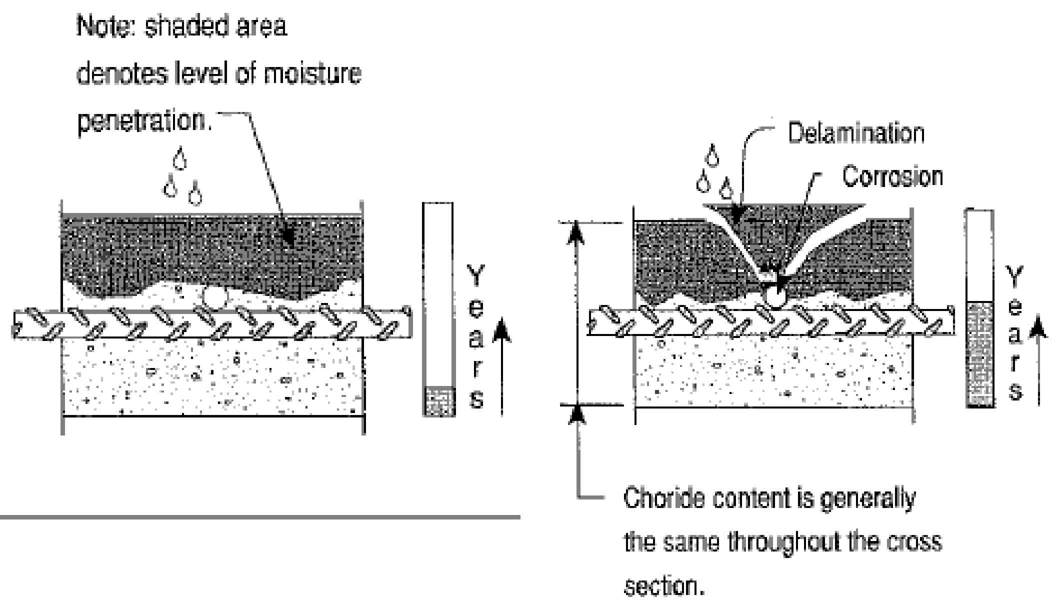


Steel corrosion: chlorides

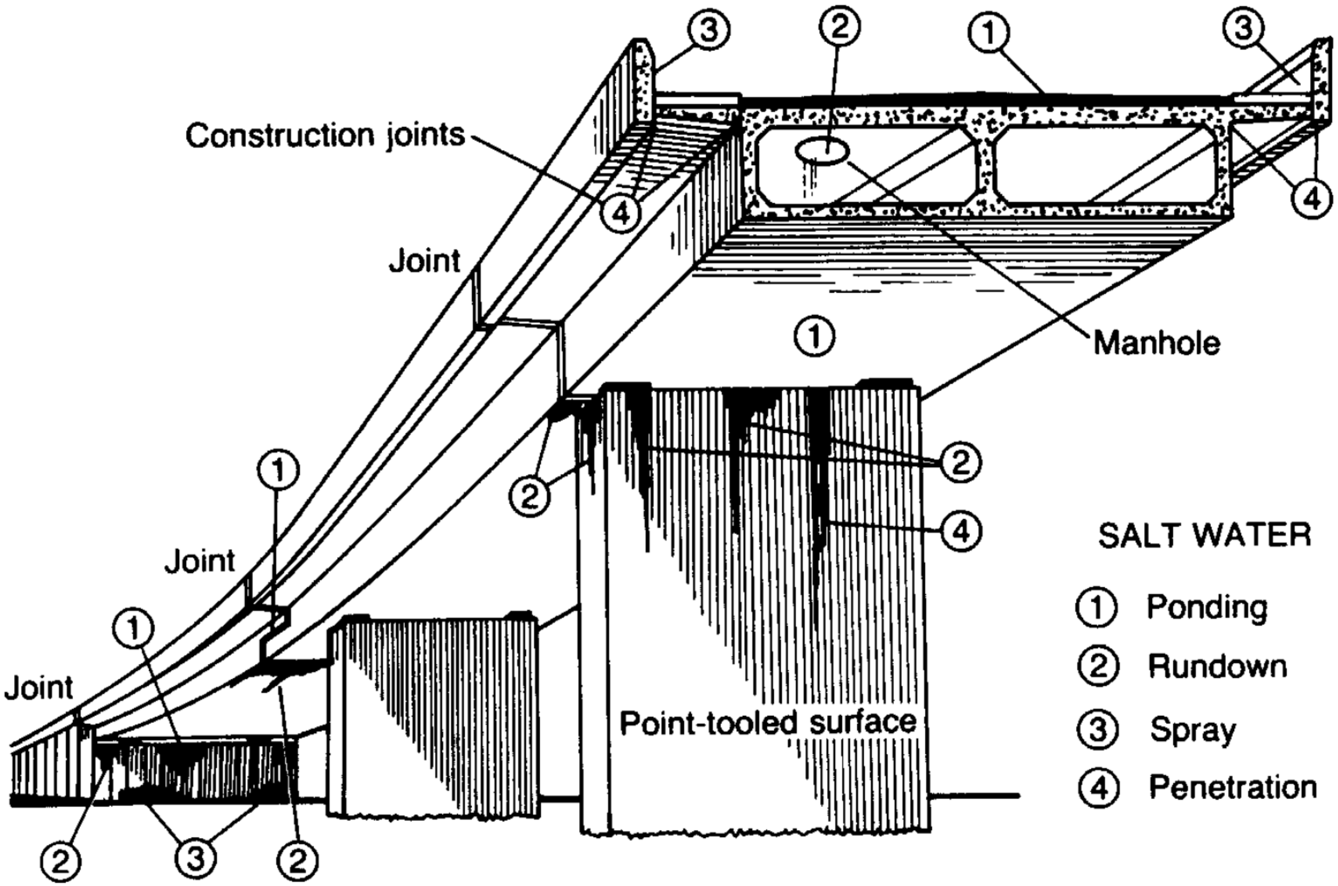
ACI 201.2R-90

- External chlorides
- Cast-in chlorides
  - $CaCl_2$ as accelerator
  - Natural ingredients with aggregates (beach sand) or water (seawater)

Service Condition	**% of Cl to weight of cement**
Prestressed concrete	0.06
Conventionally reinforced concrete in a moist environment and exposed to chloride	0.10
Conventionally reinforced concrete in a moist environment not exposed to chloride	0.15
Above-ground building construction where concrete will stay dry	no limit



Steel corrosion: chlorides



Typical zones affected by chlorides
[tiré de Pritchard B. 1992 Bridge design for economy and durability, Thomas Telford Services, London, 172 p.]

Steel corrosion: carbonation

- Chemical reactions
  - **$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$**
- Effects
  - Compressive strength ↑
  - Porosity ↓: $Ca(OH)_2 \rightarrow CaCO_3$ with ↑ volume 11%
  - pH ↓ due to $Ca(OH)_2$ consumption
- Evolution
  - $s = k.\sqrt{t}$
    - s = carbonation depth
    - t = time
    - k = constant

Steel corrosion: carbonation

Steel corrosion: carbonation

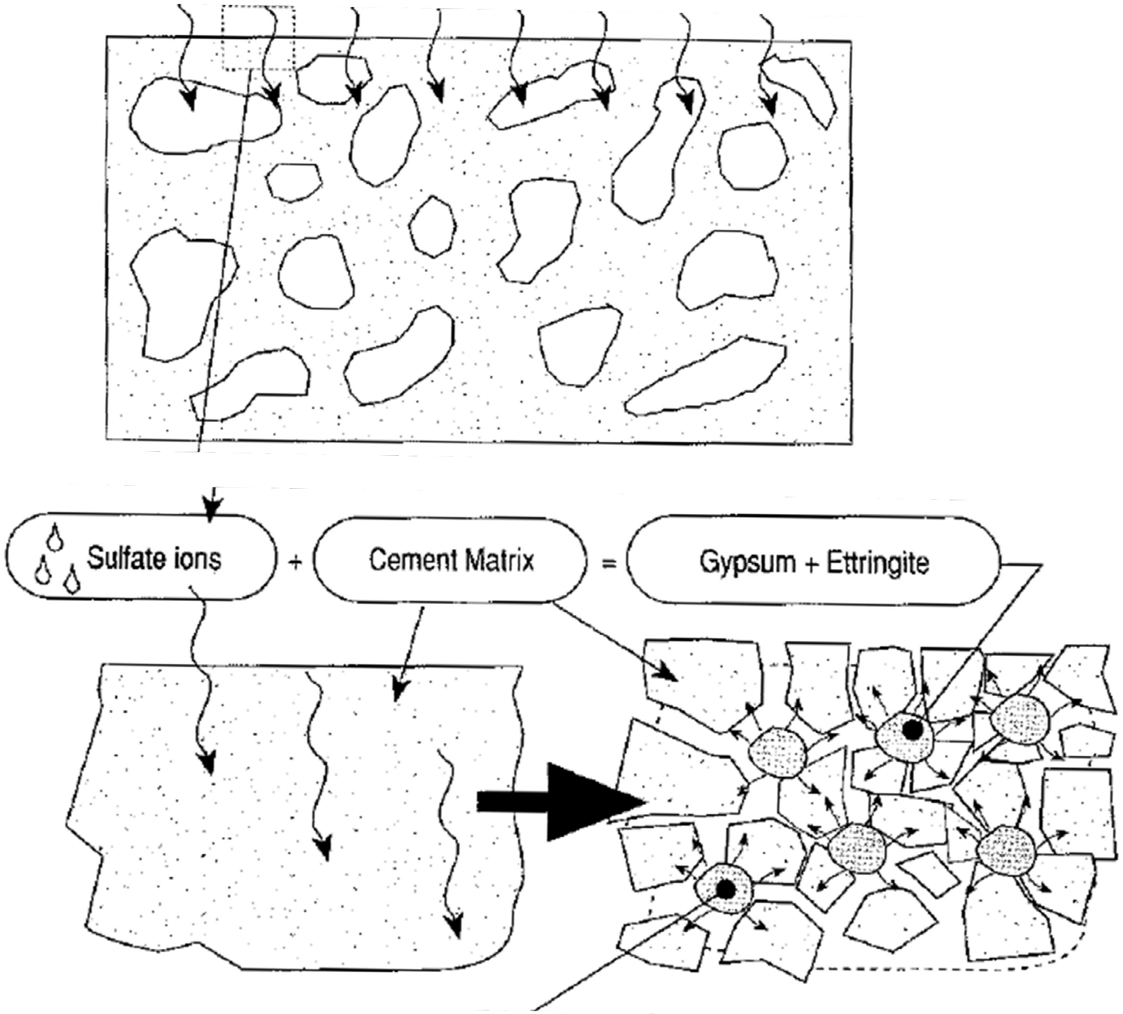
Jezoraskiego,

Railway bridge,

Warsaw

Disintegration mechanisms: sulphates

- Sulphate attack
  - Reaction with $Ca(OH)_2$ and hydrated calcium aluminates
  - Formation of gypsum and ettringite
  - Volume (reaction products) > volume (reactives)
  - Effect: surface scalling and disintegration, mass deterioration

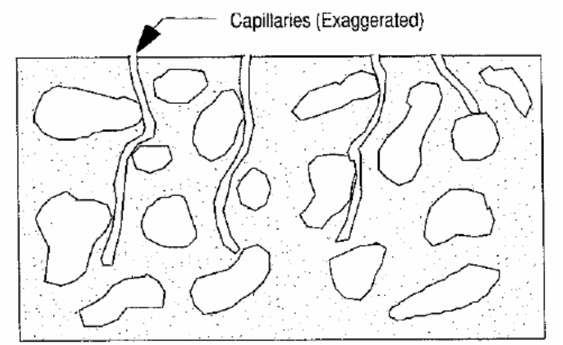


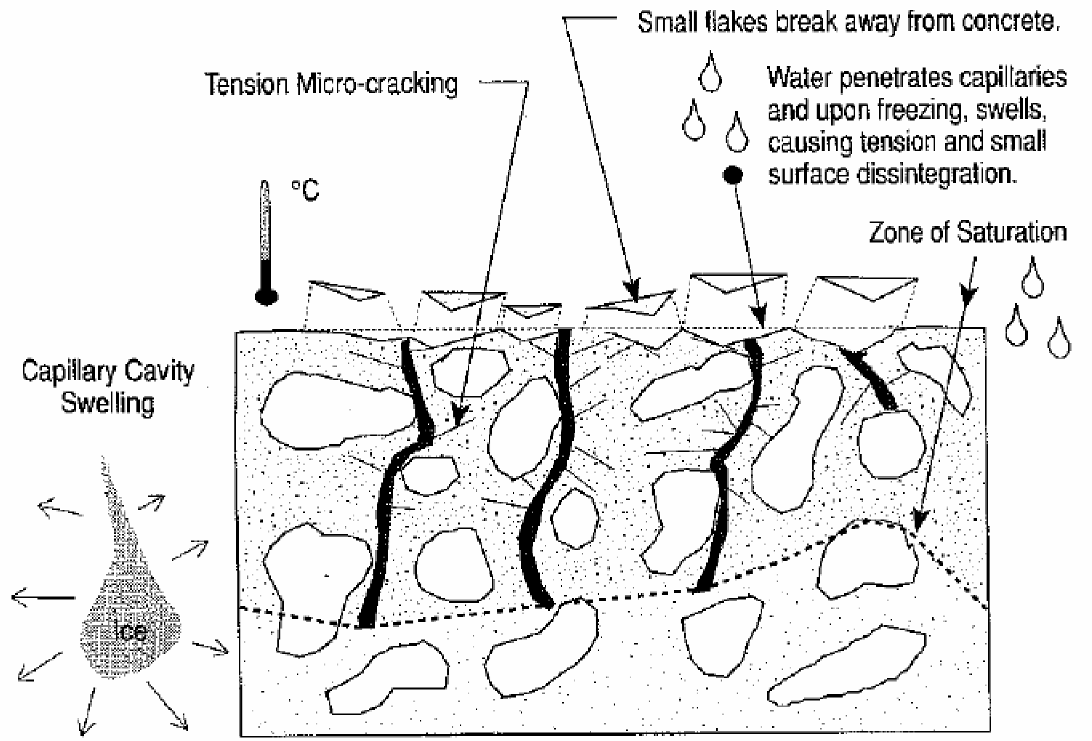
Disintegration mechanisms: sulphates

Fort Peck dam on Missouri river (Montana. U.S.A.) [Tiré de MEHTA, P. K. Concrete Structures, Properties and Materials 1986, Prentice Hall, USA, 450 p.].

Disintegration mechanisms: freezing

- Freeze-thaw disintegration



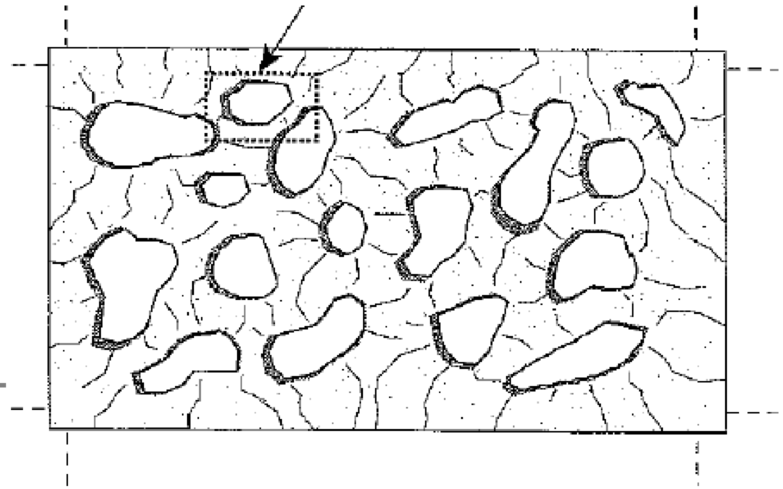


Freeze-thaw cycling and deicing salts

University campus, Sart-Tilman

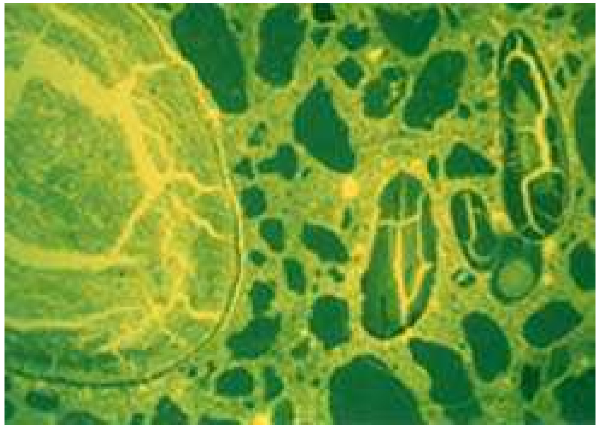
Disintegration mechanisms

- Alkali-aggregate reactions: effects
  - Reactive silica or silicate in the aggregate reacts with alcalis of cement
  - $SiO_2 + 2NaOH \rightarrow Na_2SiO_3 + H_2O$
  - Gel forming around aggregate when moisture (80% at 21-24°C)
  - Swelling of gel when moisture



Disintegration mechanisms: AAR

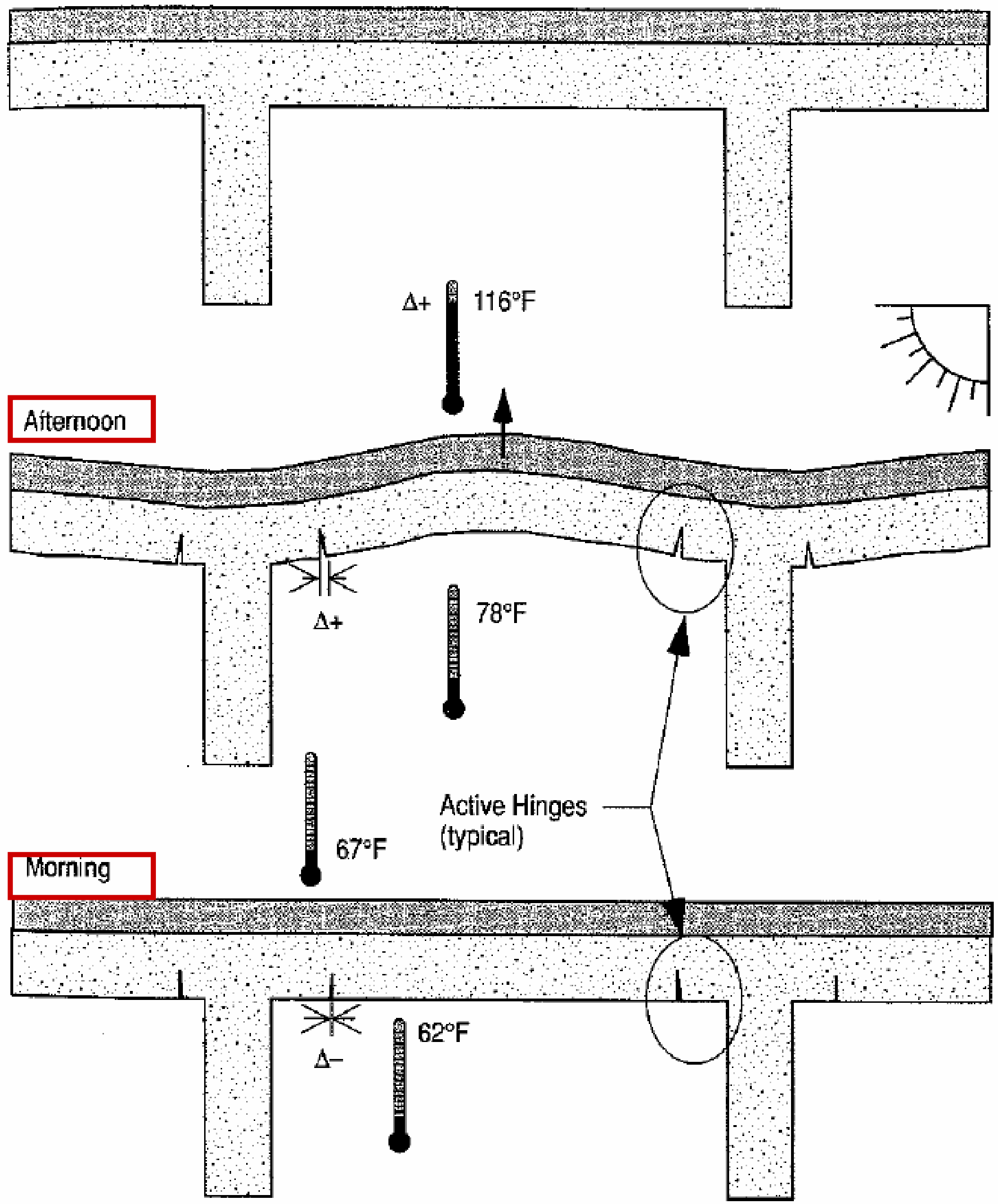
Habour installation from the 1970's containing Diorite and granites with opaline veining coarse and fine aggregate (BRE-UK).



Internal and external cracks caused by ASR in porous chert (RBL-DK).

Various causes

- Thermal effects
- Humidity gradients
- Overloading
- Design errors

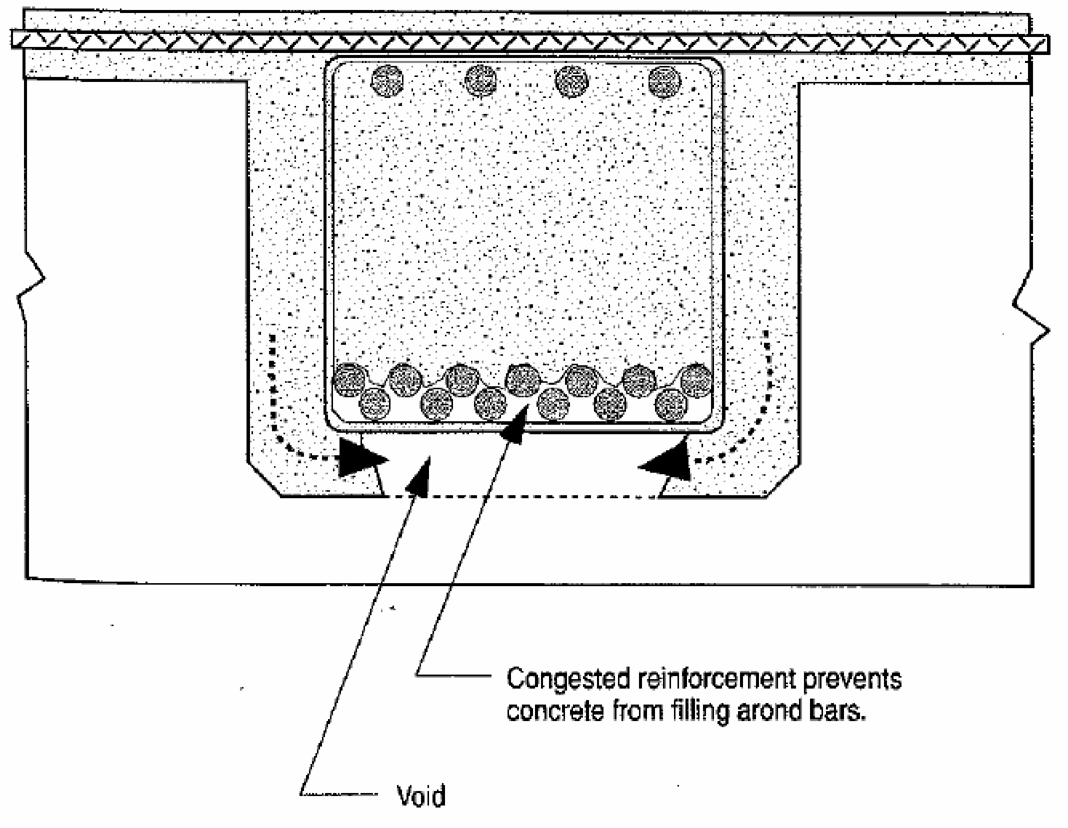


Faulty workmanship

- Improper reinforcing steel placement

Cause: *mat of steel that concrete cannot pass through during placement and consolidation*

Risk: *visible or latent void around reinforcement*



What to do?

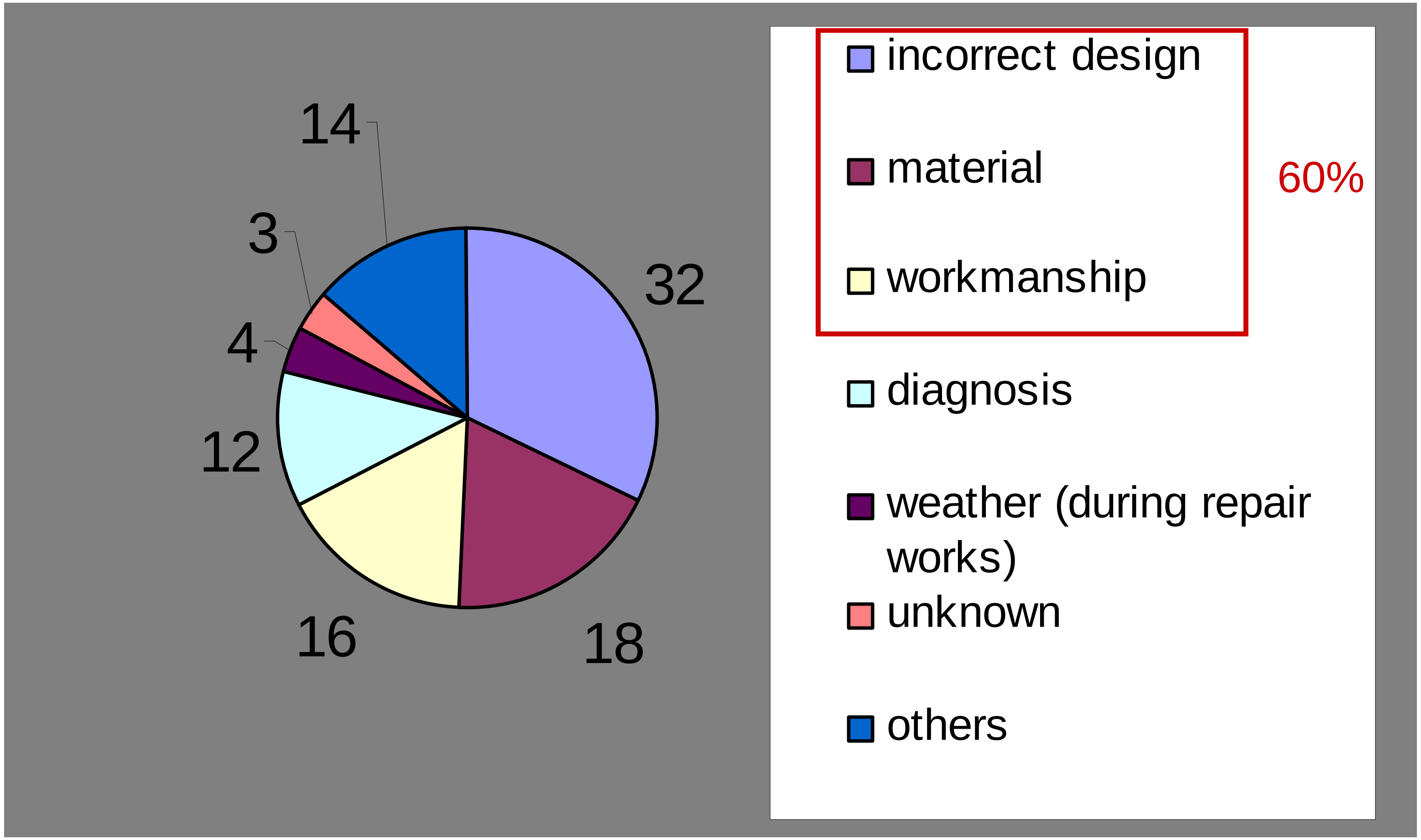
... to avoid this ...

Skaryszewski Park, Warsaw

or this …

Nowy swiat, Warsaw

Causes of repair failure by corrosion, cracking, debonding *(Tilly, 2004)*



The reliability and durability of a repaired concrete substrate and its remaining service life depends on the behavior of the repair material, which is controlled by the **compatibility** between the two materials making up the repair system.

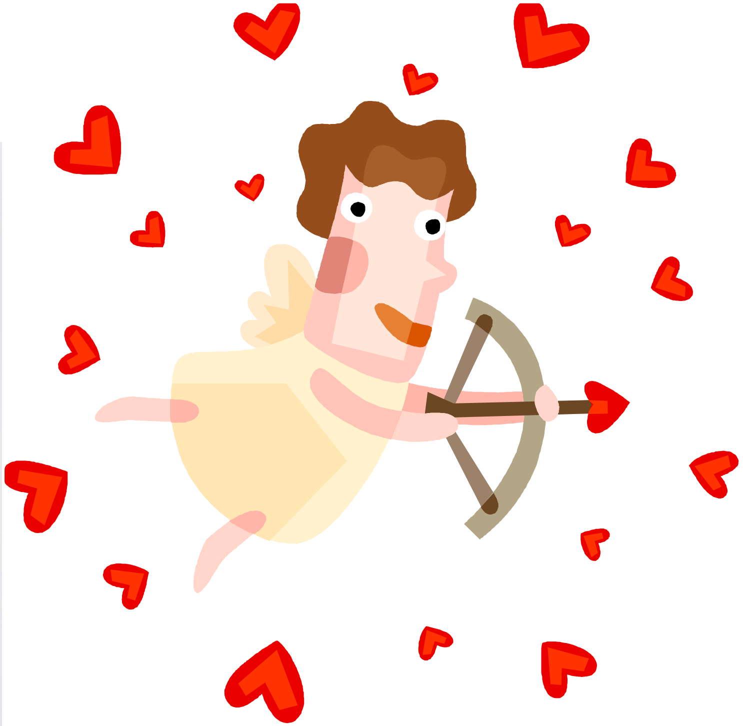
(Czarnecki, 2004)

… the heterogeneity of the components in a composite repaired structure requires an **understanding of the interaction** of the existing materials and the repair materials …

(Vaysburd et al., 2004)

We are waiting for compatibility …

Przystąpienie Polski do Unii Europejskiej pozwoli zoptymalizować podejmowane wysiłki przy współpracy dwustronnej oraz programach wielostronnych funkcjonujących w ramach Unii Europejskiej, przede wszystkim w dziedzinie wspierania rozwoju regionalnego. Wybrano ponad 40 projektów, które zostaną zrealizowane w latach 2005-2007.



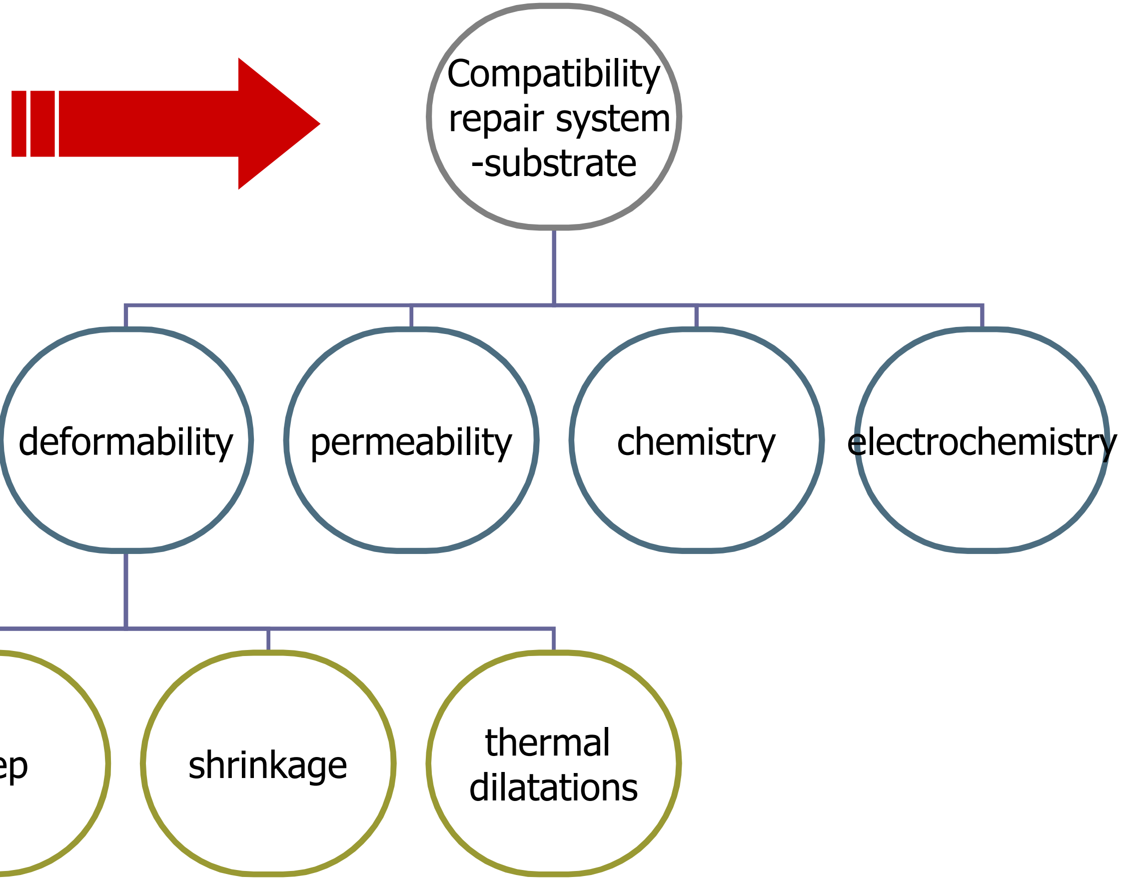
… but what is compatibility ?

How to define compatibility?

Compatibility for repair … *(Bissonnette et al., 2004)*

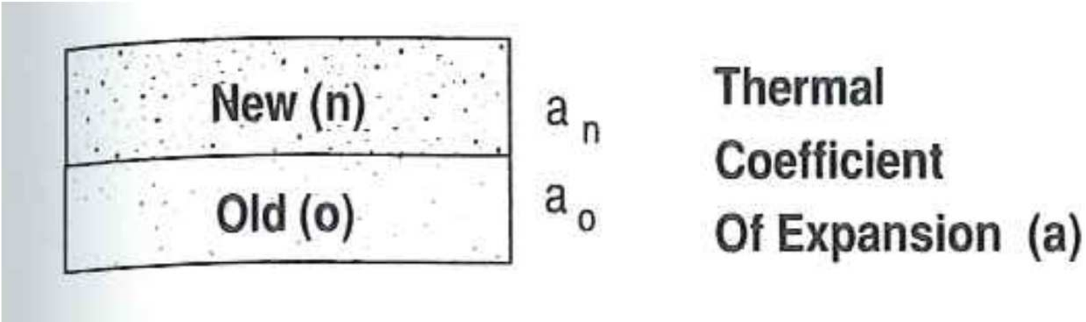
… is a 3D marriage:

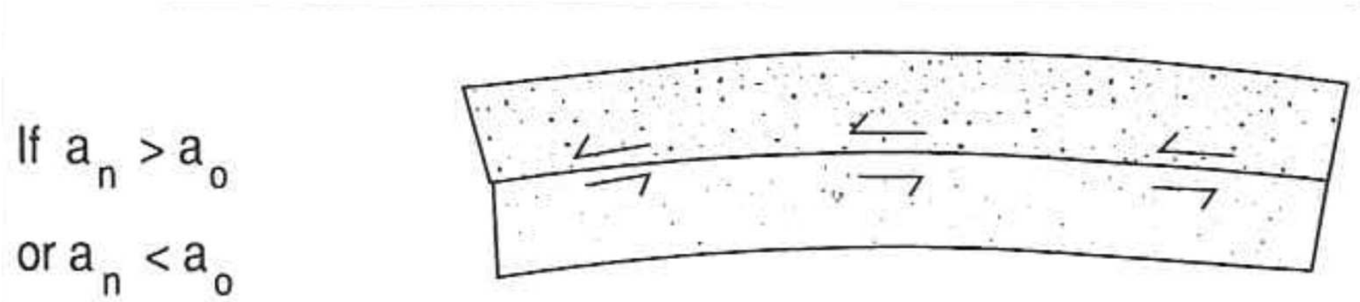
- substrate
- repair material
- environment



Compatibility: deformations

- Thermal coefficient of expansion

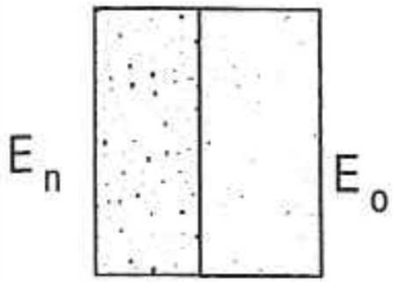




Shear bond is stressed.

Compatibility: deformations

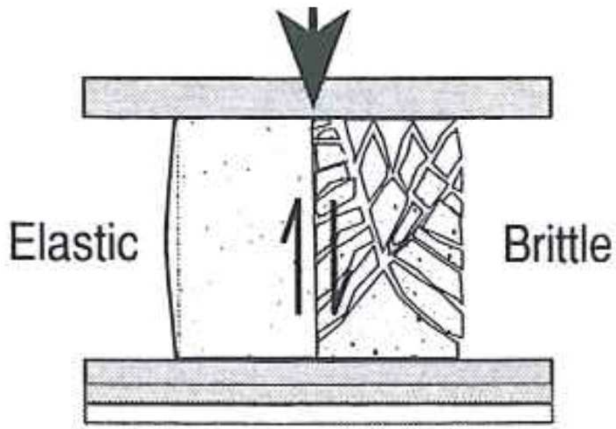
- Modulus of elasticity



Modulus Of Elasticity (E)

If $E_n > E_o$

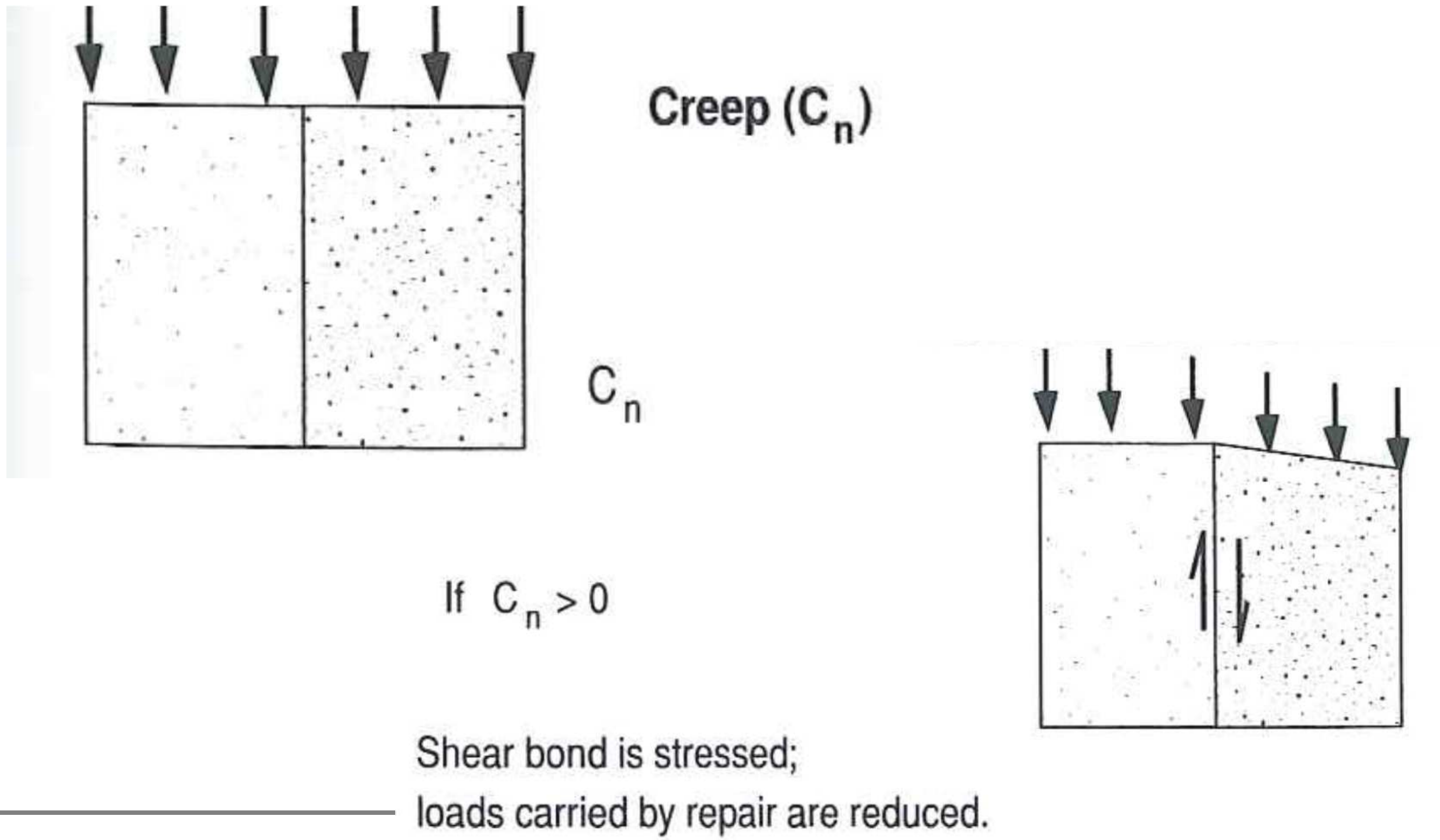
or $E_n < E_o$



Shear bond is stressed.
Brittle material may become overstressed.

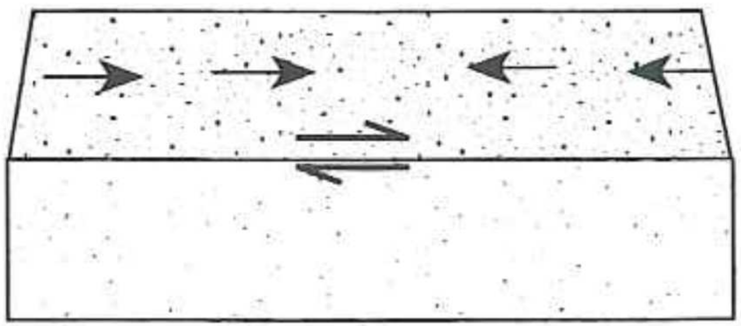
Compatibility: deformations

- Creep



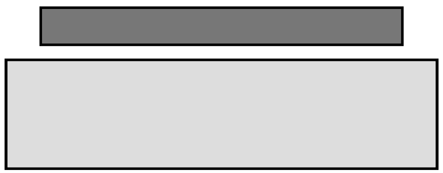
Compatibility: deformations

- Drying shrinkage
  - Water evaporation
  - Tensile stresses in the overlay
  - Cracking if tensile stresses >tensile strength

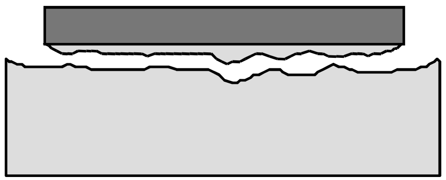


Potential effects of shrinkage – repaired system *(Bissonnette, 2004)*

$$\Sigma(\varepsilon) = (\varepsilon_{shrinkage} - (\varepsilon_{elastic} + \varepsilon_{creep} + \varepsilon_{microcraking}))$$

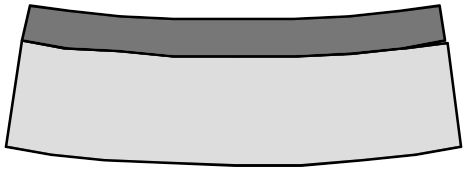


a) debonding



c) delamination

b) cracking



d) curling

Compatibility: deformations

- Lower W/C

Water/Cement Ratio

Aggregate/Cement Ratio	0.4	0.5	0.6	0.7
3	.08	.12		
4	.055	.085	.105	
5	.04	.06	.075	.085
6	.03	.04	.055	.065
7	.02	.03	.04	.05

High Shrinkage

Moderate Shrinkage

Low Shrinkage

Main parameters affecting the quality of repair

(Silfwerbrand, 2004)

- Concrete properties
- Removal deteriorated concrete
- Cleaning after removal
- Surface properties
- Surface preparation
- Bonding agents
- Mechanical devices across the interface
- Concrete placement
- Concrete curing
- Time dependance
- Traffic, ..

Predominant factors

Method of concrete removal

Absence of laitance layer

Cleanliness before to concrete placement

Compaction of the overlay

Curing of the overlay

Compatibility is … adhesion *(Deryagin, 1973)*

- **a process through which two bodies are brought together and attached (bonded) to each other**
- **the process of breaking a bond between bodies that are already in contact**

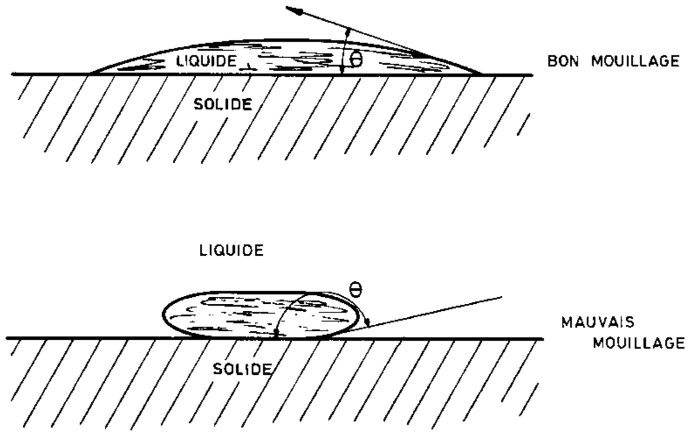
conditions and kinetics of contact

separation process

adhesion is love …

Adhesion

- **Specific adhesion**
  - **Physico-chemical interactions**
  - **Thermodynamic approach**
  - **Chemical bonding**
- **Mechanical adhesion**

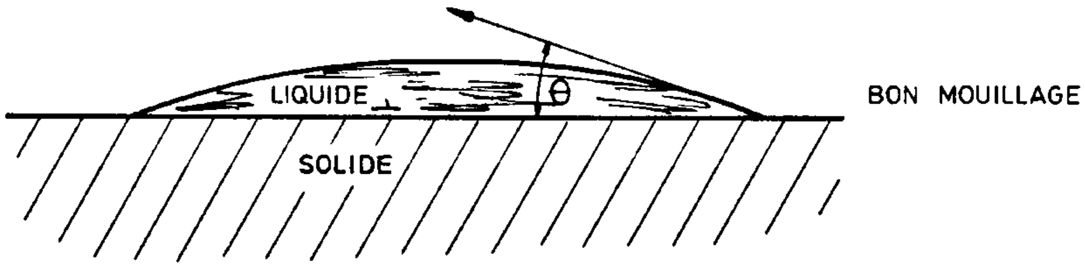


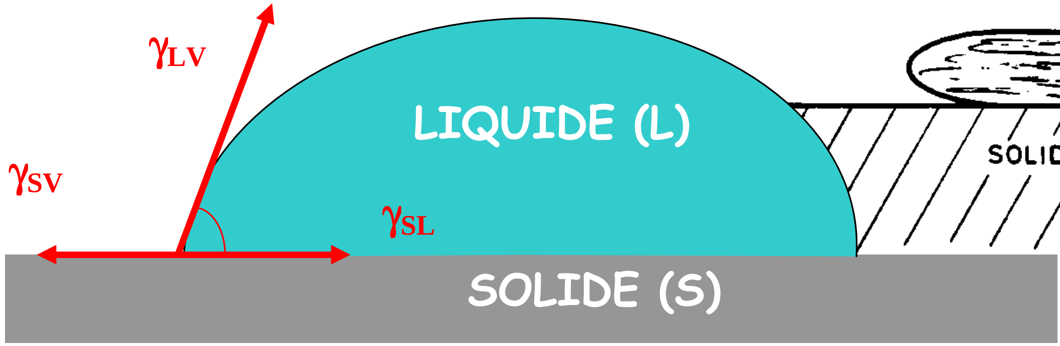
Condition 1 : spreading and wettability

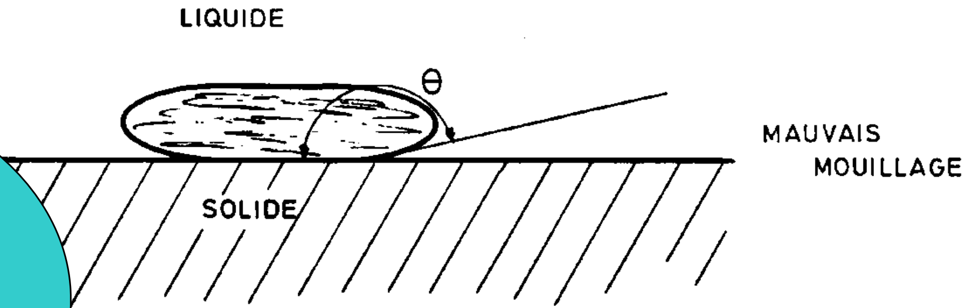
Condition 2 : physico-chemical interactions

Condition 3 : mechanical interlocking

Condition 1 : spreading



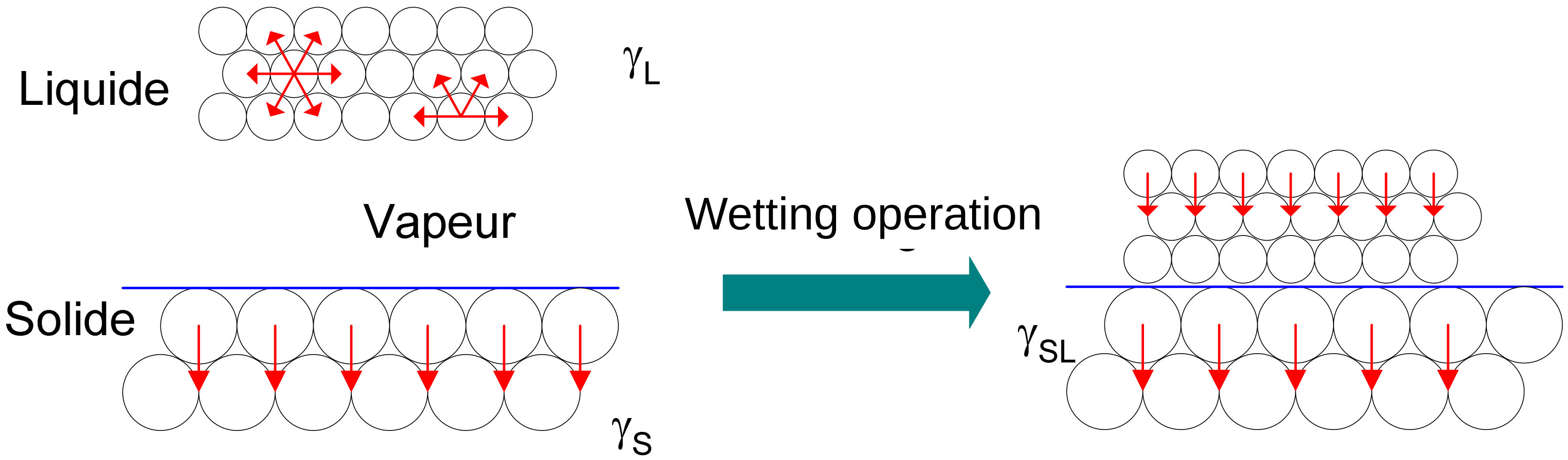




$$\gamma_{SV} = \gamma_{SL} + \gamma_{LV} \cos \theta$$

Better wettability of the solid by the liquid if contact angle is LOW

Evaluation of interfacial free energy



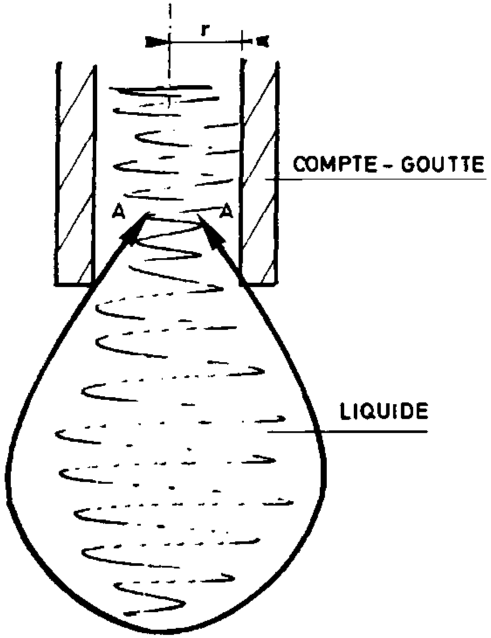
- Geometric average (OWENDS et WENDT) :

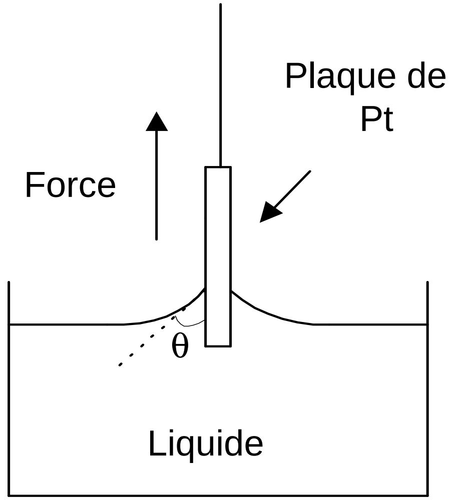
$$\gamma_{SL} = \gamma_L + \gamma_S - 2\left(\gamma_L^d \cdot \gamma_S^d\right)^{1/2} - 2\left(\gamma_L^p \cdot \gamma_S^p\right)^{1/2}$$

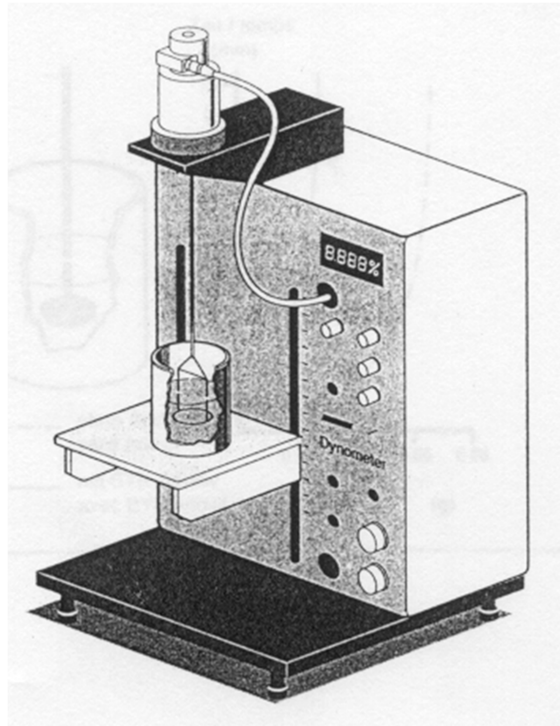
- Harmonic average (WU)

$$\gamma_{SL} = \gamma_L + \gamma_S - 4\,\frac{\gamma_L^d\ \gamma_S^d}{\gamma_L^d + \gamma_S^d} - 4\,\frac{\gamma_L^p\ \gamma_S^p}{\gamma_L^p + \gamma_S^p}$$

Surface energy of products: measurements





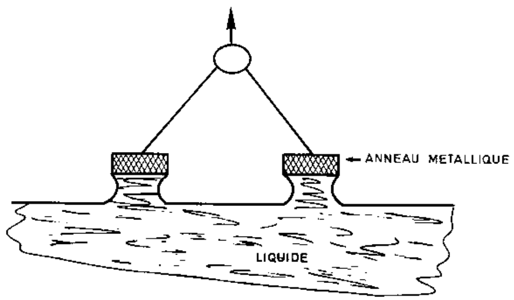


$$\gamma_L = \frac{F_W}{L.\cos\theta}$$

total volume + number of drops

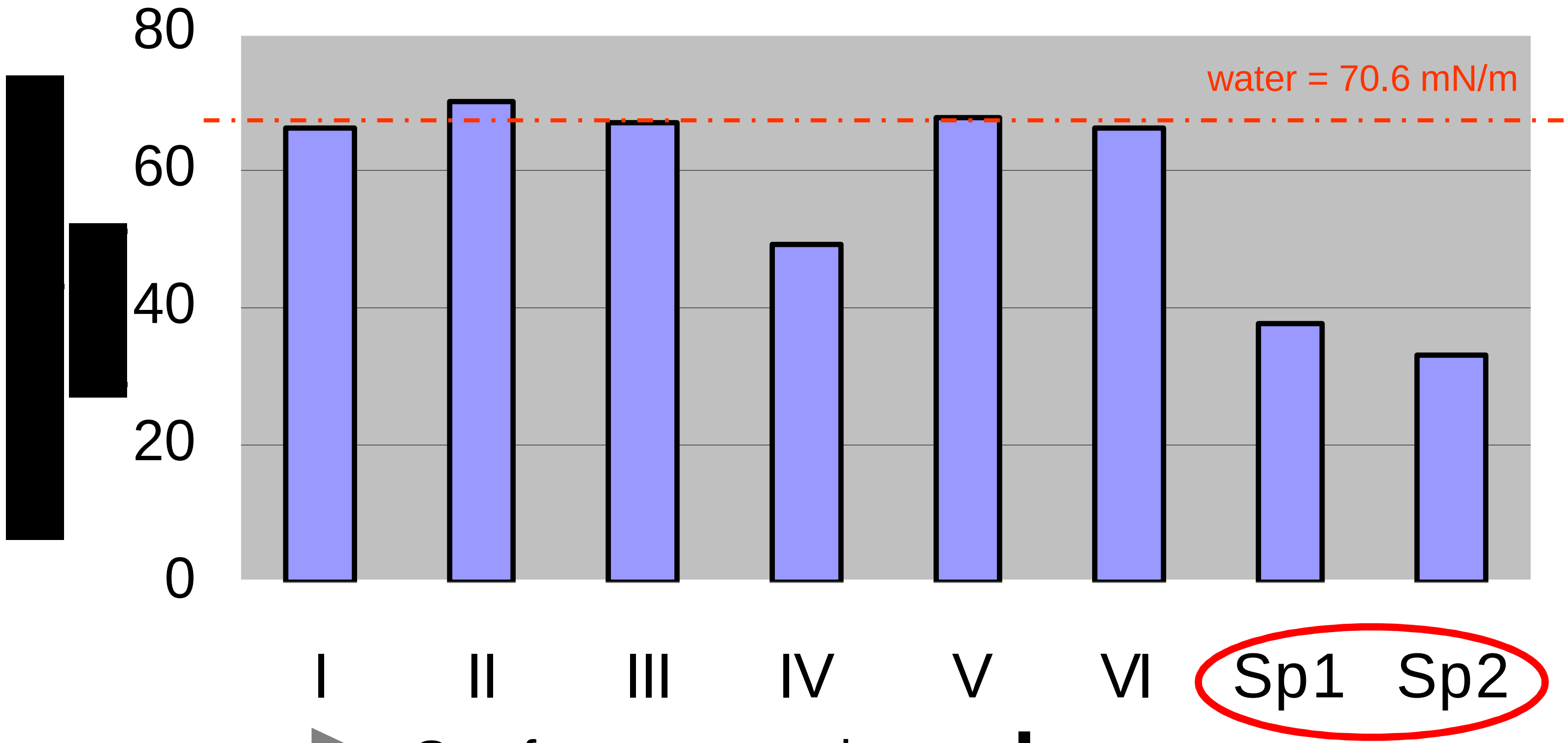
→ drop’s weight

$$2\pi r \gamma_L = \frac{4}{3}\pi r^3 \rho g$$



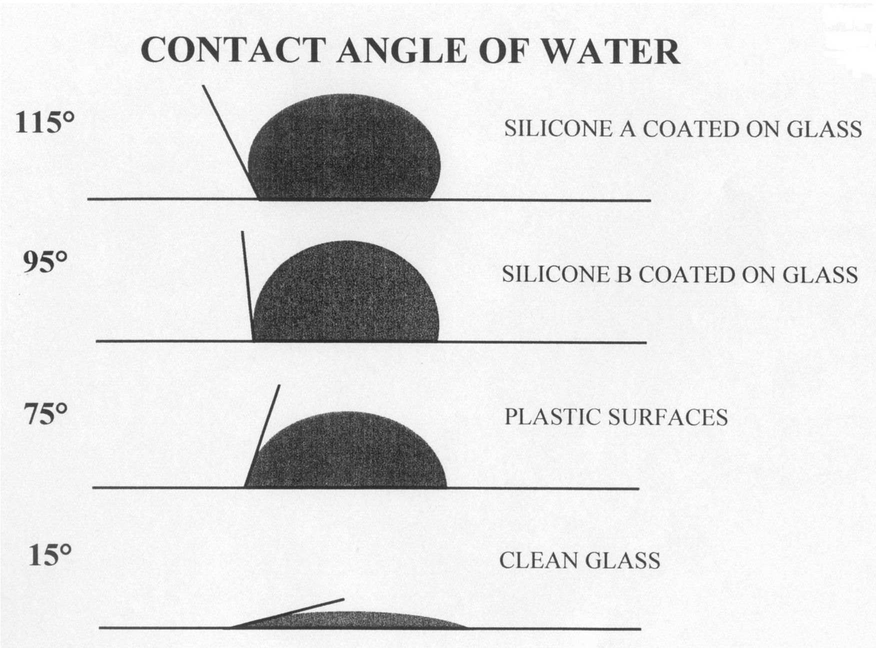
Surface free energy of superplasticizers

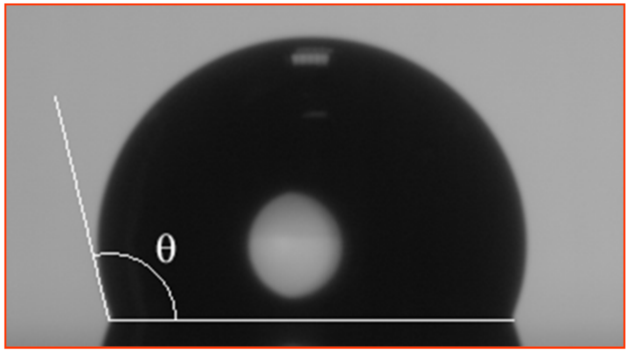
Liquide	***ID***
Sp mélamine (macromolécules)	I
Sp mélamine	II
Sp naphtalène	III
Sp copolymère vinyle	IV
Sp acide maléique	V
Sp ligno-sulfonate de sodium	VI
CEM I 42,5N, E/C = 0.4	VII



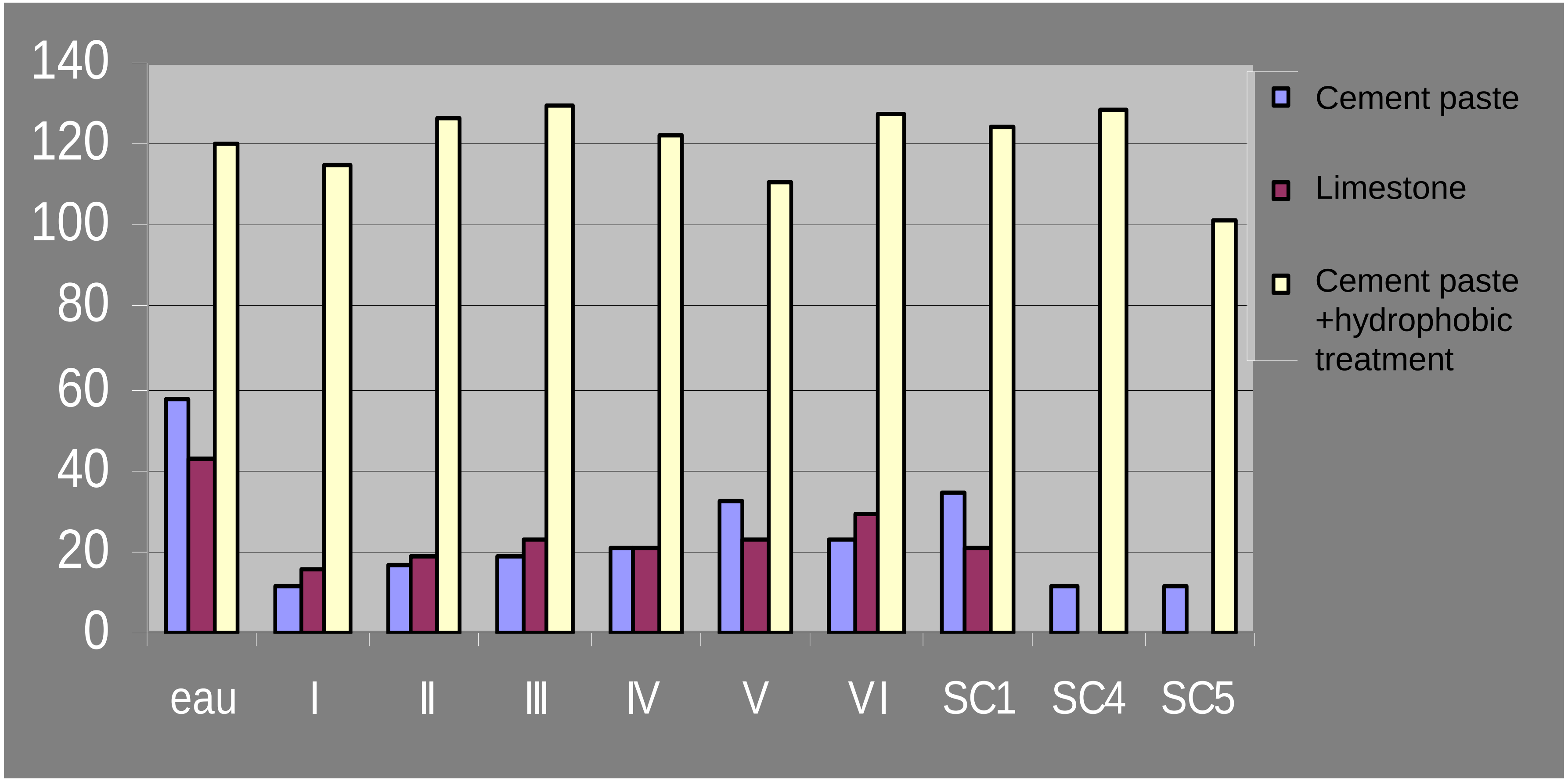
Sp of new generation : γ_L ↓

Contact angle measurement



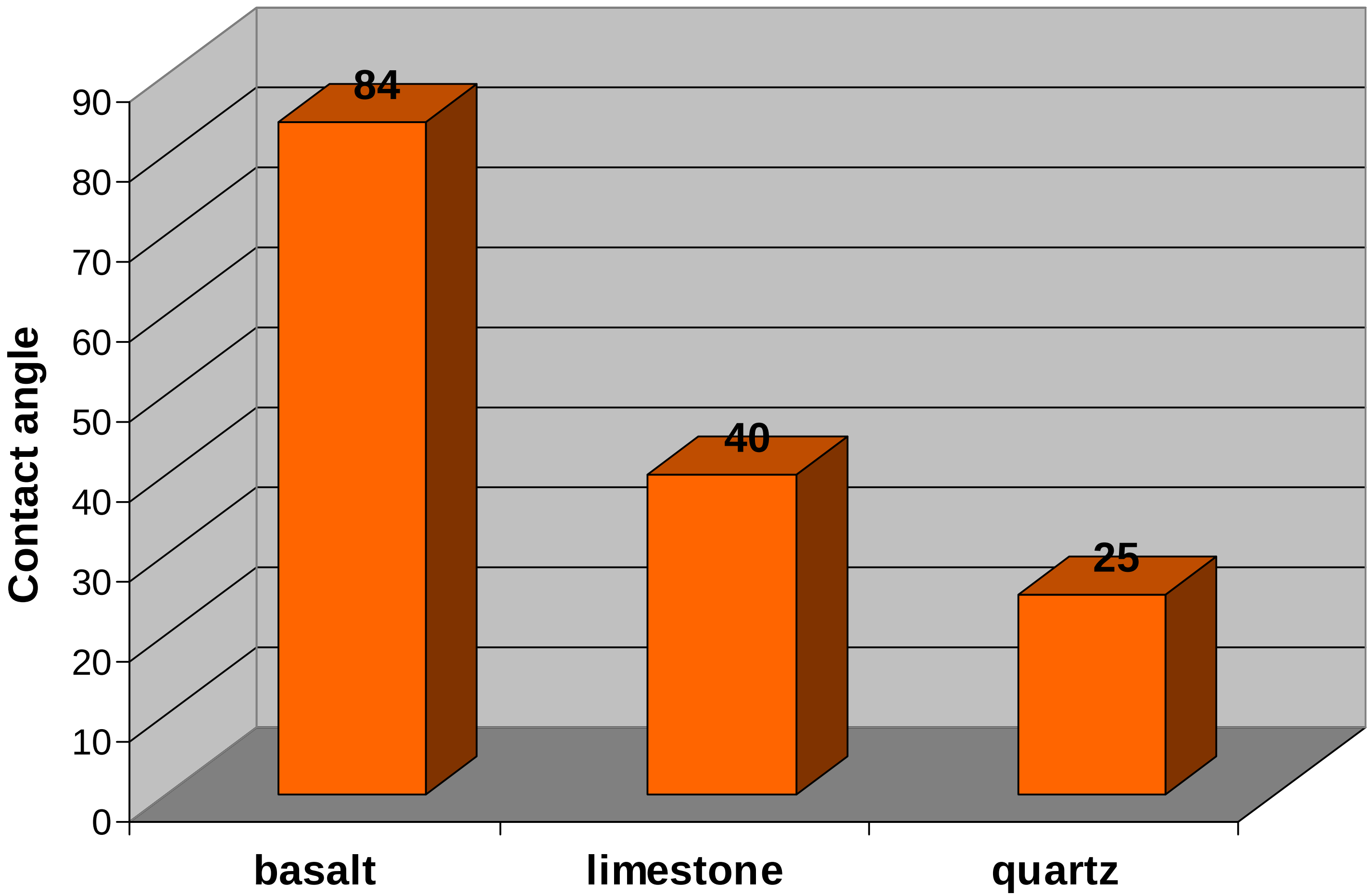


Contact angles of slurries on different substrates



Contact angle of epoxy resin on aggregates

(*Fiebrich,1994*)



Surface free energy of solids

$$1 + \cos\theta = \frac{2}{\gamma_L}\left[\left(\gamma_S^d \gamma_L^d\right)^{1/2} + \left(\gamma_S^p \gamma_L^p\right)^{1/2}\right]$$

Substrate	Surface free energy (mN/m -0.001 J/m²)		
	Dispersive component	Polar component	Total
Multiplex	14.94	4.24	19.18
Cement paste	31.65	12.69	44.34
Cement paste + hydrophobic treatment	14.86	0.01	14.87
Limestone	37.08	12.4	49.48
Glass	20.54	22.85	43.39

Evaluation of γ_S : indirect and difficult!

Selection criteria

- work of adhesion
- spreading
- interfacial energy
- critical energy of solid surfaces

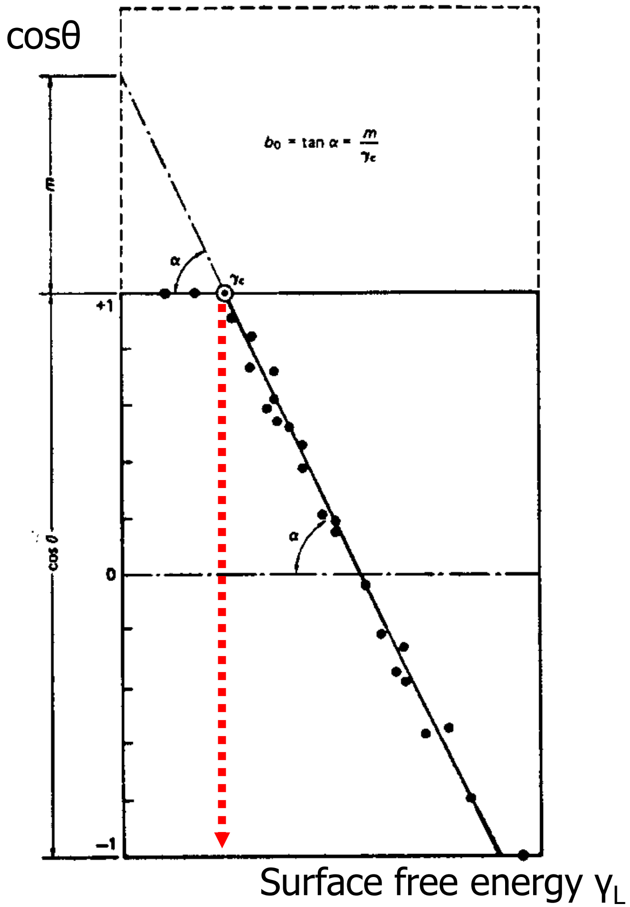
$$W_a = \gamma l + \gamma s - \gamma sl$$

Liquids	Supports			
	Cement paste	Cement paste + hydrophobic treatment	Limestone	Concrete
I	99.76	36.96	103.49	102.18
II	102.36	37.63	106.14	104.82
III	102.99	40.37	107.15	105.7
IV	84.04	29.73	86.98	85.95
V	100.58	37.03	104.31	103
VI	98.58	35.58	102.13	100.89
VII	106.69	43.02	111.18	109.61
VIII	83.62	34.75	87.28	86.01
Water	102.49	37.32	106.23	-

Work of adhesion (mJ/m²) different cement slurries on concrete

Critical surface energy is the maximum surface free energy of liquid that will spread on specific solid surface

Substrate	Critical surface energy (mN/m)
Cement paste	25.5
Limestone	42.5
Epoxy resin (EP)	43-44
PolyVinyl Chloride (PVC)	39
PolyEthylen (PE)	31
PolyTetraFluorEthylen (PTFE)	18.5



Selection criteria

CONCLUSION: good adhesion needs INTIMATE CONTACT (→ good wetting) which means:

☺γ_S maximum: to avoid dust, oil or to promote surface treatment

☺γ_{SL} minimum: adhesive performances

BUT: necessary but not sufficient:

☺kinetics of contact: surface roughness and viscosity of repair system

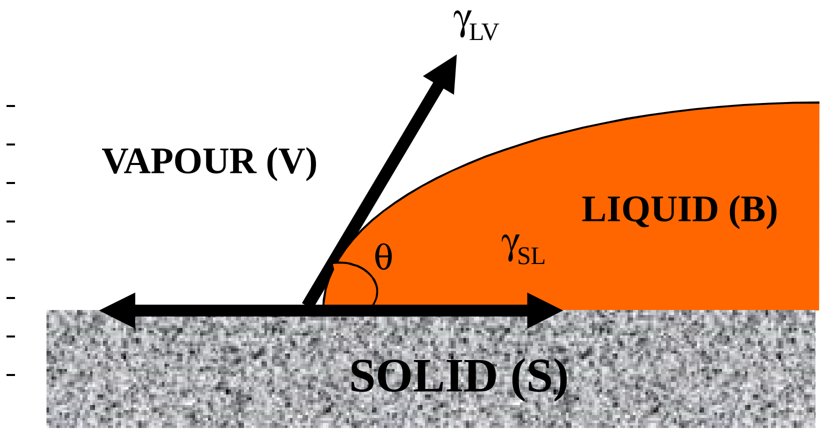
☺mechanical aspects of adhesion

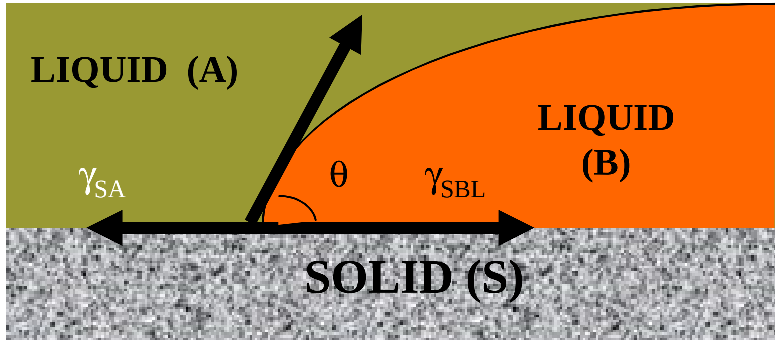
Disturbance of the equilibrium: water

$$\gamma_{SV} = \gamma_{SB} + \gamma_{BV} \,.\, \cos\theta$$

$$\gamma_{SA} = \gamma_{SB} + \gamma_{AB} \,.\, \cos\theta$$

$$\begin{cases} \gamma_S = \gamma_{SA} + \gamma_A \,.\, \cos\theta_A \\ \gamma_S = \gamma_{SB} + \gamma_B \,.\, \cos\theta_B \end{cases}$$





Equilibrium : the difference between tensions of adhesion is inferior to interfacial tension

$$\gamma_B \,.\, \cos\theta_B - \gamma_A \,.\, \cos\theta_A < \gamma_{AB}$$

No equilibrium : liquid B will expulse liquid A

$$\gamma_B \,.\, \cos\theta_B - \gamma_A \,.\, \cos\theta_A > \gamma_{AB}$$

the liquid with the higher tension of adhesion will expulse the other one from the surface

Work of adhesion for interfaces without (W_A) and with (W_{AL}) water

$$W_A = \gamma_A \cdot (1 + \cos \theta_A)$$

A = air

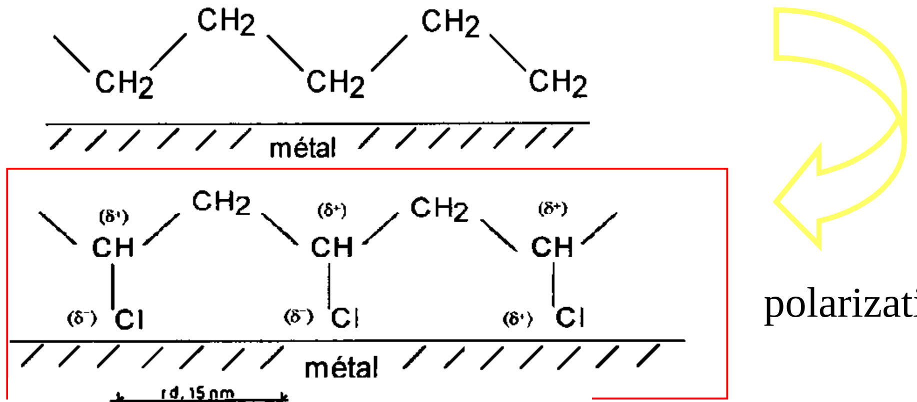
L = water

Interface	W_A (mJ/m²)	W_{AL} (mJ/m²)
Mortar/concrete	87.8	No sense
Acrylic/Concrete	74.1	22.7
Acrylic/Acrylic	80.4	53.7
Acrylic/Hydrophobic treatment	52.2	66.7
Epoxy/Concrete	79.6	21.8
Epoxy/Epoxy	92.4	53
Epoxy/Hydrophobic treatment	56	42.2

→ **Loss of adhesion when water**

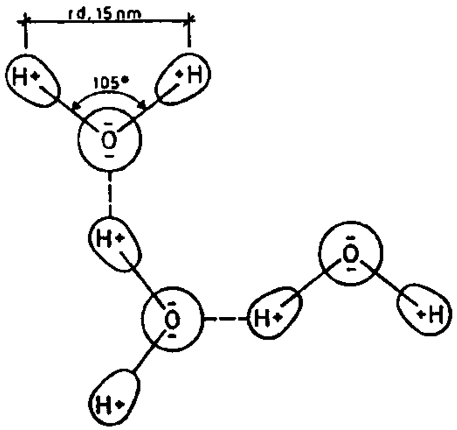
Condition 2 : physico-chemical interactions

Van der Waals

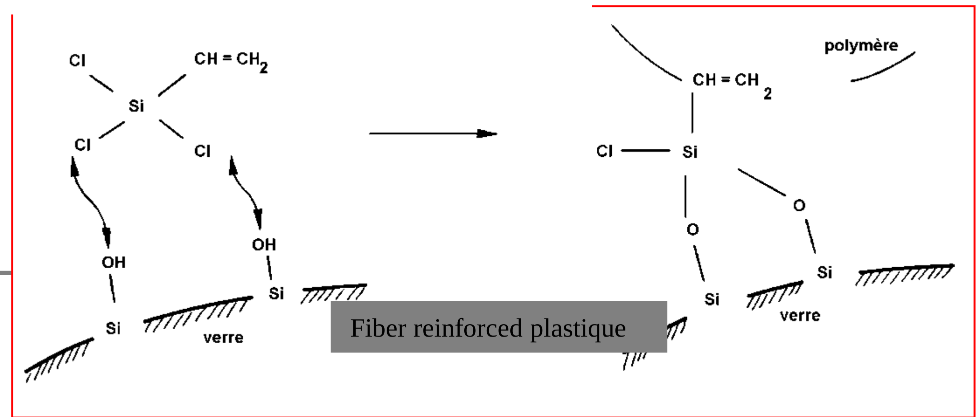


polarization

Hydrogen bond

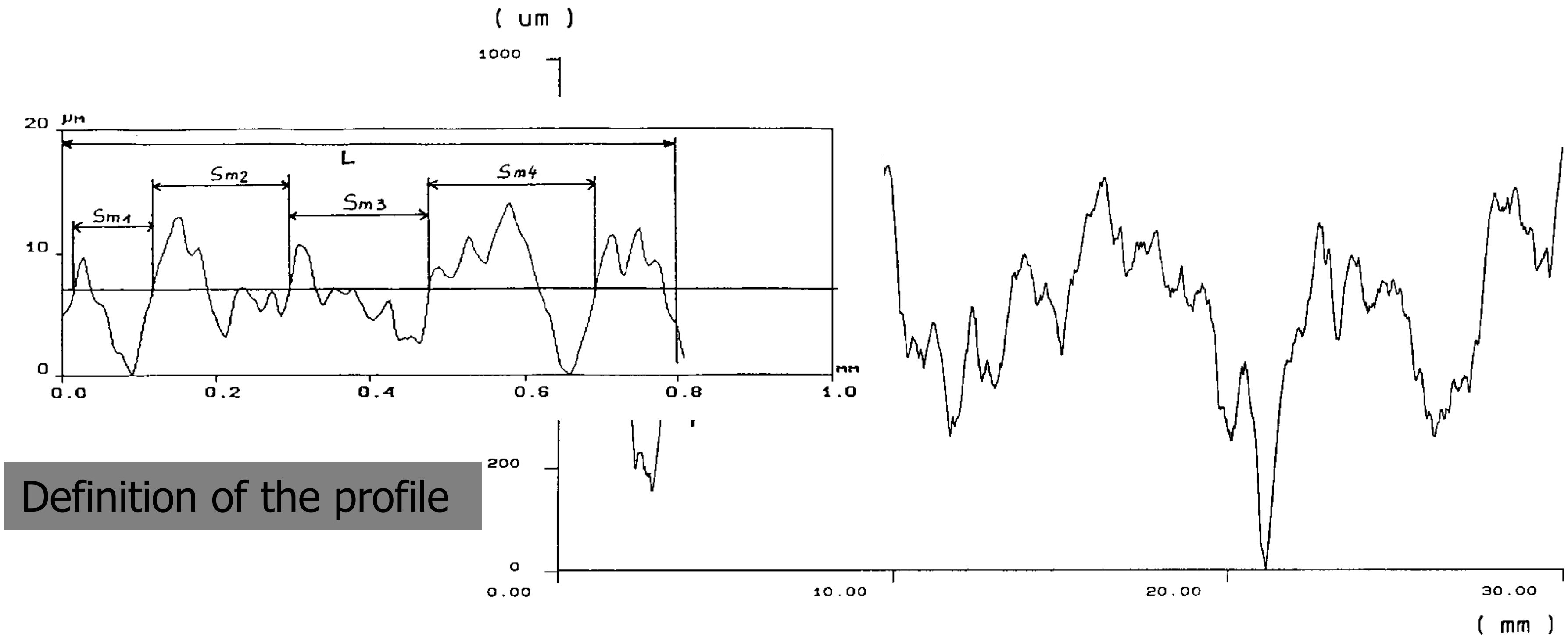


Chemical bonds

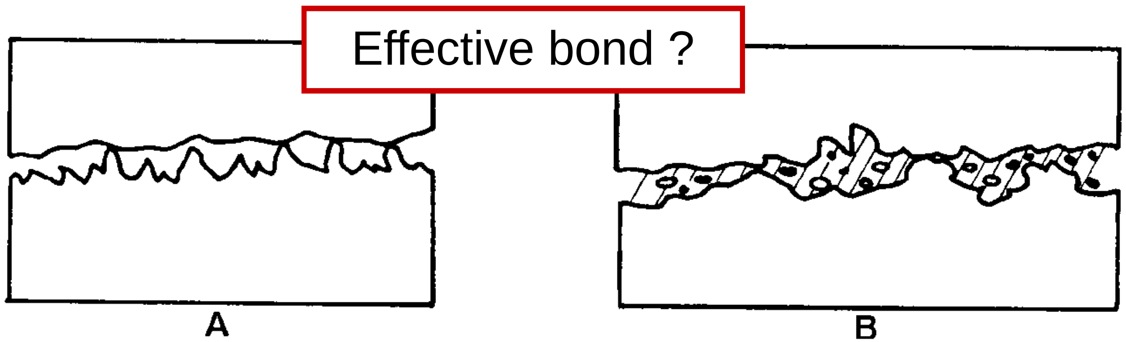


Fiber reinforced plastique

Condition 3 : mechanical interlocking



Definition of the profile



How is roughness influence?

Surface preparation: effects

polishing

scabbling

Surface preparation: effects

Water-jetting

sandblasting

Description of Surface Preparation

PTW
Polished troweled surface

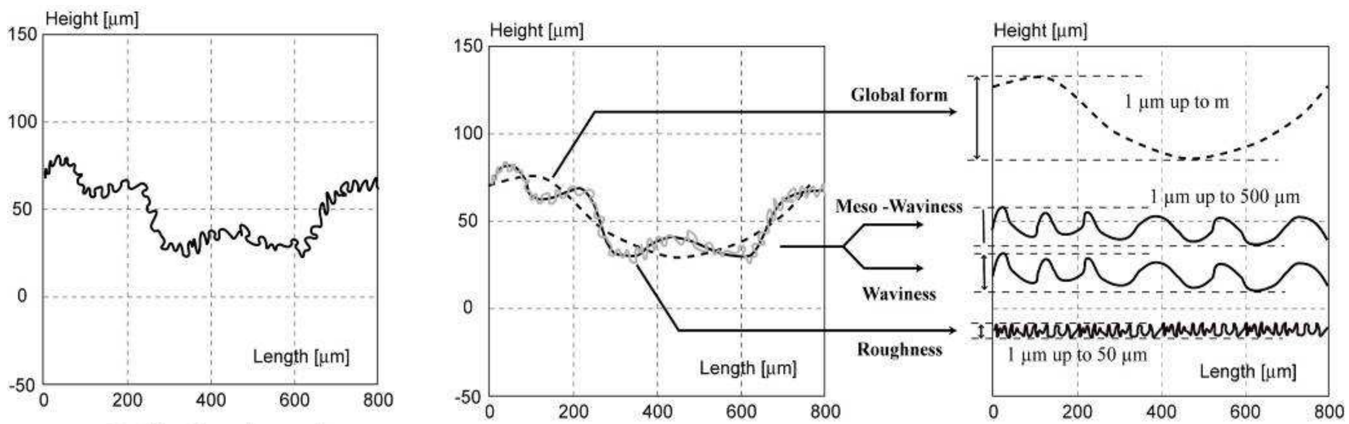
SC2
Scarifying

HPW
Water jetting

Increasing apparent roughness

Scale effects

- Concrete surface presents fractals topography
- Each identification technique has specific resolution
- Possible to break up total profile in sum of under profile in terms of wavelengths
  - Separation in 4 complementary profiles



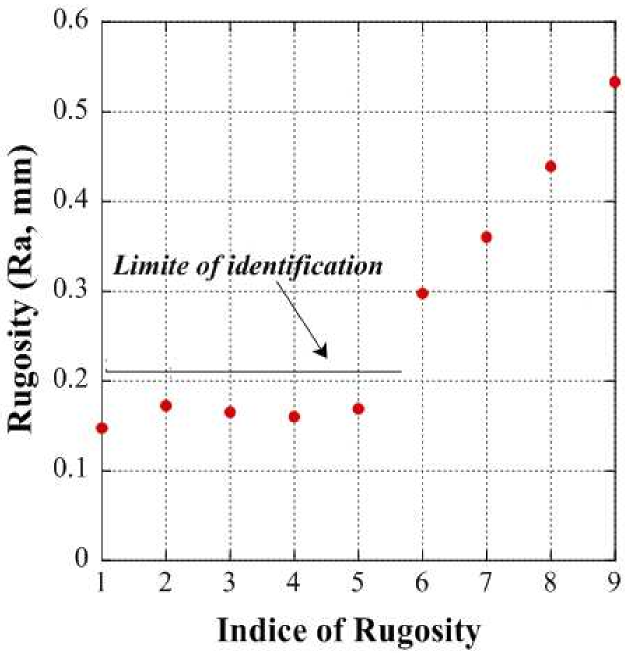
Profile of roughness of a surface of study

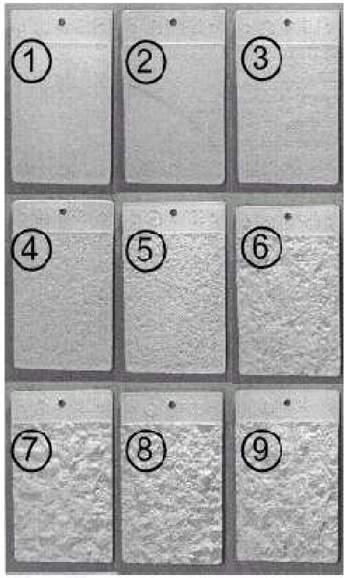
Decomposition of the profil roughness

Result of this decompostion for 4 scales

Scale effects (...)

- Resolution limits of opto-metric method
  - The limit of identification depends on the camera characteristics
  - For R_a > 0.250 mm, differentiation is satisfactory





Sand method

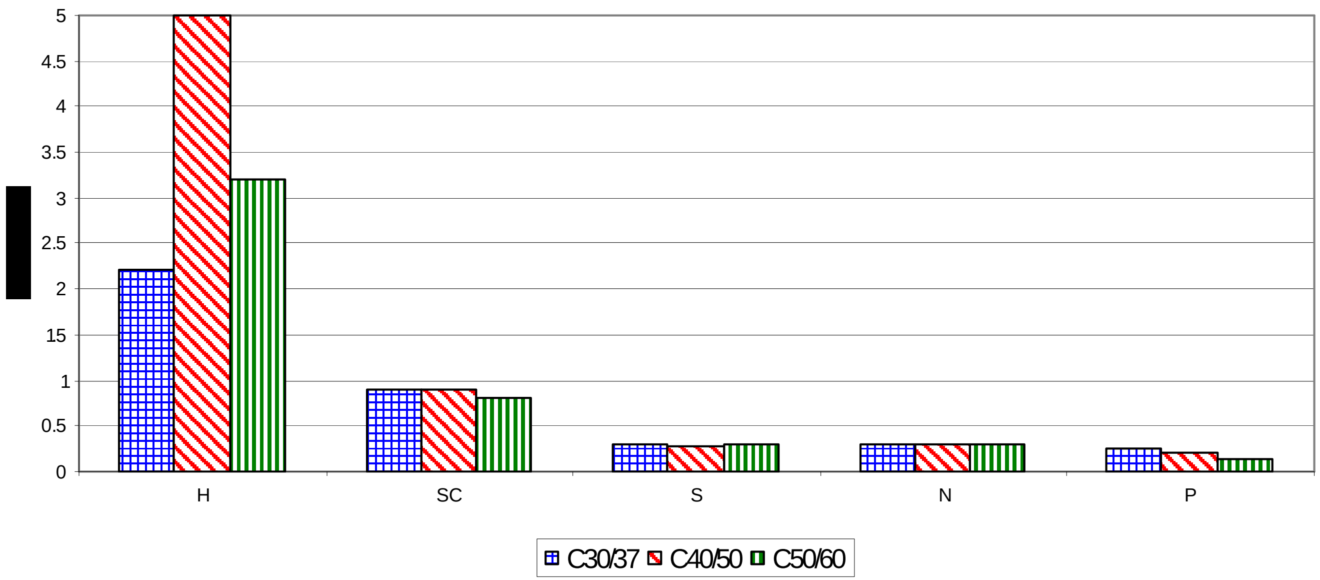
Profondeur moyenne de (macro-)texture :

H = water-jetting

SC = scarification

S = sandblasting

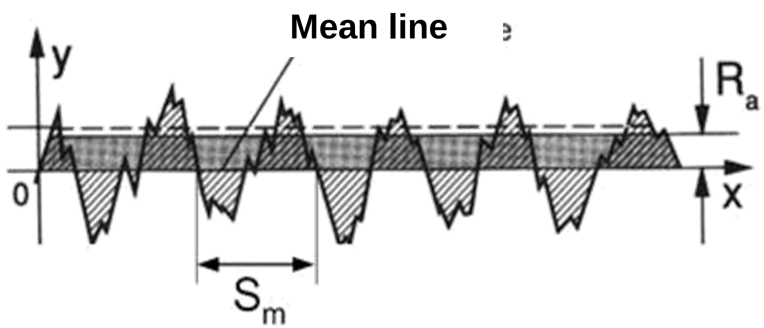
P = polishing

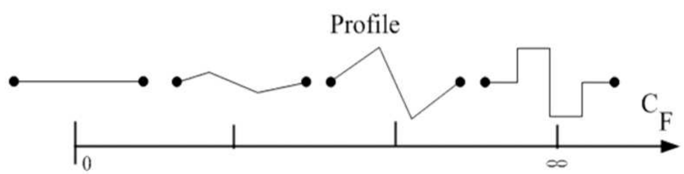


Roughness parameters (…)

- Based on specific approach [Courard,1999]

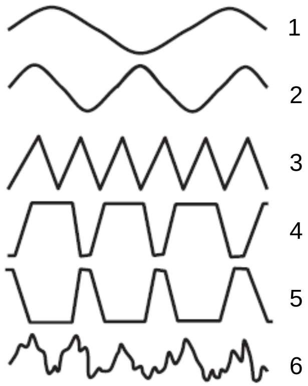
Parameters	***Definition***
X_t	*total height of the profile*
X_v	*maximum depth of the profile (holes)*
X_p	*maximum height of the profile (peaks)*
X_a	*arithmetic mean of the deviation of the profile from the mean line*
X_q	*quadratic mean of the deviation of the profile from the mean line*
S_k	*skewness of surface height distribution*
S_m	*mean spacing between profile peaks at the mean line, measured over the assessment length*
C_F, C_L, C_R	*Bearing ratio parameters*





Roughness parameters

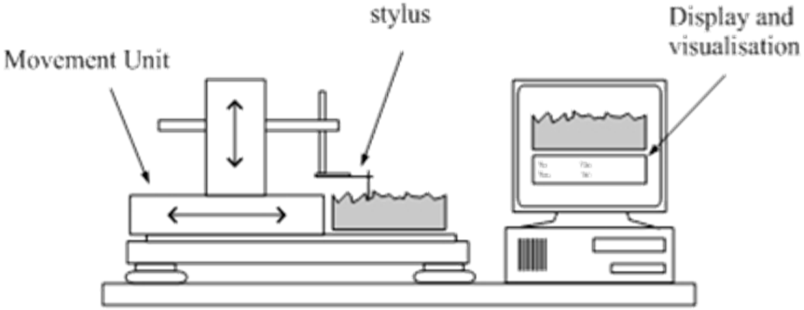
- Two parameters are not enough to describe roughness
  - Profiles 1 to 6 have same R_a
  - Profiles 4 and 5 have same S_m

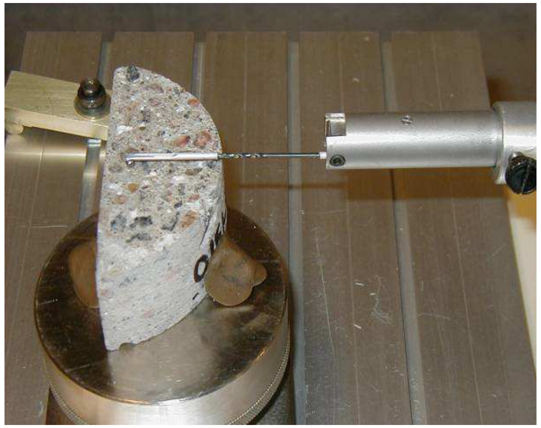


►Consequences on adhesion are probably very different …

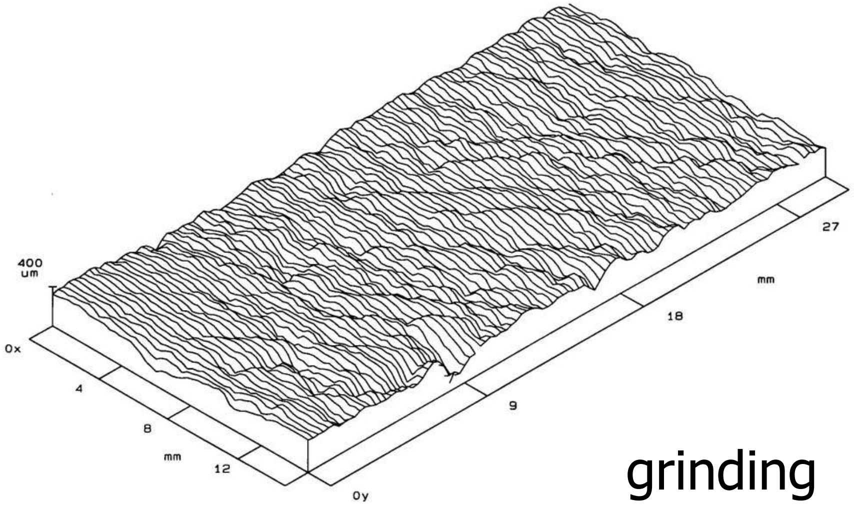
Profilometry

- Principle
  - A stylus walks along the surface. His vertical movement provides profile's description
  - Precision depends on stylus dimensions and path length between two measurements

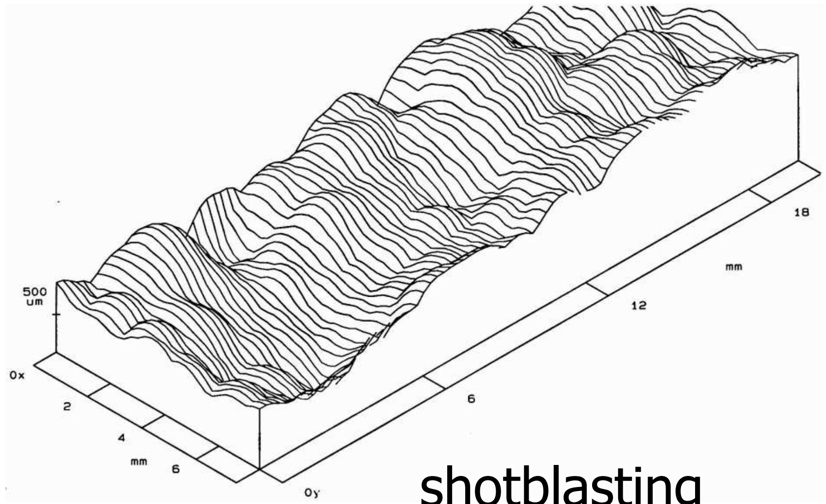




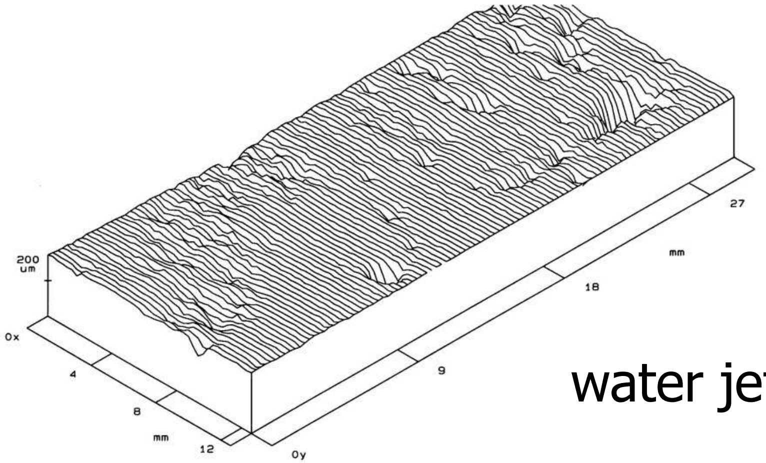
Surfometry *(Gorka et al., 2002)*



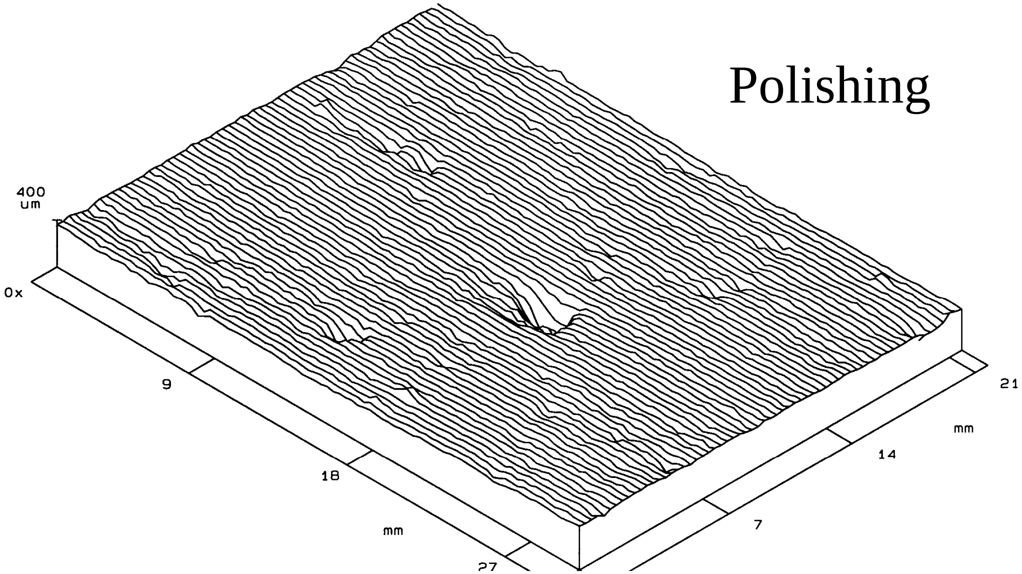
grinding



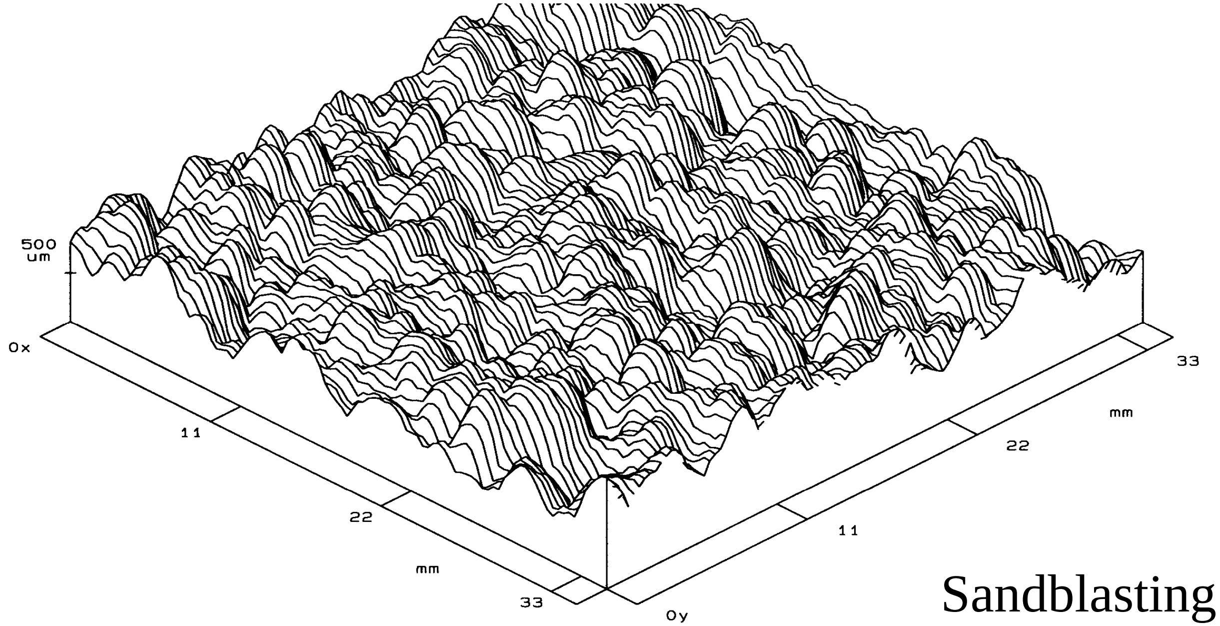
shotblasting



water jetting



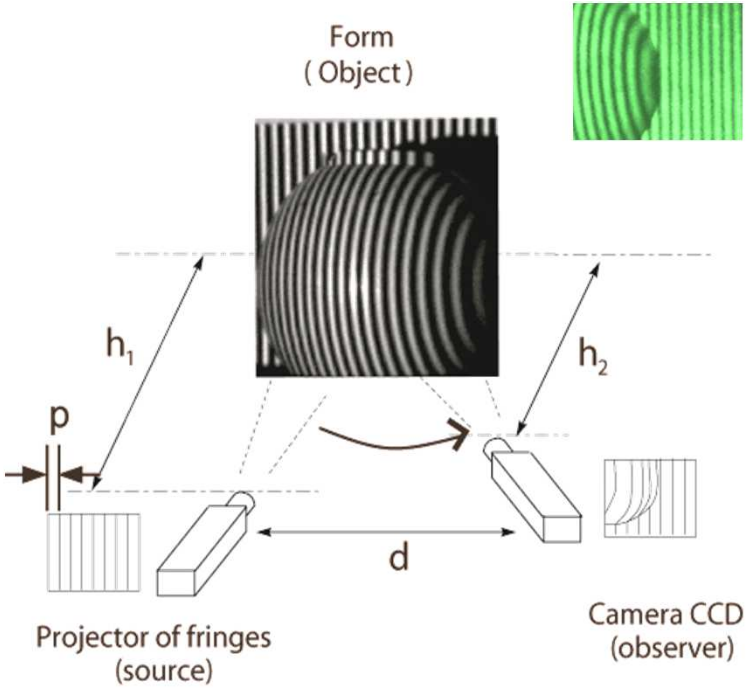
Polishing

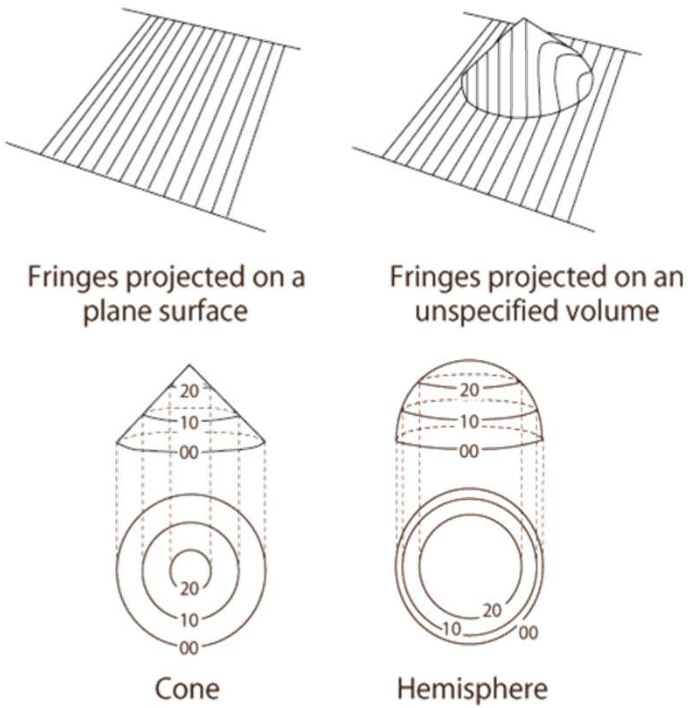


Sandblasting

Principe of *Moiré* projected method

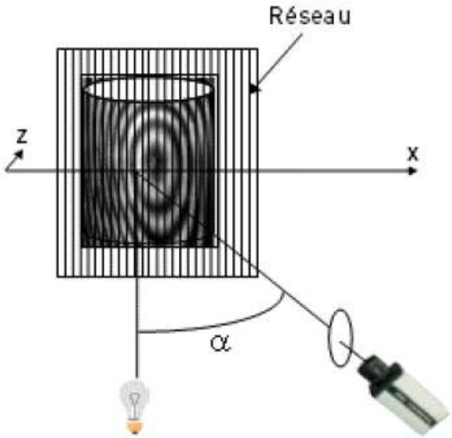
- Deformation of parallel and periodic fringes (level line)



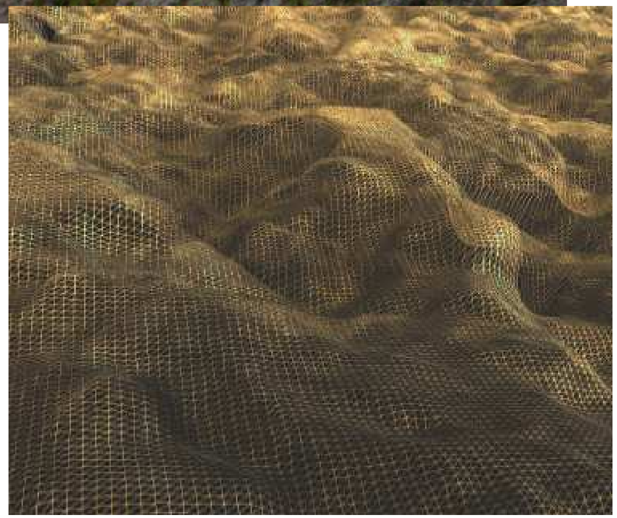


Relation between form and level line

Surface preparation: evaluation



Mathematical treatment



(Schwall, Courard)

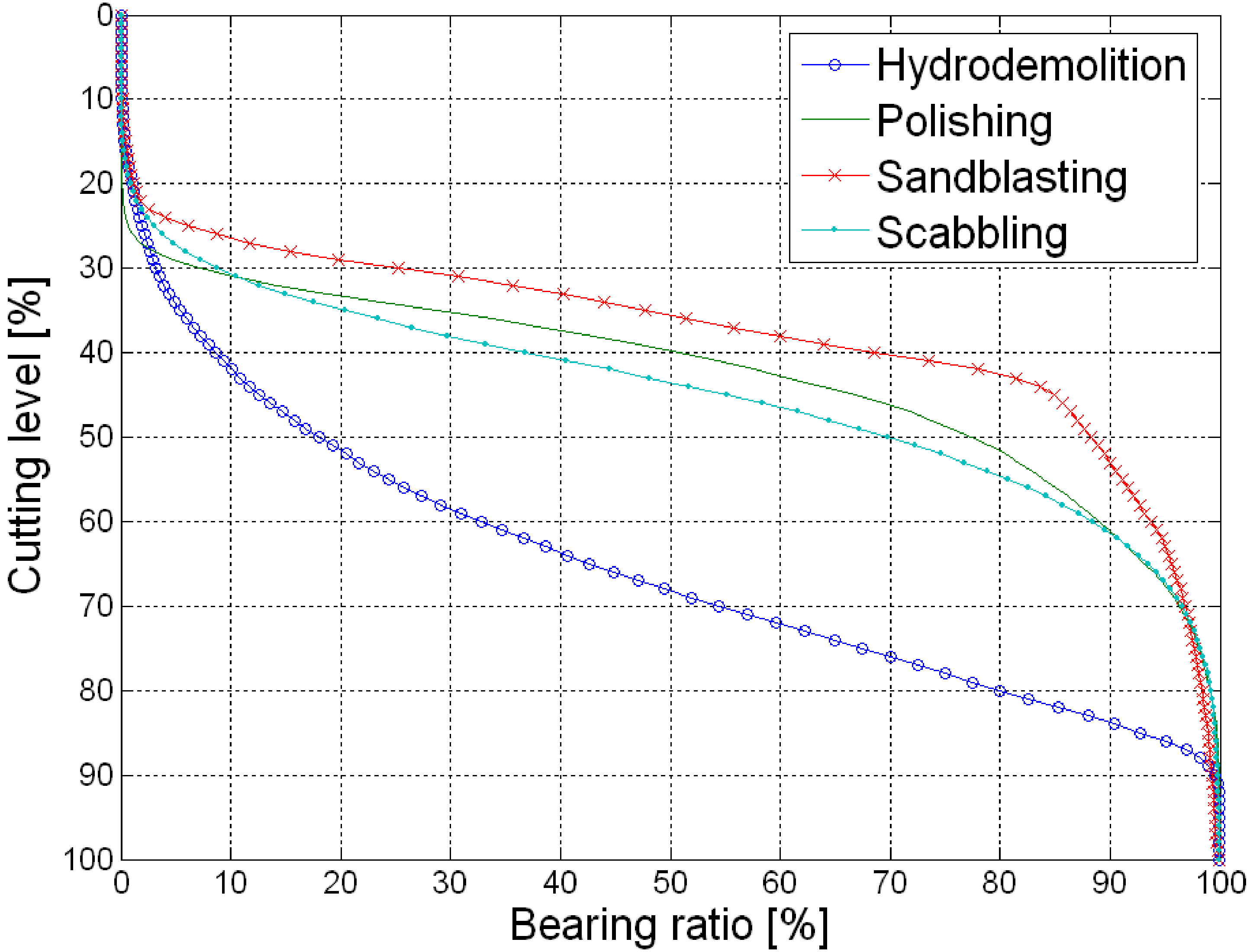
Results (...)

- Optometric method
  - Dimension in mm

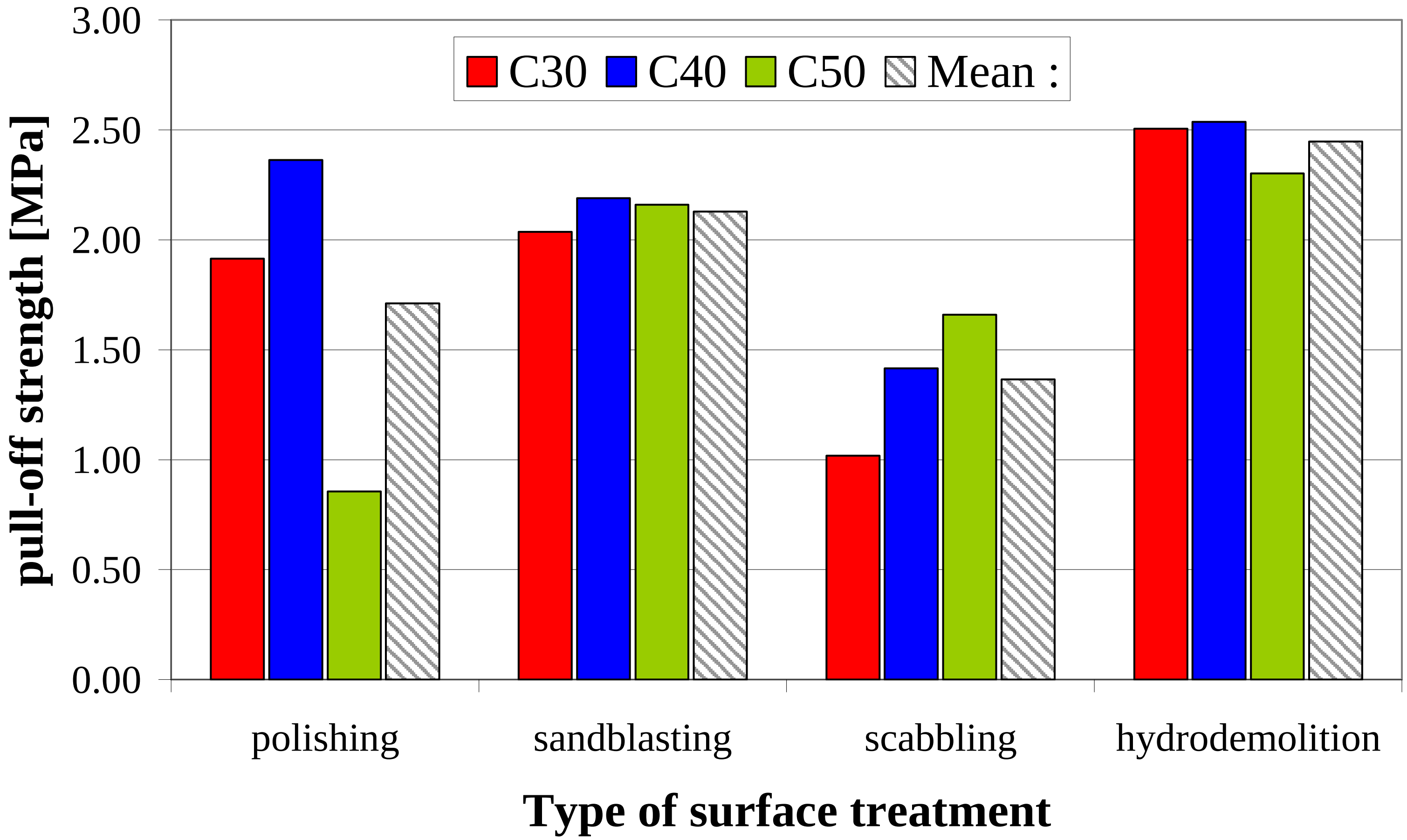
At this scale HPW presents biggest roughness but the difference with SCA2 is not so high

Treatment	**PTW**	***HPW***	***SCA2***
F_a	0.137	0.358	0.326
F_t	4.1	10.8	12.6
$F\ S_m$	129	85.3	102.3
M_a	0.169	2.85	0.315
M_t	19.7	27.8	10.2
$M\ S_m$	15.3	36.5	22.5
C_R	0.30	4.65	0.41
C_F	0.29	5.76	0.55
C_L	0.35	5.71	0.81

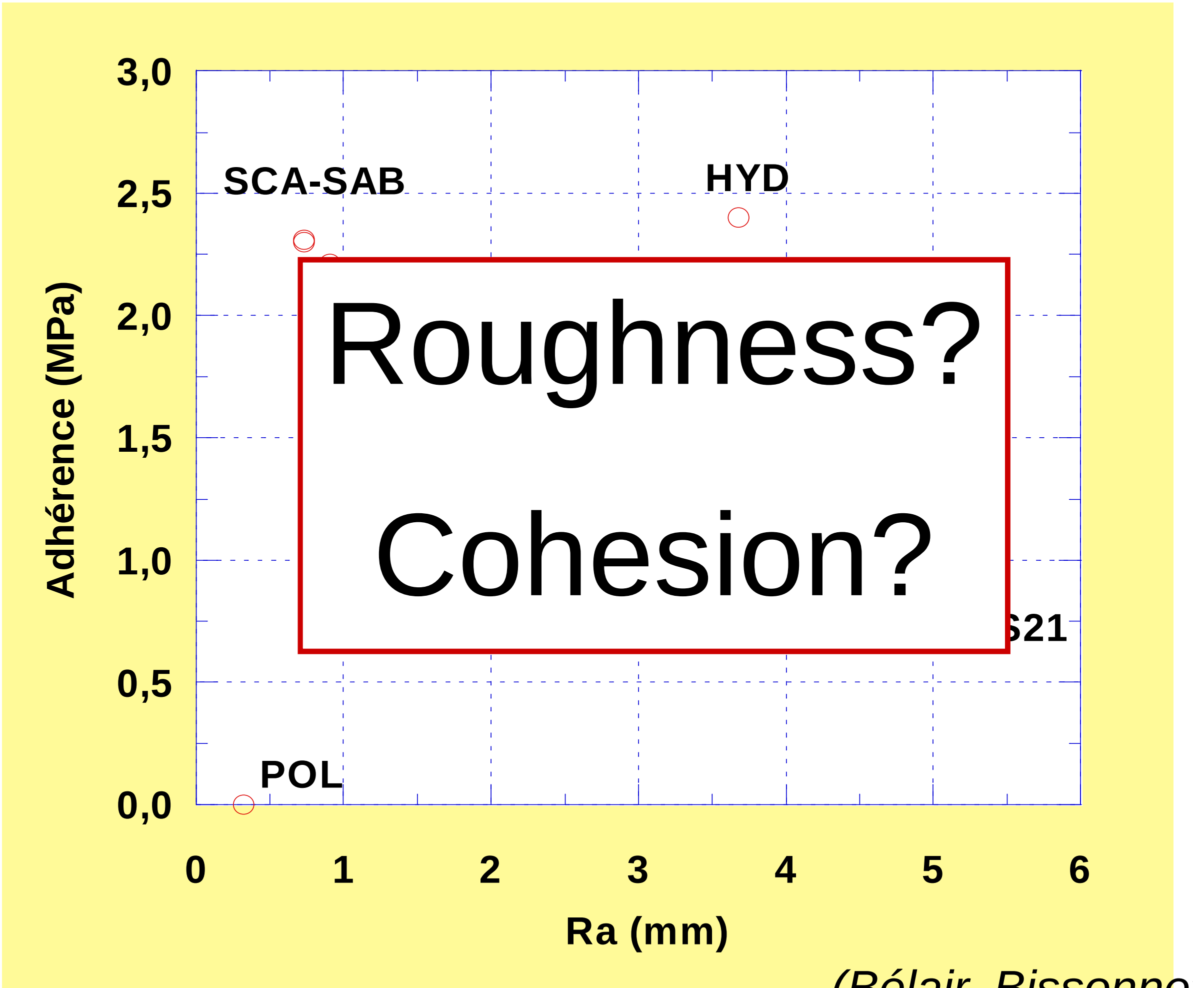
Abbott's curve C40/50 (Profile)



Surface roughness: bond strength



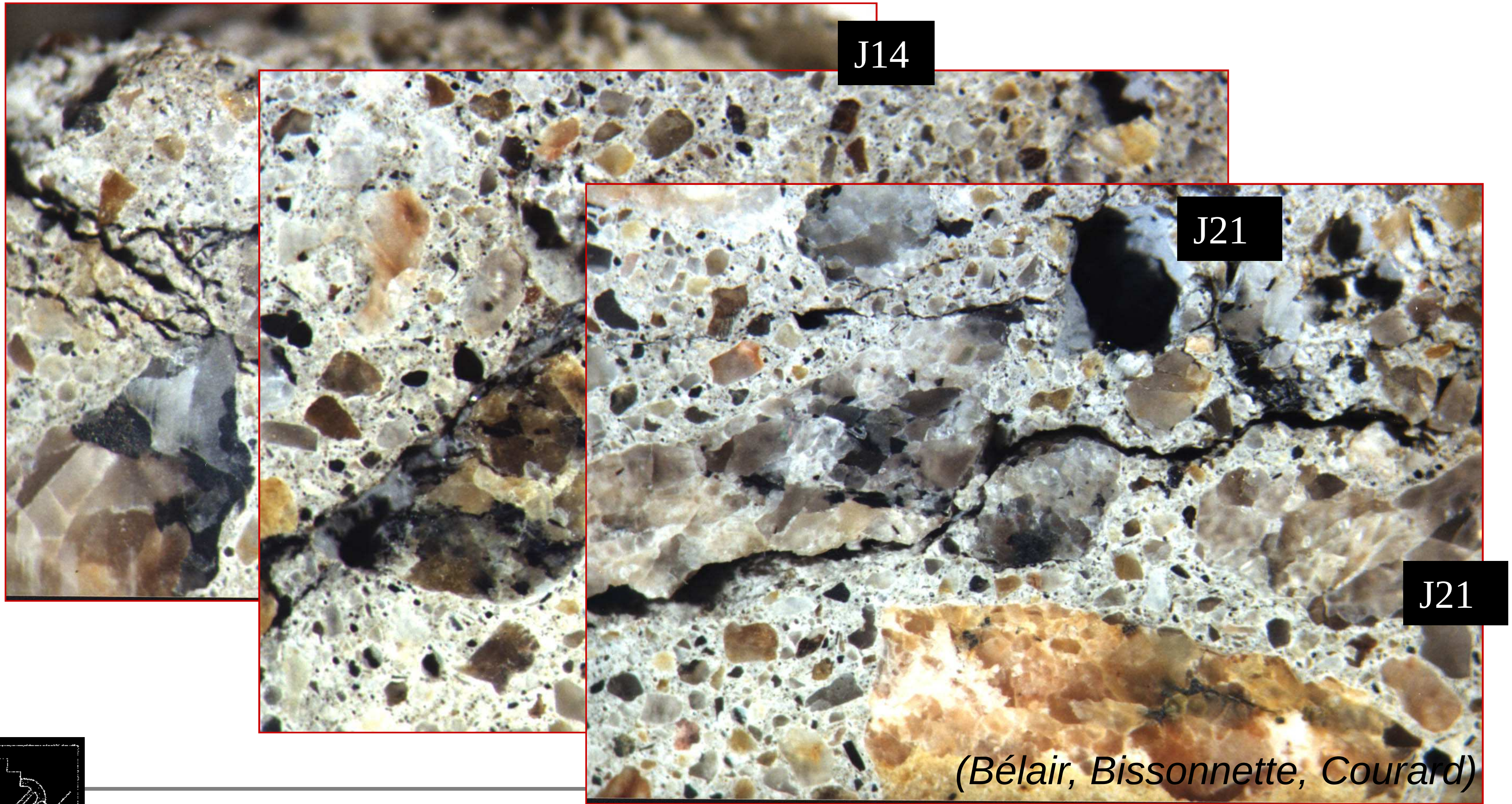
Why and How?



(Bélair, Bissonnette, Courard)

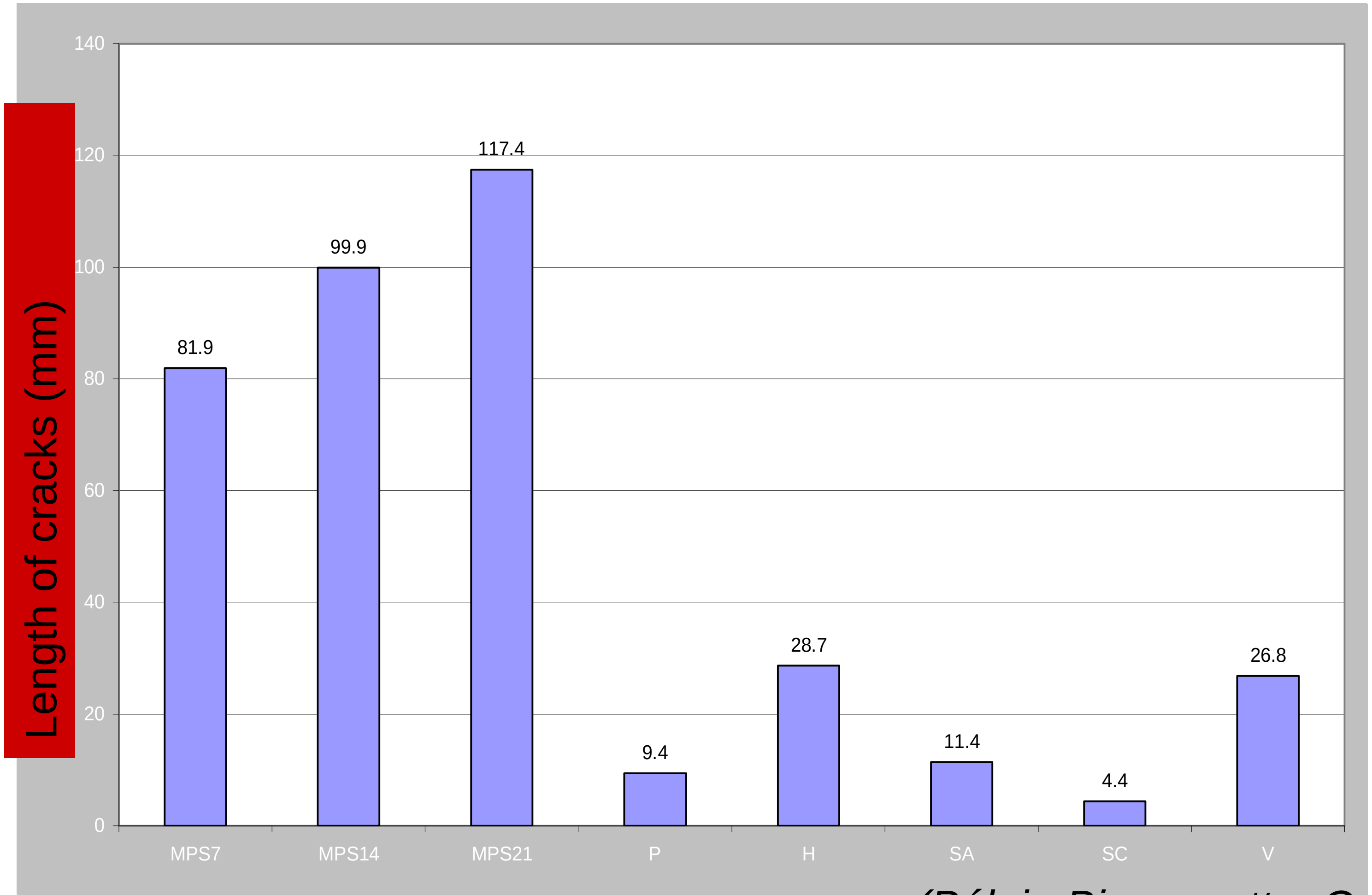
Surface preparation

Microscopical observations



Surface preparation

Total length of cracks



(Bélair, Bissonnette, Courard)

Adhesion of a repair mortar

Treatment type	Mean value [MPa] (coefficient of variation in %)	
	Repair mortar with bond coat	Repair mortar without bond coat
NT	1.92 (23.4)	2.28 (17.1)
GR	1.82 (15.9)	1.16 (50.9)
SB	1.93 (11.4)	1.82 (32.4)
SHB20	1.68 (18.5)	0.78 (39.7)
SHB35	1.94 (11.3)	1.25 (28.8)
SHB45	1.96 (32.7)	0.83 (25.3)
HMIL	1.42 (12.7)	1.01 (40.6)
MMIL	1.60 (24.4)	0.49 (57.1)

Conclusions and recommendations

Recommendations

Information needed	FUNDAMENTAL PRINCIPLES	Observation means

- Cohesion of superficial concrete
- Cracks
- Porosity
- Chemical damages of concrete
- Chemical damages of steel rebar
- Saturation level

Mechanical properties

Permeability

Chemical

Electrochemical

- Visual inspection of the whole structure
- Sampling in « risk zones »
- Non Destructive and Destructive Techniques
  - Mechanical properties
  - Delamination
  - cracks
- Chemical analysis

Recommendations: values?

Information needed	Quality values

- Cohesion of superficial concrete
- Cracks
- Porosity
- Chemical damages of concrete
- Chemical damages of steel rebar
- Saturation level

surface preparation, bonding agent, corrosion inhibitors …

- Cohesion
  - min equal to adhesion (1.5-2MPa)
  - equal to bulk concrete
  - min 1MPa
- Cracks
  - no crack parallel to surface
- Porosity
  - ???
- Chemical damages of concrete
  - carbonation profile vs rebar
  - chloride or … profile vs rebar
  - AAR
- Chemical damages of steel rebar
  - no corrosion
- Saturation level
  - vs repair material and system

Conclusions

- Repair is a compatibility challenge
- Adhesion: two or three partners
- Repair is not only material: it is a *repair system*
- Repair is based on better knowledge of materials
  - Thermodynamics: necessary but not sufficient
  - Kinetics of contact: substrate roughness and viscosity of material
- Environment is an *uncontrollable* parameter
  - Water, temperature, relative humidity, wind
- *Workmanship quality is fundamental*

We discovered the surroundings and local habits - Belgium


Liege 2004


Bruxelles 2005


Brugge 2004


Antwerpen 2004


St Nicolas


Trottinettes

We discovered the surroundings and local habits - Poland



Krakow

Warsaw



Traditional Polish Wedding

Sharing Christmas-Eve wafer

Traditional Polish costumes

Dziękuję

Merci

Thank you

Dank u

Grazie

Danke

Gratias

Arigato

Efkaristos

Hvala

Takk

Mulțumesc