# Materials Properties, Use and Conservation: Construction Materials and Binders

# Structural composites

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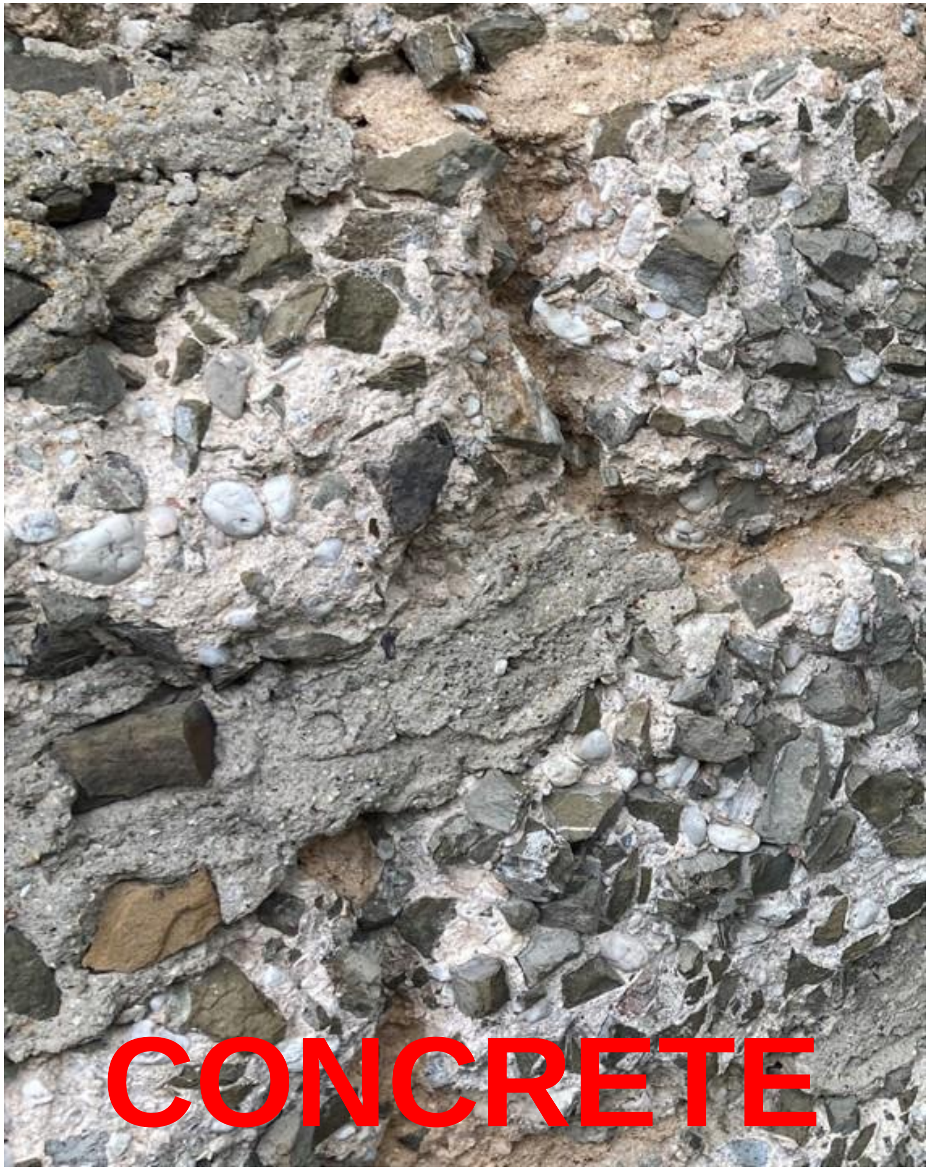
# Structural composites

MASONRY

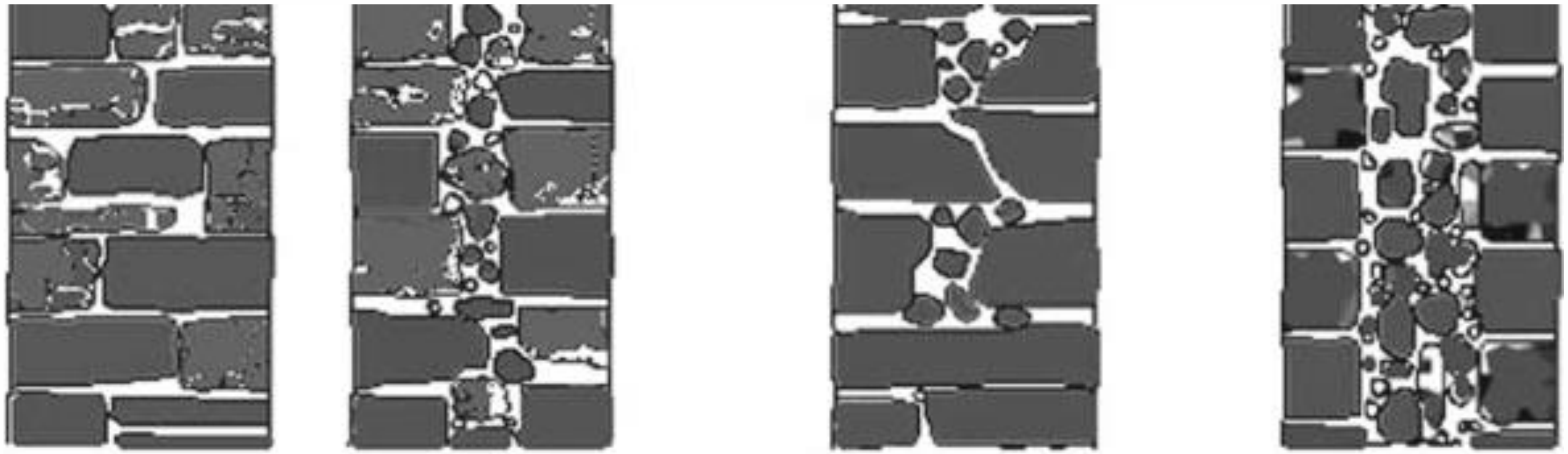


CONCRETE

# Masonry

**Masonry** is the building of structures from individual **units**, which are often laid in and bound together by **mortar**; the term masonry can also refer to the units themselves. The common materials of masonry construction are brick, building stone, cast stone, concrete block, glass block, and adobe.

# Masonry leaves



single leaf

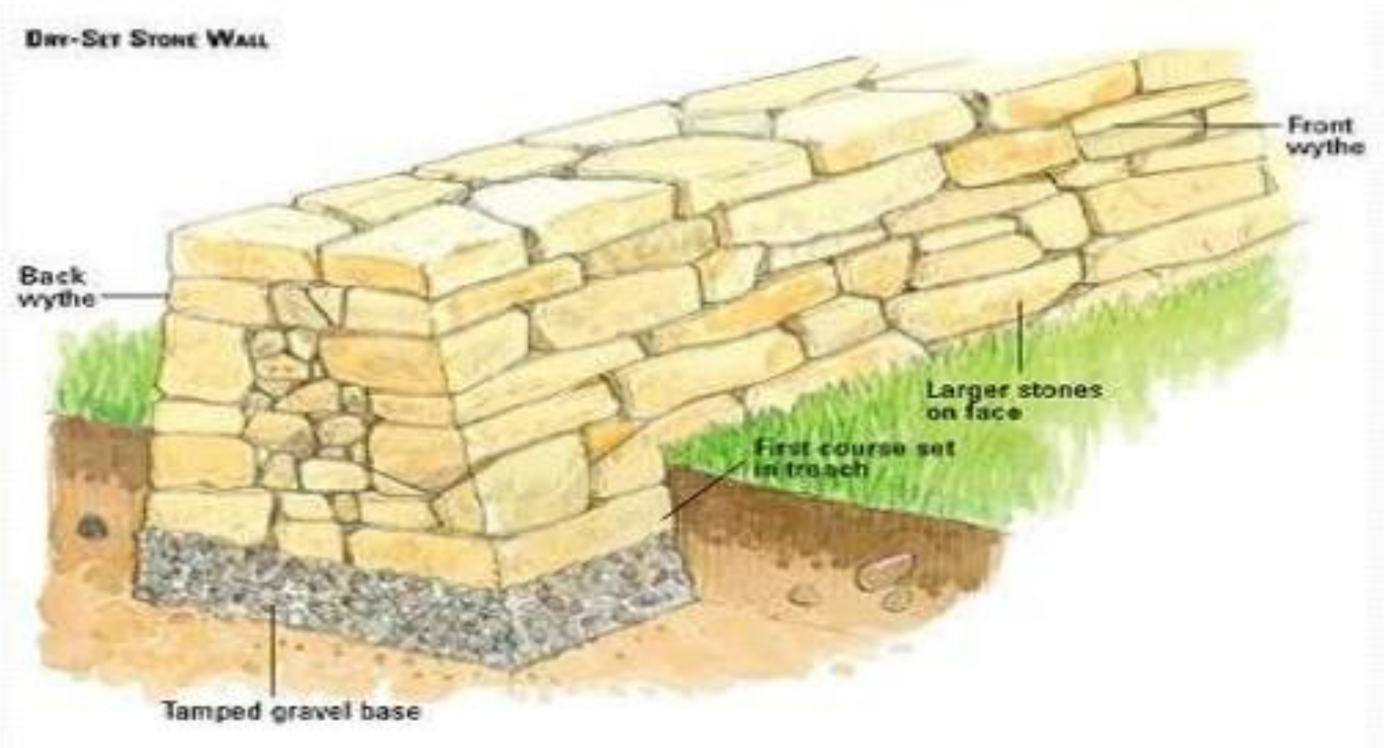
double leaf

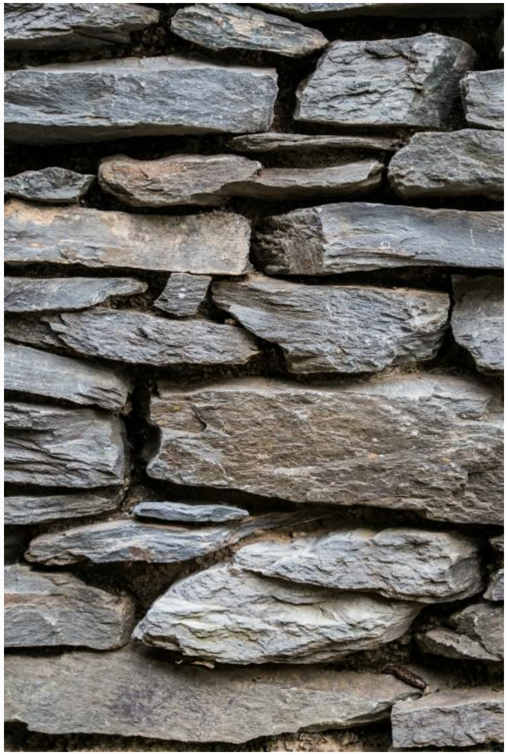
double leaf with transversal connection

three leaf

# Dry masonry

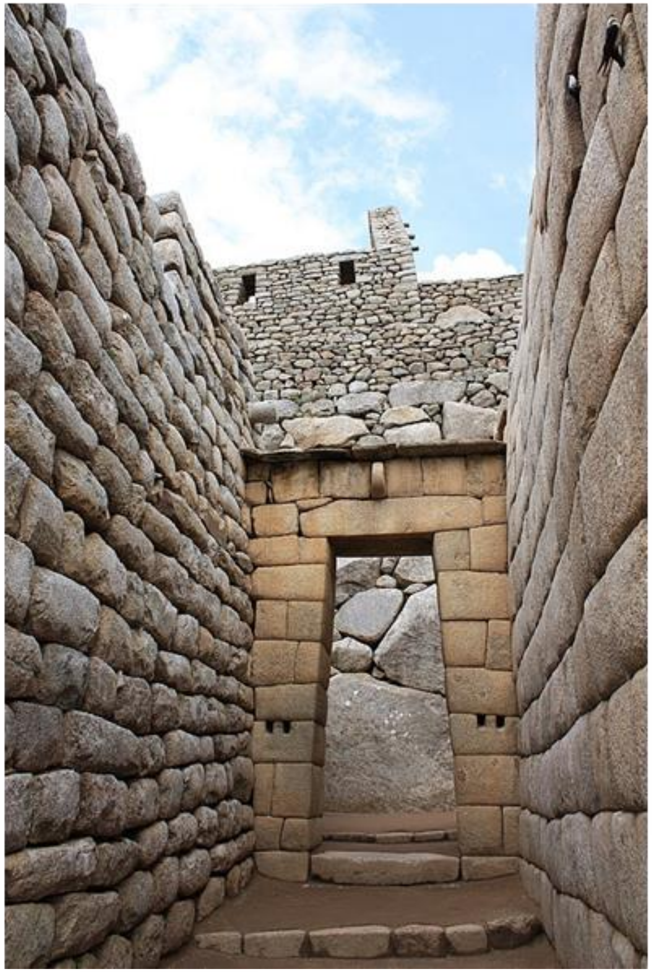
In this type of masonry, mortar is not used in the joints. This type of construction is the cheapest and requires more skill in construction. This may be used for non-bearing walls (compound walls, etc…).





# Dry masonry

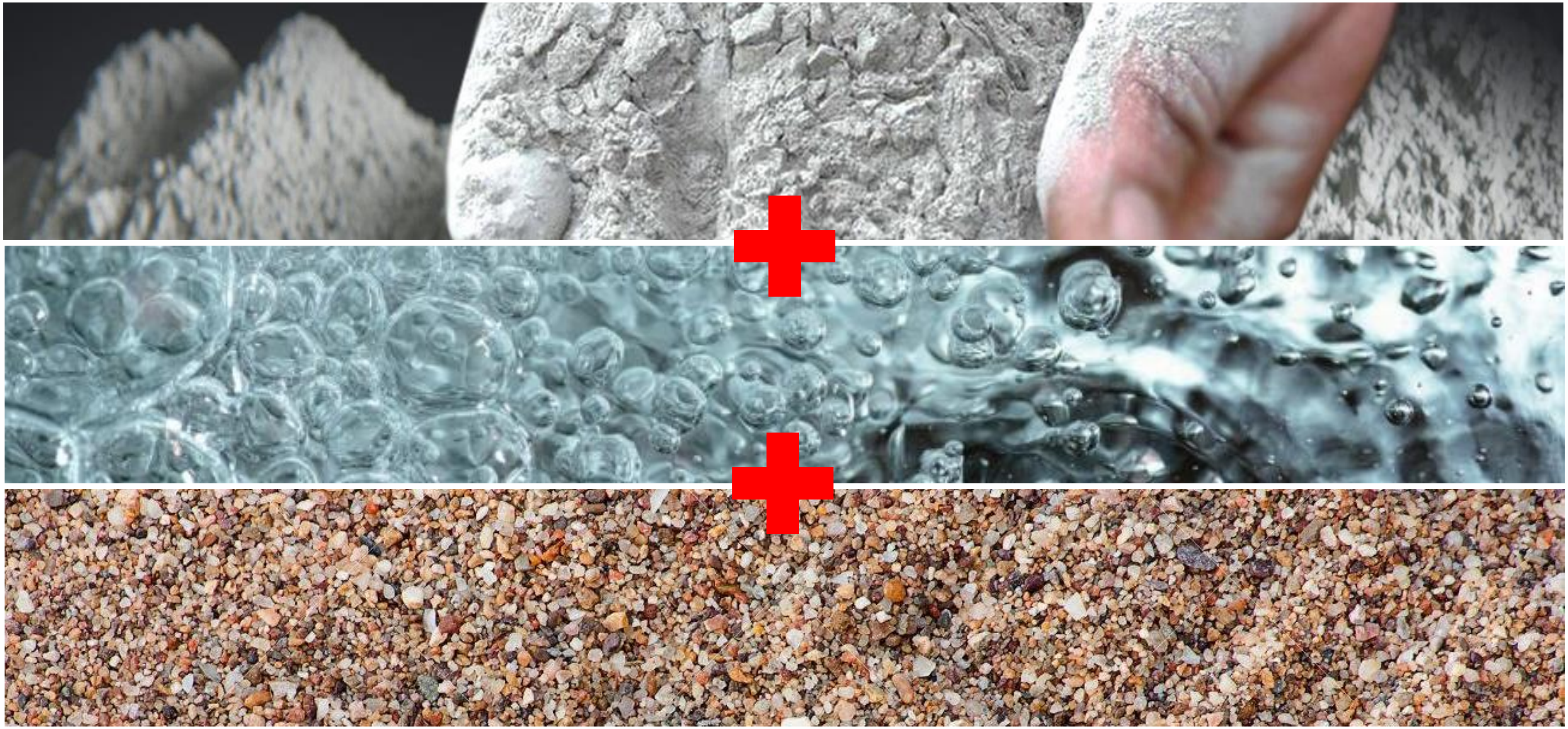
## Inca world: Ollantaytambo and Cuzco



# Mortar

**Mortar** is a workable paste constituted by a mixture of **sand**, a **binder**, and **water**, which hardens to bind masonry units, to fill and seal the irregular gaps between them, spread the weight of them evenly, and sometimes to add decorative colors or patterns to masonry walls.

# Mortar



# Mortar

MORTAR = BINDER + AGGREGATE

*Component of the mortar that limits shrinkage phenomena (cracks) following the loss of mixing water. Diameter generally below 4 mm.*

**NATURAL ORIGIN**: incoherent material of sedimentary origin

- FLUVIAL SAND
- MARINE SAND (WASHED!)
- QUARRY SAND
- FINE GRAVEL FROM GROUNDWATER DEBRIS
- PYROCLASTIC DEPOSITS

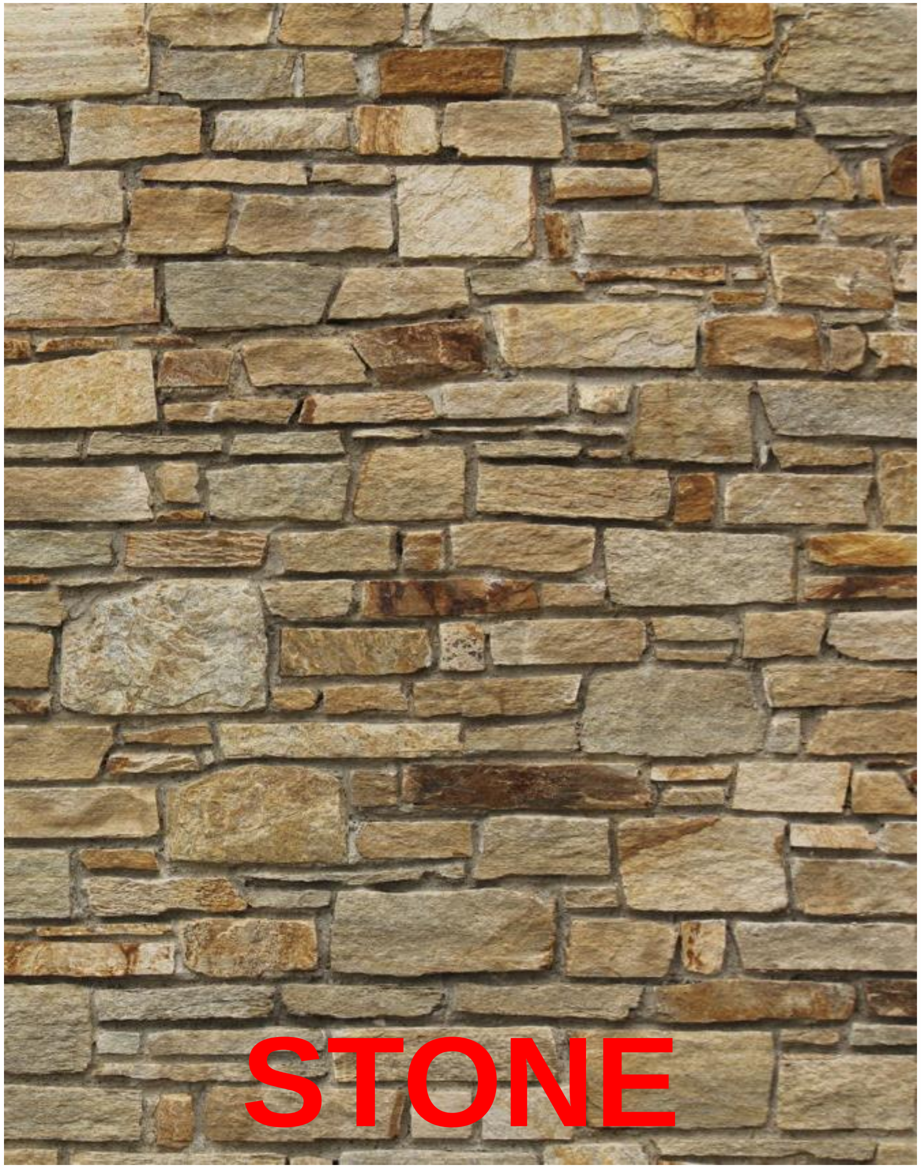
**CRUSHING ORIGIN**: material with a sandy grain size obtained by grinding rocks or minerals of sedimentary origin

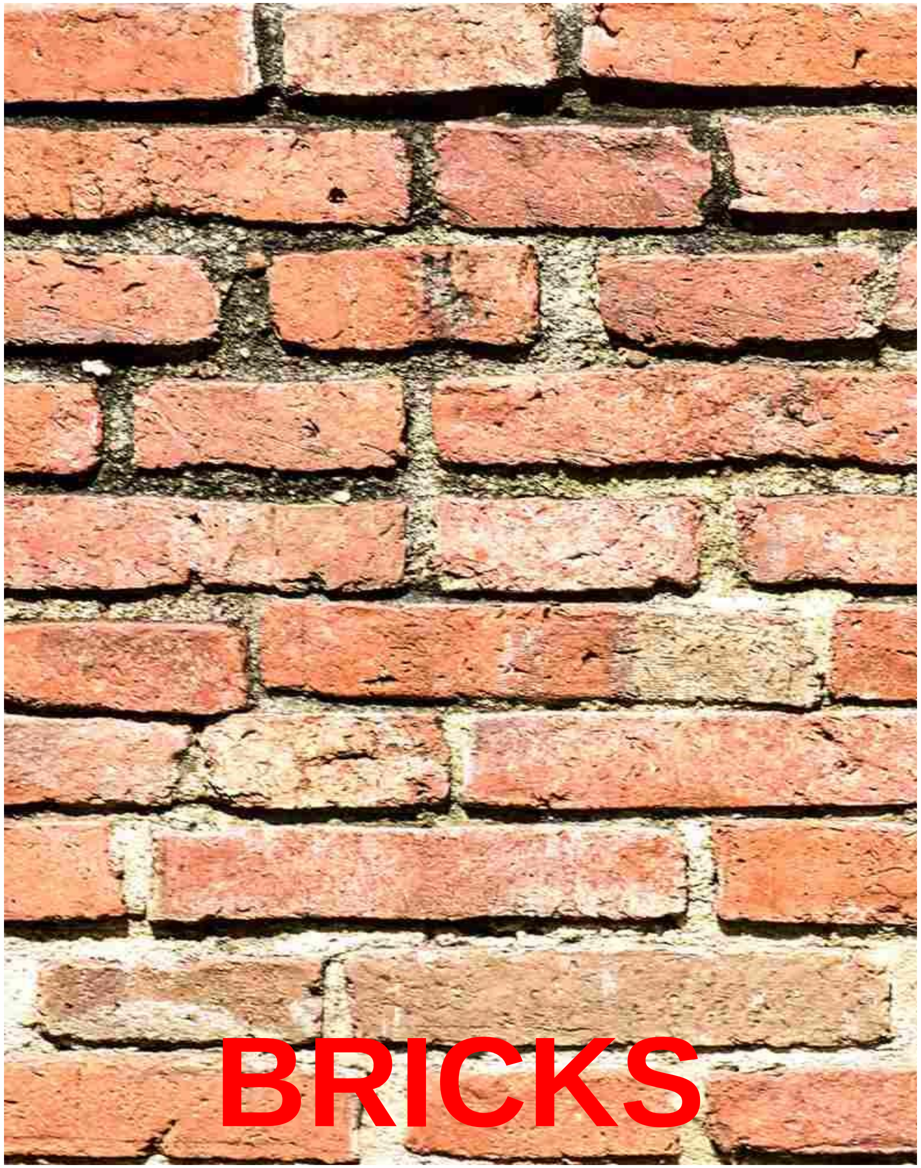
- ROCKS
- MINERALS
- REUSED MATERIALS: CERAMIC SHARDS, MOSAIC TESSERAE, BRICKS, CONSTRUCTION AND DEMOLITION WASTES

# Bedding mortar

# Infill mortar

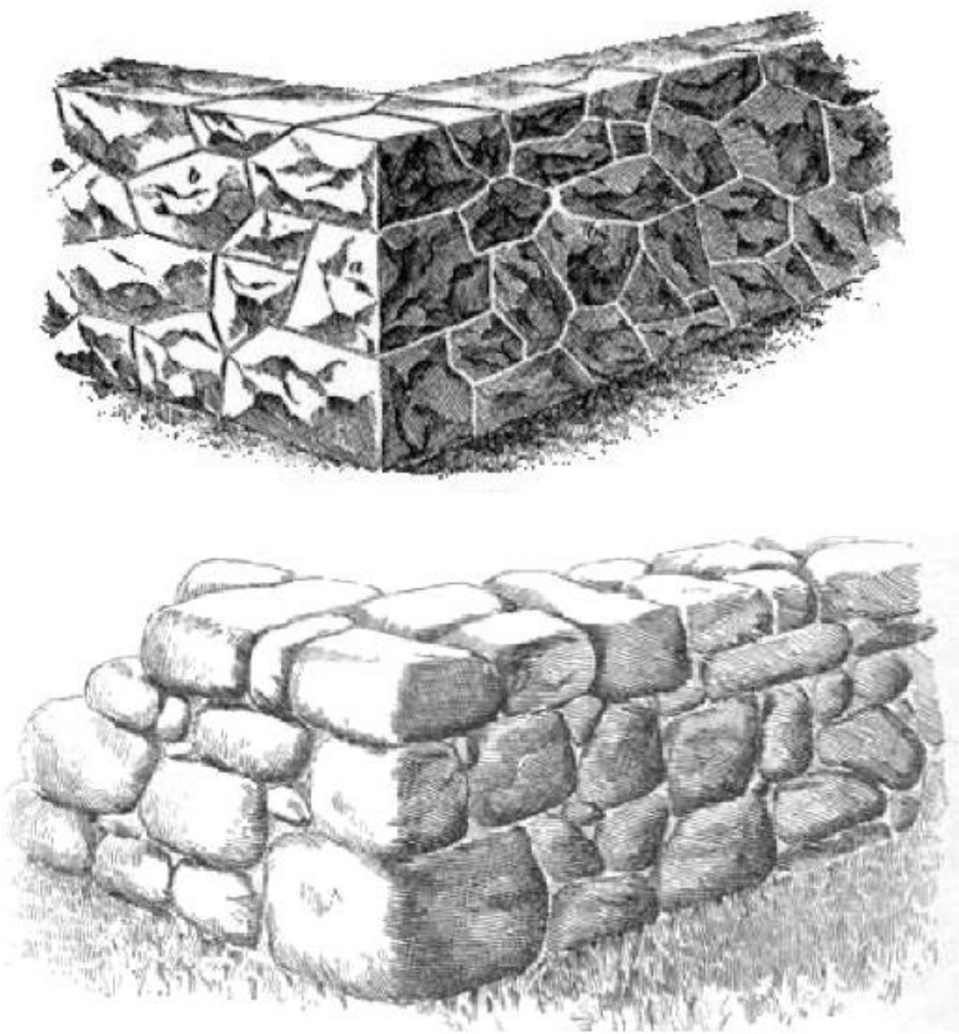
# Masonry units



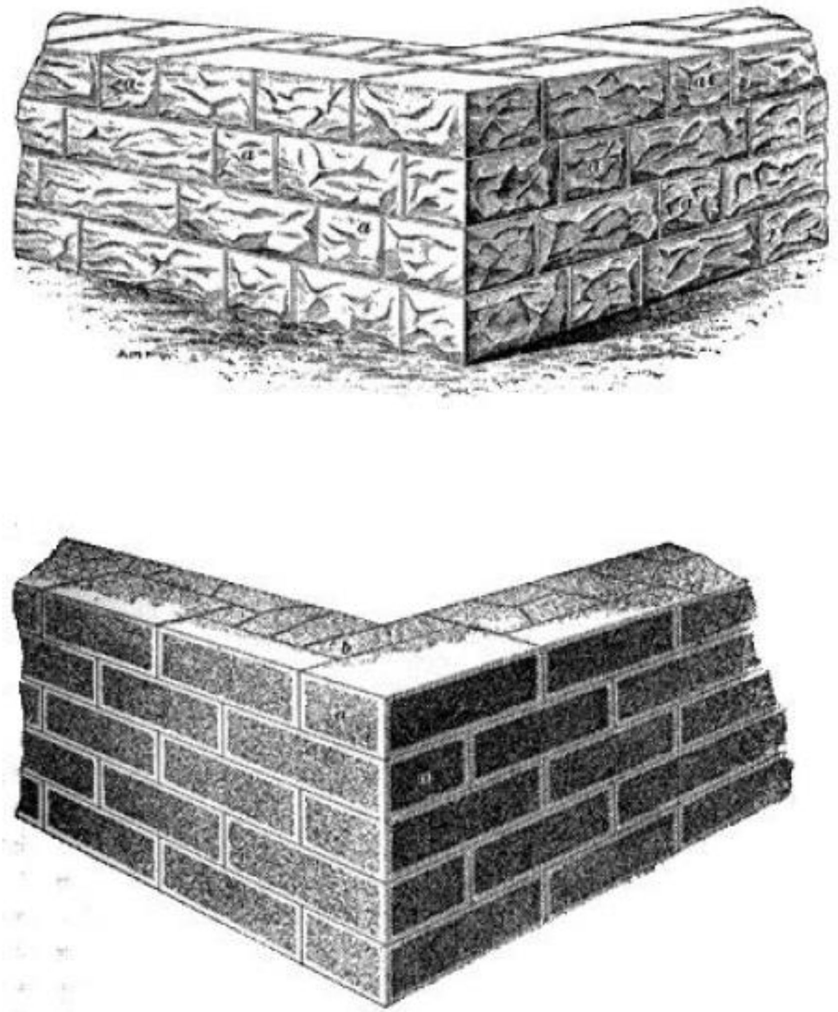


# Stone masonry

## RUBBLE MASONRY



## ASHLAR MASONRY



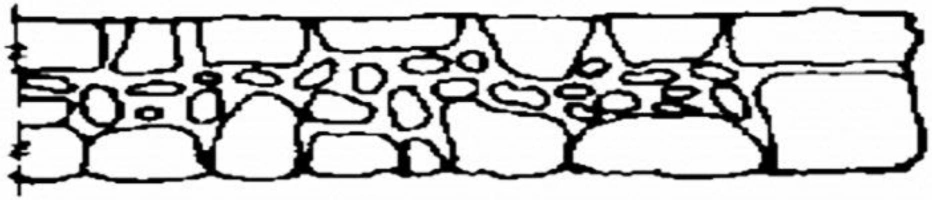
# Rubble masonry

- **Stone masonry in which either undressed or roughly dressed stones are laid;**
- **In this masonry, the joints of mortar are not of uniform thickness;**
- **The strength of rubble masonry depends on: a) the quality of mortar; b) the use of long-through stones; c) the proper filling of mortar between the spaces of stones.**

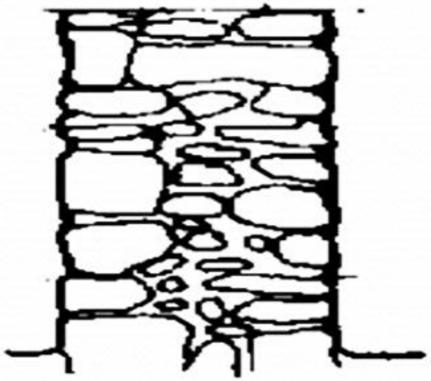
# Rubble masonry

## Coursed rubble masonry

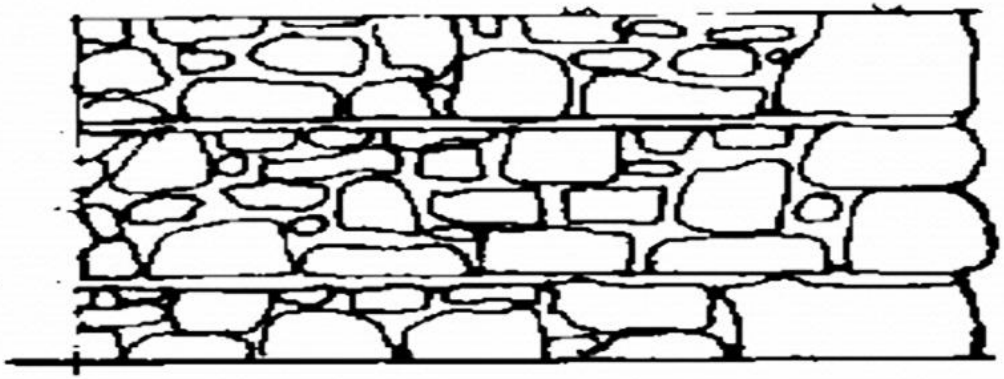
The masonry work is carried out in courses such that the stones in a particular course are of equal height.



PLAN



SECTION



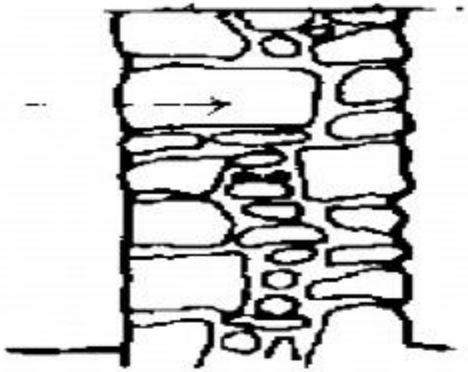
ELEVATION

# Rubble masonry

## Uncoursed rubble masonry

The courses are not mantained regularly. The larger stones are laid first and the spaces between them are then filled.

PLAN



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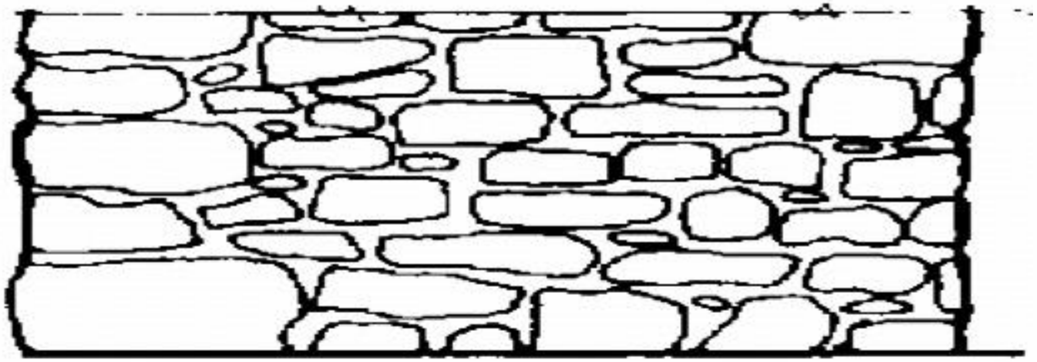


ELEVATION

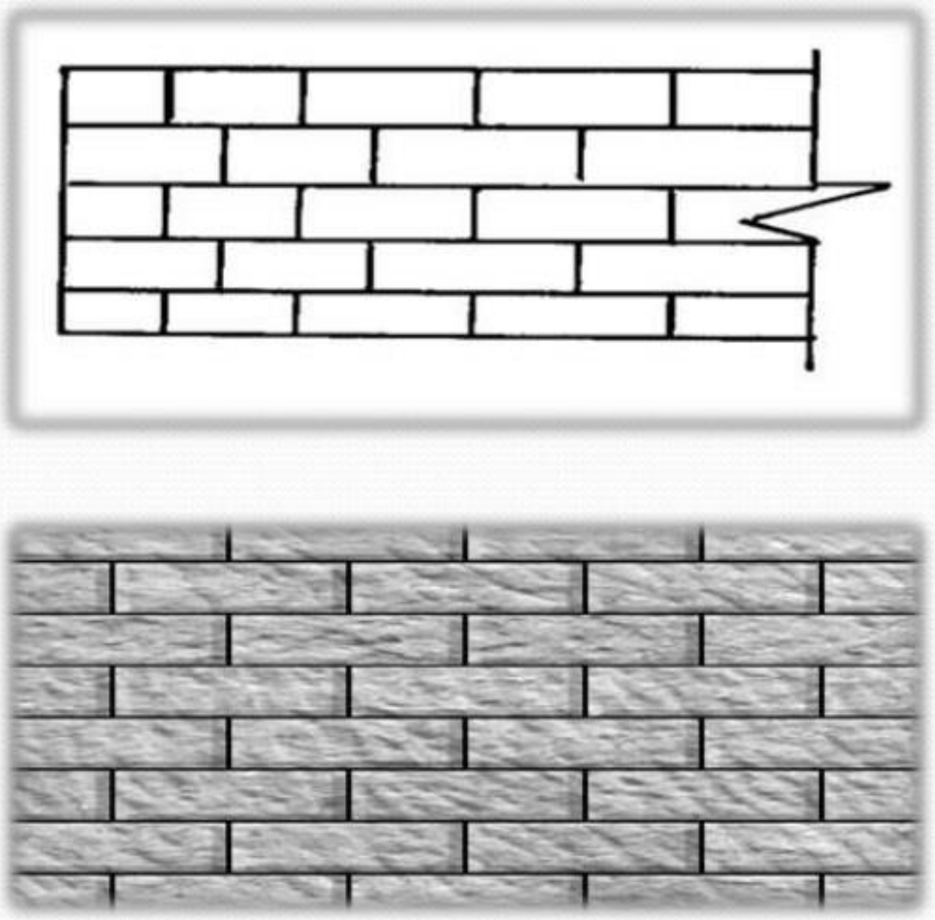
# Ashlar masonry

- Stone masonry in which finely dressed stones are laid in thin mortar beds;
- All the joints are regular and of uniform thickness;
- This type of masonry is costly in construction, as involves heavy cost of dressing of stones;
- This masonry is used for heavy structures, arches, architectural buildings, high piers, abutments of bridges, etc…

# Ashlar masonry

## Ashlar fine masonry

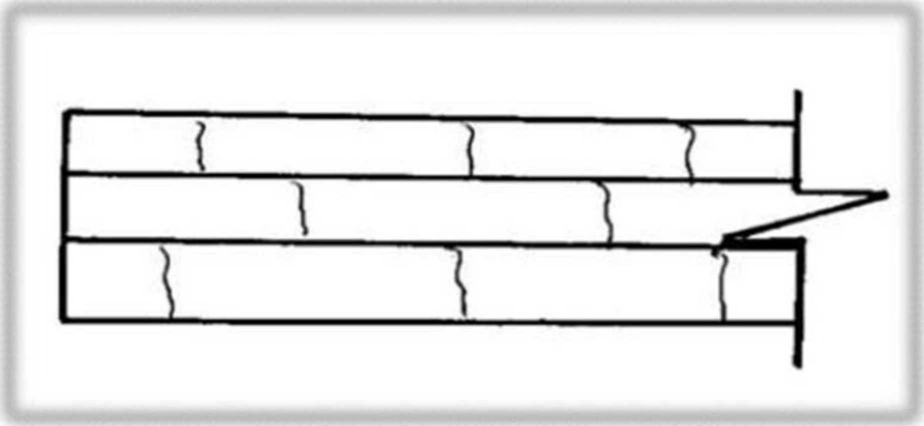
Each stone is cut to uniform size and shape with all sides rectangular, so that the stone gives perfectly horizontal and vertical joints with the adjoining stone. This type of ashlar masonry is very costly.



# Ashlar masonry

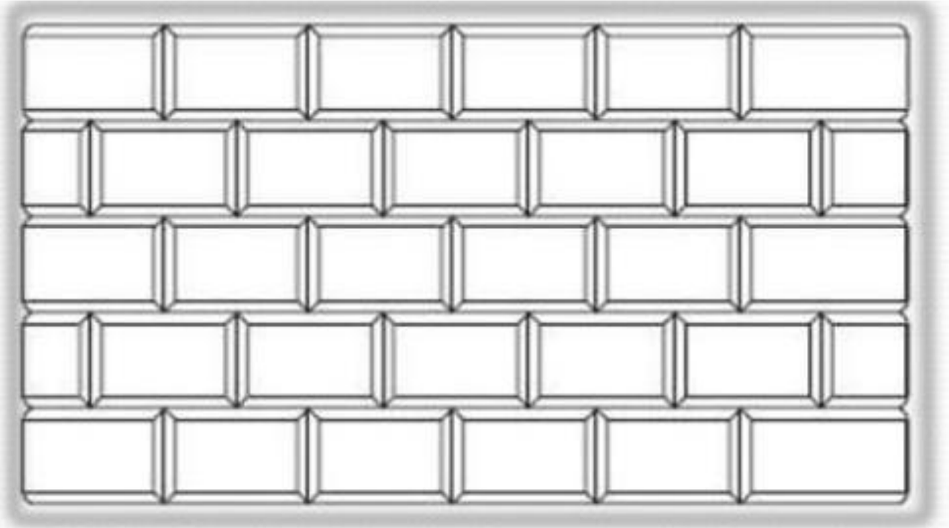
## Ashlar rough masonry

The beds and sides are finely chisel-dressed, but the face is made rough by means of tools. A strip made by means of chisel is provided around the perimeter of the rough dressed face of each stone.



# Ashlar masonry

## Ashlar chamfered masonry

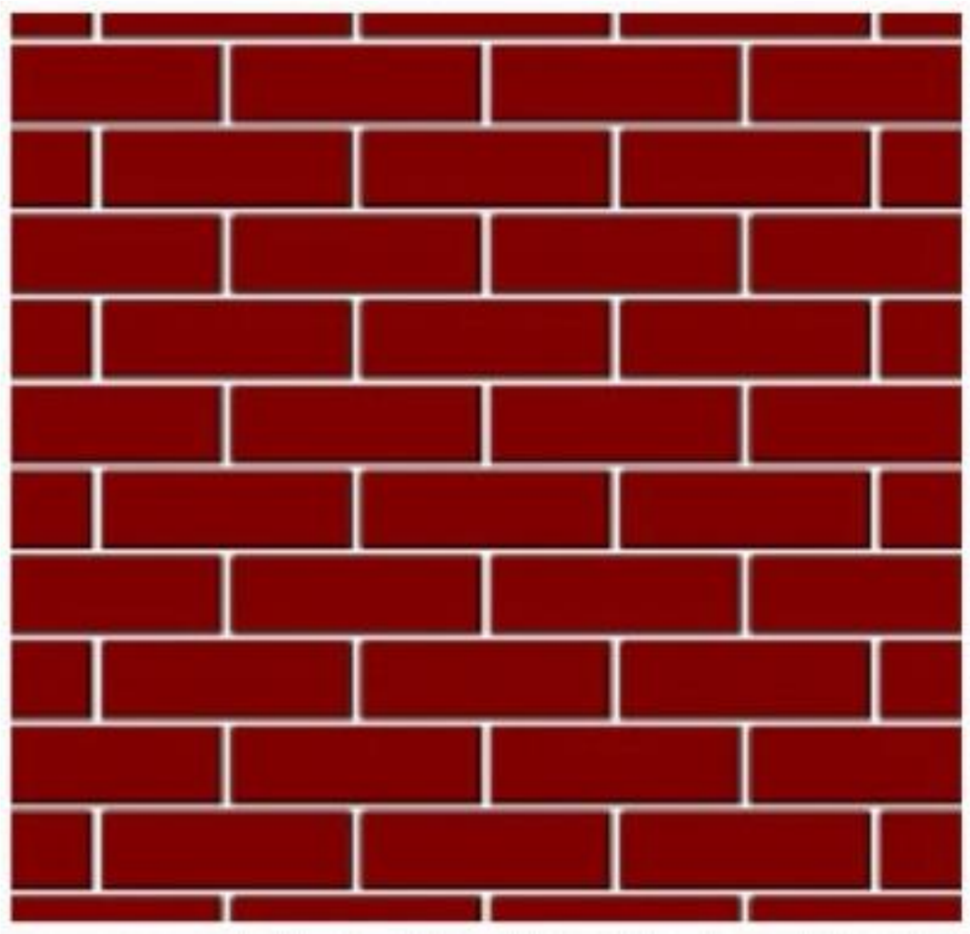


The ashlars are chamfered with a chisel at an angle of 45 degrees for a depth of about 25 mm.

# Brick masonry

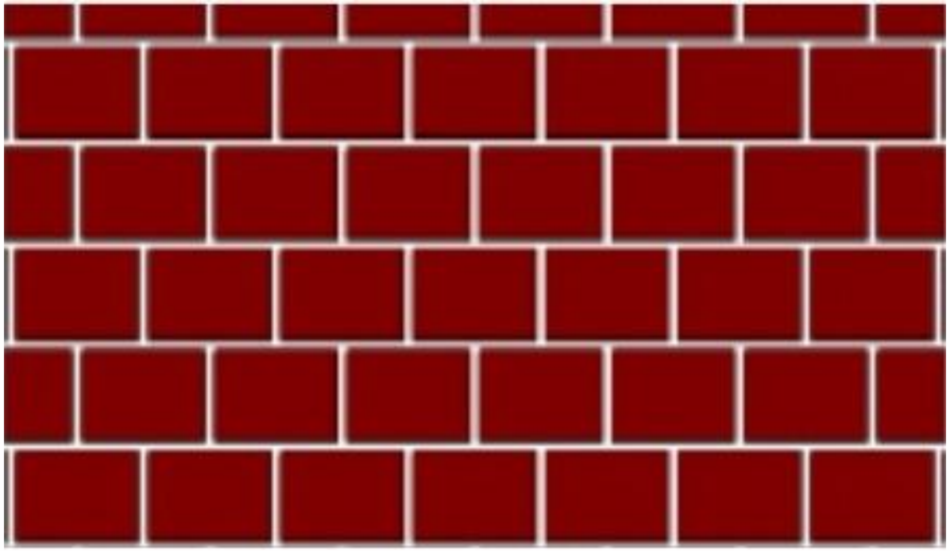
## Stretching bond

The bond in which all the bricks are laid as stretchers.



# Brick masonry

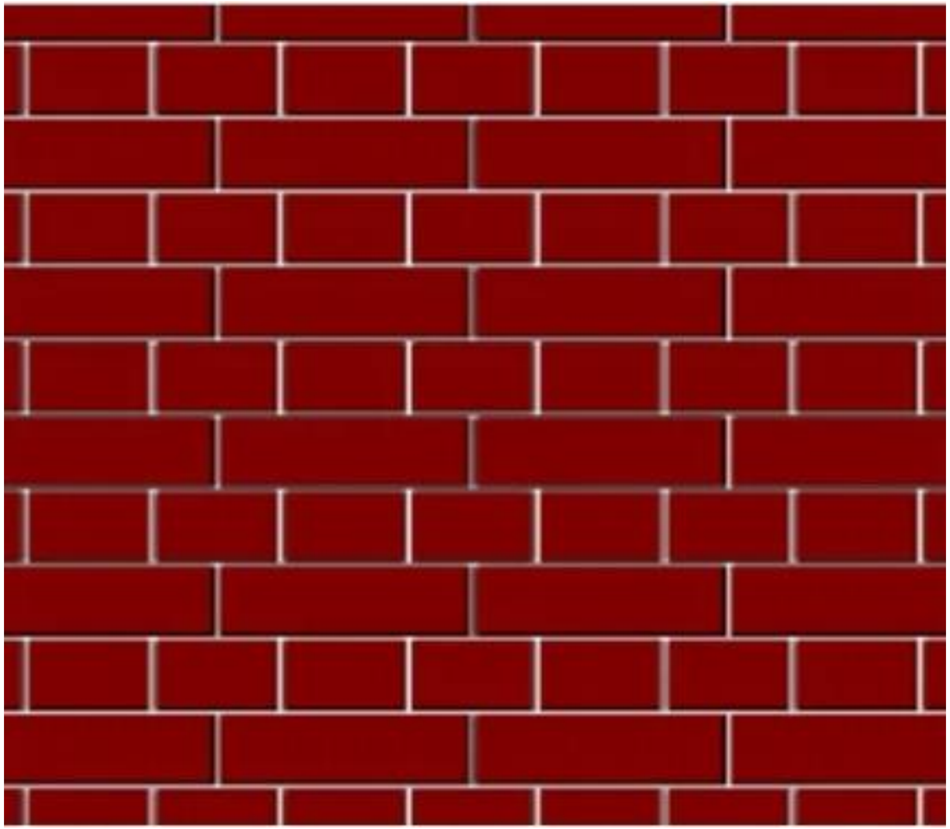
## Heading bond



The bond in which all the bricks are laid as headers.

# Brick masonry

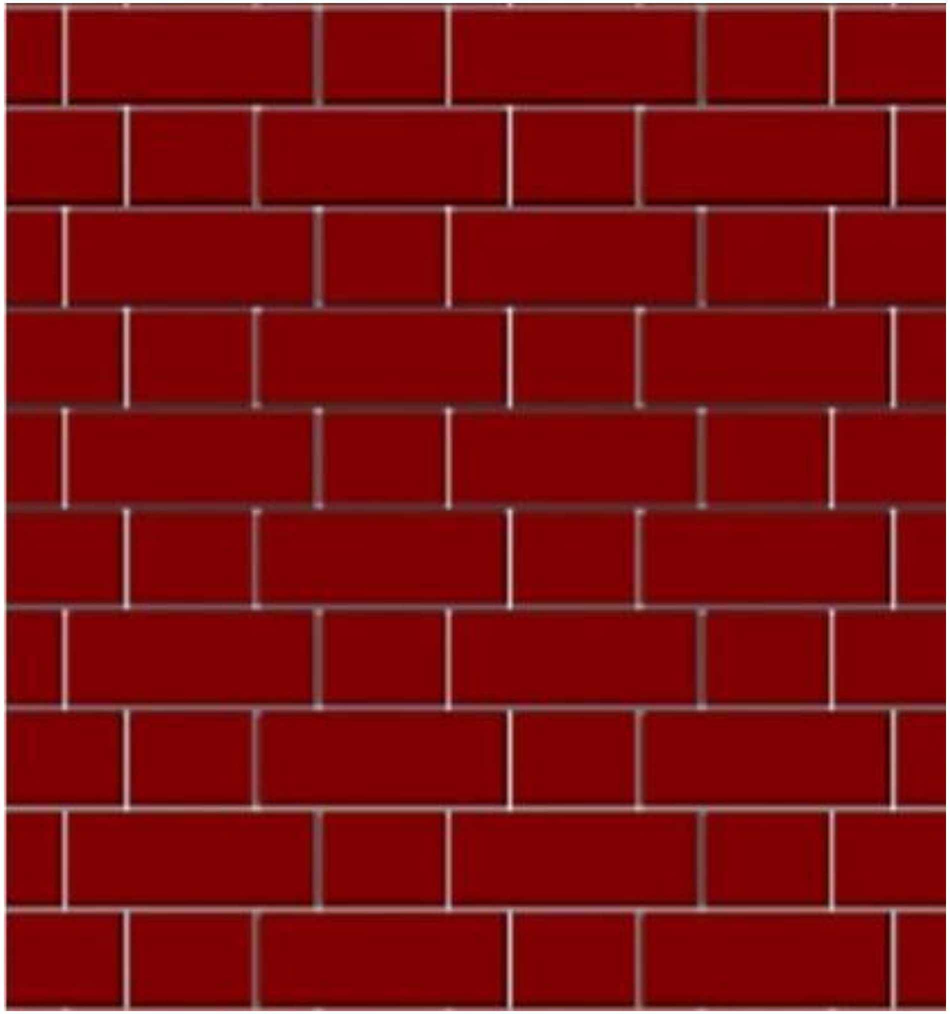
## English bond



This bond consists of headers and stretchers laid in alternate courses. It is stronger than the previous ones.

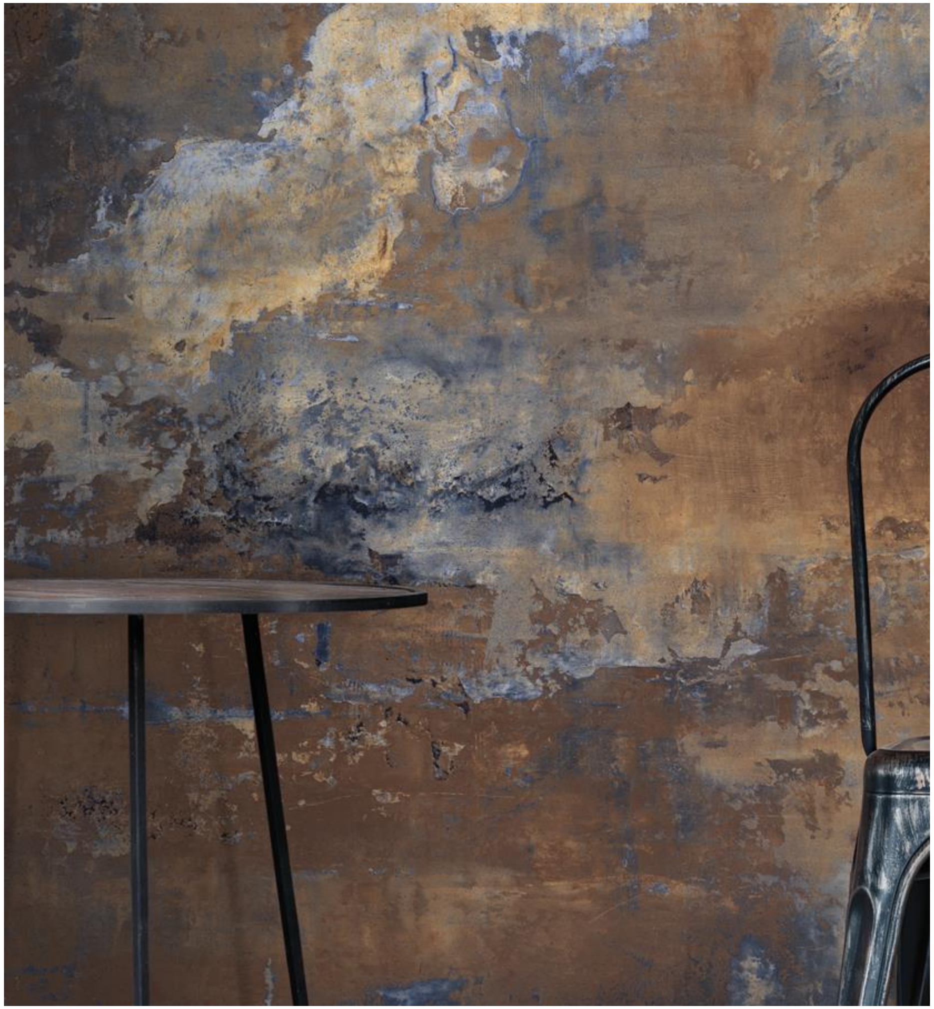
# Brick masonry

## Flemish bond



The bond in which headers and stretchers are laid alternately in the same course. It is the strongest of all bonds.

# Covering mortars: plasters and renders



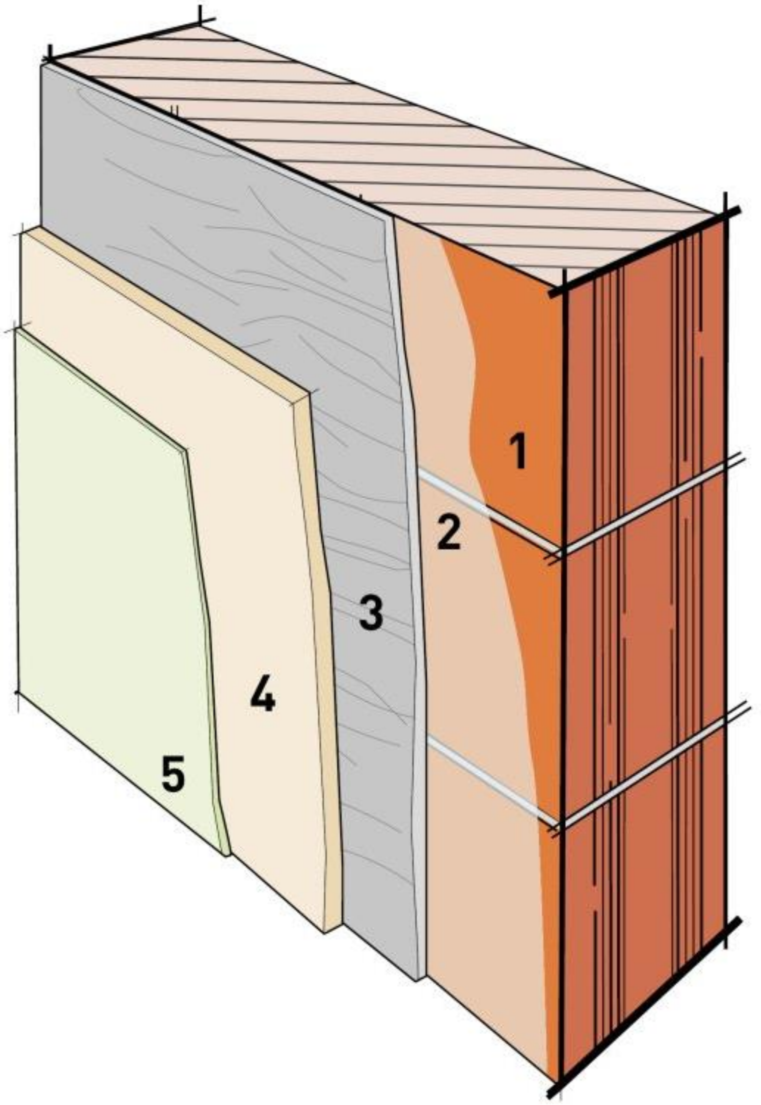
Covering mortar for internal walls: plaster

Covering mortars for external walls: render

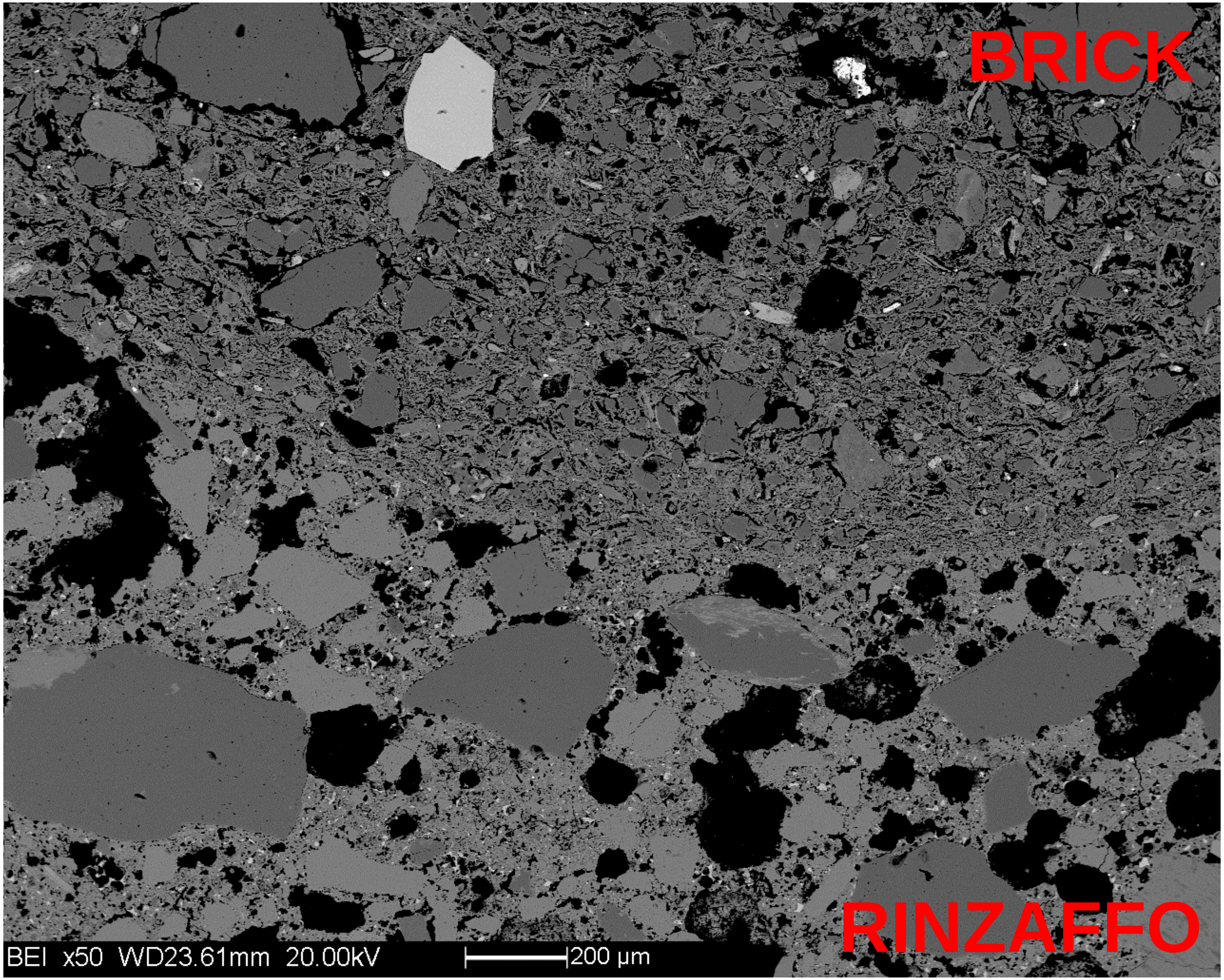
# Covering mortars: plasters and renders

## Plaster and render layering

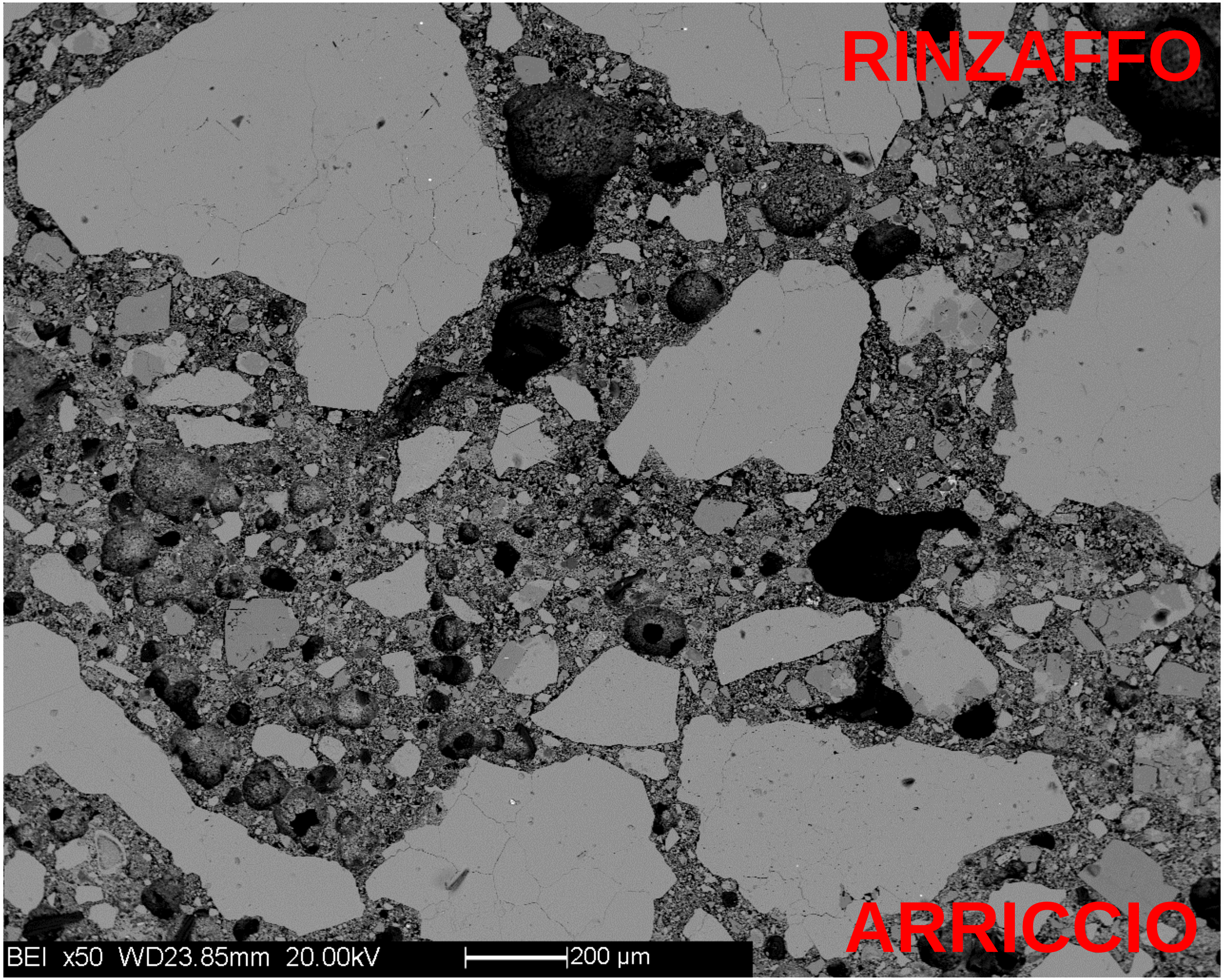
1, 2: Support wall;
3: *Rinzaffo*;
4: *Arriccio*;
5: *Intonaco*.



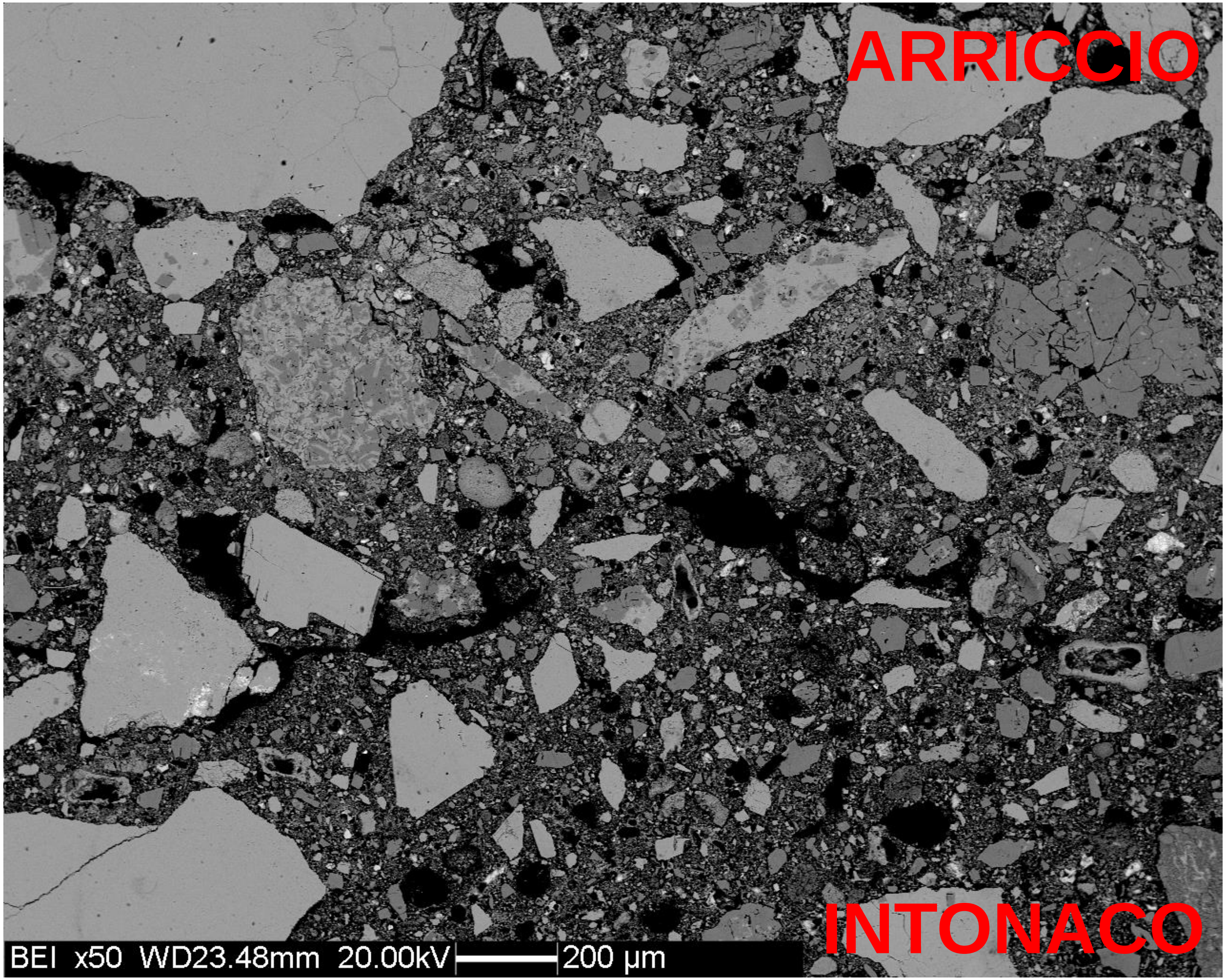
# Covering mortars: plasters and renders



# Covering mortars: plasters and renders



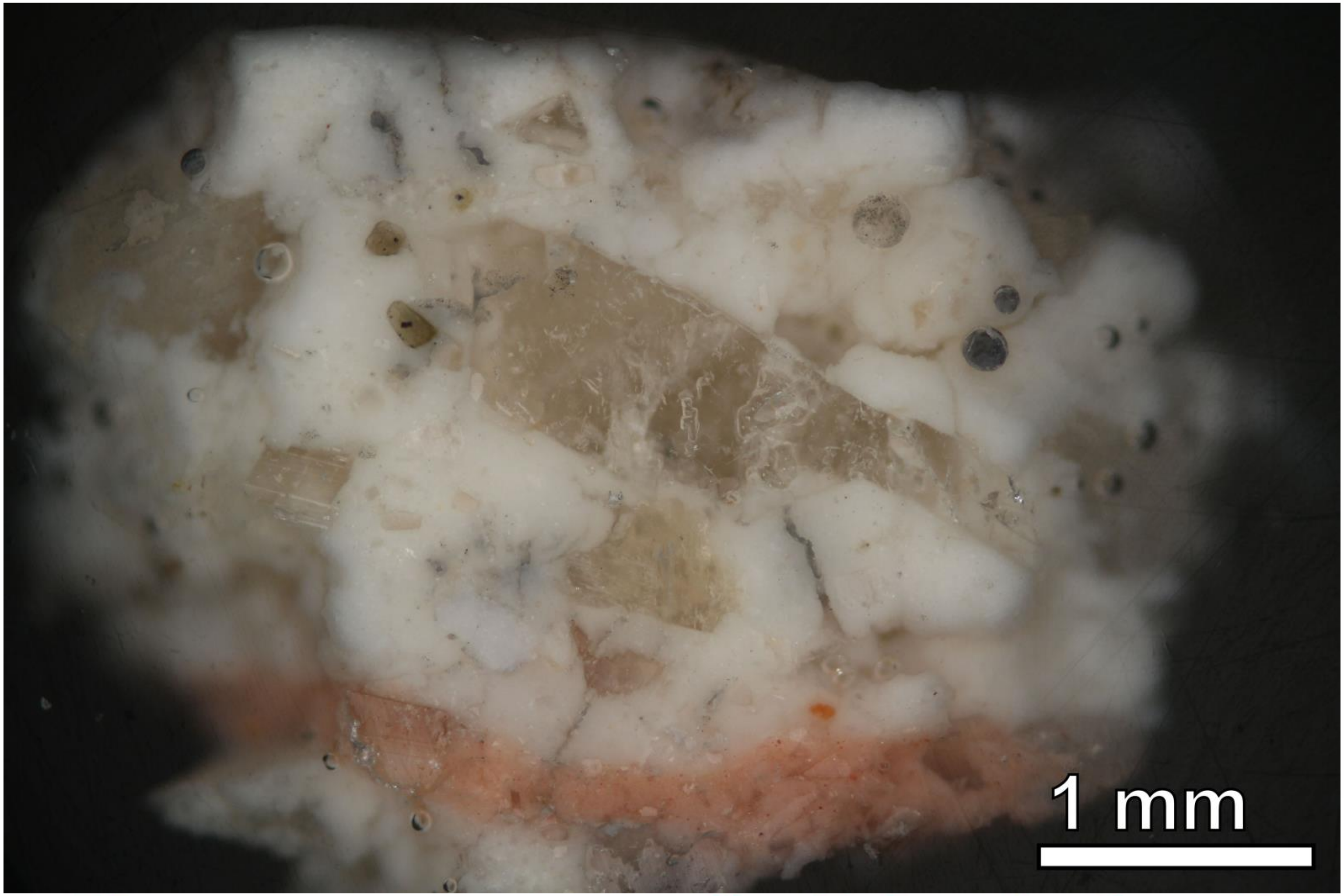
# Covering mortars: plasters and renders



# Painted plasters/renders

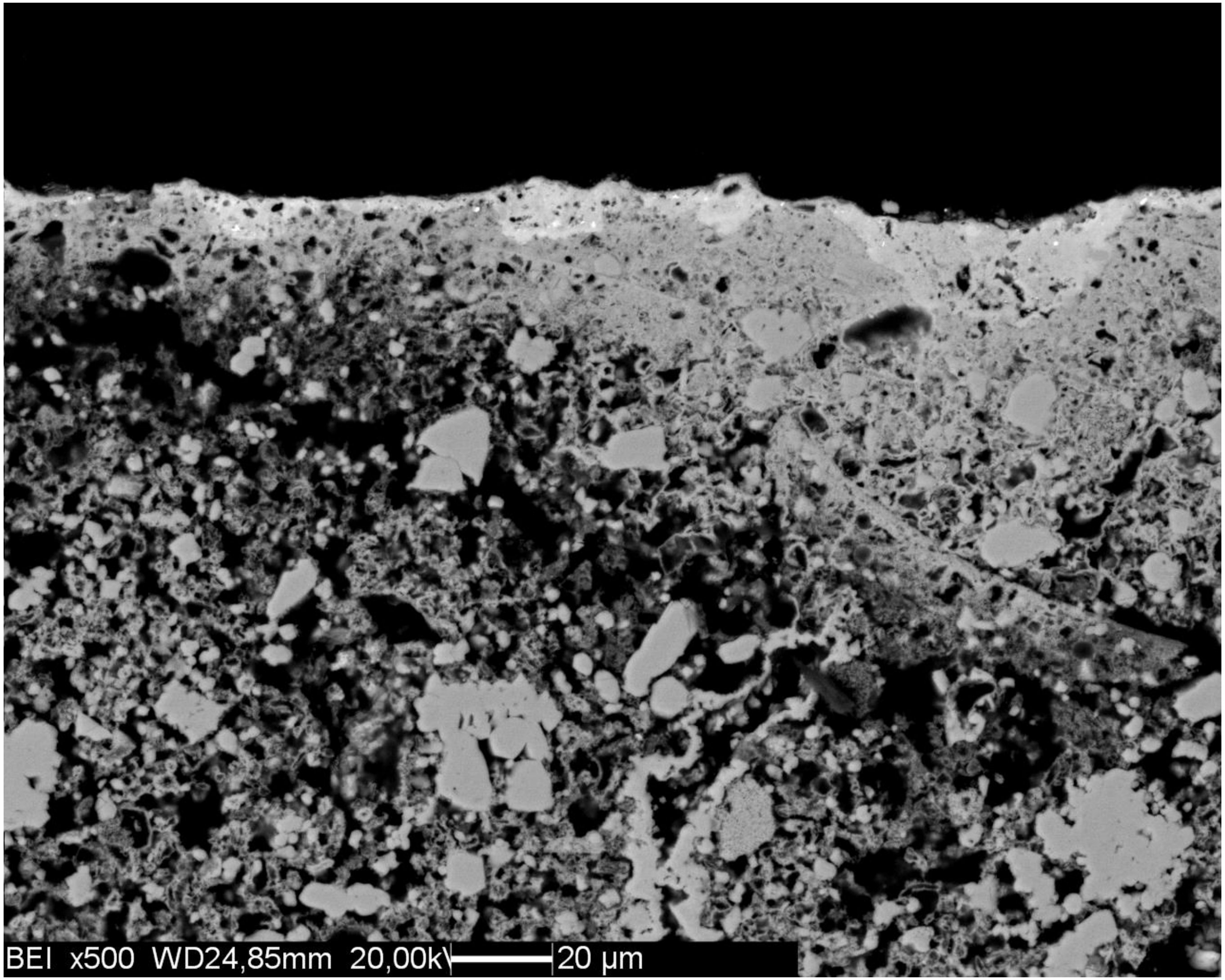
# Painted plasters/renders

## Marble powder in the external plaster/render layer (*intonachino*): luster enhancement



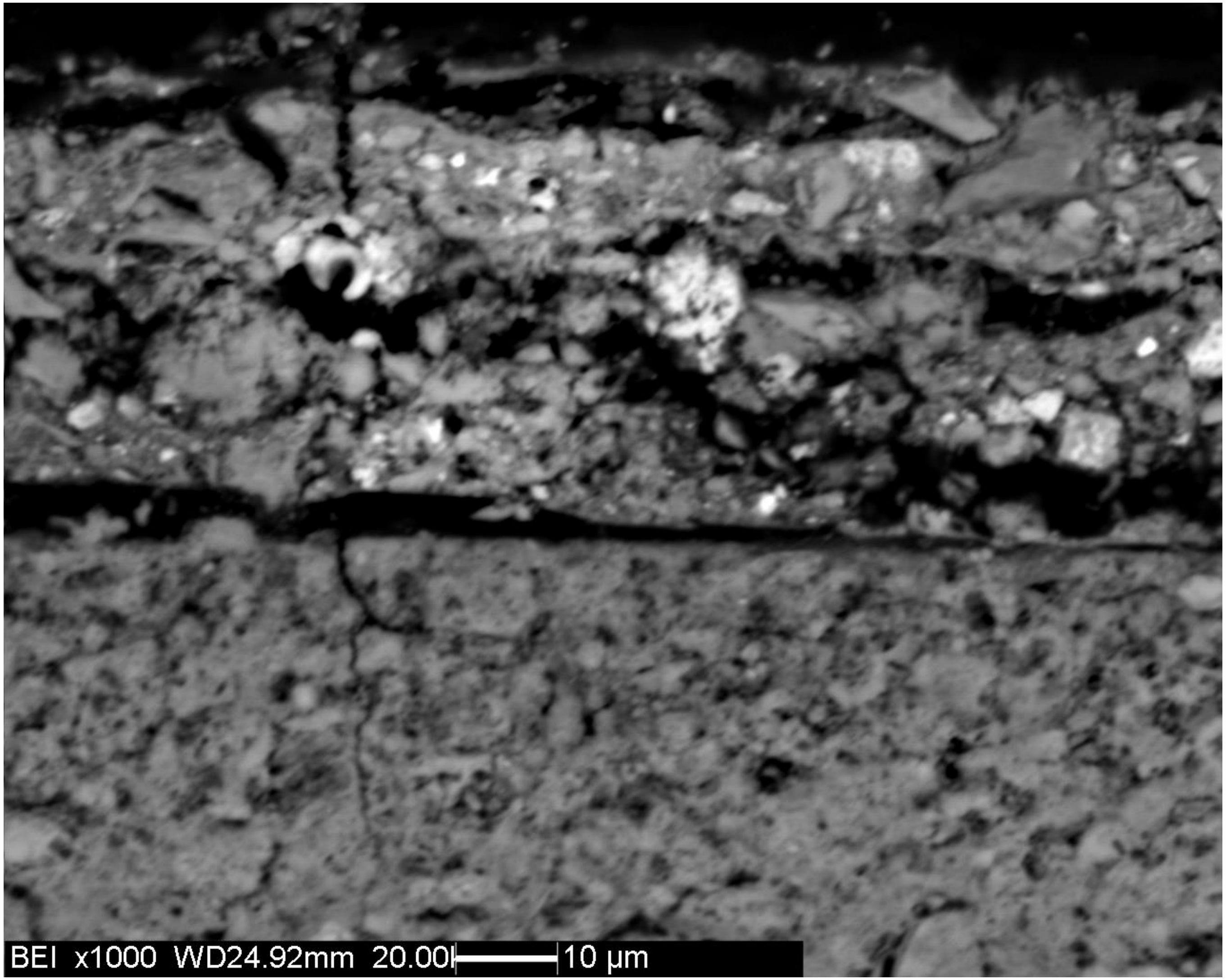
# Painted plasters/renders

## Wet-on-wet pigment application: *fresco* technique



# Painted plasters/renders

## Wet-on-dry pigment application: *secco* technique



# Concrete

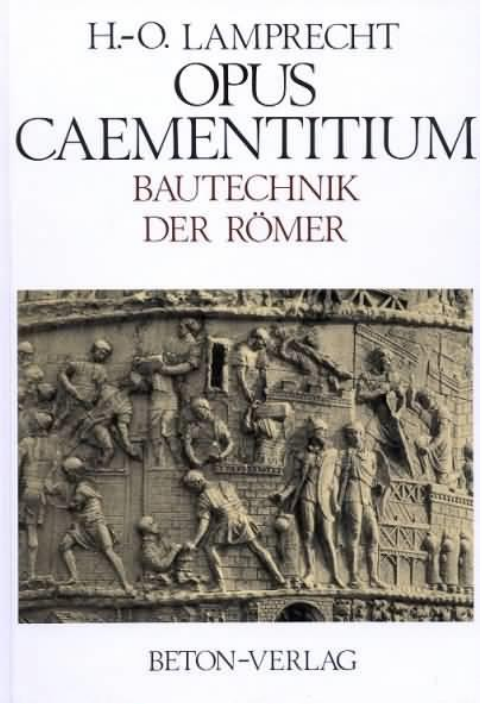
**Concrete** is a composite material composed of fine and coarse aggregate bonded together with a fluid cement (cement paste) that hardens (cures) over time. The mixture forms a fluid slurry that is easily poured and molded into shape.

# Concrete

# Concrete

- It is to be remarked that the world cement (***Opus caementicium***) in ancient Roman times was referred to the concrete masonry of the monuments composed of centimeter sized brick and tuff fragments (*caementa*), which are bonded by hydraulic mortars with alkali-rich, calcium-alumino-silicate volcanic ash sands.

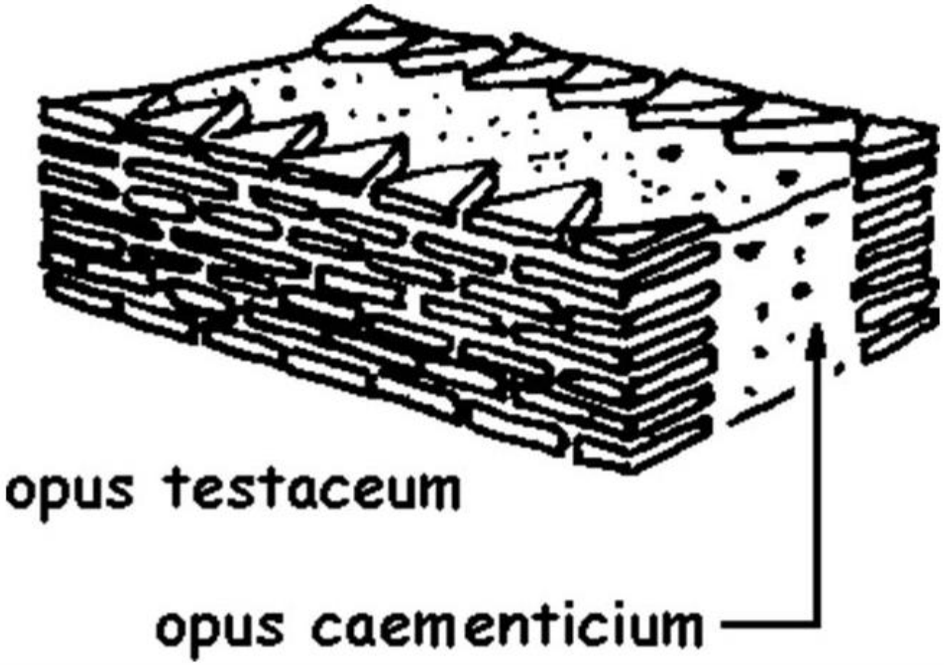
- Only in recent times the significance changed to refer to modern clinker-based materials. The Romans also developed the concept of lightweight concrete by casting jars into wall arches as well as using extensively pumice aggregates, which were obtained by crushing porous volcanic rocks. The arches of the Colosseum and the Pantheon dome are reported to be made with such materials.



H.-O. LAMPRECHT
OPUS
CAEMENTITIUM
BAUTECHNIK
DER RÖMER

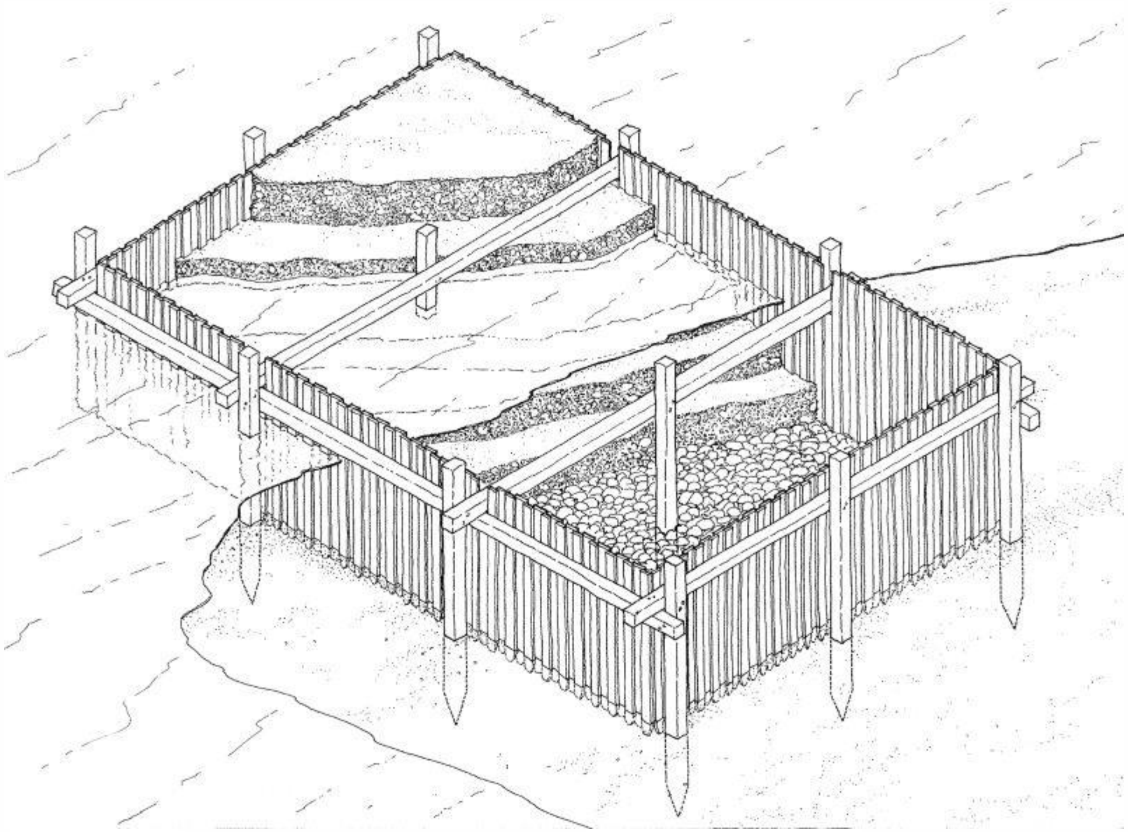
BETON-VERLAG

# *Opus caementicium* in the middle leaf of a masonry wall (external leaves as disposable formworks)

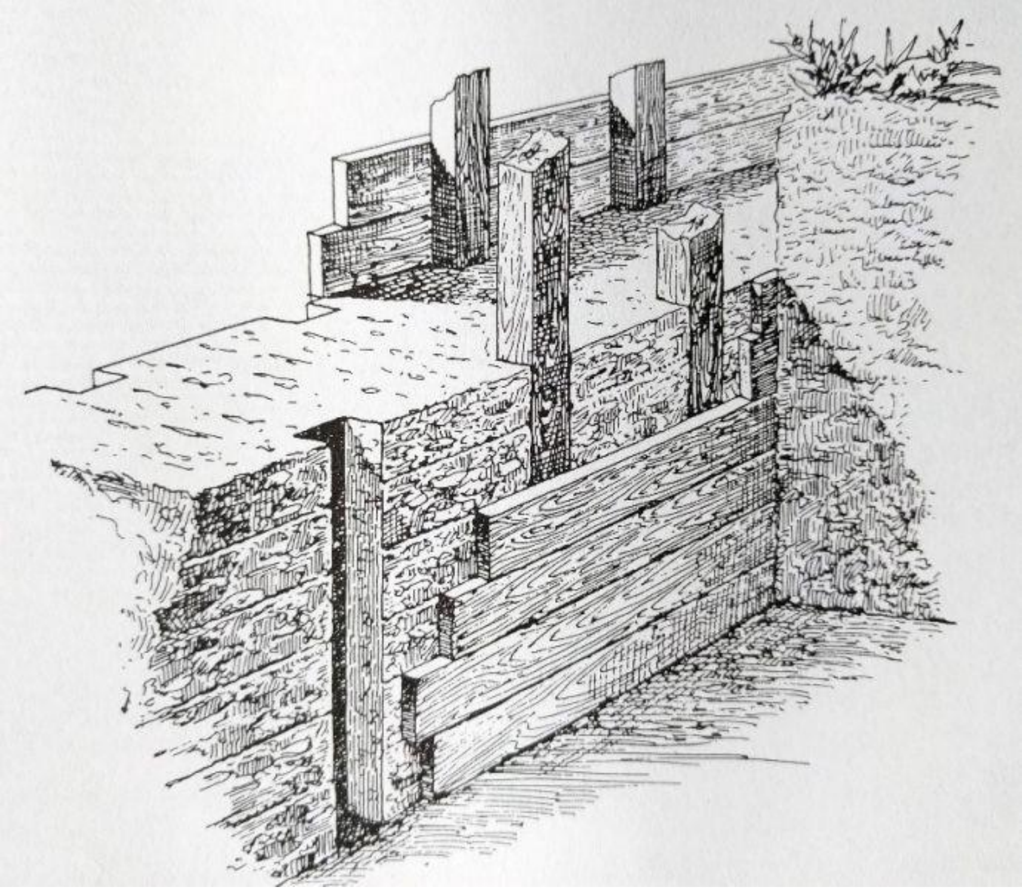


# Concrete

## Disposable timber formworks for *opus caementicium*



# Removable timber formworks for *opus caementicium*

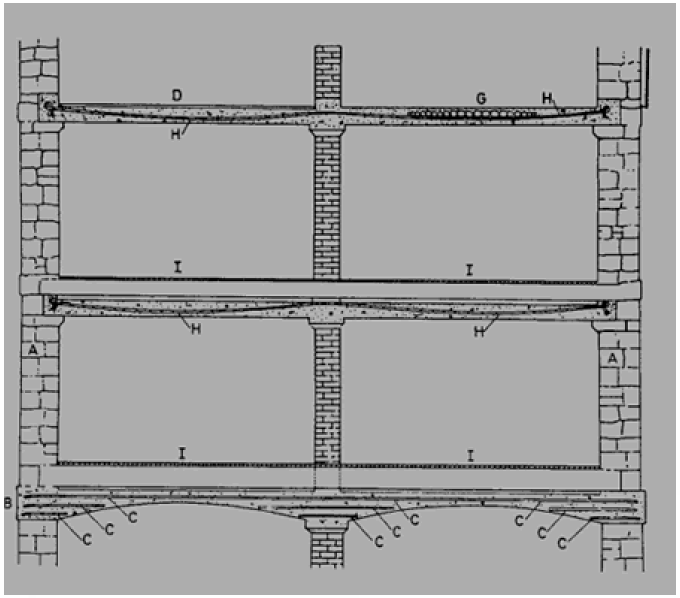


# Reinforced concrete

**Reinforced concrete (RC)**, also called **reinforced cement concrete (RCC)**, is a composite material in which concrete's relatively low tensile strength and ductility are compensated for by the inclusion of reinforcement having higher tensile strength or ductility. The reinforcement is usually, though not necessarily, steel bars (rebars) and is usually embedded passively in the concrete before the concrete sets.

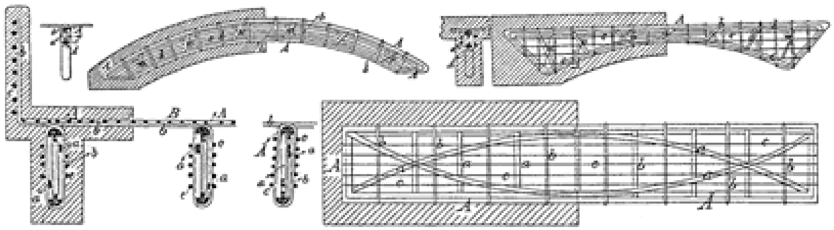
# Reinforced concrete

- 1848, Lambot: boat consisting of a wire mesh immersed in concrete conglomerate. Presented at the 1855 Paris World's Fair.
- 1854, Wilkinson: introduction of reinforced concrete in construction. Patent for "improvement in the construction of fireproof dwellings, warehouses, other buildings and parts thereof". Construction of the first building with reinforced concrete floors.
- 1861, Coignet: Publication of the first data on experiments on beams, slabs and vaults with embedded steel profiles.



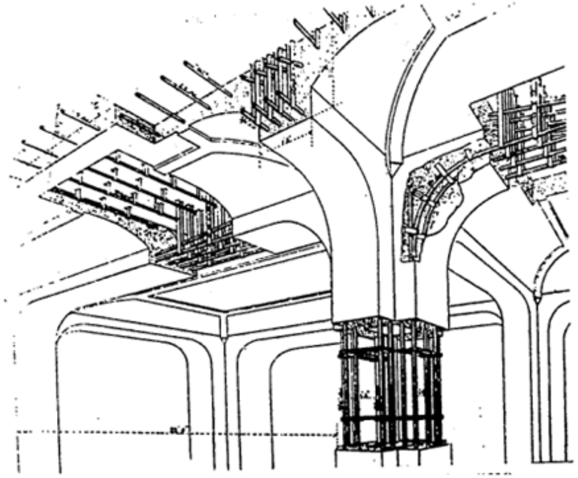
# Reinforced concrete

- 1867, Monier: patented procedure for constructing pots from cement mortar reinforced with iron wires. System later extended to pipes and tanks (1868), slabs (1869), bridges (1873), stairs and vaults (1875). Elements and principles of reinforcement layout still based on empirical concepts.
- 1871-1875, Ward: construction of the first complex reinforced concrete building in the U.S. (Port Chester, N.Y.).
- 1884-87, Wayss and Bauschinger: first systematic studies on reinforced concrete, theories on the steel-concrete interface, design of the positioning of reinforcement in the tensile portion.
- 1886, Könen: first fundamentals of calculation.



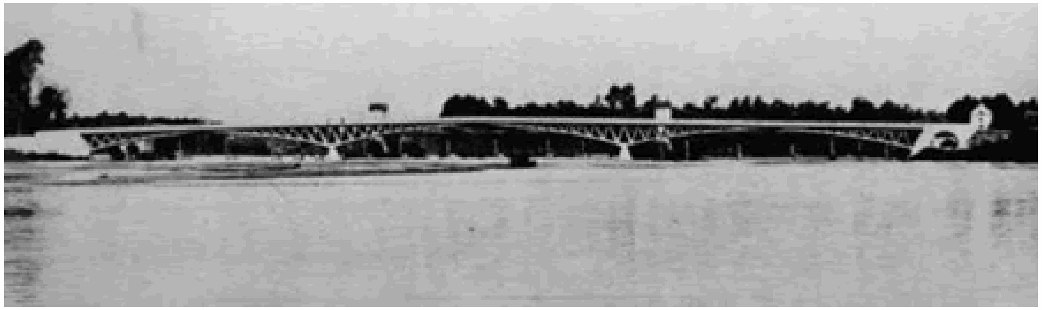
# Reinforced concrete

- 1892: Hennebique system patent (reinforcements in tension zone, stirrups to counteract shear stress). First reinforced concrete construction system to become widespread and successful worldwide, through a dense network of national dealers (Italy: Porcheddu Company).



- 1903, Perret: construction of Rue Franklin palace, Paris. First building without load-bearing walls, replaced by a load-bearing reinforced concrete frame.

- 1928, Freyssinet: first patent for the use of prefabricated and prestressed reinforced concrete (experiments started as early as 1911 with the construction of the Le Veurdre bridge).



# Concrete

- Concrete differs from cement by virtue of its large content of mineral aggregate; it is a *composite*

*Mineral aggregates- sand, crushed stone, gravel- are very cheap and do not significantly reduce strength until they exceed about 80-85 volume %. The result is a composite material bound by cement.*

- Mortar is a fine- aggregate concrete

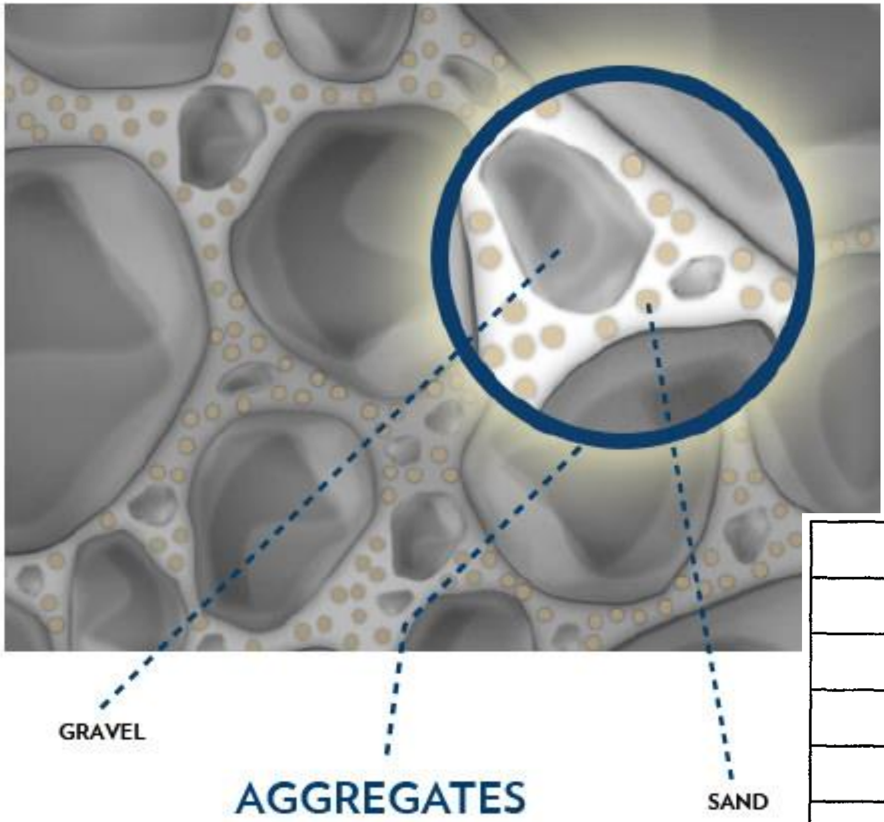
*(Aggregate sizes usually less than 4 mm )*

# Aggregate

- Aggregate- especially for concrete – has to be *graded*: the sizing should fill space efficiently, so that the remaining space, which has to be filled with cement, is kept to a minimum.
- Aggregate should be physically strong, inert towards cement and have low permeability and water sorption.

*Many commercial aggregates do not fill all the above criteria*

# Reinforced concrete



| Diameter (mm) | Passing % |
|---|---|
| 0.002 | 5-12 |
| 0.005 | 10-13 |
| 0.01 | 15-20 |
| 0.1 | 30-40 |
| 0.2 | 40-60 |
| 0.4 | 50-75 |
| 0.7 | 60-85 |
| 1 | 70-90 |
| 2 | 85-95 |

# Reinforced concrete

## Granulometric distribution of aggregate

Sieving with a series of standard sieves

Fuller: maximum packing

$$P = \frac{100\sqrt{d/D} - C}{100 - C}100$$

P = percentage of passing aggregate
d = sieve aperture
D = maximum diameter of aggregate
C = cement percentage
A = workability coefficient

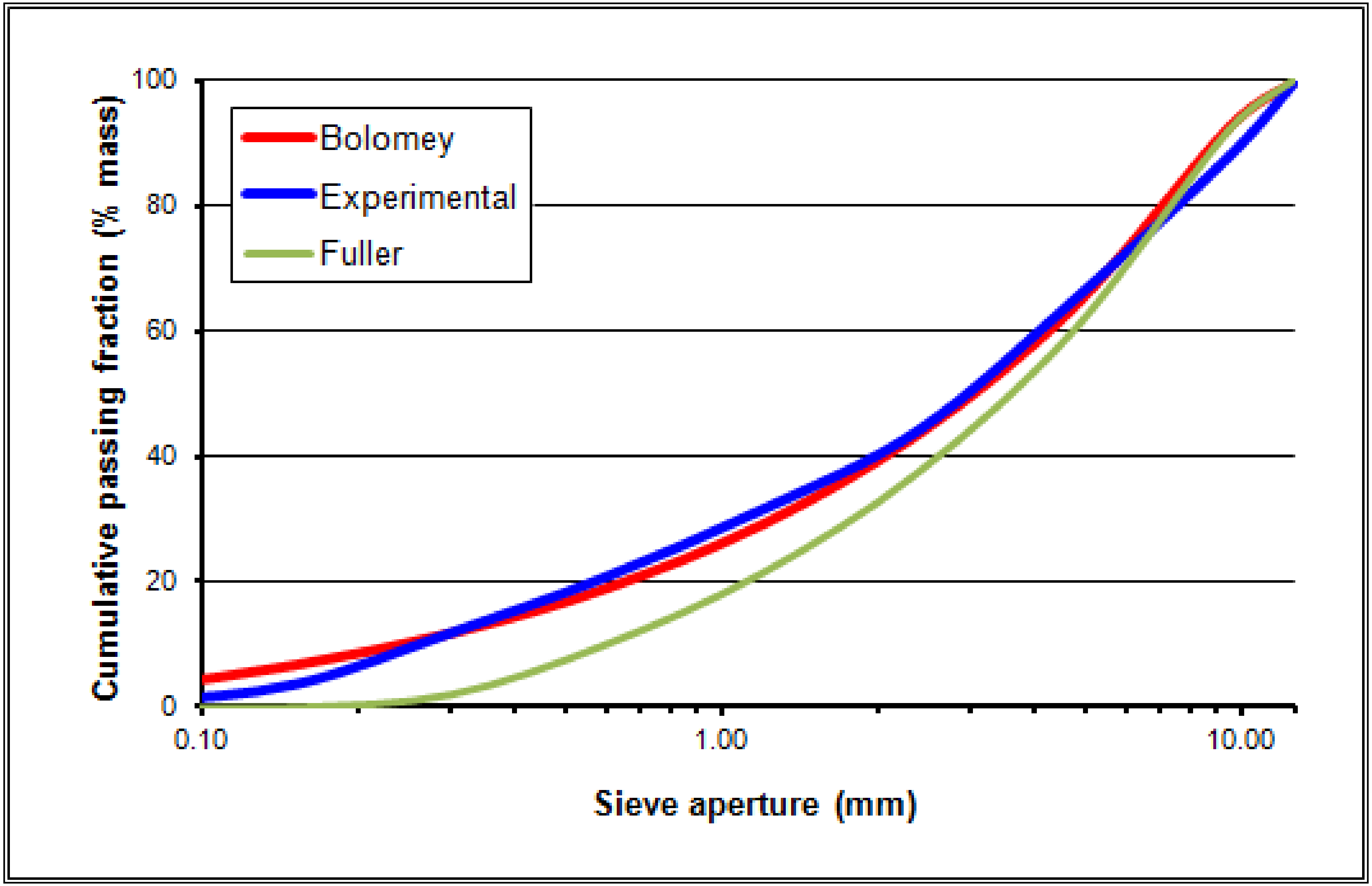
Bolomey: maximum workability

$$P = \frac{A + (100 - A)\sqrt{d/D} - C}{100 - C}100$$

| **Aggregate type** | **A value according to concrete viscosity:** | | |
|---|---|---|---|
| | **Humid** | **Plastic semifluid** | **Fluid/superfluid** |
| Natural | 8 | 10 | 12 |
| Crushed | 10 | 12 | 14 |

# Reinforced concrete

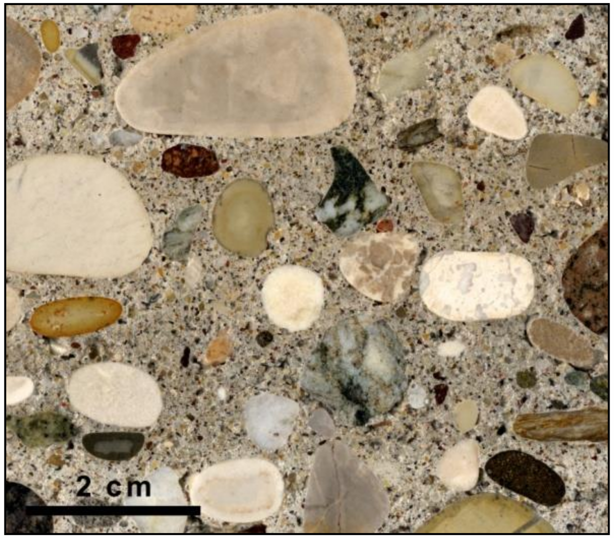
## Granulometric distribution of aggregate



# Reinforced concrete

## Aggregate supply

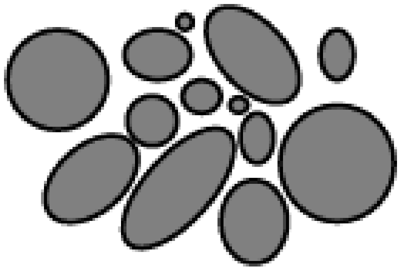
- Historic times: sands and gravels quarried from the river beds (rounded shapes, high mineralogical and petrographic etherogeneity).



- Today: sands and gravels quarried from alluvial fans and/or from crushing of quarried stone (subangular shapes, low mineralogical and petrographic etherogeneity).

# Reinforced concrete

## Aggregate shape



Natural gravel

Crushed gravel

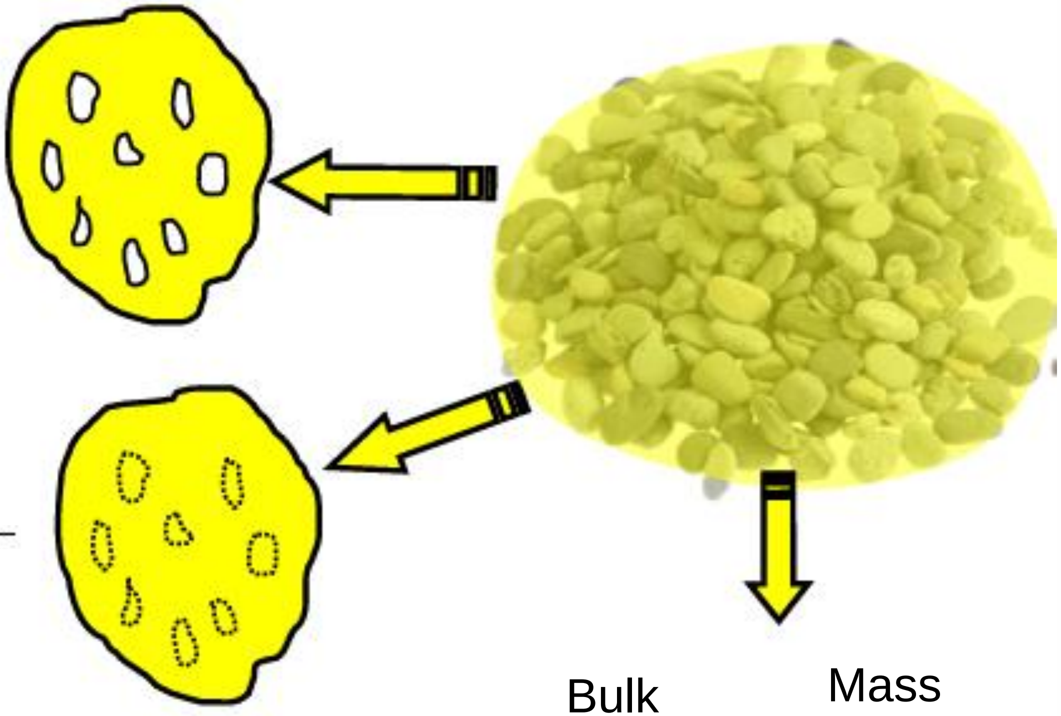
**Aggregate shape can modify:**

- Mix workability
- Volume filling (optimal by a sphere)
- Escape of air and bleeding water from the mix
- Degree of compaction
- Adhesion with the cement paste
- Direct tensile and bending strength

- Angularity (presence of edges)
- Form factor (similarity with a sphere)

# Reinforced concrete

## Aggregate density



$$\text{Absolute density} = \frac{\text{Mass}}{\text{Solid volume}}$$

$$\text{Granule density} = \frac{\text{Mass}}{\text{Granule volume}}$$

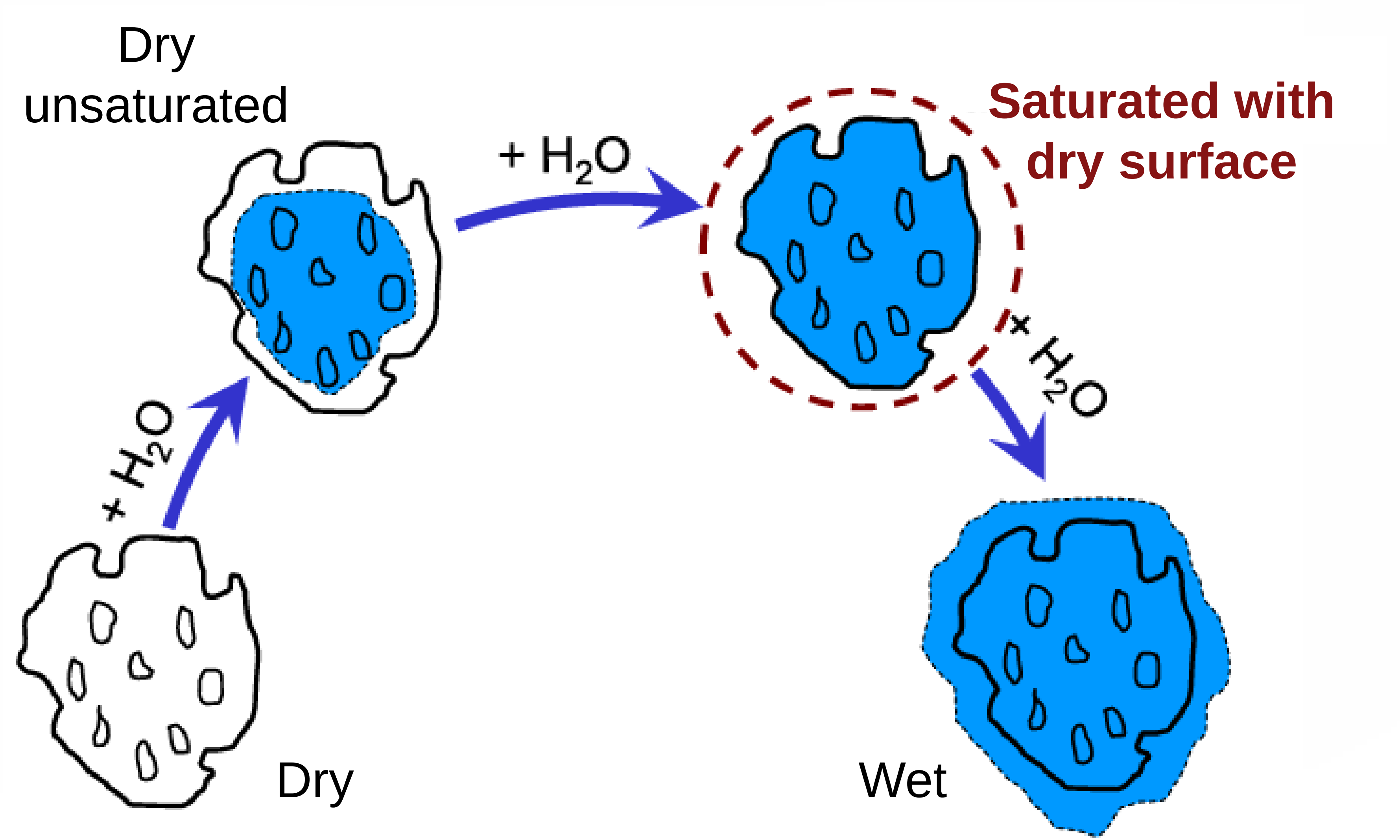
$$\text{Bulk density} = \frac{\text{Mass}}{\text{Bulk volume}}$$

**Standard aggregates**

- Granule density : $2600 \div 2800$ kg/m$^3$
- Bulk density : $1500 \div 1600$ kg/m$^3$

# Reinforced concrete

Aggregate density



# Reinforced concrete

## Aggregate maximum diameter

**$D_{max}$ is constrained by:**

- Density of rebars
- Thickness of concrete cover
- Dimensions of the structural elements

**The designer decides the $D_{max}$**

# Reinforced concrete

## Aggregate maximum diameter

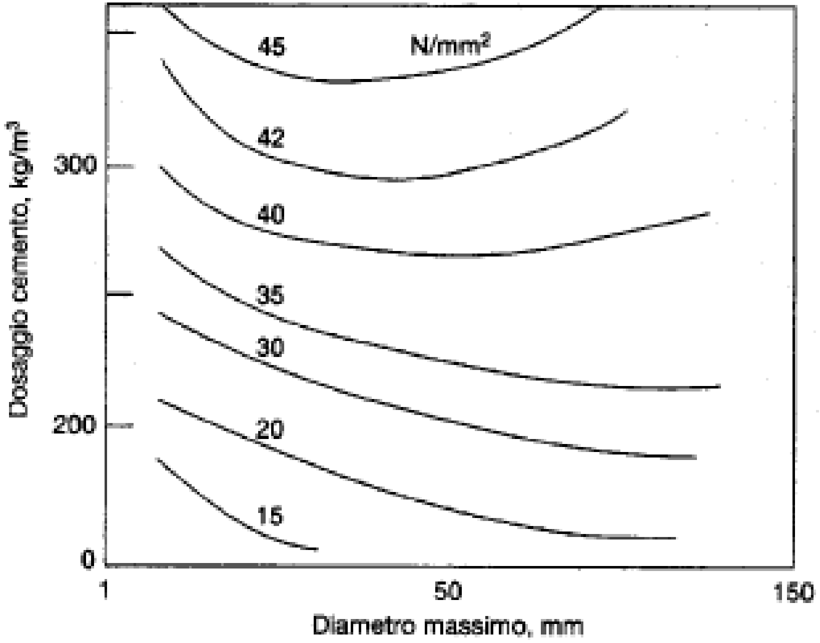
**$D_{max}$ increase:**

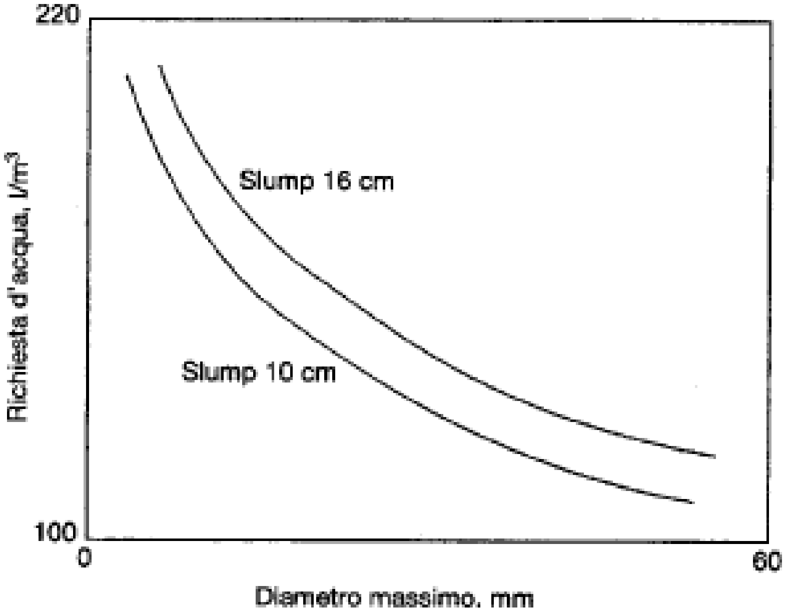
**+**

- Less water and cement required
- Less shrinkage, heat of reaction and costs

**-**

- Geometric limitations
- Segregation tendency





# Reinforced concrete

## Aggregate further requirements (EN 12620)

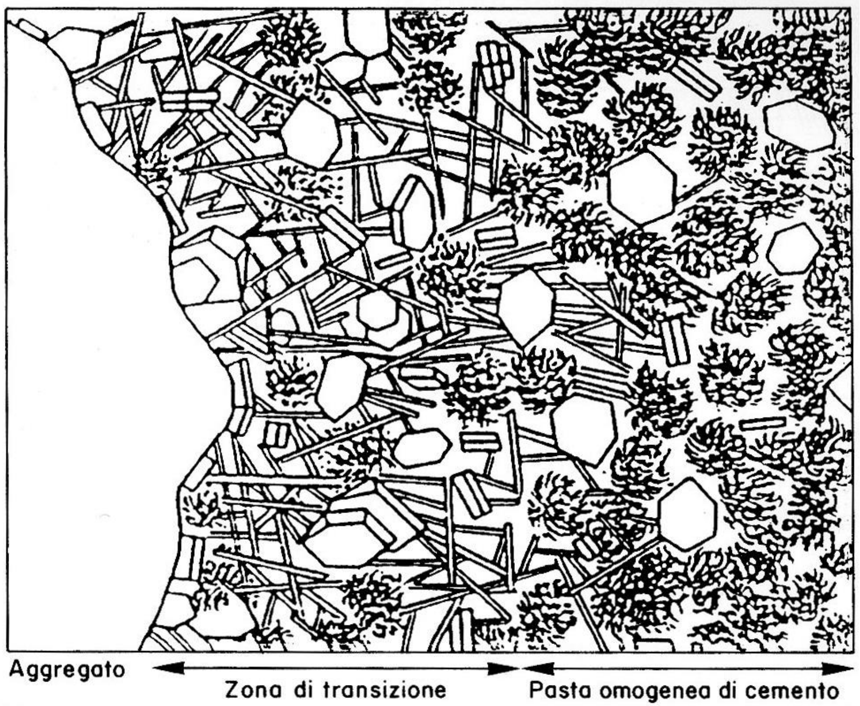
- Adequate compressive strength
- Fragmentation resistance of the coarse aggregate
- Wear and abrasion resistance of the coarse aggregate
- Freeze/thaw resistance
- Volume stability
- Low alkali/silica reaction
- Low chlorides content
- Low sulphates content

# Reinforced concrete

## Interfacial transition zone (ITZ)

- Interfacial region between the cement matrix and the medium-coarse aggregate (mean thickness 50 μm) with higher porosity and different distribution of hydrated phases.

- Formation due to wall effects (accumulation of clinker finer granulometric fractions around the coarse aggregate particles) and bleeding (water confinement under the coarse aggregate particles due to gravity effects) during the first hydration stages.

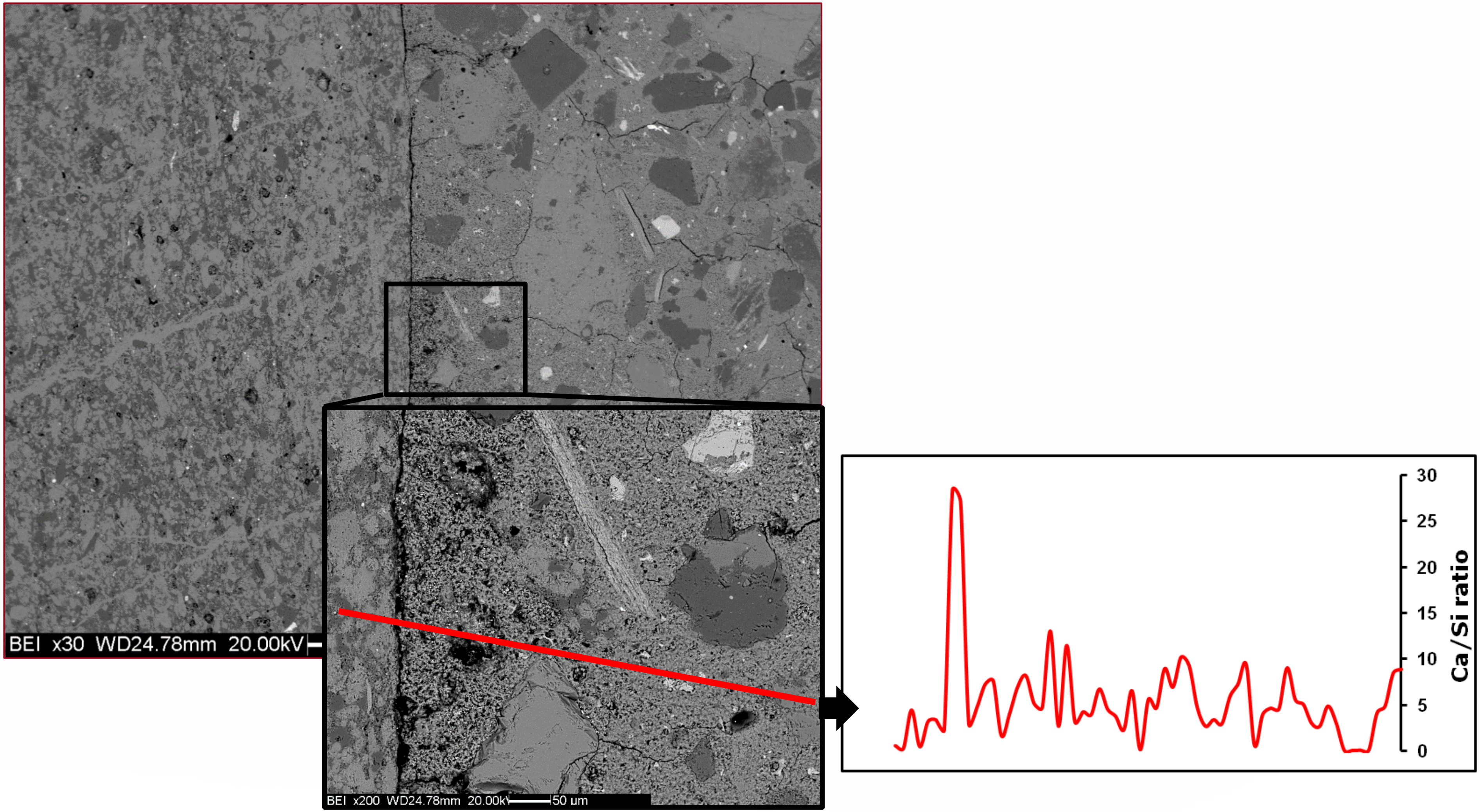


- Microstructural consequences: higher porosity (higher water amount), enrichment in AFm and Aft phases and lower CSH (higher amount of interstitial phase in the smaller particles), higher portlandite crystal growth (more space).

- Mechanical and durability consequences: preferential area for microcracking formation, lower rigidity, easier penetration of aggressive agents.

# Reinforced concrete

## Interfacial transition zone (ITZ)



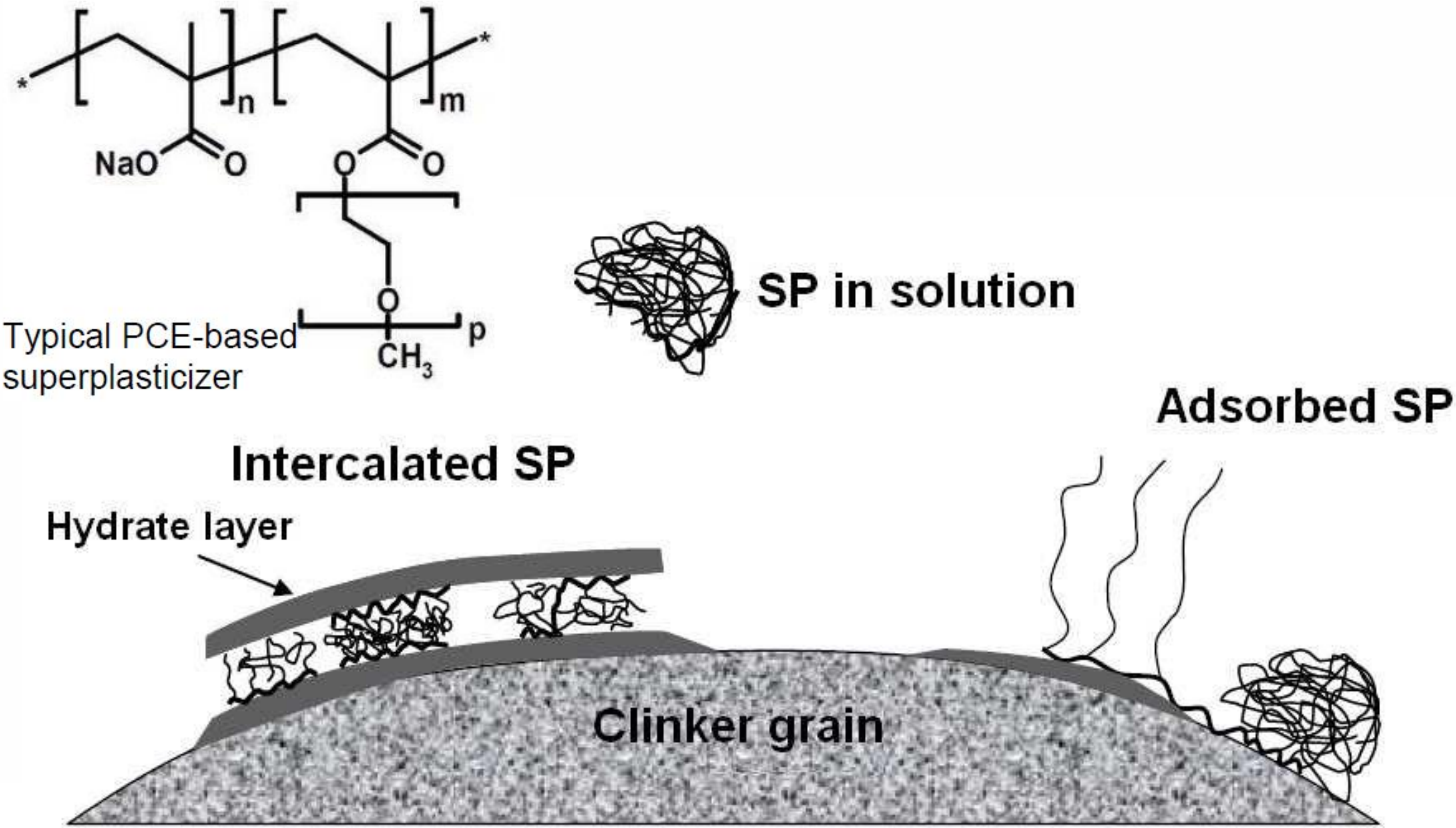
# Reinforced concrete

## Chemical admixtures

- Chemical compounds, mainly of polymeric nature, added in low amounts to the fresh paste and cabable of modifying specific cement properties during setting and hardening.
- Mostly used: superplasticizers (chemical compounds with dispersant action toward the cement particles in water solution).
- Cement particles within fresh concrete: coagulated in agglomerates due to electrostatic interactions between the clinker particles (necessity to put more water with respect to the proper stoichiometric amount).
- Addition of superplasticizer: adsorption of the additive in the surfaces of the clinker particles, with consequent prevention of the agglomeration.
- Possibility to increase workability at a fixed w/c ratio and/or to gain strength and durability lowering the w/c ratio.
- Discovering of superplasticizers: during the Thirties (lignin-sulphonates, hydroxycarboxylic acids, hydroxilated polymers, dispersion due to electrostatic repulsion). Modern superplasticizers: acrylic/acrilate copolymers (dispersion due to a combination of electrostatic repulsion and steric hindrance).

# Reinforced concrete

## Chemical admixtures



Typical PCE-based superplasticizer

# Reinforced concrete

**Nowadays: study of the compositional ratios**

⬇

Concrete mix design

⬇ ⬇

Water/cement ratio

⬇

0.4 – 0.6 (without superplasticizers)

Cement/aggregate ratio

⬇

Lean concrete: 1:3, 1:5

Standard concrete: 1:1.5, 1:3

Fat concrete: 1:1.5, 1:1

Historic times: mixing according to empirical criteria (Hennebique system ratios: 300 kg of cement, 0.400 $m^3$ of sand, 0.850 $m^3$ of gravel)

# Reinforced concrete

## Prescriptions

- Strength class
- Exposure class
- Consistence class
- $D_{max}$ of aggregates

*Mix design* →

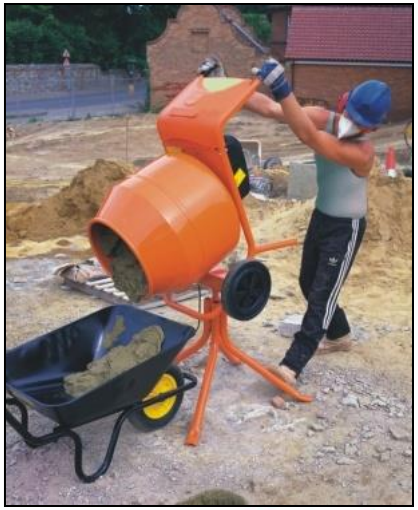
## Recipe

- Cement
- Water
- Aggregates
- Additives

# Reinforced concrete

## Production

- Historic times: manual mixing of the components to obtain a even mixture.



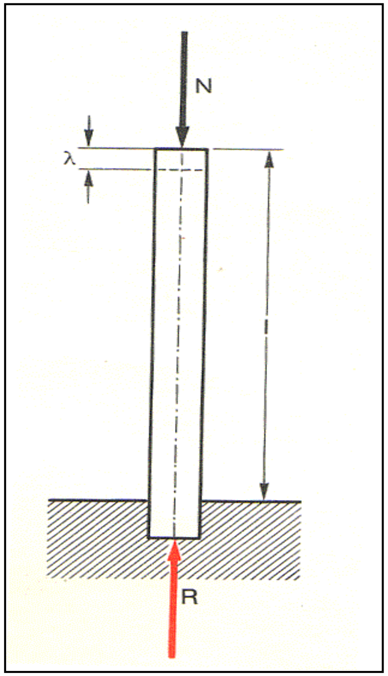
- Today: automatic mixing in the construction site (concrete mixers), production in ready-mixed concrete production plants and transportation to the production site with truck mixers.

# Reinforced concrete

## Standard concrete properties

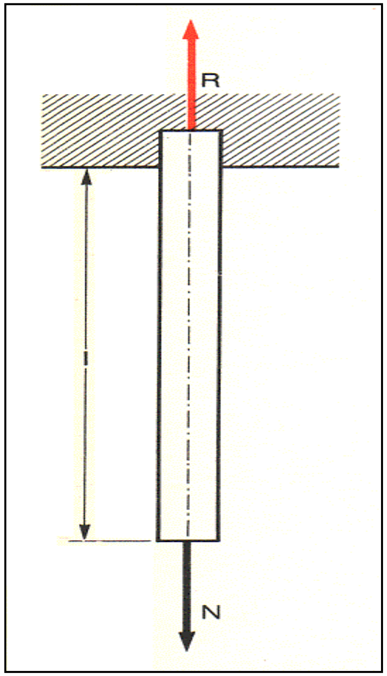
☺

Good compressive strength (>100 MPa for modern ultra-high performance concretes, historical concretes: 15-40 MPa)



☹

Poor tensile strength (10% of the compressive strength)



⇩

Concrete reinforcement with steel bars, characterized by excellent tensile strength (>100 MPa for modern rebars)

# Reinforced concrete

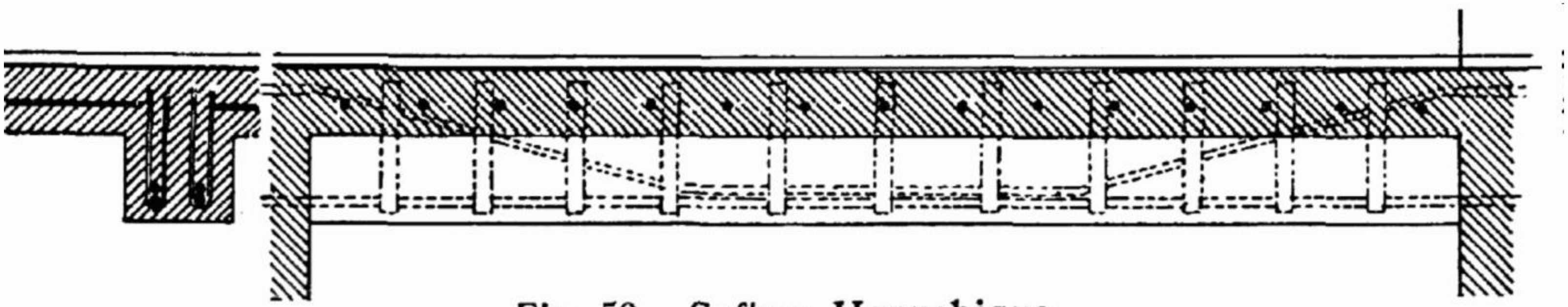


Fig. 50. Syſtem Hennebique.

- Steel embedded within concrete in the portions subjected to higher tensile stresses.
- Variable diameter of the rebars (5-32 mm).
- Used both as longitudinal reinforcement and as stirrups perpendicular to the longitudinal rebars (increase of shear strength).
- Adequate concrete thickness over the rebars (concrete cover) to prevent steel oxidation (passivating layer due to the alkaline environment of concrete).
- Use of both plain and shaped rebars to increase adherence.

# Reinforced concrete

The combined utilization of such etherogeneous materials is justified by two relevant factors:

1. The adherence between steel and concrete allows a transmission of the tensions between the two materials. Steel absorbs the tensile stresses, while concrete withstands the compressive ones;
2. The thermal expansion coefficients of the two materials are similar at standard temperatures.

# Reinforced concrete

## Reinforced concrete production

- Construction of formworks to shape the concrete.
- Placement of rebars.
- Concrete pouring.
- Homogenization of poured concrete to avoid segregation of the constituents (external vibration of formworks and/or internal homogenization with needle vibrators).
- Concrete curing (preservation of humid conditions by water sprinkling and covering of the poured elements to facilitate the hydration processes avoiding cracking phenomena).
- Removal of formworks after setting.

# Reinforced concrete

## Reinforced concrete production:prefabrication

- Pouring and shaping *ex situ* of modular structural elements.
- Transportation in the construction site.
- Placing of the elements with cranes.
- If necessary, soldering and cementation of the structural elements.
- Advantages: better control of the concrete production process.
- Disadvantages: logistics of transportation.

# Degradation

Like all materials, binders, mortars and cements undergo degradation processes, alteration, and structural modifications, as they tend to equilibrate with the thermodynamics of the surrounding .

The amount and kinetics of the degradation processes depend

(a) on the nature of the binder, and

(b) on the environmental conditions acting upon it.

In most cases the degradation processes of chemical nature are slow and continuous, though of course catastrophic events and mismanagement can severely and abruptly damage the artifact.

# Degradation

As a first approximation, most of the alteration and degradation processes are caused or mediated by water, therefore the prime parameter affecting the speed of degradation is the **porosity** of the material, that is its capacity to absorb and diffuse water in the bulk.

In the binder, the **amount and distribution of the pores** is controlled by the nature of the paste and the aggregate system. Key factors affecting porosity are:

(a) the water/binder ratio in the paste,
(b) the paste/aggregate ratio in the composite mortar or concrete,
(c) the nature of the aggregate,
(d) the use of additives as dispersants and surfactants,
(e) the environmental conditions of setting and hardening.

**Water percolation** causes, among other effects:

(a) dissolution of structural components and binder phases,
(b) dissolution and re-crystallization of soluble salts,
(c) formation of secondary phases (volume expansion/contraction),
(d) progression of the carbonation reactions,
(e) corrosion of the steel reinforcements.

# Degradation

In the case of masonry and binders, humidity and temperature fluctuations are natural components of the environment. Day/night and seasonal climatic changes induce thermal gradients, expansion shocks, and numerous cycles of evaporation/condensation through the **dew point**, inducing water formation and transport through the structures. We may distinguish between weakly physiosorbed (**absorbed**) water molecules from the more tightly chemisorbed (**adsorbed**) water molecules. In all cases the changes in the water content of the material is going to activate chemical reactions, mobilization of components, and mechanical damages.

The most common ones are related to the **soluble salts** already dissolved in the water, such as in marine spray (i.e. sulphates, chlorides), or dissolved in the material by the presence of water. The salt recrystallization within the pores and the micro-fractures of the binder is one of the most pernicious alteration mechanisms of building materials:

- The **crystallization pressure** exerted by the salt growing in confined spaces (Scherer 2004, Steiger 2005) is not dissimilar to the one produced by the freeze and thaw cycles of water and ice: the volume of the crystal is always larger that the volume of the same amount of molecules in the liquid state, because of the ordered arrangement due to chemical bonding in the crystal lattice.
- **Salt weathering** however induces other damages related to differential thermal expansion, osmotic swelling of clays, hydration pressure, and enhancement of wet/dry cycles (Goudie and Viles 1997, Charola 2000, Doehne 2002, Al-Naddaf 2009). The use of surfactants as agents interfering with the salt crystallization behaviour is being tested (Rodriguez-Navarro et al. 2000, Selwitz and Doehne 2002).

# Degradation

Concerning historical gypsum-based mortars (Section 3.2.2), even the low humidity may be a problem if combined with high temperature. As a matter of fact gypsum is a dihydrate phase, and at T>30 °C and RH<30-40 % it may undergo slow dehydration. The process has been detected in the plaster of the Nefertari tomb in the King’s Valley, Egypt (Plenderleith et al. 1970, Preusser 1991, McDonald 1996).

The chemical equilibrium of lime-based mortars is related both to absorbed water and to atmospheric carbon dioxide. The $CO_2$ dissolved in the water forms carbonic acid, which dissolves calcite and produces soluble calcium bicarbonate that migrates and re-precipitates elsewhere as Ca carbonate, in many cases producing a thin white veil on the surface. Such a carbonate layer frequently covers frescoes and cave paintings. The major problems involving wall paintings of all ages are: pigment alteration and fading, detachment of the painted layer and plaster support, surface corrosion, and salt precipitation. (Figs. 3.d.5, 3.d.6, 3.d.7).

# Classification of degradation

From the operational standpoint, two groups of processes occur:

- Internal: mass does not to be gained or lost;
- External: where transport of mass into or out of binder (or both) drive reaction.

# Reinforced concrete degradation

COSTRUZIONI IN CALCESTRUZZO ARMATO

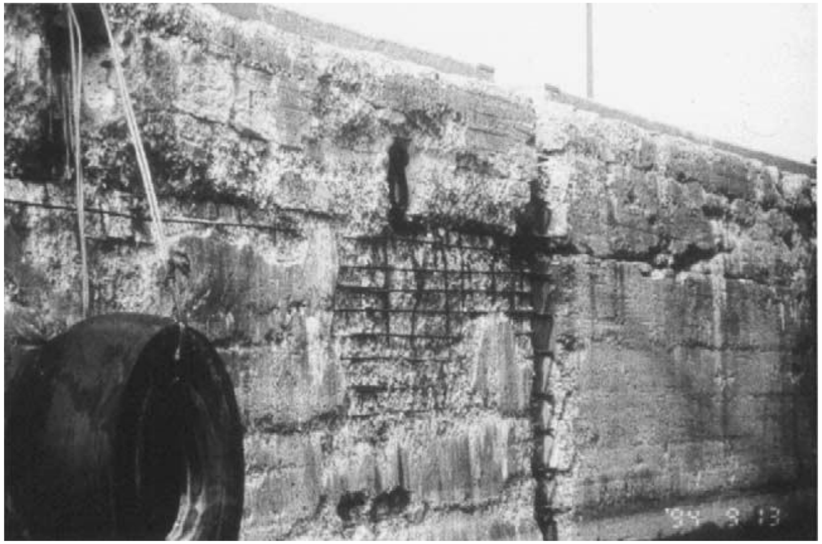
SISTEMA “HENNEBIQUE„ BREVETTATO IN TUTTI I PAESI

DURATA INDEFINITA - SICUREZZA ASSOLUTA CONTRO GL'INCENDII - ELASTICITÀ PERFETTA

ALTA RESISTENZA AL CARICO, ALL'URTO, ALLE SCOSSE - GRANDE PORTATA - ECONOMIA RILEVANTE

?

# Reinforced concrete degradation



# Reinforced concrete degradation

## Reinforced concrete degradation due to:

Intrinsic factors

Inhomogeneity
Porosity

Environmental factors

Temperature
Presence of water
Relative humidity
Dangerous environments

# Reinforced concrete degradation

## Concrete primary porosity

Pores (setting/hardening of concrete)

- ✓ Gel pores
- ✓ Capillary pores

Voids (mixing and placing of concrete)

- ✓ Entrained air voids
- ✓ Entrapped air voids / water voids

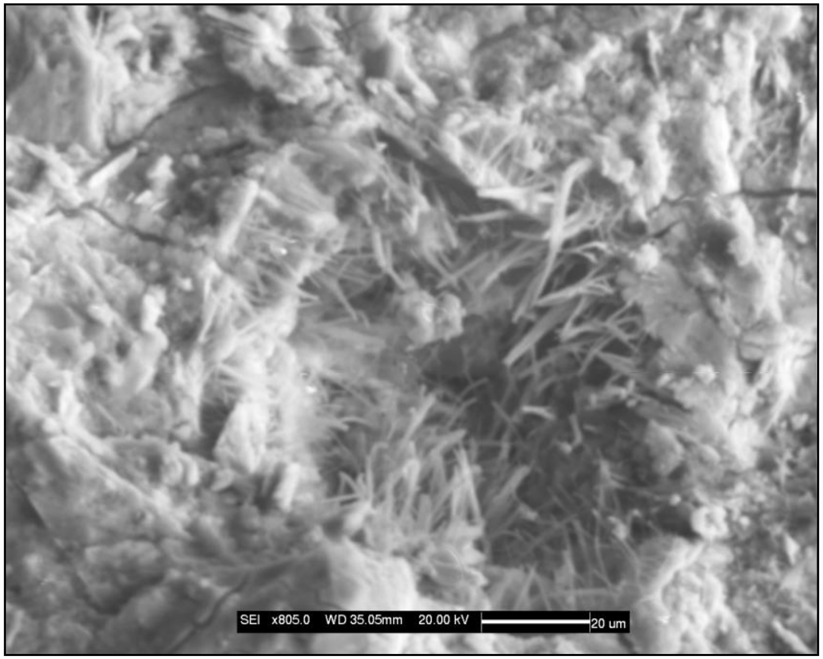
Cracks (setting/hardening of concrete)

- ✓ Plastic shrinkage cracks
- ✓ Drying shrinkage cracks

# Reinforced concrete degradation

## Pores

- Gel pores: few nm in diameter, they are due to the fibrous shape of C-S-H crystals.
- Capillary pores: diameter between 10 nm and 10 µm, they constitute the interstitial spaces between the hydration products of the hardened cement paste.
- Capillary pores potentially dangerous (tensile stresses under freeze/thaw cycles due to their reduced diameter).



# Reinforced concrete degradation

## Entrained air voids

- Formed after inclusion of air bubbles during mixing and casting.
- Homogeneously dispersed within concrete.
- Dimensions: < 1 mm (generally 1/10 mm).
- Spherical shape.

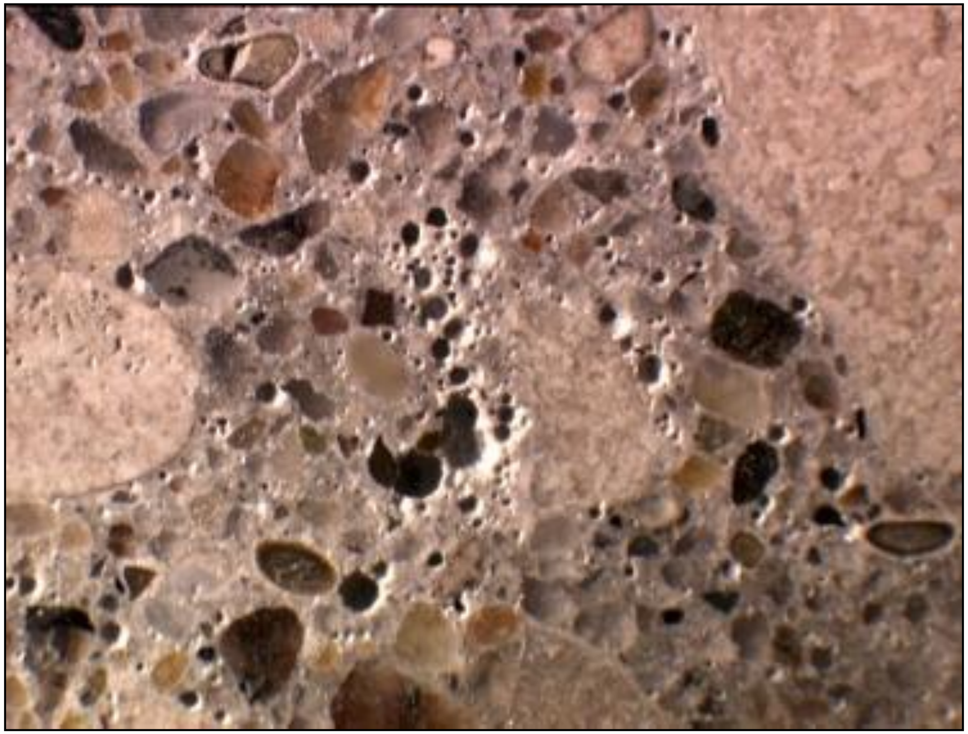
Connected with capillary pores

⇩

Fluids migration from capillary pores to entrained air voids

⇩

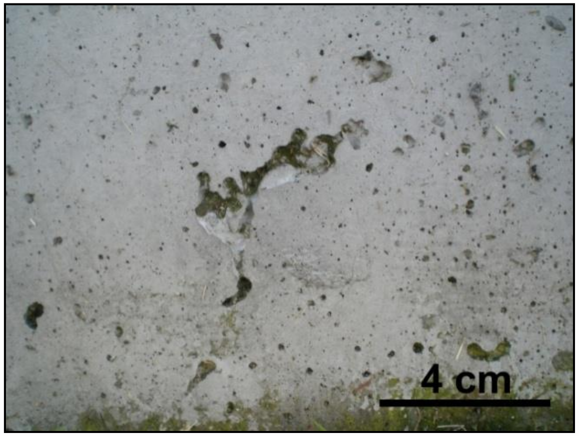
Absorption of freeze/thaw tensional states



Concrete, stereomicroscope image: air voids (field size: 7 mm) (Stutzman, 1999)

# Entrapped air voids/water voids

- Origin: inclusion of air macrobubbles during mixing and casting of concrete, accumulation and subsequent evaporation of excess water (bleed water).
- Position: concrete surface (wall effect of the formwork), around coarse aggregates, around rebars.
- Dimensions: millimetric-centimetric.
- Shapes: from spherical to irregular/channel like.
- Potentially dangerous (overall reduction of compressive strength).



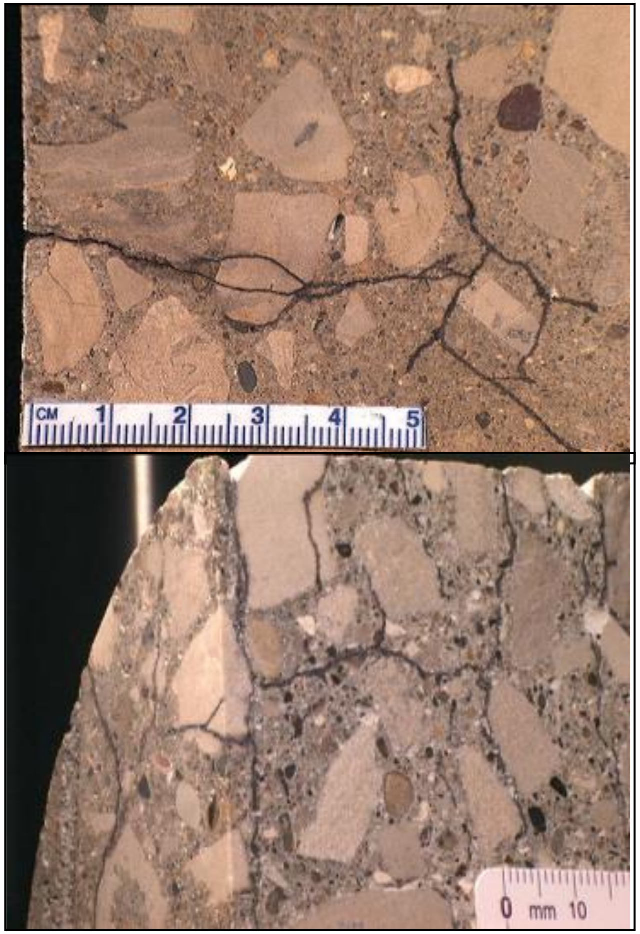
Concrete, external surface: entrapped air voids

Padova castle concrete beam: entrapped air voids

# Reinforced concrete degradation

## Cracks

- According to dimensions: macrocracks (>0.1mm), fine cracks (between 0.01 and 0.1 mm), microcracks (<0.01 mm).
- Generated by dimensional variations of concrete due to water evaporation and chemical shrinkage.
- Plastic shrinkage cracks: accumulated toward the surface. Formed after excessive superficial evaporation of water, few hours after casting.
- Drying shrinkage cracks: radial to the aggregate fine fraction. Formed after a slow water loss within concrete.
- Highly dangerous (loss of mechanical strength, higher permeability to degrading agents).
- The can be avoided through accurate curing.



Concrete cracking (Stutzman, 1999)

# Reinforced concrete degradation

Two (correlated) factors of concrete degradation:

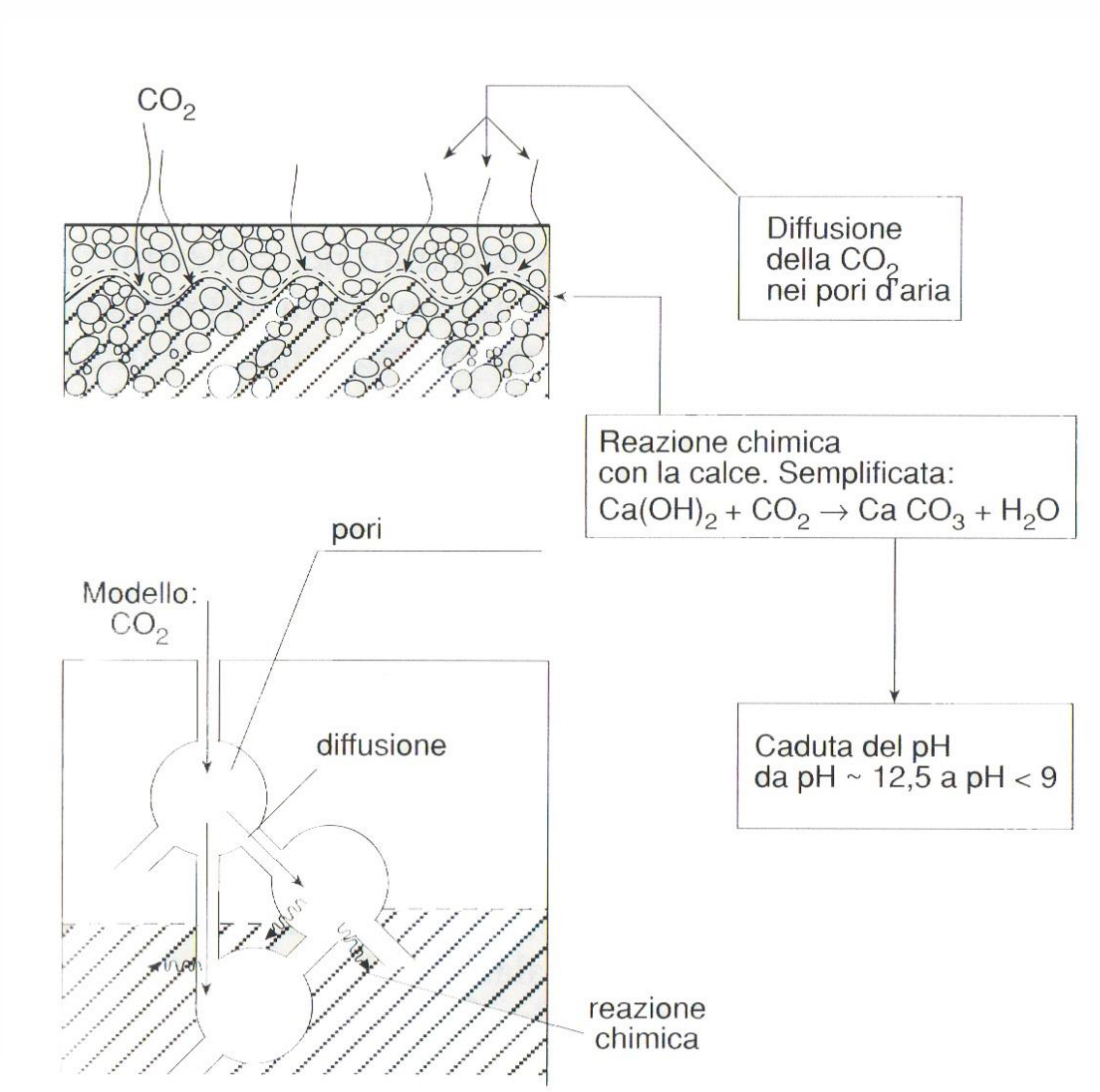
External factors (due to environmental effects)

✓ Chemical factors
✓ Physical factors
✓ Mechanical factors

Internal factors (due to concrete components and production/design procedures)

✓ Technological factors
✓ Design factors

# Chemical degradation: carbonation



Diffusione della $CO_2$ nei pori d'aria

Reazione chimica con la calce. Semplificata:
$Ca(OH)_2 + CO_2 \rightarrow Ca\,CO_3 + H_2O$

Caduta del pH da pH ~ 12,5 a pH < 9

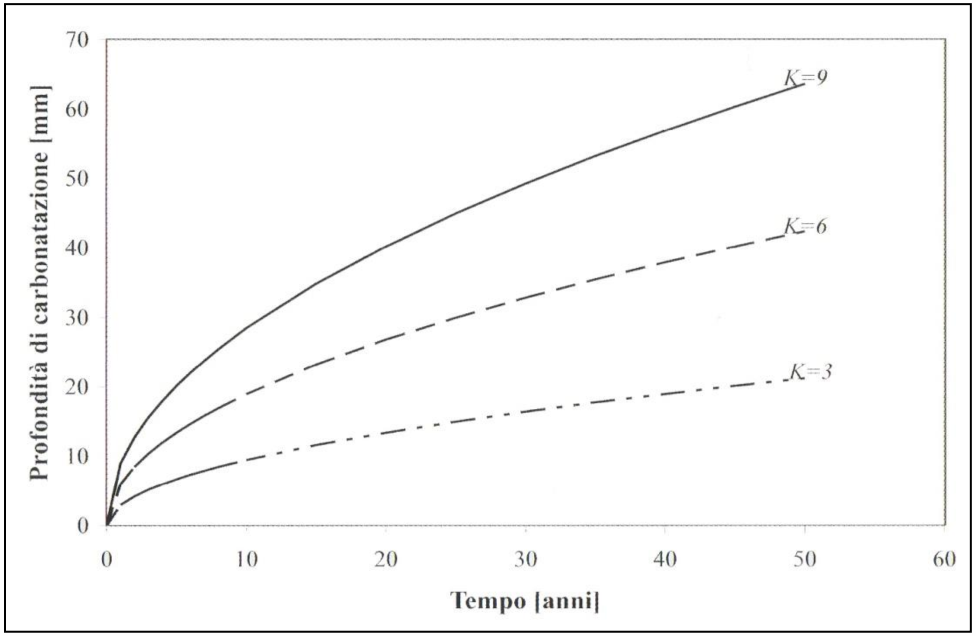
# Chemical degradation: carbonation

Carbonation speed:

$$s = K\sqrt{t}$$

K related to:

- Relative humidity;
- $CO_2$ concentration;
- Temperature;
- Concrete alkalinity;
- Water/cement ratio;
- Casting and curing procedure.



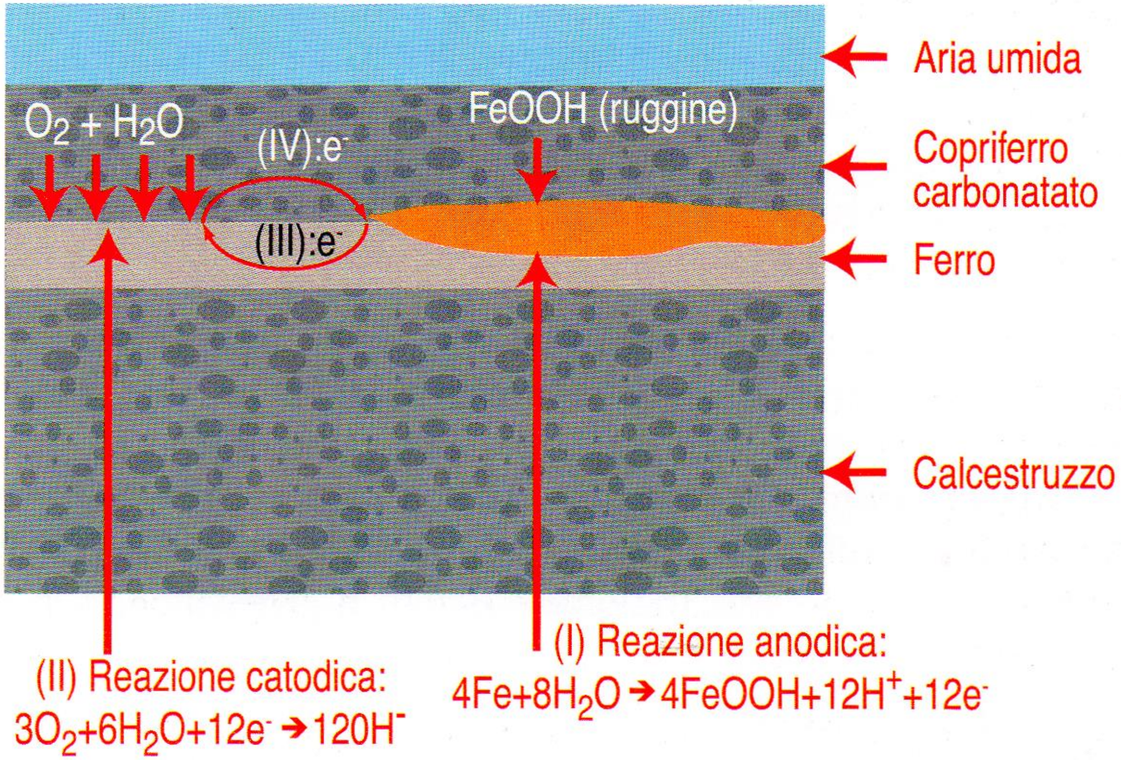
Movement of carbonation front (Pucinotti, 2005)

# Chemical degradation: carbonation

Carbonation front > concrete cover

Neutralization of rebars alkaline passivating layer

Oxidation and corrosion of rebars (anode/cathode reaction)



Rebars oxidation (Collepardi, 2005)

# Chemical degradation: carbonation

Further effect: collapse of concrete cover due to tensional states

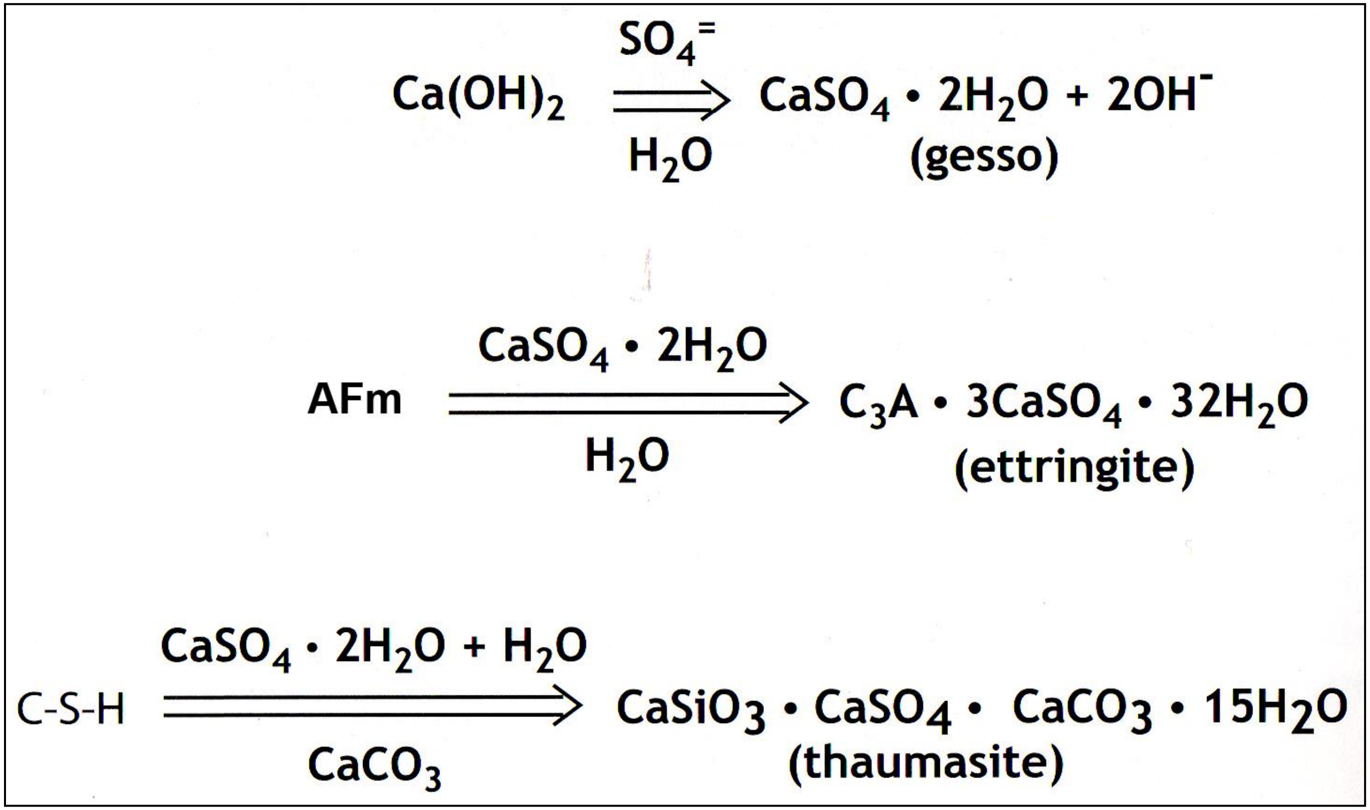
Lido di Venezia, complesso Ex Tiro al Volo

# Chemical degradation: sulphate attack

- Due to the interaction between $SO_4^{2-}$ ions and hydration products within the cement matrix;
- Sulphate ions coming from the external environment: ESA (external sulphate attack). Sulphates found in marine water, coastal aerosols, air polluted by industrial gases, mainly oil refineries (extraction of sulphates from petroleum);
- Sulphate ions present within concrete: ISA (internal sulphate attack). In form of gypsum contaminating the aggregate fraction or formed after thermal decomposition of primary ettringite during steam curing;
- Secondary phases formed after sulphate attack: gypsum (from CH), secondary ettringite (from AFm), thaumasite (from C-S-H);
- Formation favored in humid, cold and $CO_2$-rich environments.

# Chemical degradation: sulphate attack

Reactions of formation of secondary sulphate phases



$$\mathrm{Ca(OH)_2} \xrightarrow[\mathrm{H_2O}]{\mathrm{SO_4^{=}}} \mathrm{CaSO_4 \cdot 2H_2O + 2OH^-}$$

(gesso)

$$\mathrm{AFm} \xrightarrow[\mathrm{H_2O}]{\mathrm{CaSO_4 \cdot 2H_2O}} \mathrm{C_3A \cdot 3CaSO_4 \cdot 32H_2O}$$

(ettringite)

$$\mathrm{C\text{-}S\text{-}H} \xrightarrow[\mathrm{CaCO_3}]{\mathrm{CaSO_4 \cdot 2H_2O + H_2O}} \mathrm{CaSiO_3 \cdot CaSO_4 \cdot CaCO_3 \cdot 15H_2O}$$

(thaumasite)

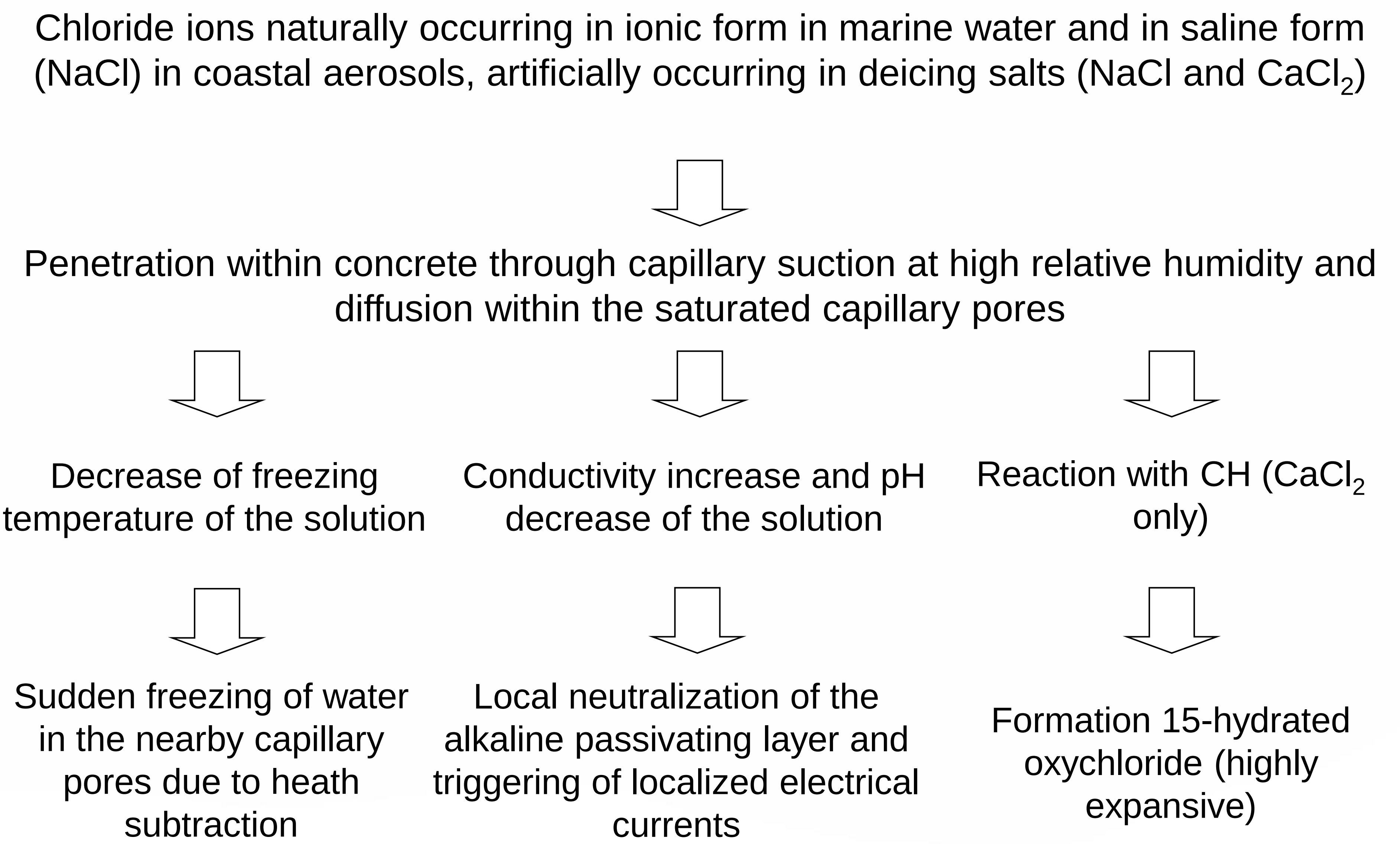
Highly expansive hydrous phases!

# Chemical degradation: sulphate attack

## Effects:

- Expansive processes in the concrete cortical layer causing detachments from the internal umperturbed nucleus.
- Dissolution of C-S-H phases responsible for the mechanical properties of concrete (thaumasite).

# Chemical degradation: chloride attack



Chloride ions naturally occurring in ionic form in marine water and in saline form (NaCl) in coastal aerosols, artificially occurring in deicing salts (NaCl and $CaCl_2$)

Penetration within concrete through capillary suction at high relative humidity and diffusion within the saturated capillary pores

Decrease of freezing temperature of the solution

Sudden freezing of water in the nearby capillary pores due to heath subtraction

Conductivity increase and pH decrease of the solution

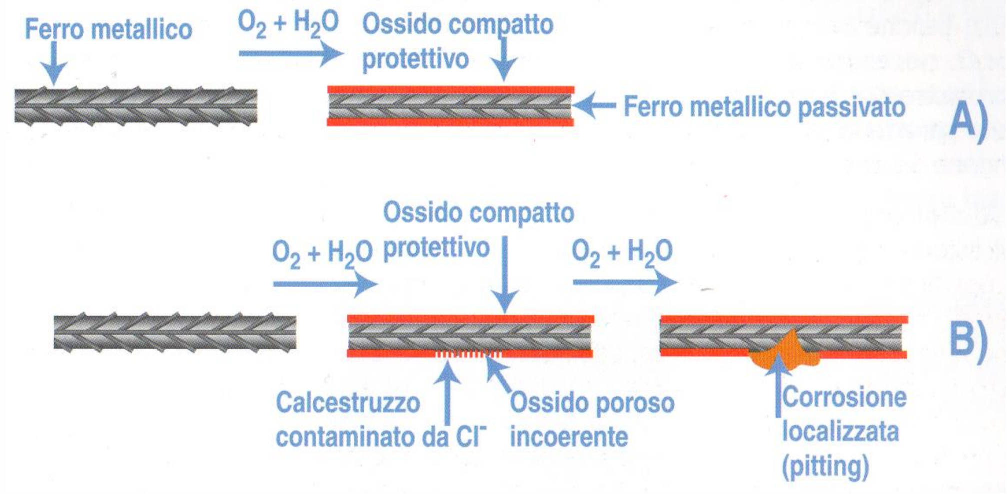
Local neutralization of the alkaline passivating layer and triggering of localized electrical currents

Reaction with CH ($CaCl_2$ only)

Formation 15-hydrated oxychloride (highly expansive)

# Chemical degradation: chloride attack

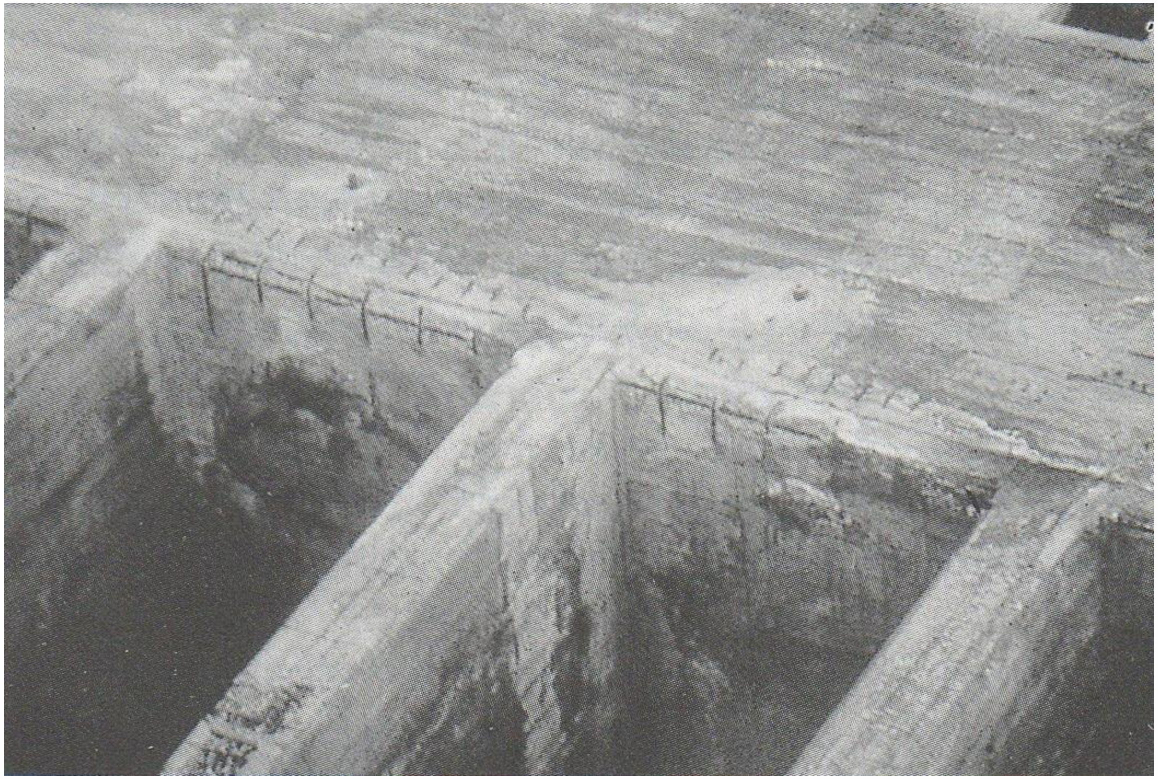
Effects on the rebars: pitting corrosion



Chloride corrosion dynamics (Collepardi, 2005)

# Chemical degradation: chloride attack

Effects on concrete: cracking, delamination and pulverization due to expansive processes induced by rebars corrosion, higher incidence of freeze-thaw phenomena, formation of expansive oxychloride



Calcium chloride-induced degradation (Siviero, 1995)

# Chemical degradation: soluble salts attack

High concentration of sulphates and alkaline ions in concrete pore solution (alkaline ions due to leaching of aggregate and cement)

⇩

High R.H. levels: penetration and diffusion of the saturated solutions within concrete capillary pores

⇩

R.H. decrease in the external portions of concrete: water evaporation and crystallization of soluble alkaline sulphates (sodium sulphates thenardite, mirabilite, eugsterite)

⇩

Detachment of concrete portions due to tensional states related to crystallization pressure and volume increase

# Chemical degradation: alkali/aggregate reactions

High concentrations of alkaline ions in pore solution
(from leaching of aggregate and cement or from the external environment)

↓

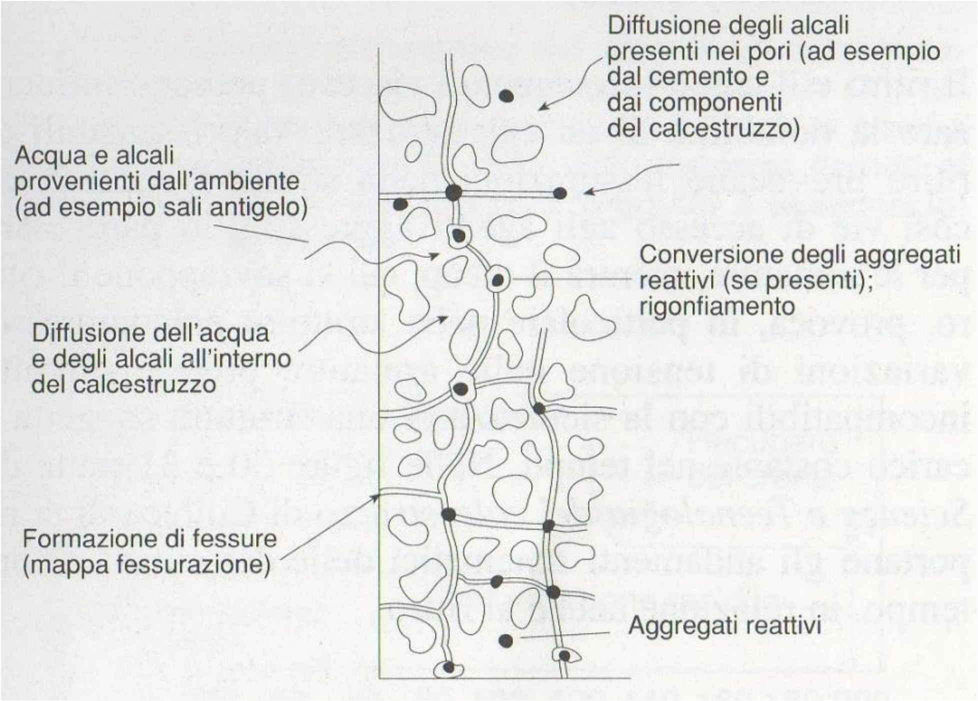
Hot and humid environments: alkali/aggregate reactions with soluble silicates from the dissolution of glassy matrices of reactive aggregates (chert, opal, chalcedony)

↓

Formation of highly expansive alkaline hydrous silicate gels

↓

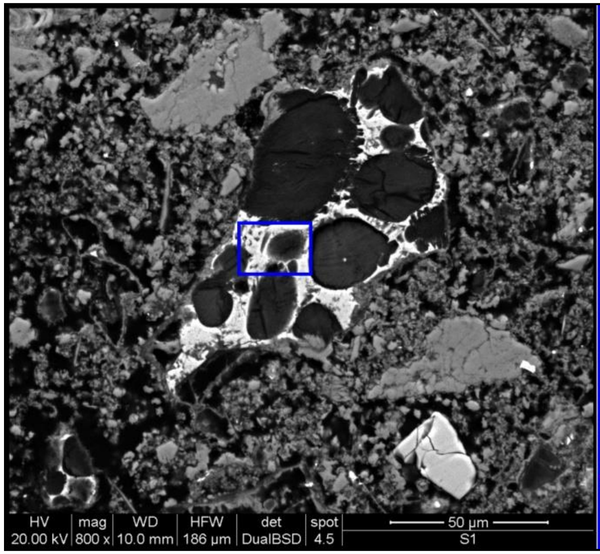
Diffuse and dendritic cracks and localized expulsions of cementitious material

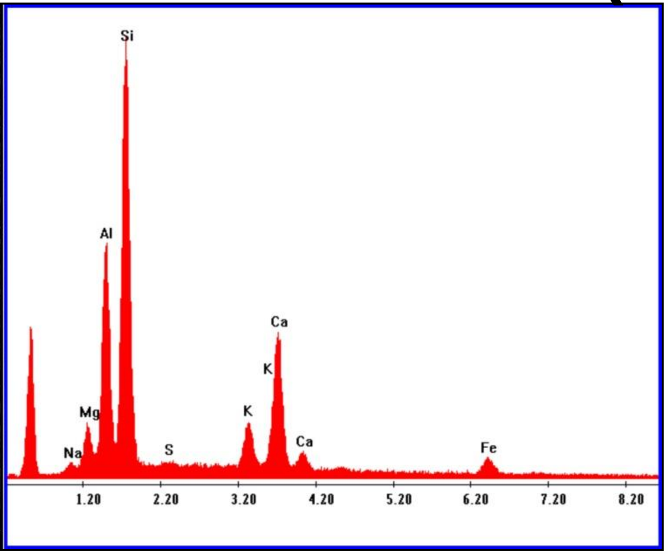


Alkali-aggregate reactions dynamics (Siviero, 1995)

# Chemical degradation: alkali/aggregate reactions

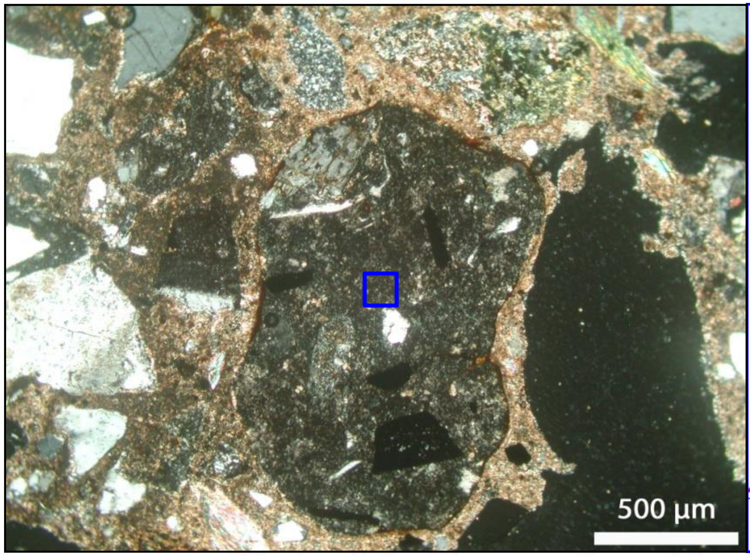
## Monumento alla Vittoria (Bolzano)

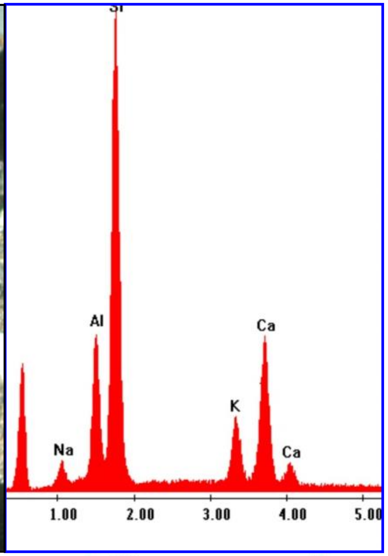




**Alkalis Source 1**
**cement**

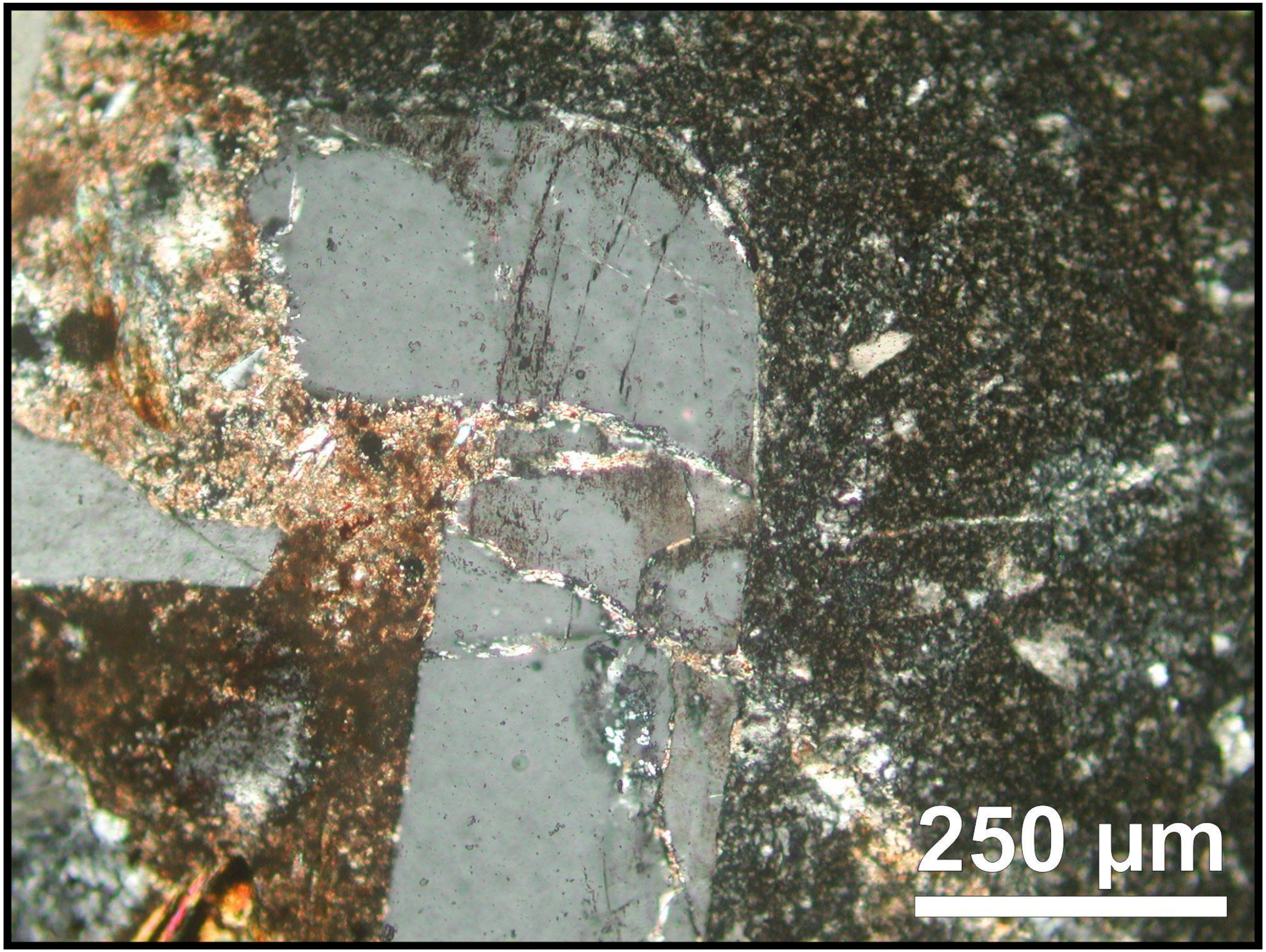
**Alkalis Source 2**
**ingnimbrites**





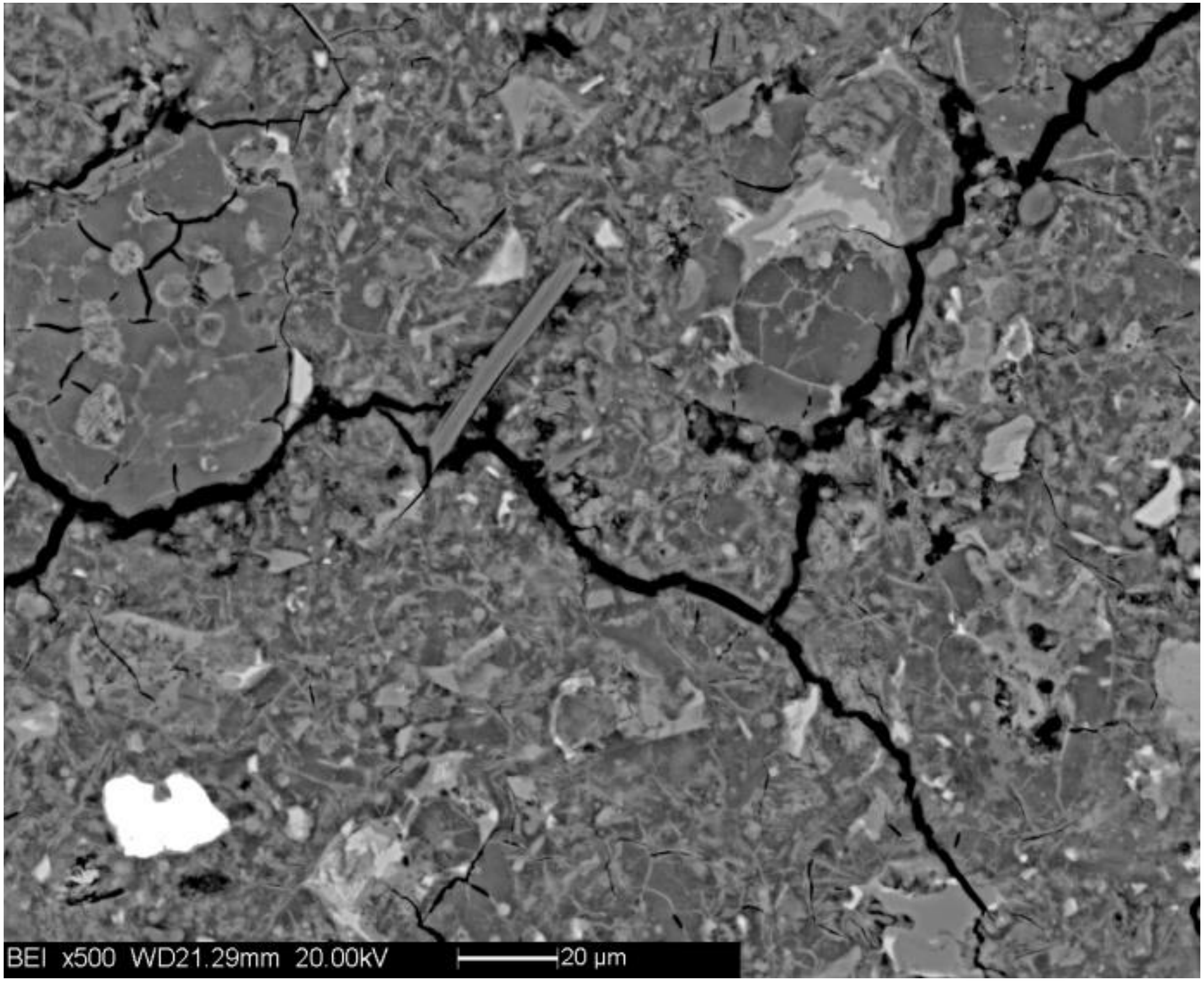
# Chemical degradation: alkali/aggregate reactions

## Monumento alla Vittoria (Bolzano)



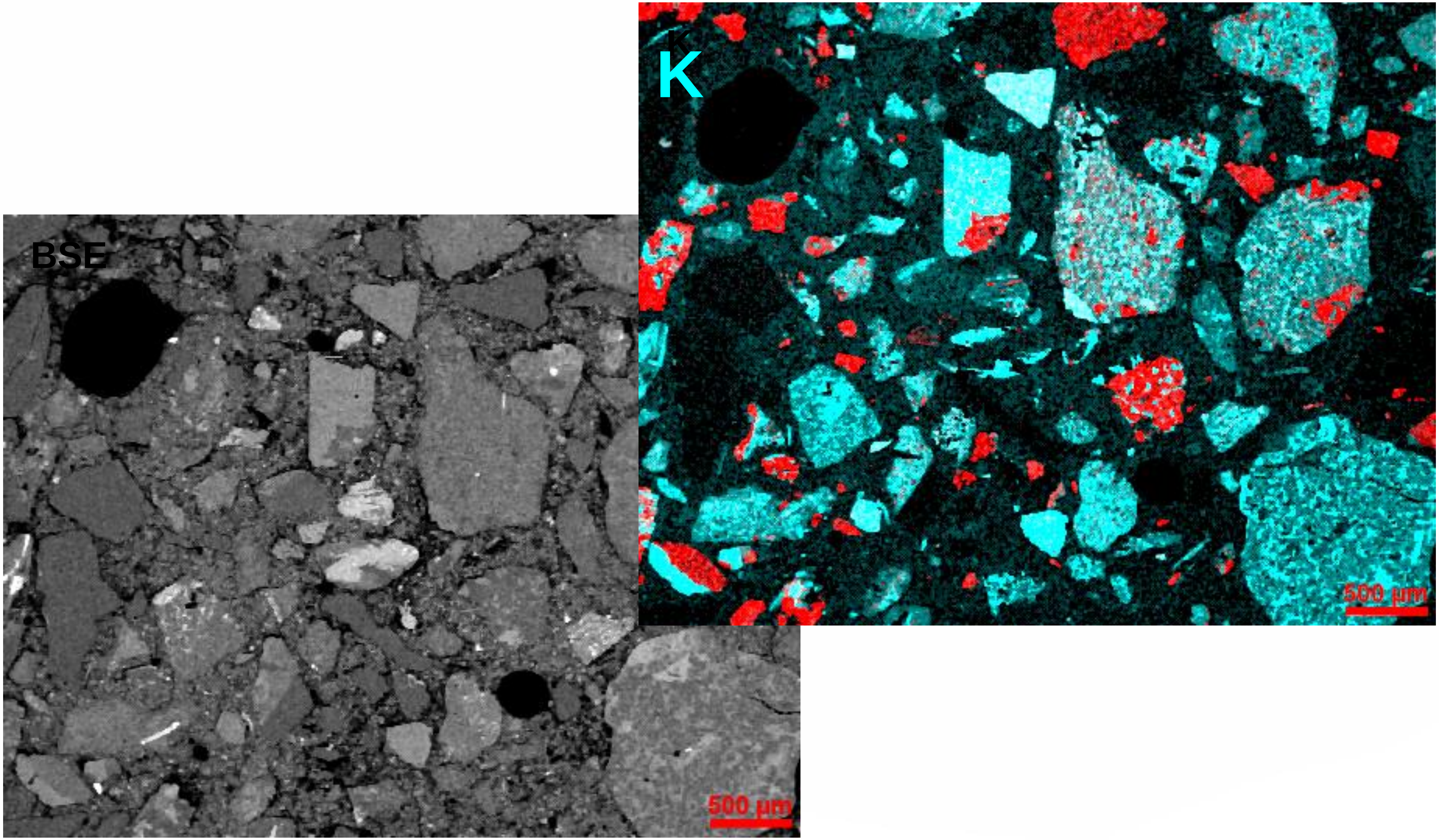
# Chemical degradation: alkali/aggregate reactions

## Monumento alla Vittoria (Bolzano)



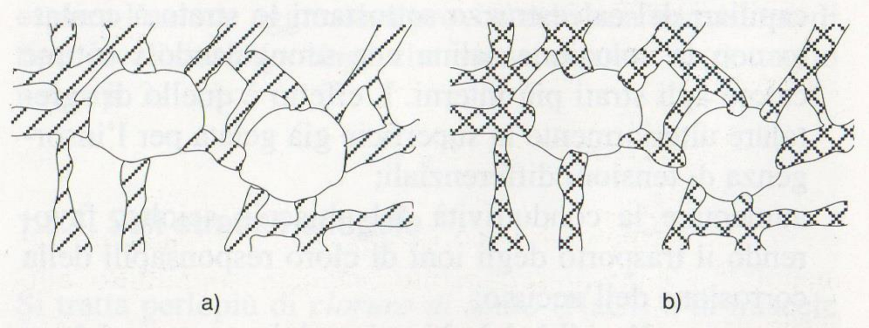
# Chemical degradation: alkali/aggregate reactions

## Monumento alla Vittoria (Bolzano)



# Physical degradation: freeze/thaw cycles

- Temperatures lower than 0°C: freezing of water saturating concrete capillary pores.
- Volume increase (ca 9%) due to the change of state.
- Increase of hydraulic pressure of the liquid water.
- Excessive tensile stresses, concrete damage starts.
- Cyclic repetition of the effect: superficial cracking of the concrete elements, progressive disintegration.
- The effect may be limited by the presence of entrained air voids (absorption of the tensile stresses through ice expansion in the larger spherical voids).



Absorption of the tensional stresses by the air voids (Siviero, 1995)

# Physical degradation: fire

- 100-200°C: evaporation of water saturating concrete.
- 250°C: dehydration of the hydrated phases starts.
- 550°C: portalandite dehydroxilation, aggregate starts to deteriorate.

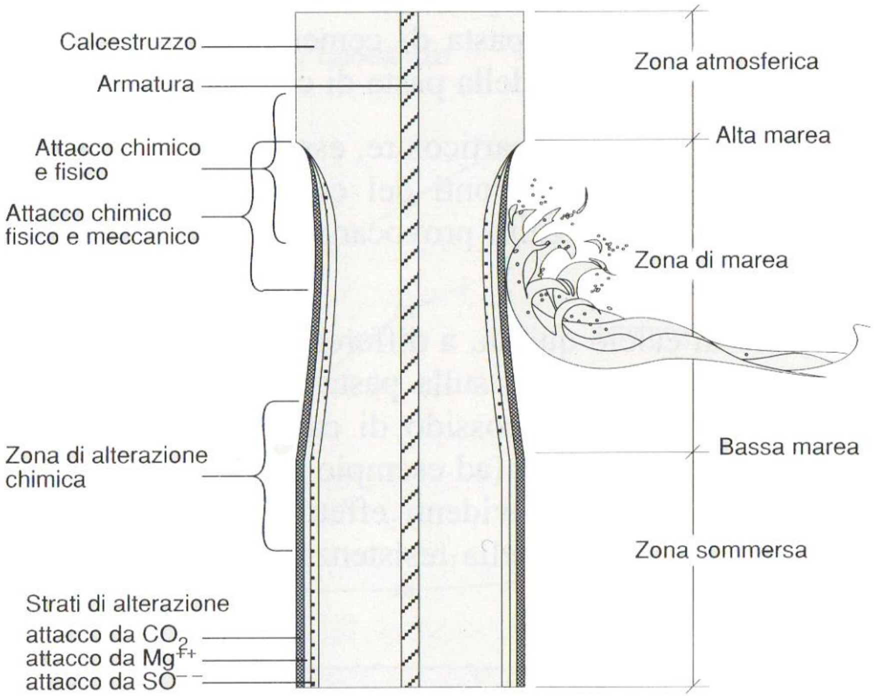
⇩

- Spalling (internal explosion of the aggregate).
- Cracking/delamination of concrete.
- Compressive strength reduction (-80% at 600°C).
- Reduction of tensile strength and elastic modulus of rebars.
- Development of further tensional states due to the higher thermal expansion coefficient of concrete at high temperatures.

Damage by fire on a reinforced concrete building (Pucinotti, 2005)

# Physical degradation: abrasion, erosion

- Particularly relevant for marine structures under the dynamic action of waves and tides.
- Mechanical degradation associated to the chemical alteration of sulphates and chlorides dissolved in marine water.
- Abrasion resistance strictly correlated to the mechanical properties of the aggregate and to the adhesion between aggregate and cement paste.



Degradation of concrete structures in marine environment (Siviero, 1995)

# Physical degradation: mechanical stresses

Development of impulsive energies (explosions, impacts, earthquakes) and their action on the structural elements

Microcracking

Relevant degenerative phenomena (macrocraking, partial collapse)

Full structural collapse

L’Aquila: seismic effect on the Duca degli Abruzzi hotel

# Technological degradation

## Poor mix design

Common in historical structures (no mix design)

Wrong W/C ratio (excess/defect of water)
Wrong C/A ratio (cement under-overdosage)
Wrong granulometric distribution of the aggregate (unbalanced ratios between fine and coarse aggregate)

⇩

Poor concrete coherence
Inhomogeneity/segregation of the components (gravel nests)
Development of excessive porosity (voids)

⇩

Poor mechanical properties, triggering of external degradation phenomena

# Technological degradation

## Poor mix design

Padova castle, second floor slab

Schio civic theatre, slab

# Technological degradation

## Reduced thickness of concrete cover

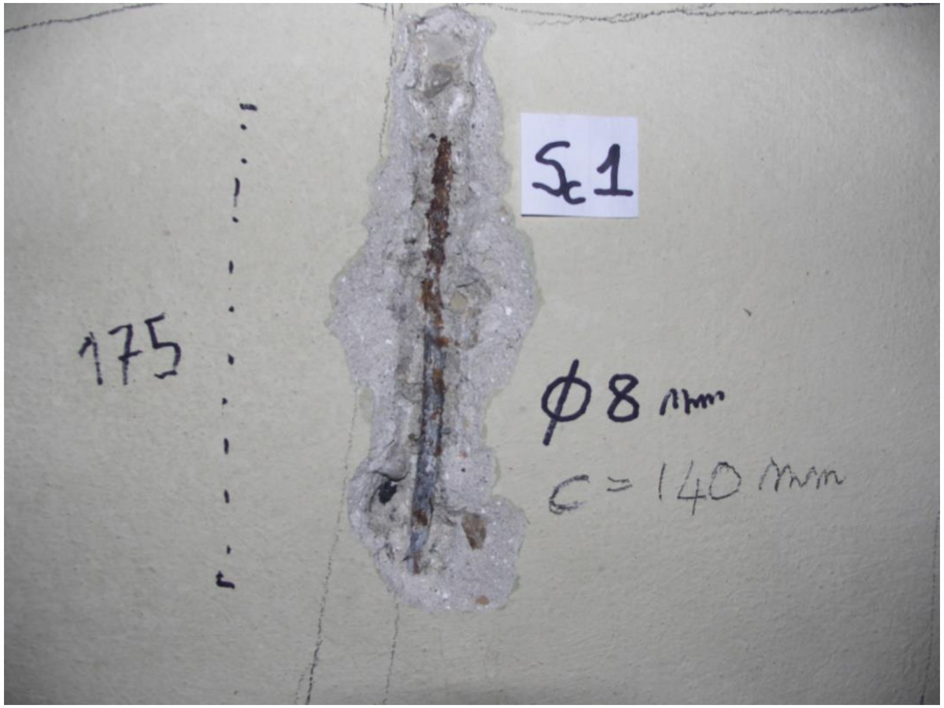
Oxidation and corrosion of rebars (concrete carbonation)

↓

Development of tensile stresses

↓

Cracking and disgregation of concrete



Schio civic theatre, slab

# Technological degradation

## Bad casting procedures

Lack of concrete vibration (historical structures)
Incorrect vibration
Casting from excessive heights (accumulation of coarse aggregate in the lower part)

⇩

Poor concrete coherence
Inhomogeneity/segregation of the components (gravel nests, sand accumulation)
Development of excessive porosity (voids)

⇩

Poor mechanical properties, triggering of external degradation phenomena

# Technological degradation

## Bad casting procedures

Castello di Padova, first floor slab

# Technological degradation

## Incorrect curing

Poor wetting of the fresh conglomerate
Excessive exposure to air (water evaporation)
Premature removal of the formworks

Cracks development

Poor mechanical properties, triggering of external degradation phenomena

# Design degradation

## Lack of or inadequate structural calculations

Proportioning of structural elements according to obsolete construction practices
Increase of overloads due to changes of use or consolidation/improvement interventions

⇩

Uncontrolled increase of the tensional and deformative state of the structural elements
Redistribution of stresses not foreseen by the original design

⇩

Cracking, failure, collapse

# THANK YOU FOR YOUR ATTENTION!