Building Materials

Lecture 6

Building materials

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Other properties

Building materials

Radioactivity

- natural radioactivity of materials

Periodic Table of the Radioactive Elements

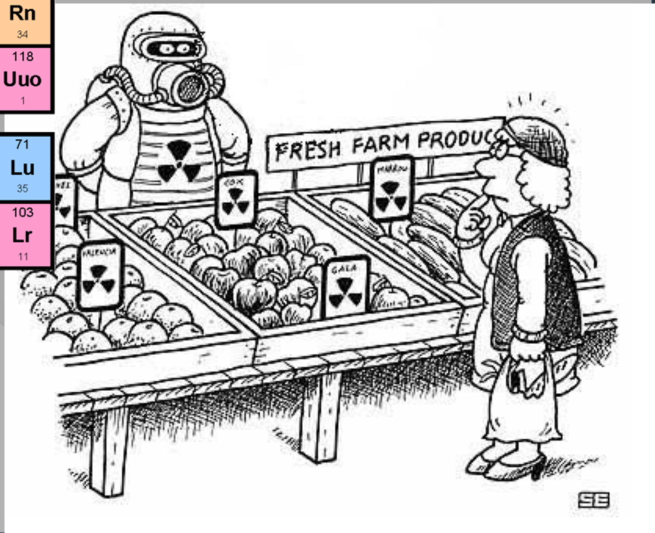
http://chemistry.about.com
©2011 Todd Helmenstine
About Chemistry

Atomic Number / Symbol / # of Isotopes

Half-life of Most Stable Isotope:
- Stable
- $h_{1/2} > 10^6$ years
- 10^3 yrs < $h_{1/2}$ < 10^6 yrs
- 1 yr < $h_{1/2}$ < 10^3 yrs
- 1 day < $h_{1/2}$ < 10^3 yrs
- $h_{1/2}$ < 1 day
- unknown

1A	2A	3B	4B	5B	6B	7B	8B	8B	8B	1B	2B	3A	4A	5A	6A	7A	8A
1 H 6																	2 He 8
3 Li 8	4 Be 10											5 B 11	6 C 13	7 N 14	8 O 14	9 F 16	10 Ne 19
11 Na 18	12 Mg 21											13 Al 22	14 Si 23	15 P 22	16 S 21	17 Cl 22	18 Ar 22
19 K 23	20 Ca 23	21 Sc 20	22 Ti 24	23 V 23	24 Cr 25	25 Mn 25	26 Fe 28	27 Co 26	28 Ni 31	29 Cu 28	30 Zn 30	31 Ga 27	32 Ge 28	33 As 29	34 Se 29	35 Br 29	36 Kr 31
37 Rb 29	38 Sr 33	39 Y 33	40 Zr 32	41 Nb 33	42 Mo 33	43 Tc 33	44 Ru 33	45 Rh 34	46 Pd 33	47 Ag 38	48 Cd 36	49 In 38	50 Sn 38	51 Sb 36	52 Te 37	53 I 36	54 Xe 38
55 Cs 40	56 Ba 39	57-71 Lanthanides	72 Hf 35	73 Ta 34	74 W 33	75 Re 35	76 Os 35	77 Ir 36	78 Pt 37	79 Au 36	80 Hg 38	81 Tl 32	82 Pb 33	83 Bi 35	84 Po 33	85 At 33	86 Rn 34
87 Fr 34	88 Ra 33	89-103 Actinides	104 Rf 13	105 Db 12	106 Sg 10	107 Bh 10	108 Hs 8	109 Mt 6	110 Ds 7	111 Rg 5	112 Cn 4	113 Uut 4	114 Uuq 4	115 Uup 2	116 Uuh 6	117 Uus unknown	118 Uuo 1

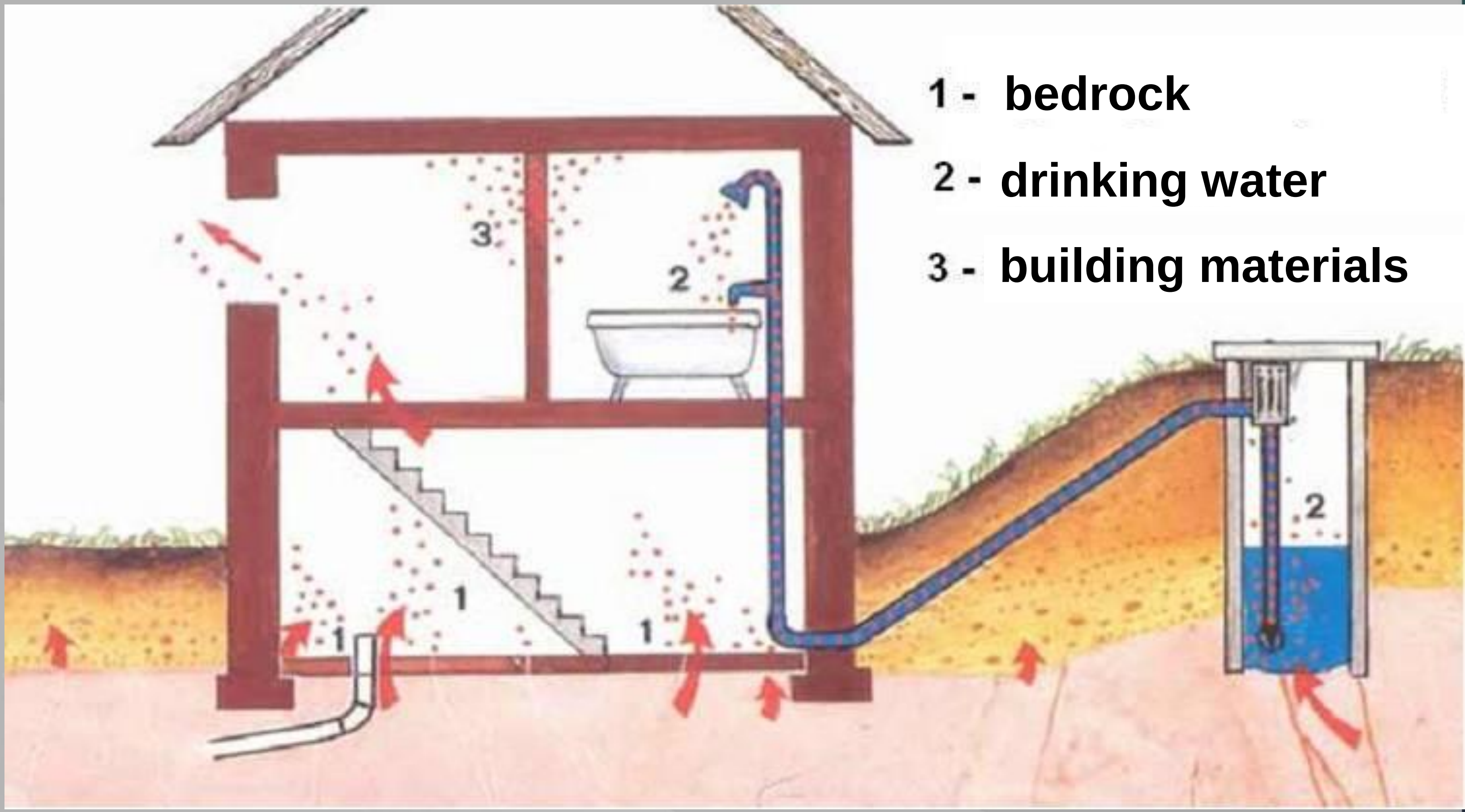
Lanthanides	57 La 34	58 Ce 35	59 Pr 33	60 Nd 34	61 Pm 31	62 Sm 33	63 Eu 33	64 Gd 32	65 Tb 31	66 Dy 31	67 Ho 33	68 Er 32	69 Tm 31	70 Yb 32	71 Lu 35
Actinides	89 Ac 29	90 Th 30	91 Pa 28	92 U 24	93 Np 20	94 Pu 20	95 Am 17	96 Cm 20	97 Bk 14	98 Cf 20	99 Es 17	100 Fm 18	101 Md 16	102 No 12	103 Lr 11



- **^{40}K, ^{226}Ra, ^{228}Th**

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Sources of radioactivity in the building



Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Radioactive materials

Radioactive could be (but not necessary!) e.g.:

- **aggregate from uranium ores**
- **blast–furnace slag**
- **cinder**
- **coal fly ash**
- **phosphogypsum**

Asbestos is not radioactive !

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Radioactivity of building materials

- ^{226}**Ra mass activity concentration** [Bq.kg^{-1}]
- **activity concentration index I** [unitless]

$$I = \frac{a_K}{3000} + \frac{a_{Ra}}{300} + \frac{a_{Th}}{200}$$

where a_K, a_{Ra} , a_{Th} are radium, thorium and potassium activity concentrations in material

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Activity concentration

Activity concentration range (Bq/kg) of common building materials.

Building material	^{226}Ra [Bq/kg]	^{232}Th [Bq/kg]	^{40}K [Bq/kg]
Concrete	18 - 67	3 - 43	16 - 1100
Light weight concrete	10 - 60	6 - 66	51 - 870
Bricks	7 - 140	8 - 127	227 - 1140
Gypsum	1 - 67	0.5 - 190	22 - 804
Cement	13 - 107	7 - 62	48 - 564

Activity concentration range (Bq/kg) of selected covering building materials.

Building material	^{226}Ra [Bq/kg]	^{232}Th [Bq/kg]	^{40}K [Bq/kg]
Ceramics	25 - 193	29 - 66	320 - 1049
Granite	ND - 160	ND - 354	24 - 2355
Tiles	33 - 61	45 - 66	476 - 788
Marble	1 - 63	0.4 - 142	9 - 986

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Radioactivity of building materials

- most countries with reference levels for radioactive elements in building materials apply activity indices or maximum permissible/recommended concentrations
- some countries - one reference level for Ra^{226}
- other countries – level for each Ra^{226}, Th^{232} and K^{40}
- in most of the countries the levels are enforced, only in Norway are the reference levels advisory

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Reference Levels for Radioactive Elements in Building Materials

Czech Republic:

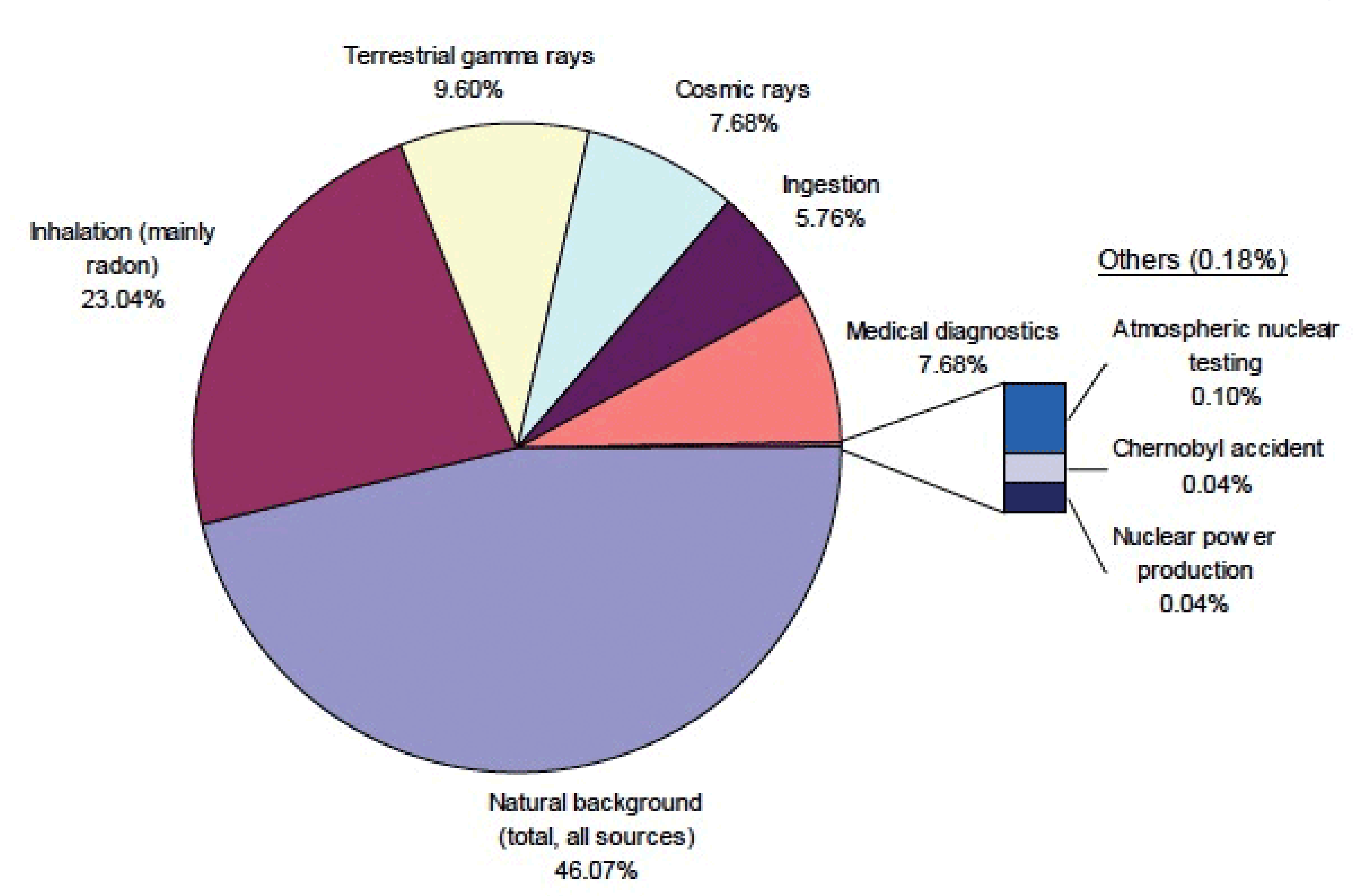
- **enforced level**: **150-200 Bq/kg** - materials in buildings where people could stay more than 1000 h/year (depending on the type of material); 1000 Bq/kg for materials in other buildings.
- **advisory level**: **80-120 Bq/kg** in buildings where people normally stay more than 1000 h/year; 300-500 Bq/kg for materials in other buildings

Reference Levels for Radioactive Elements in Building Materials

I	Type of building material	Example
0,5	materials used in bulk amount	bricks, cement, concrete, gypsum
1	raw materials	aggregates, stones, clay
2	materials used in „small“ amount	ceramic tiles

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Doses from radiation sources



Department of Materials Engineering
and Chemistry
Faculty of Civil Engineering

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Radon

- colorless, odorless, tasteless gas
- radioactive product of decay uranium or thorium
- half-life 3,8 days → **radon daughters** (solids Po, Pb, Bi) stick to surfaces such as dust particles in the air
- if contaminated dust is inhaled, these particles can stick to the airways of the lung and increase the risk of developing lung cancer

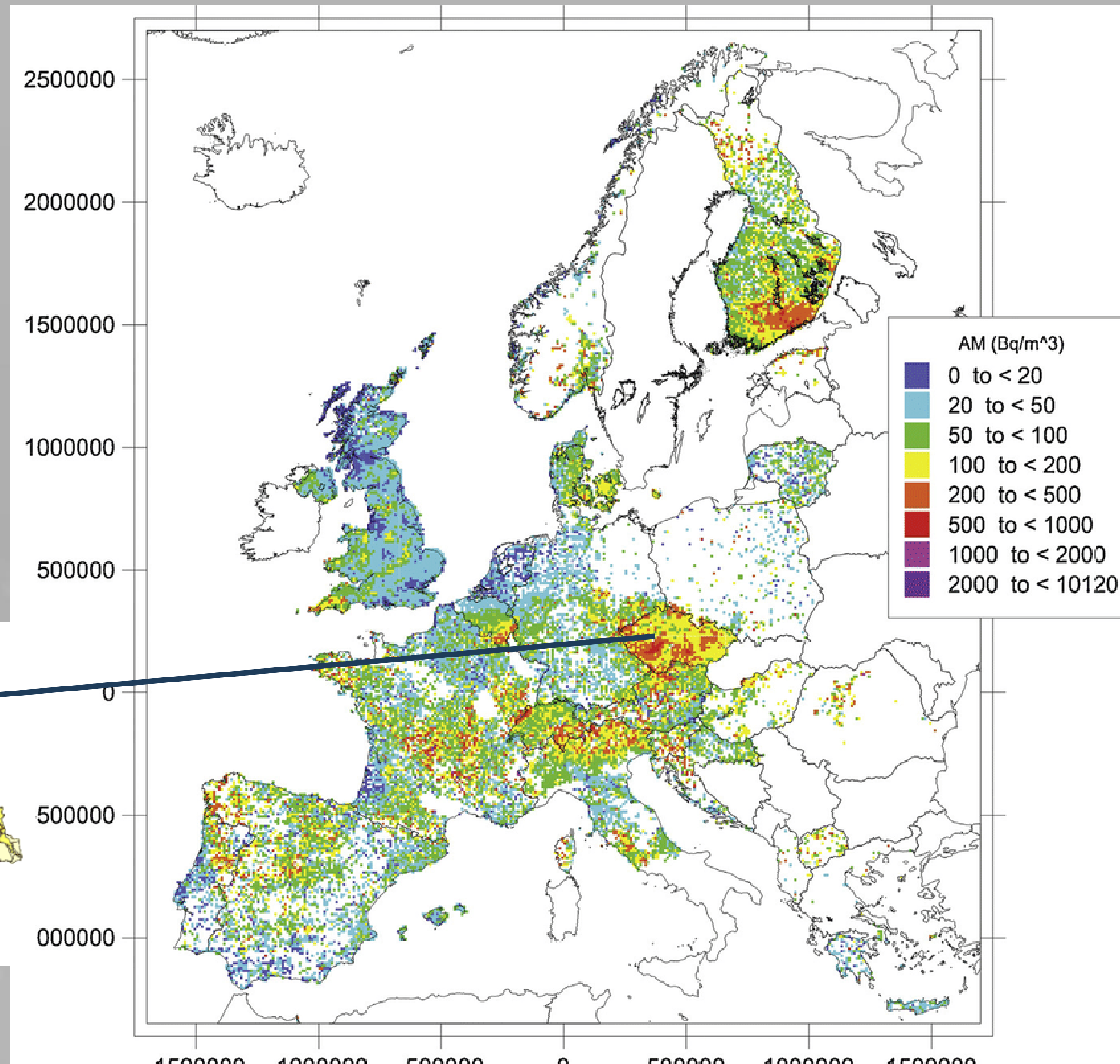
Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

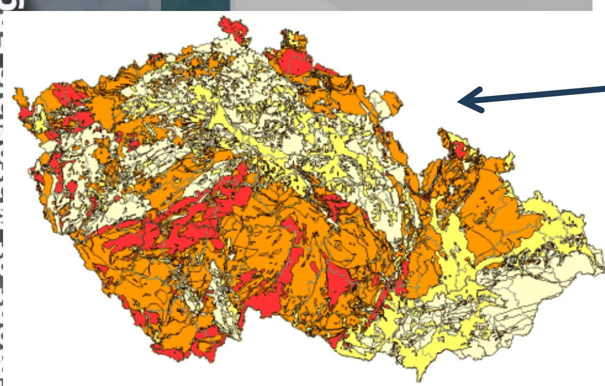
Radon in houses

- Cracks in solid floors
- Construction joints
- Cracks in walls
- Gaps in suspended floors
- Gaps around service pipes
- Cavities inside walls
- The water supply

Radon map

Europe

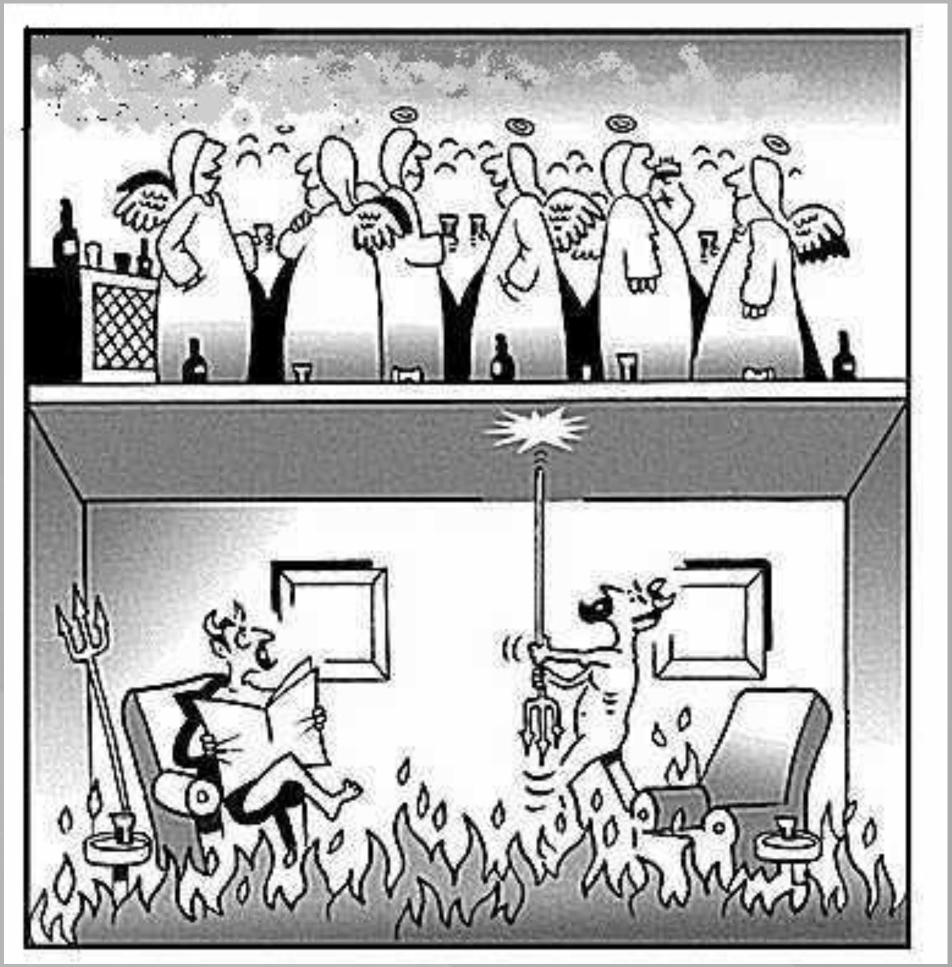




Czechia

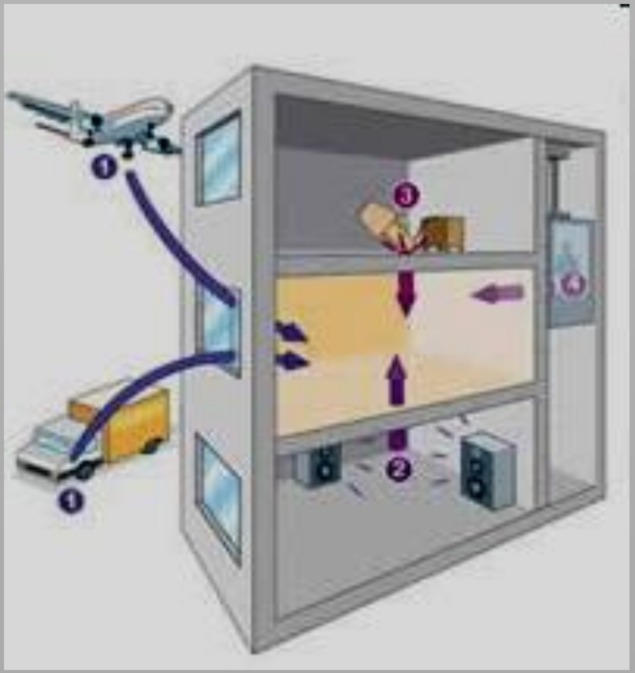
Department of Materials Engineering and Ch
Faculty

Acoustic properties



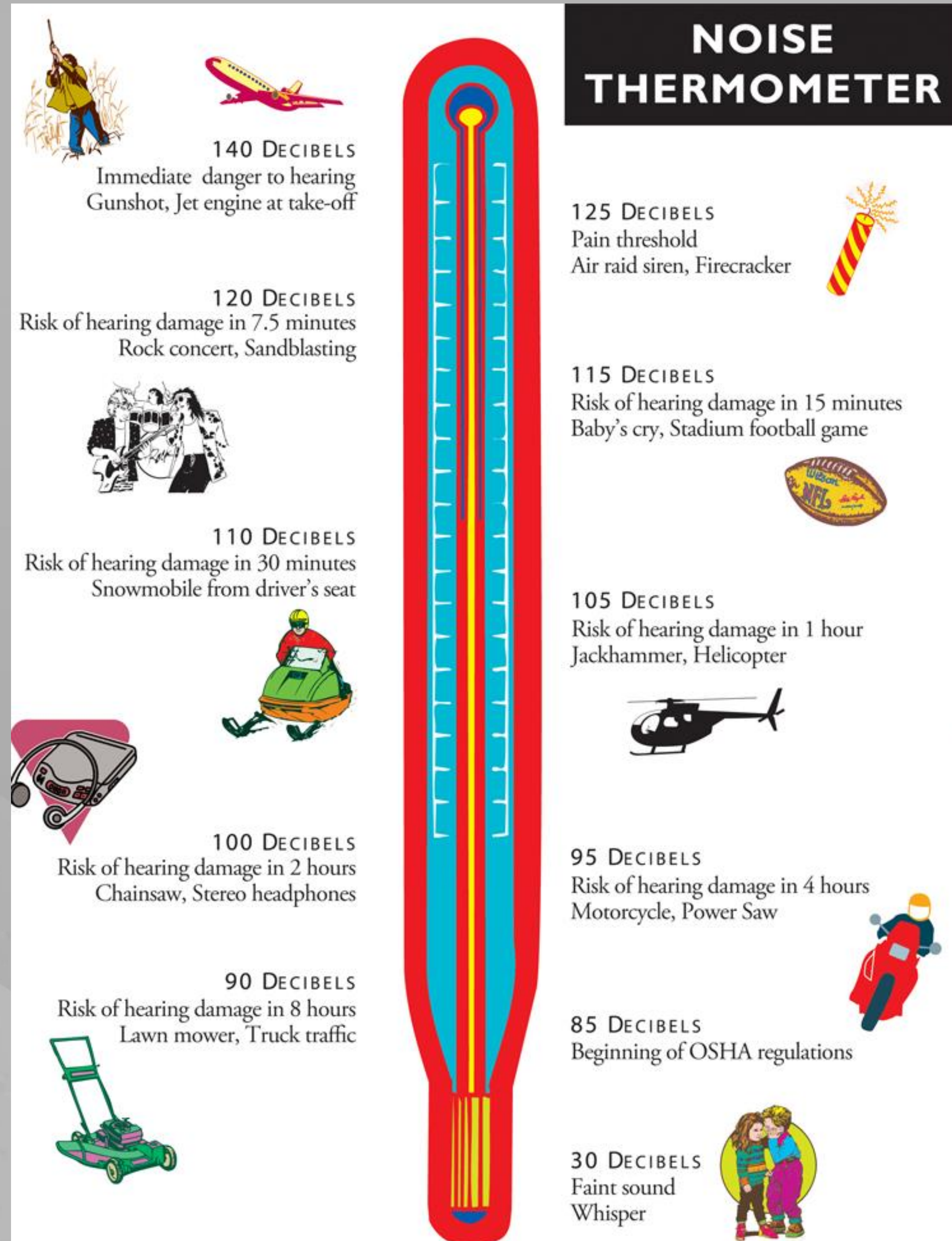
Noise sources

- **Outside air-borne noises**: road, rail or air traffic
- **Inside air-borne noises**: conversations, hi-fi, TV...
- **Impact**: movement of people or furniture, falling objects...
- **Equipment noises**: lift, taps, mechanical ventilation, heating or air conditioning installation.



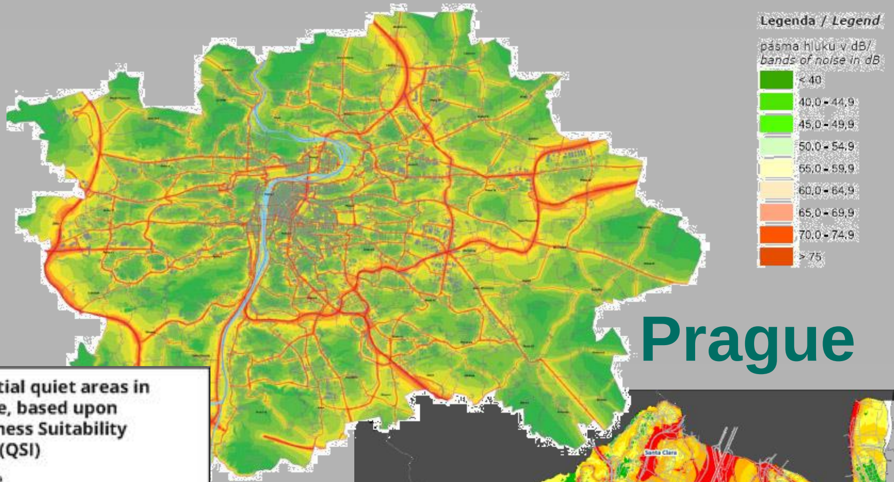
Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Noise level

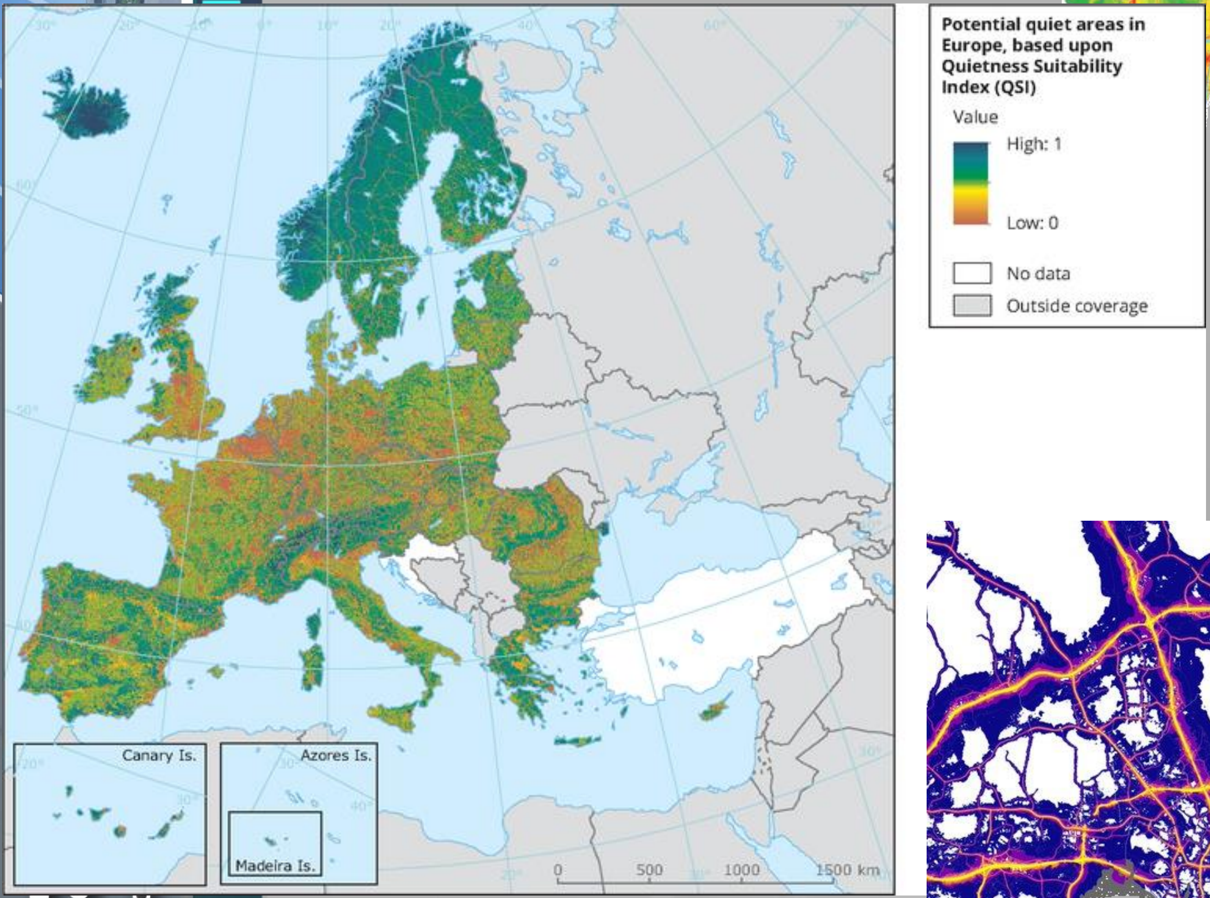


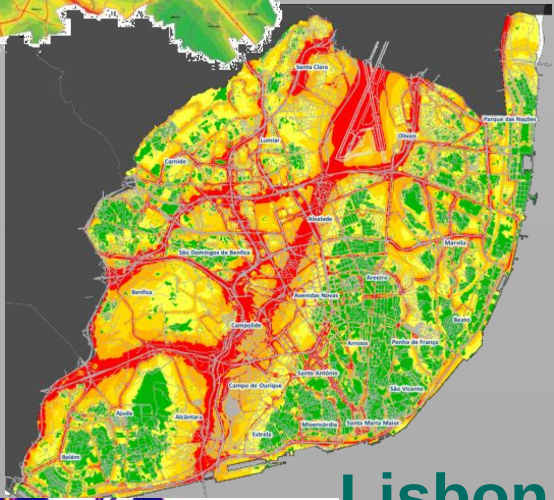
Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Noise maps

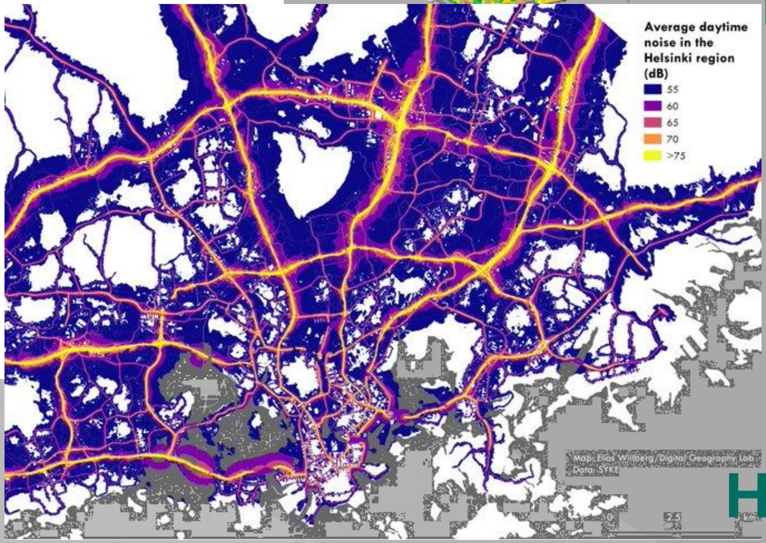


Prague





Lisbon

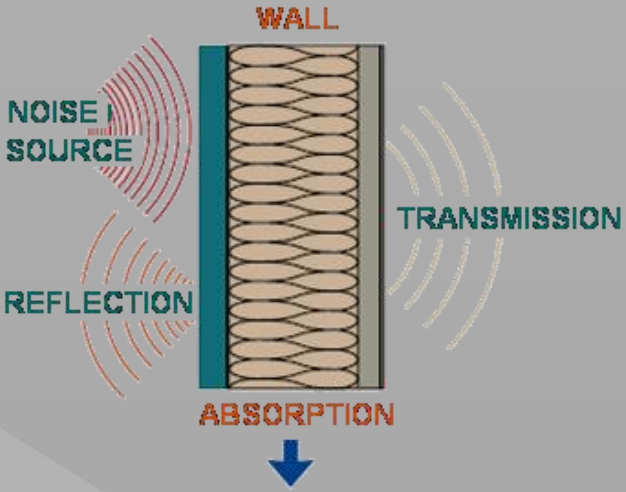


Helsinki

Basic acoustic parameters

Acoustic absorptivity

- **sound energy is reduced when sound waves pass through a medium or strike a surface** - the incident sound that strikes a material is not reflected back



Reverberation

- **the collection of reflected sounds from the surfaces**

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Sound absorption coefficient

- how much of the sound is absorbed in the material

$$\alpha = \frac{I_a}{I_i}$$

I_a ….. sound intensity absorbed [W/m²]

I_i …. incident sound intensity [W/m²]

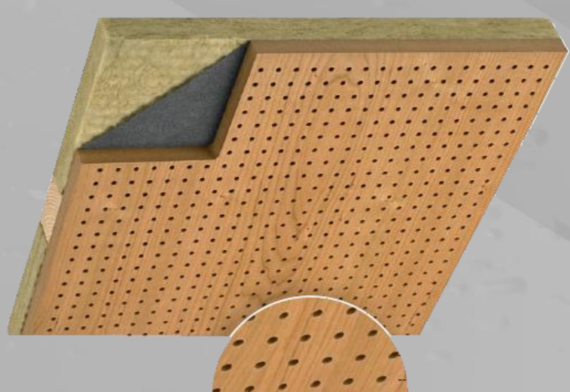
Material	α
Plaster walls	0.01 - 0.03
Unpainted brickwork	0.02 - 0.05
Painted brickwork	0.01 - 0.02
3 mm plywood panel	0.01 - 0.02
6 mm cork sheet	0.1 - 0.2
Hardwood	0.3
100 mm mineral wool	0.65
Persons, each	2.0 - 5.0

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Acoustic constructions

- against sound reflection – **materials with good sound absorptivity**
  - – soft, pliable, porous materials
- against sound transmission – **sound insulating materials**

  - materials with high surface density

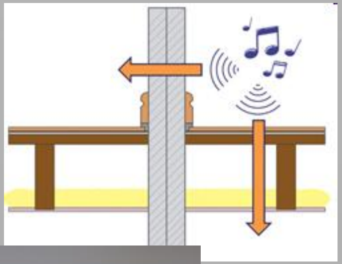


Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

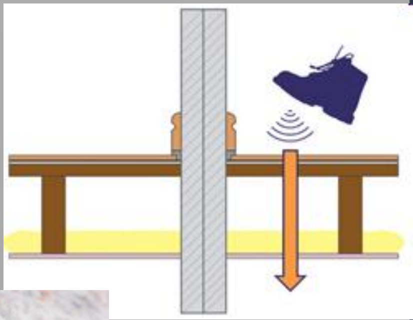
Noise insulation

Airborne noise (voices, music)



- materials with high surface density (mass per unit area) - min 350 kg.m^{-2}

Impact noise (feet, moving furniture, dropped items)



- padding or cushioning - soft, sound absorbing materials (carpets, mineral wool)

Soundproofing

= sound blocking

- reducing the sound pressure
- to stop sound from entering or leaving a space

Sound absorption

= acoustic enhancement

- to enhance the properties of sound by improving speech clarity and sound quality

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Acoustic comfort

- **good sound environment**
  - lower sound level
    - an acoustic ceiling with high absorption factor
  - reduced sound propagation
  - increased speech intelligibility
    - combination absorbers which enhance early reflections and minimize late reflections
  - appropriate reverberance
    - the room volume, the amount of absorbing material and the position of absorbers and reflectors

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Building materials

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Chemical properties

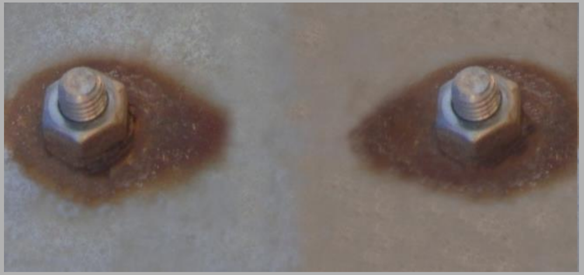
- **Chemical reactions in materials:**
  - **processing** (setting and hardening , foaming…)
  - **materials (in)compatibility**
  - **ageing**
  - **corrosion** (degradation) (inorganic materials, metals, biocorrosion…)

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Materials incompatibility

Metals:

- **galvanic corrosion** (dissimilar metal corrosion)
  - contact of two metals with different electrical potentials
- **aluminum** + **alkali** environment
- **copper** + **low pH** water, + **aggressive** soils
- **steel + gypsum**



Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Materials incompatibility

Plastics:

- **EPS + solvents** (in the paints)
- **PVC + formaldehydes**
- **phenolic foam** (acid pH) + steel

	ABS	ABS/PC	LCP	PA	PBT	PC	PC/PBT	PE	PEEK	PEI	PET	PMMA	POM	PP	PPO	PPS	PS	PVC	SAN
ABS	X	X										X					O	O	O
ABS/PC	X	X				X	O					O							
LCP			X																
PA				X															
PBT					X		O			O									
PC		X				X	O					X			O				
PC/PBT		O			O	O	X					O							
PE								X											
PEEK									X										
PEI					O					X									
PET											X								
PMMA	X	O				X	O					X							O
POM													X						
PP														X					
PPO						O									X		X		O
PPS																X			
PS	O														X		X		O
PVC	O																	X	
SAN	O											O			O		O		X

X COMPATIBLE O OCCASIONALLY

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Materials incompatibility

Cement, concrete:

- **cement + wood**
  - sugar content in the wood
- **concrete + glass fibers**
- **cement + some type of aggregates**
  - ASR - alkali-silica reaction

Corrosion

- the deterioration of a material due to interaction with its environment
- the disintegration of an engineered material into its constituent atoms due to chemical reactions with its surroundings
- **metals** – atmospheric corrosion
- **non-metal materials** -
  - ceramic
  - plastics
  - concrete
  - glass
  - biodegradation

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Corrosion of non-metal materials (degradation)

Ceramic

- refractory materials + wood combustion gases
- bricks + flue gases

Concrete

- decalcification (water without minerals)
- leaching
- sulphates
- bacteria

Biodegradation

Caused by:

– microorganism
– fungi
– insects
– birds
– plants
– rodents

Biodegradation is natural process!

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Biodegradation - examples

- **wood + fungi** (dry rot - Merulius Lacrymans)
- **wood + insects** (old house borer - Hylotrupes Bajulus)
- **nitrifying bacteria** on the **asbestos-cement** roofs
- **sulphur oxidizing bacteria** on **concrete**




Biodegradation - examples

- stone + lichen
- building + plants
- termites + thermal insulation

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Biodegradation - examples

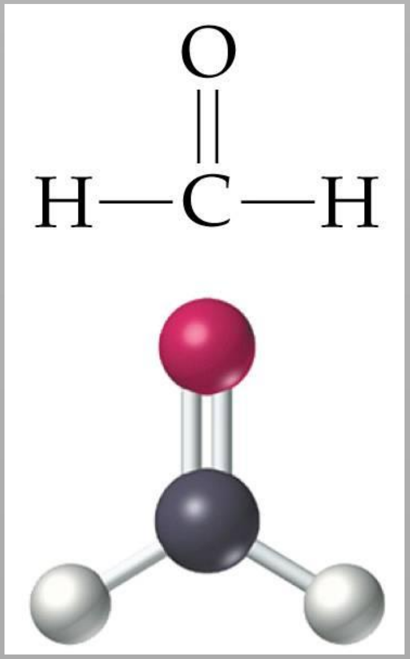
- insulated facade + woodpeckers

- rodents

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Hygienic properties

- pollutants in air (styrene, formaldehyde, plasticizers in PVC)
- contact with the skin (biocides, paints)
- respirable fibers (asbestos, glass)



The higher amount of pollutants can be caused by more accurate measuring methods, not in reality !

Environmental safety

- low energy consumption at production
- the renewable resources
- recycling possibility
- low liquidation costs

- PVC – bad recyclability, toxicity at incineration

Building materials
Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Durability of materials

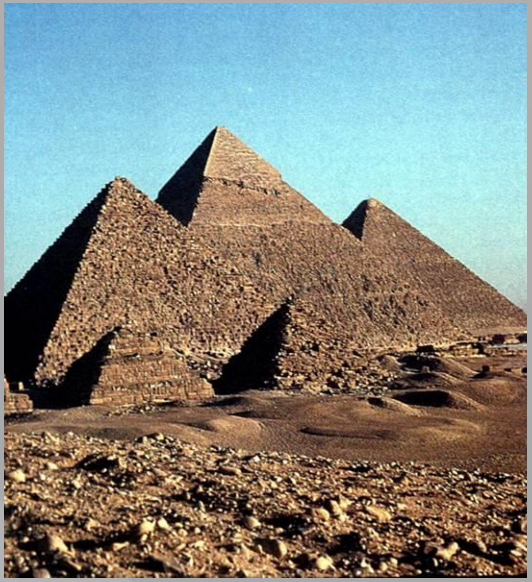
- ability to be used over a desired period

Factors affecting durability:

- **age**
- **maintenance**
- **high temperature**
- **UV radiation**
- **load**
- **chemical attacks**
- **weathering actions** (frost)

Life span of buildings

- **40 – 100** years – industrial buildings
- **50 – 100** y. - residential buildings
- **70 – 500** y. – bridges and monuments
- special causes: **2 – 5 millennia** – nuclear waste disposals



Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Building materials

Durability of some materials

Roofing

- Ceramic tiles 100 years
- Concrete tiles 100 years
- Steel sheets 50 years
- Asphalt shingle less than 50 years

Waterproof insulation

- asphalt felts 15 years
- modified bitumen membranes 100 years (exp.)
- rubber membrane 70 years
- PVC membrane 25 years

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Binders

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Binders

- materials, that binds other materials together

0 **processing** 1 **setting** 2 **hardening**

0 ..... activation (mixing water and binder)

1 ..... initial setting time

2 ..... final setting time

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Binders - terminology

Processing

- mixing, transport, placing

Setting

- change from liquid to solid phase

Initial setting time

- material begins to stiffen to such a degree that, although still soft, it becomes unworkable

Final setting time

- material may be regarded as a rigid solid

Hardening

- increase of strength

Binders

- in the building industry mostly inorganic

Non-hydraulic

(air binders)

- **need air to set**

Hydraulic

- **can set and harden in water**
- **water resistant**

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Hydraulic binders

- binders which set and harden by chemical reactions with water and continue to harden even if subsequently placed under water
- presence of **hydraulic oxides** is necessary: SiO_2, Al_2O_3, Fe_2O_3

Non-hydraulic binders:

- gypsum
- lime
- magnesia binder
- water glass

Hydraulic binders:

- hydraulic lime
- cement

Hydraulic modulus

$$HM = \frac{CaO}{SiO_2 + Al_2O_3 + Fe_2O_3}$$

- air (non-hydraulic) lime **$HM > 6$**
- hydraulic lime **$HM < 6$**
- portland cement **$HM < 2{,}5$**
- high alumina cement **$HM < 1{,}5$**

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Hydraulic binders

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Hydraulic binders

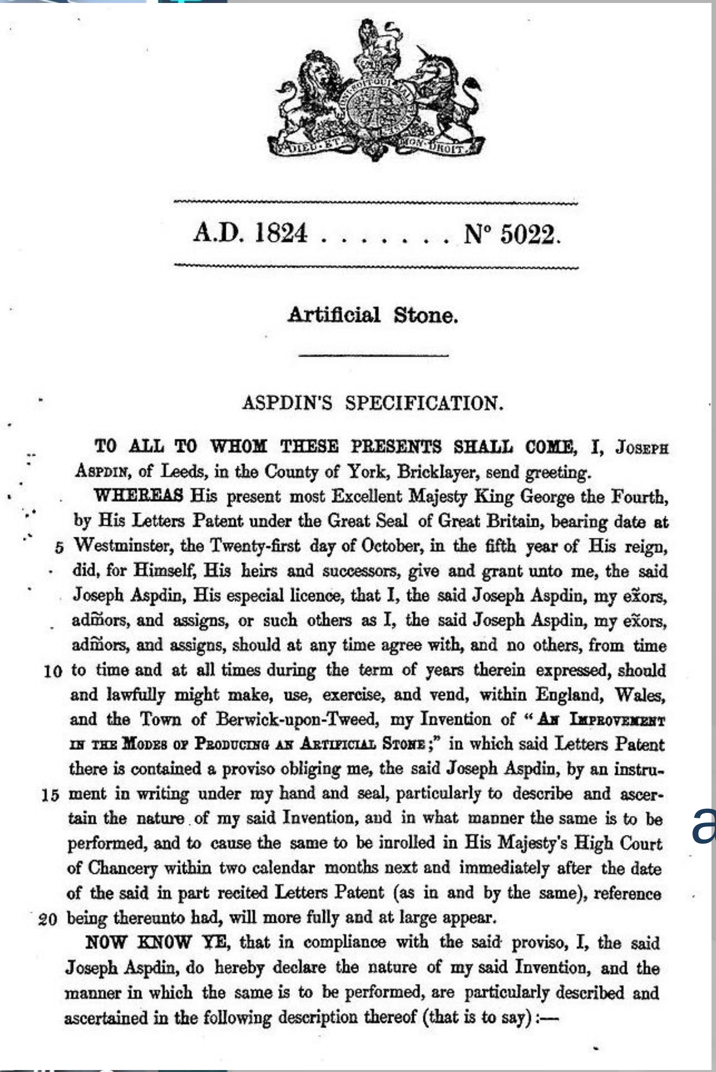
- **opus caementicium**

  "There is also a kind of powder from which natural causes produces astonishing results. This substance, when mixed with lime and rubble, not only lends strength to buildings of other kinds, but even when piers are constructed of it in the sea, they set hard under water."

Marcus Vitruvius Pollio, 13 B.C.

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Cement



A.D. 1824 . . . . Nº 5022.

Artificial Stone.

ASPDIN'S SPECIFICATION.

TO ALL TO WHOM THESE PRESENTS SHALL COME, I, Joseph Aspdin, of Leeds, in the County of York, Bricklayer, send greeting.

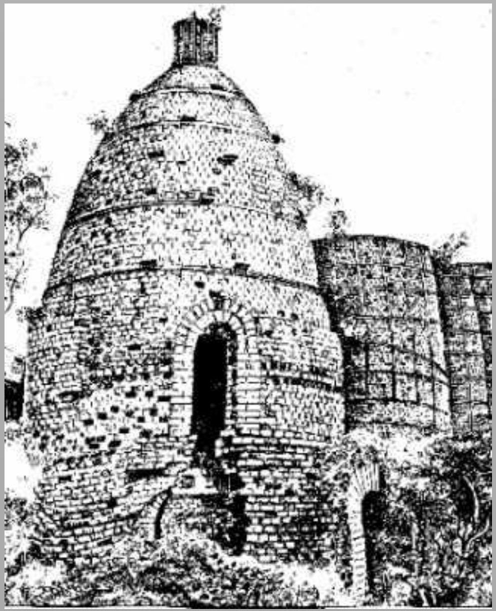
WHEREAS His present most Excellent Majesty King George the Fourth, by His Letters Patent under the Great Seal of Great Britain, bearing date at Westminster, the Twenty-first day of October, in the fifth year of His reign, did, for Himself, His heirs and successors, give and grant unto me, the said Joseph Aspdin, His especial licence, that I, the said Joseph Aspdin, my exors, admors, and assigns, or such others as I, the said Joseph Aspdin, my exors, admors, and assigns, should at any time agree with, and no others, from time to time and at all times during the term of years therein expressed, should and lawfully might make, use, exercise, and vend, within England, Wales, and the Town of Berwick-upon-Tweed, my Invention of "An Improvement in the Modes of Producing an Artificial Stone;" in which said Letters Patent there is contained a proviso obliging me, the said Joseph Aspdin, by an instrument in writing under my hand and seal, particularly to describe and ascertain the nature of my said Invention, and in what manner the same is to be performed, and to cause the same to be inrolled in His Majesty's High Court of Chancery within two calendar months next and immediately after the date of the said in part recited Letters Patent (as in and by the same), reference being thereunto had, will more fully and at large appear.

NOW KNOW YE, that in compliance with the said proviso, I, the said Joseph Aspdin, do hereby declare the nature of my said Invention, and the manner in which the same is to be performed, are particularly described and ascertained in the following description thereof (that is to say):—

Cement

Joseph Aspdin

author of the patent for „Portland cement“ (1824)



First cement kiln „Beehive“

More information – cement history:

https://www.dartfordarchive.org.uk/technology/cement.shtml

Cement manufacture

Raw material:

- **minerals containing $CaCO_3$ + SiO_2** (+ other hydraulic oxides)
  - impure limestone, marl, chalk
- **secondary raw materials** (as source of hydraulic oxides)
  - clay, shale, fly ash, slag
- **calcium sulphate** (as setting retarder)
  - gypsum, anhydrite

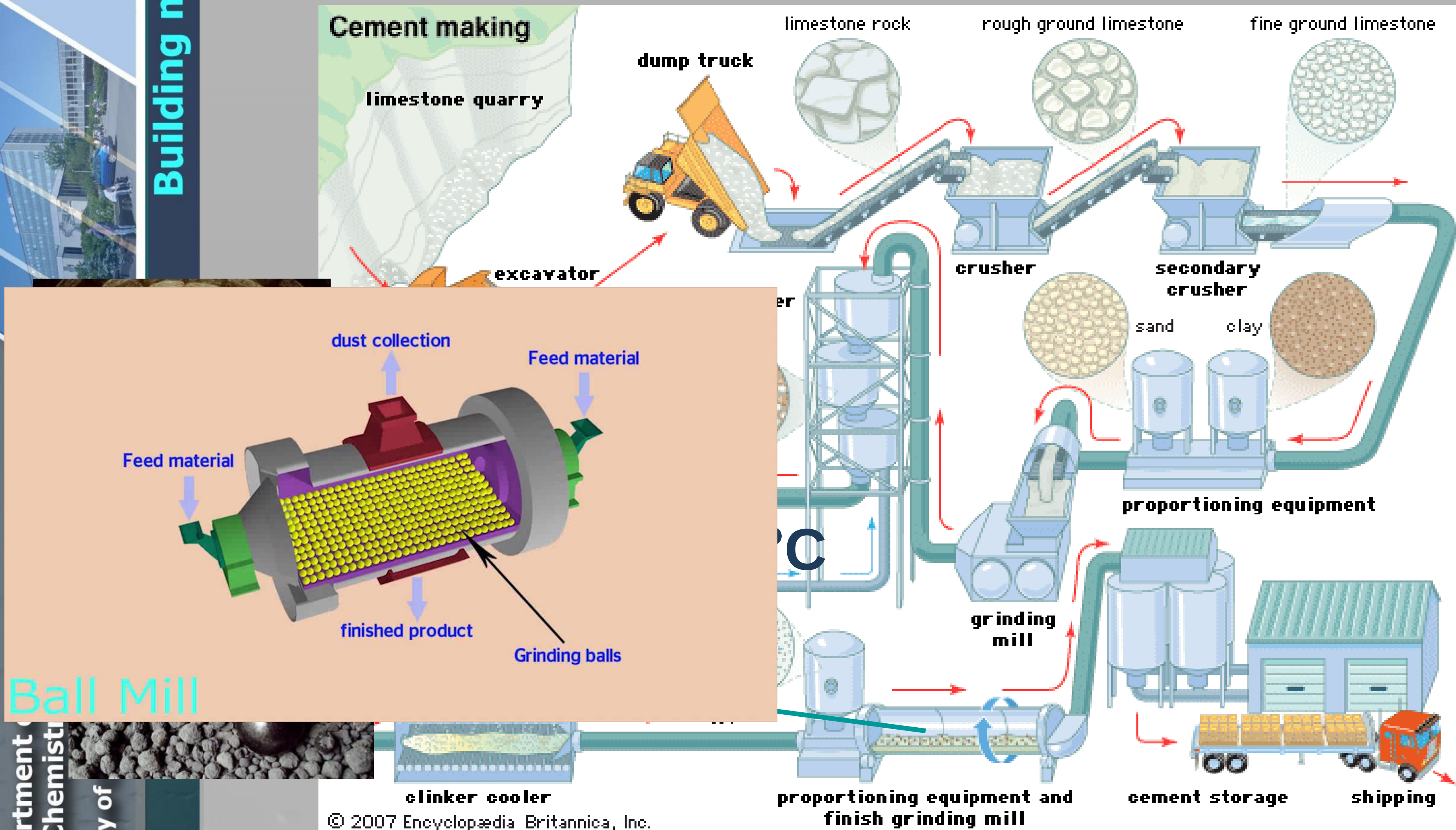
Limestone quarry „America“, Czech Rep.

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Cement manufacture

Building materials
Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Cement manufacture

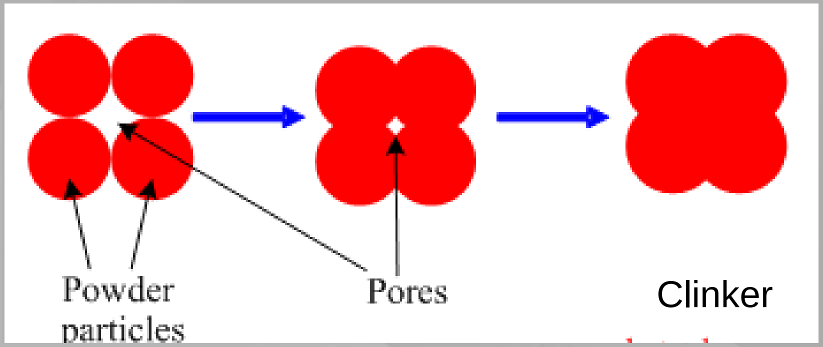


Building materials

Department ... and Chemistr...
Faculty of

Sintering

- consolidation of powder particles by heating at 1300 - 1400°C $\rightarrow$ **clinker**
  - the separate particles diffuse to the neighboring powder particles



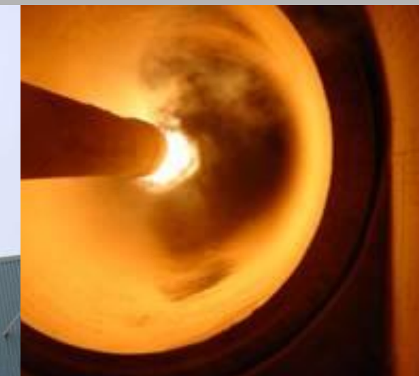
  - chemical reactions $\rightarrow$ formation of **cement compounds – clinker minerals** (calcium silicates)

Building materials

Department of Materials Engineering and Chemistry

Faculty of Civil Engineering

Rotary kiln



about 1480 °C

Chemical composition of cement

- expressed as amount of oxides in mass %
- determined by chemical analysis (EN 196-2)

• Ca	46,4 %
• Si	9,8 %
• Al	3,2 %
• Fe	2,1 %
• Mg	1,2 %
• S	1,0 %
• O	35,3 %
• Σ	99,0 %

• CaO	65 %
• SiO_2	21 %
• Al_2O_3	6 %
• Fe_2O_3	3 %
• MgO	2 %
• SO_3	2 %
• Σ	99,0 %

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Main clinker minerals

- cement oxides are (mostly) not free, but form **clinker minerals**

Tricalcium silicate	Alite	$3CaO \cdot SiO_2$
Dicalcium silicate	Belite	$2CaO \cdot SiO_2$
Tricalcium aluminate	-	$3CaO \cdot Al_2O_3$
Tetracalcium aluminoferrite	Ferrite (brown-millerite)	$4CaO \cdot Al_2O_3 \cdot Fe_2O_3$

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Cement chemist notation (CCN)

- an abbreviated record of the cement compounds

Compound	Name	CCN	Formula
Calcium oxide	lime	**C**	CaO
Silicon dioxide	silica	**S**	SiO_2
Aluminum oxide	alumina	**A**	Al_2O_3
Iron oxide	rust	**F**	Fe_2O_3
	water	**H**	H_2O

Clinker minerals in cement notation

Mineral	Abbreviation	Formula
Tricalcium silicate	**C_3S**	$3CaO \cdot SiO_2$
Dicalcium silicate	**C_2S**	$2CaO \cdot SiO_2$
Tricalcium aluminate	**C_3A**	$3CaO \cdot Al_2O_3$
Tetracalcium aluminoferrite	**C_4AF**	$4CaO \cdot Al_2O_3 \cdot Fe_2O_3$

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Cement minerals properties

C_3S

- hydrates and hardens rapidly
- responsible for initial set and early strength

C_2S

- hydrates and hardens slowly
- responsible for later strength increase
- low hydration heat

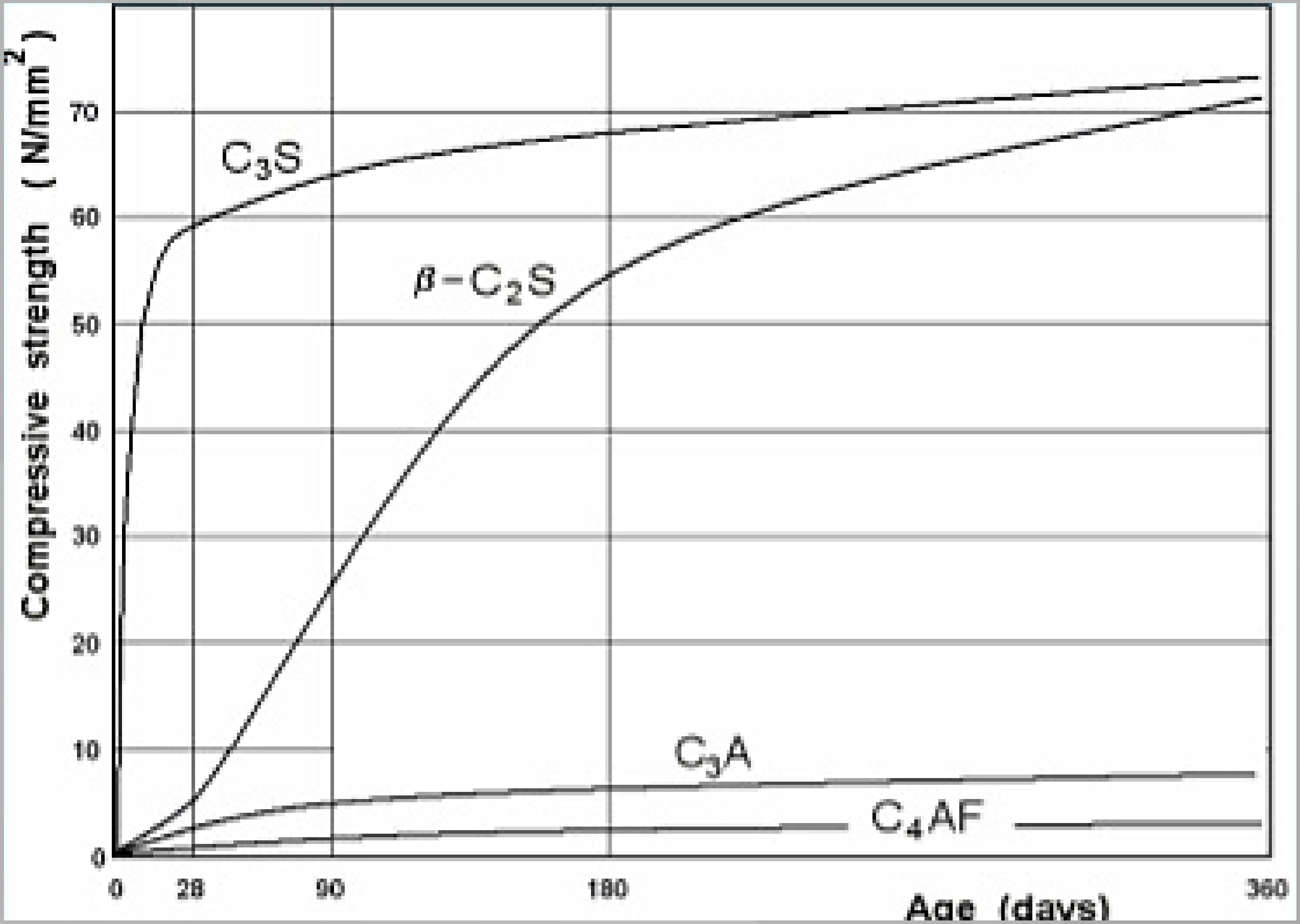
C_3A

- hydrates and hardens the quickest
- a large amount of heat
- important in sulphate corrosion of concrete

C_4AF

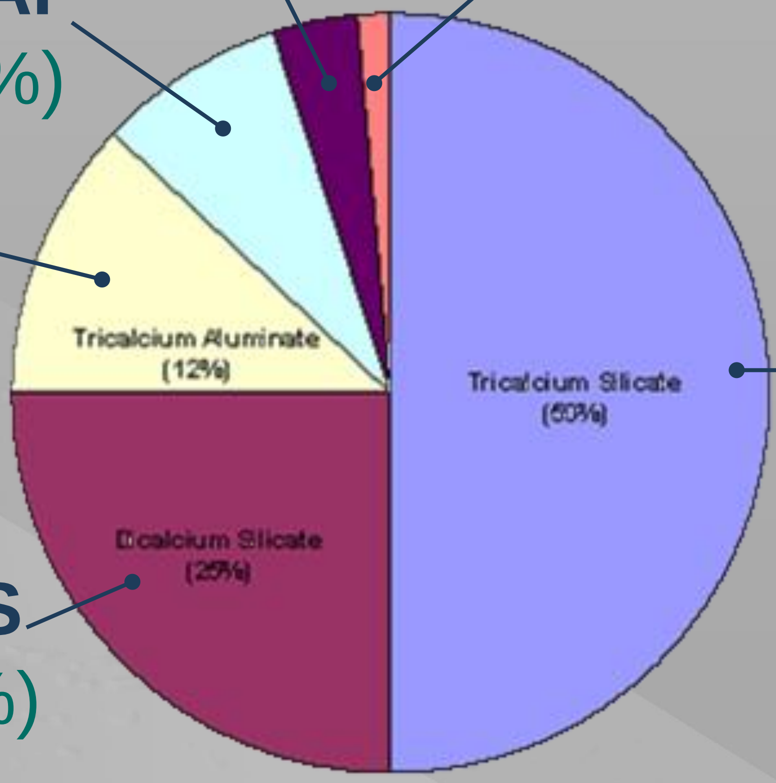
- contributes little to strength
- color effects

Contribution of cement minerals to strength



Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Composition of Portland cement



Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

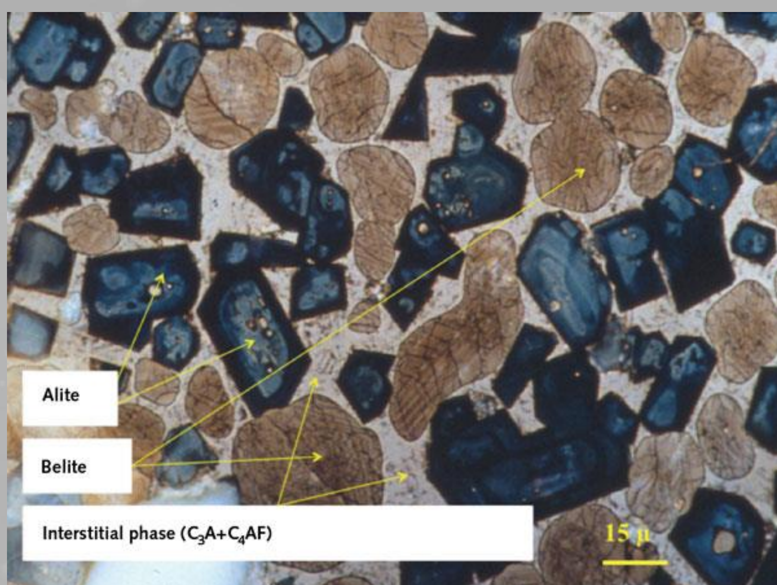
Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

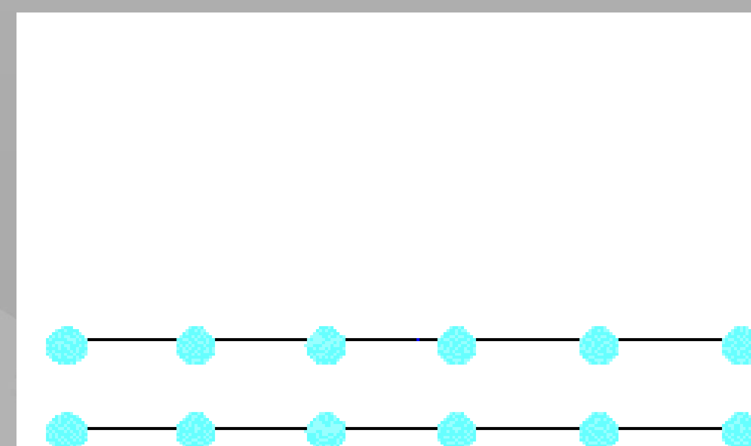
Composition of different cements

Cement type \ Comp.	C_3S	C_2S	C_3A	C_4AF
Portland cement	65	15	8	9
C. with low heat of hydration	25	55	3	14
Sulphate resistant c.	73	9	2	13
White cement	73	14	11	0

Cement compound composition determination

- microscope
- roentgen diffraction
- Bogue calculation





Bogue calculation

- determines the approximate proportions of the four main minerals in Portland cement clinker
- the calculation assumes that the four main clinker minerals are pure minerals
- there is necessary to know chemical composition of cement (% amount of oxides)

- refers to cement clinker, but it can be adjusted for use with cement

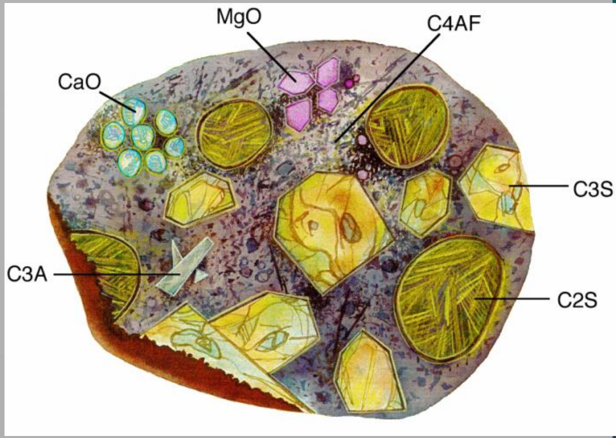
Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Bogue calculation principles

1. Ferrite is the only mineral to contain iron. Assume that all the Fe_2O_3 is in C_4AF.
2. The aluminate content is fixed by the total alumina content minus the alumina in the ferrite. This can now be calculated, since the amount of ferrite has been calculated.
3. Deduct from the CaO content the amounts attributable to C_4AF, C_3A and free lime, and solve two simultaneous equations to obtain the contents of C_3S and C_2S.

C_3A	$3CaO \cdot Al_2O_3$
C_4AF	$4CaO \cdot Al_2O_3 \cdot Fe_2O_3$

Bogue calculation



$[C_4AF] = 3.04*[F]$

$[C_3A] = 2.65*[A] - 1.69*[F]$

$[C_3S] = 4.07*[C] - 1.43*[F] - 6.72*[A] - 7.60*[S]$

$[C_2S] = 8.6*[S] - 3.07*[C] + 1.08*[F] + 5.1*[A]$

- where the [F], [C], [A], [S] are the weight percentages of the oxides F_2O_3, CaO, Al_2O_3, SiO_2 in the clinker

Cement hydration

- series of irreversible chemical reactions between cement and water
- during hydration the cement sets and hardens, “gluing” the aggregate together in a solid mass

Hydration depends on:

- cement type (chemical composition)
- fineness
- amount of water added
- presence of other admixtures

Building materials

Department of Materials Engineering and Chemistry

Faculty of Civil Engineering

Cement hydration

- when water is added - mostly exothermic reactions occur
- evolution of heat (monitored by conduction calorimetry) → **5 stages**:

1. **Pre-induction**
2. **Dormancy**
   (induction period)
3. **Setting and hardening**
4. **Cooling**
5. **Densification**

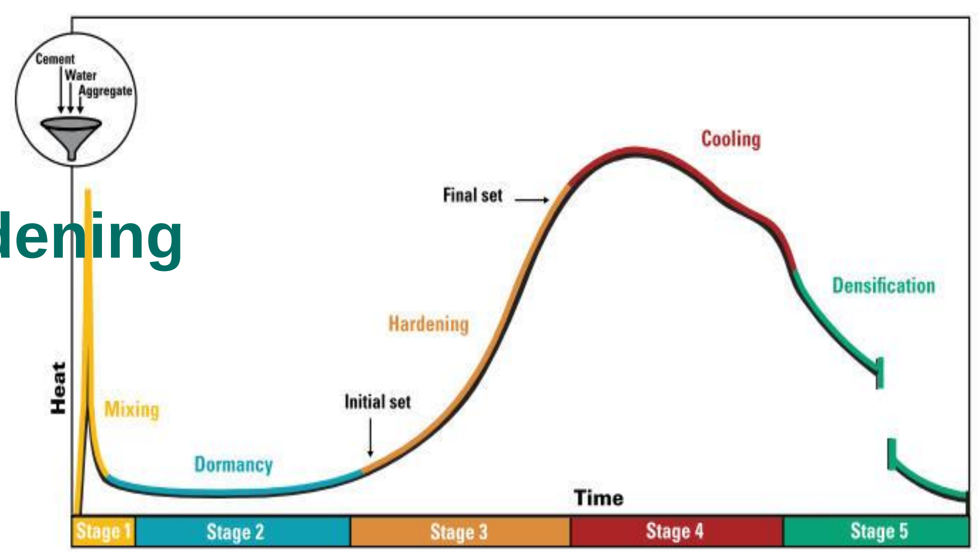
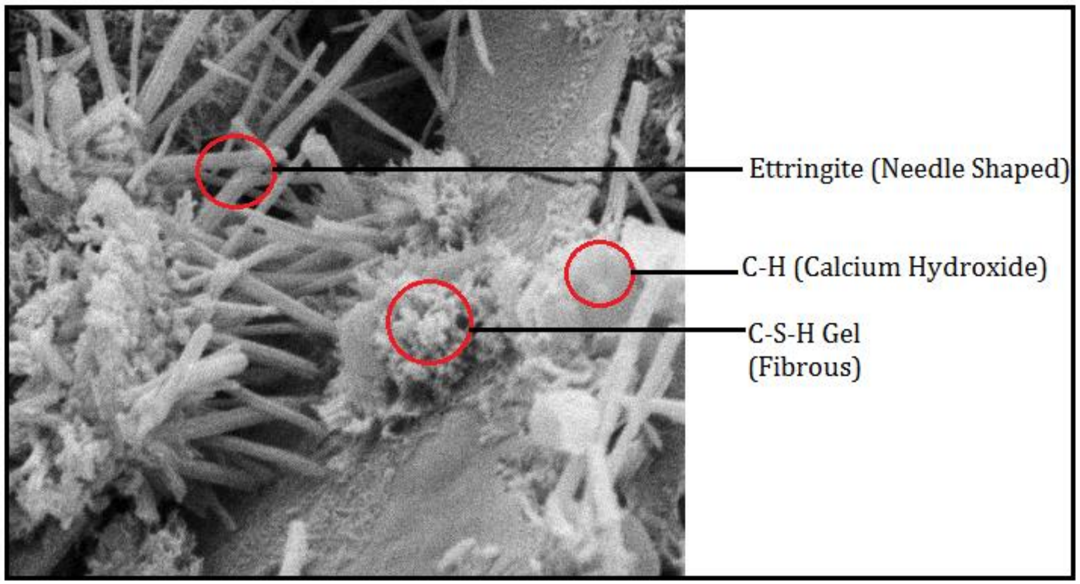


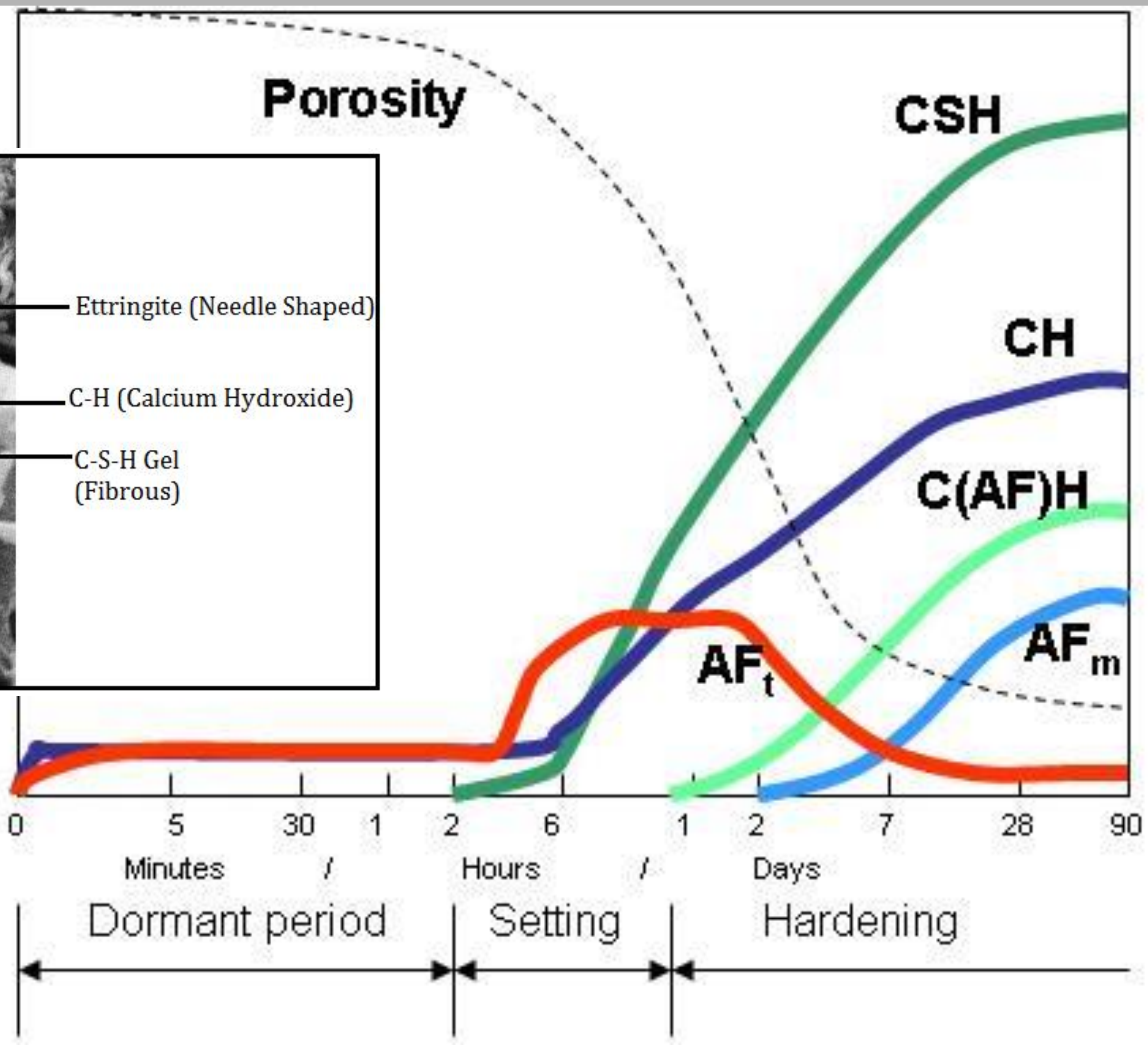
Figure 4-2. General hydration curve delineating the five stages

Products of cement hydration

- **Calcium silicate hydrate (**abbrev. C-S-H)**:**
  - main reaction product
  - main source of concrete strength.
- **Calcium hydroxide** $Ca(OH)_2$ = portlandite (abbrev. CH)
  - formed mainly from alite
- **AFm and AFt phases:**
  - most common AFm - monosulfate ($C_3A.CaSO_4.12H_2O$)
  - most common AFt - ettringite ($C_3A.3CaSO_4.32H_2O$)
- **Monocarbonate:**
  - produced in the presence of fine limestone as some of the limestone reacts with the cement pore fluid ($C_3A.CaCO_3.11H_2O$)

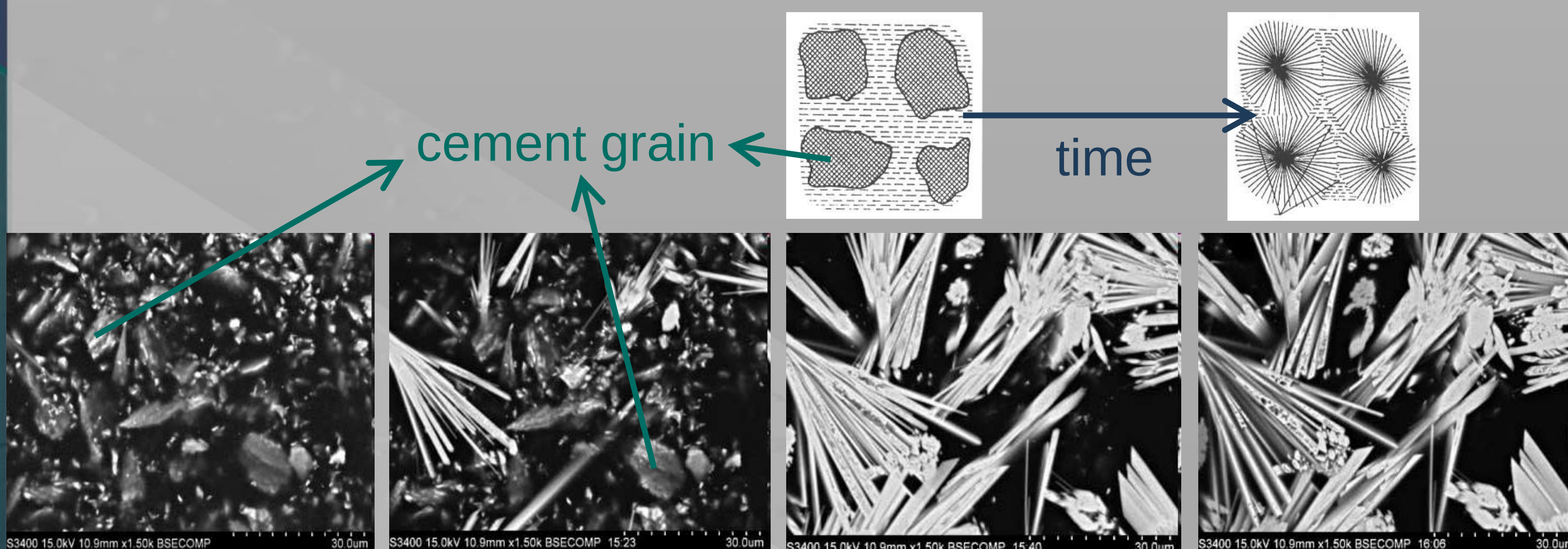
Products of cement hydration





Cement setting and hardening

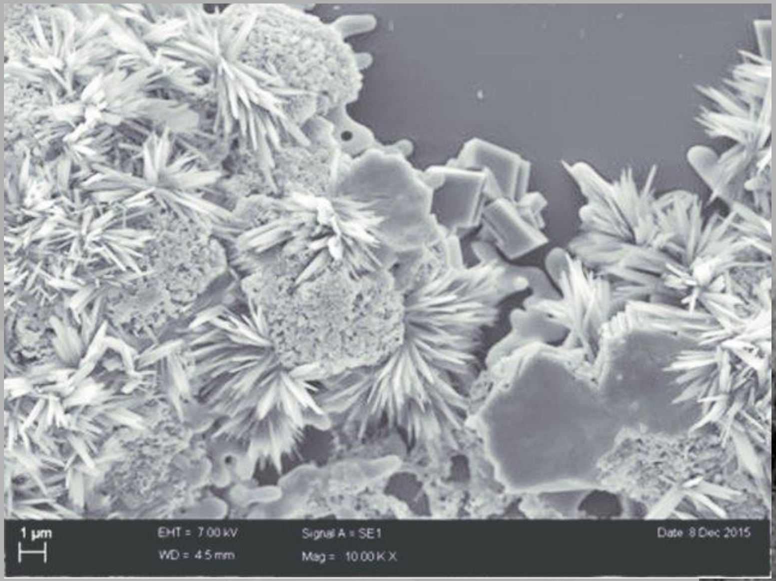
- **Setting**:
  - stiffening of the original plastic mass due to initial gel formation.
- **Hardening**
  - development of strength, due to crystallization
  - crystals form and interlock with each other

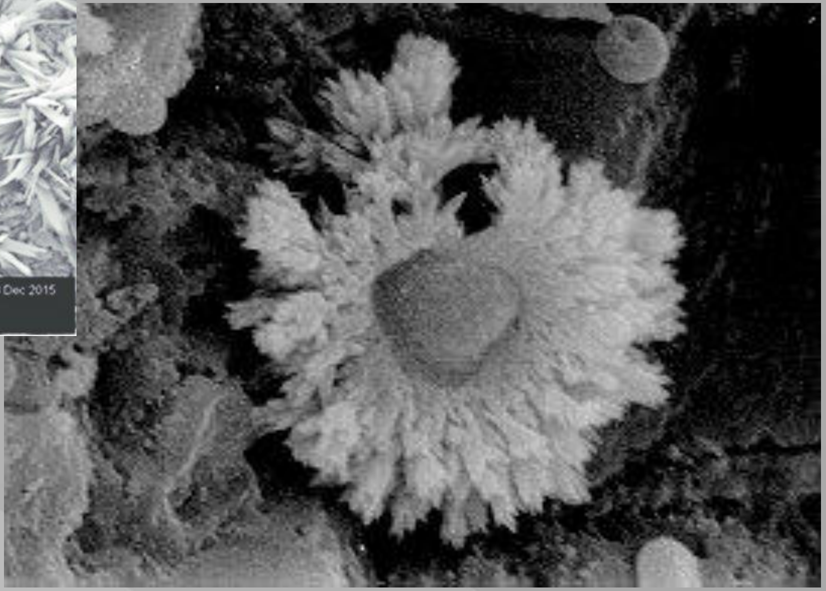


0 min 15 min 30 min 55 min

Cement hydration

- **SEM** (scanning electron microscope) **images of hydrated cement grains**





Cement types (EU)

EN 197-1: 5 main types - 27 common cements

- **CEM I** - **Portland cement**
  - min 95% of clinker
- **CEM II** - **Portland composite cement**
  - up to 35% of siliceous fly ash
- **CEM III** - **Blastfurnace cement**
  - up to 95% blastfurnace slag
- **CEM IV**- **Pozzolanic cement**
  - up to 55% of pozzolana
- **CEM V** - **Composite cement**
  - up to 80% of blastfurnace slag or fly ash and pozzolana

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

27 Products in the family of Common Cement / Cement Types

EN 197-1

Main Types	Notation of the 27 products (types of common cement)		Composition [proportion by mass[1)]] Main constituents: Clinker K	Blastfurnace slag S	Silica fume D[2)]	Pozzolana natural P	Pozzolana natural calcined Q	Fly ash siliceous V	Fly ash calcareous W	Burnt shale T	Limestone* L	Limestone* LL	Minor Additional constituents
CEM I	Portland cement	CEM I	95-100	--	--	--	--	--	--	--	--	--	0-5
CEM II	Portland-slag Cement	CEM II/A-S	80-94	6-20	--	--	--	--	--	--	--	--	0-5
		CEM II/B-S	65-79	21-35	--	--	--	--	--	--	--	--	0-5
	Portland-silica fume cement	CEM II/A-D	90-94	--	6-10	--	--	--	--	--	--	--	0-5
	Portland-Pozzolana cement	CEM II/A-P	80-94	--	--	6-20	--	--	--	--	--	--	0-5
		CEM II/B-P	65-79	--	--	21-35	--	--	--	--	--	--	0-5
		CEM II/A-Q	80-94	--	--	--	6-20	--	--	--	--	--	0-5
		CEM II/B-Q	65-79	--	--	--	21-35	--	--	--	--	--	0-5
	Portland-fly ash cement	CEM II/A-V	80-94	--	--	--	--	6-20	--	--	--	--	0-5
		CEM II/B-V	65-79	--	--	--	--	21-35	--	--	--	--	0-5
		CEM II/A-W	80-94	--	--	--	--	--	6-20	--	--	--	0-5
		CEM II/B-W	65-79	--	--	--	--	--	21-35	--	--	--	0-5
	Portland-burnt shale cement	CEM II/A-T	80-94	--	--	--	--	--	--	6-20	--	--	0-5
		CEM II/B-T	65-79	--	--	--	--	--	--	21-35	--	--	0-5
	Portland-limestone cement	CEM II/A-L	80-94	--	--	--	--	--	--	--	6-20	--	0-5
		CEM II/B-L	65-79	--	--	--	--	--	--	--	21-35	--	0-5
		CEM II/A-LL	80-94	--	--	--	--	--	--	--	--	6-20	0-5
		CEM II/B-LL	65-79	--	--	--	--	--	--	--	--	21-35	0-5
	Portland-composite cement[3)]	CEM II/A-M	80-94	← 6-20 →									0-5
		CEM II/B-M	65-79	← 21-35 →									0-5
CEM III	Blastfurnace cement	CEM III/A	35-64	36-65	--	--	--	--	--	--	--	--	0-5
		CEM III/B	20-34	66-80	--	--	--	--	--	--	--	--	0-5
		CEM III/C	5-19	81-95	--	--	--	--	--	--	--	--	0-5
CEM IV	Pozzolanic cement[3)]	CEM IV/A	65-89	--	← 11-35 →					--	--	--	0-5
		CEM IV/B	45-64	--	← 36-55 →					--	--	--	0-5
CEM V	Composite cement[3)]	CEM V/A	40-64	18-30	--	← 18-30 →			--	--	--	--	0-5
		CEM V/B	20-38	31-50	--	← 31-50 →			--	--	--	--	0-5

1) The values in the table refer the sum of the main and minor additional constituents.

2) The proportion of silica fume is limited to 10%.

3) In Portland-composite cements CEM II/A-M and CEM II/B-M, in Pozzolanic cements CEM IV/A and CEM IV/B and in Composite cements CEM V/A and CEM V/B the main constituents besides clinker shall be declared by designation of the cement.

* L: total organic carbon (TOC) shall not exceed 0.5% by mass; LL: TOC shall not exceed 0.20% by mass.

Cement constituents

- **Portland cement clinker (K)**
  - made by sintering a mixture of raw materials
- **Granulated blastfurnace slag (S)**
  - made by rapid cooling of a slag, as obtained by smelting iron ore in a blastfurnace
  - possesses hydraulic properties when suitably activated

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Cement constituents

Pozzolanic materials

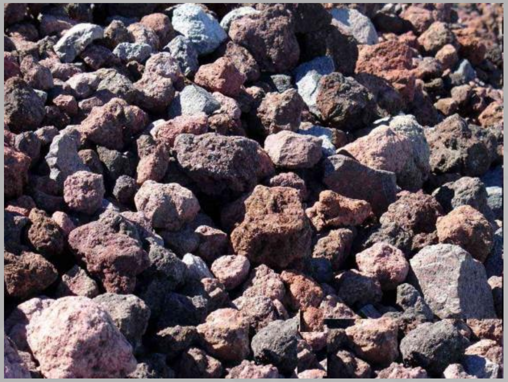
- natural substances of siliceous or silico-aluminous composition
- when finely ground and in the presence of water, they react with dissolved calcium hydroxide $Ca(OH)_2$

- **Natural pozzolana** (volcanic origin) **(P)**
- **Natural calcined pozzolana (Q)**
  - activated by thermal treatment

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Pozzolanic materials

- contain active silica (SiO_2)
- not cementitious in itself but will, in a finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form cementitious compounds
- silica must be glassy and amorphous

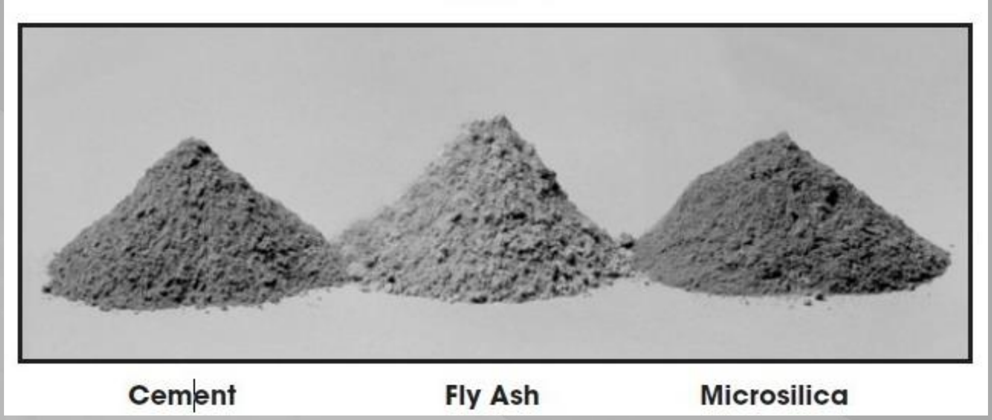


Cement constituents

Fly ashes

– obtained by electrostatic or mechanical precipitation of dust-like particles from flue gases from furnaces fired with pulverised coal

- **Siliceous fly ash (V)**
- **Calcareous fly ash (W)**



Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Cement constituents

- **Burnt shale (T)**
  - specifically burnt oil shale at approximately 800 °C
- **Limestone (L, LL)**
  - $CaCO_3$ content ≥ 75 % by mass
- **Silica fume (D)** (microsilica)
  - originates from the reduction of high purity quartz with coal in electric arc furnaces in the production of silicon and ferrosilicon alloys (very fine spherical particles)

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Cement classification

(EN 197-1)

CEM I 42,5 R

- **I** → **type**
- **42,5** → **strength class**
- **R** → **high early strength**

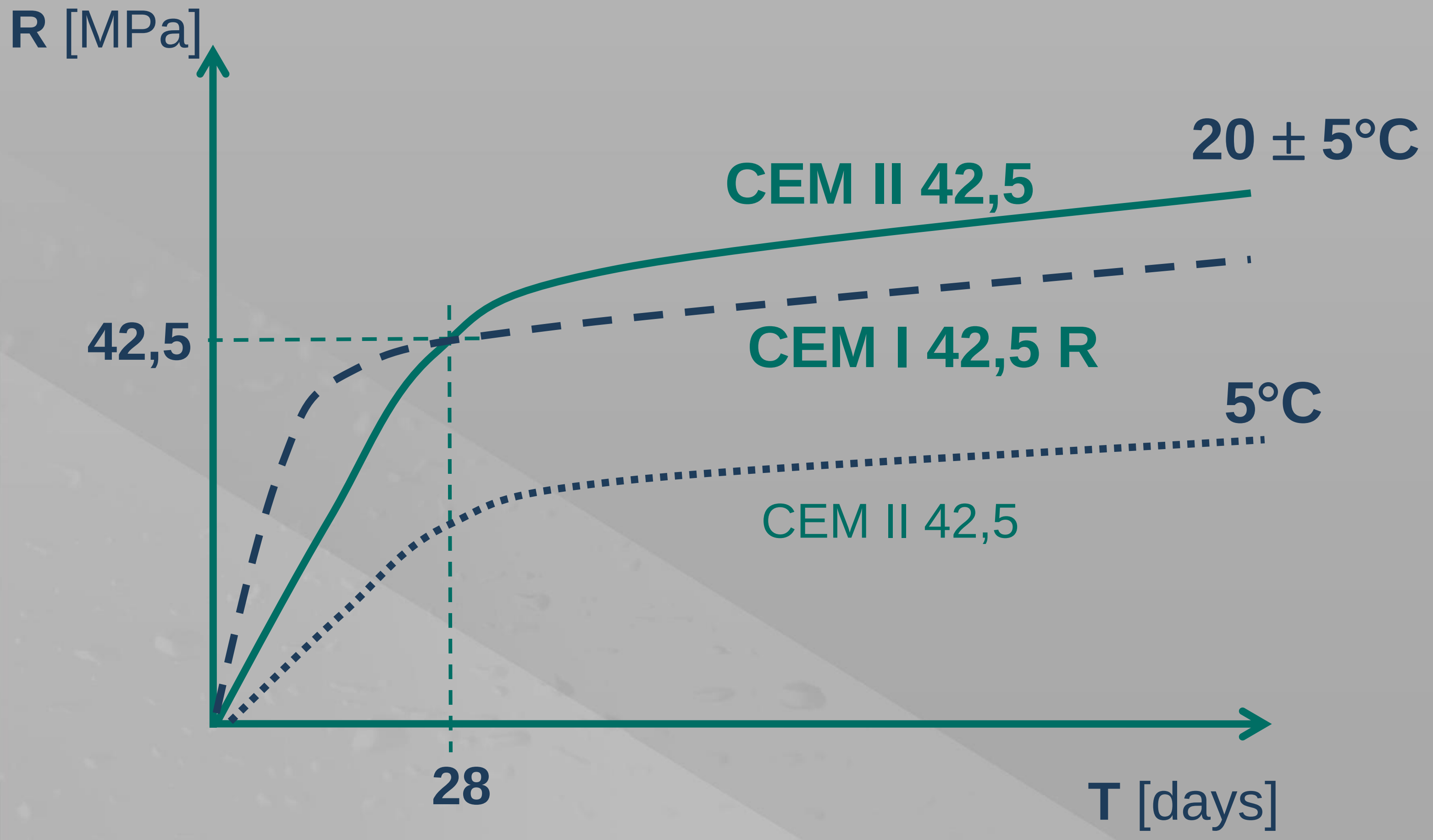
Strength classes of cement

- the **standard strength** of a cement is the compressive strength in MPa determined in accordance with EN 196-1 at 28 days
- three classes of standard strength:
  - **32,5**
  - **42,5**
  - **52,5**

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Strength increase

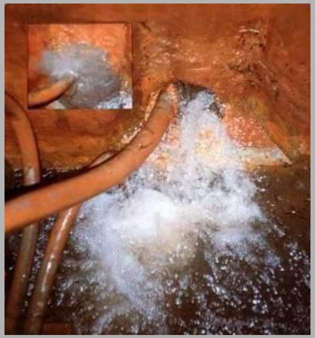


Properties of cement types

- **Portland cement**
  - high strength
  - fast increase of strength
  - big amount of hydration heat
- **Portland slag blastfurnace cement**
  - high sulphate resistance
  - low hydration heat
- **silica-fume cement**
  - low porosity of concrete
  - exceptionally high strength
- **fly-ash cement**
  - good workability,
  - lower concrete water content

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Special cements



- **expansive cement**
  - against drying shrinkage
- **fast repair cement**
- **sulphate resistant** - $C_3A < 3,5\%$
- **white** - Fe < 1%
- **colored** - 5-10 % of pigments
- **strontium and barium cements**
  - Ba or Sr instead of Ca
  - high resistance to attack by sea water,
  - resistance to high temperatures
  - radiation shields

Building materials

Masonry cement (MC)

EN 413-1

- for use in mortars for masonry construction
- lower strength

  MC5, MC 12,5, MC 22,5

- **can contain besides the portland cement lime, clay**

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Calcium aluminate cement
(High-alumina cement)

- consisting predominantly of hydraulic calcium aluminates
- over 35 % of Al_2O_3
- ultra - rapid strength development
- high chemical resistance
- refractory material (to 1750°C)

But !

- loss of strength due to „conversion“
- several failures in the 1970s

→ forbidden for the use in the bearing constructions !

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Building materials

Department of Materials Engineering and Chemistry

Faculty of Civil Engineering

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Cement testing

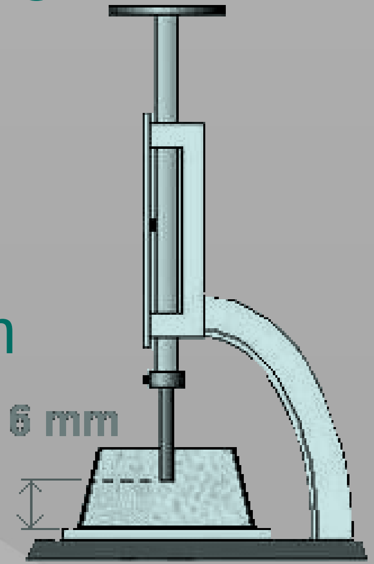
EN 196 – Methods of testing cement

- 1 Determination of strength
- 2 Chemical analysis of cement
- 3 Determination of setting time and soundness
- 4 Quantitative determination of constituents
- 5 Pozzolanicity test for pozzolanic cement
- 6 Determination of fineness
- 7 Methods of taking and preparing samples of cement
- 10 Determination of the water soluble chromium (VI) content of cement
- 21 Determination of the chloride, carbon dioxide and alkali content of cement

Building materials
Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Testing of cements - terms

- **cement paste**
  - cement + water
- **cement mortar**
  - cement + water + **fine aggregates**
- **concrete**
  - cement + water + fine + **coarse aggregates**
- **water/cement ratio w/c**
  - mass of water/mass of cement
- **standard** (normal) **consistency**
  - the Vicat plunger penetrates 5 – 7 mm from the bottom of the mould



Determination of strength (EN196-1)

compressive

flexural (bending)

$$R_t = \frac{F_{max}}{A}$$

$$R_y = \frac{M_{max}}{W}$$

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Expression of test results of compressive strength

- **test set - 3 prism → 6 halves**
- arithmetic mean of the 6 individual result
- if one result within the 6 individual results varies by more than ± 10 % from the mean, discard this result and calculate the arithmetic mean of the 5 remaining results
- if one result within the 5 remaining results varies by more than ± 10 % from their mean, discard the set of results and repeat the determination

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Chemical analysis of cement (EN196-2)

- loss on ignition
- residue insoluble
- determination of sulfate
- determination of major elements
  - silica
  - oxides Fe, Al, Ca, Mg
  - chloride
  - carbon dioxide
  - alkali

Building materials
Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Setting time (EN196-3)

- **initial seting time**
- **final setting time**

Vicat apparatus

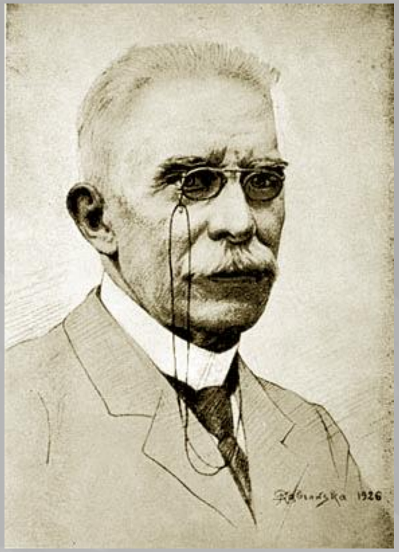
Louis **Vicat**

(1786 -1861)

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Soundness (EN196-3)

- the ability of a hardened cement paste to retain its volume after setting without delayed destructive expansion caused by CaO or MgO



Henry Louis
Le Chatelier
(1850 - 1936)

Finneness (EN196-6)

- **Blaine apparatus** (see Lecture 2)

$$S = \frac{K}{\rho} \times \frac{\sqrt{e^3}}{(1-e)} \times \frac{\sqrt{t}}{\sqrt{0{,}1\eta}}$$

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Taking and preparing samples (EN196-7)

- from bags, containers, bulk, silos, filling machines
- quartering, sampling tube, screw sampler

Water soluble chromium (VI) content (EN196-10)

- hygienic and ecological properties

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Mechanical and physical requirements (EN197-1)

Strength class	Compressive strength MPa – Early strength – 2 days	Compressive strength MPa – Early strength – 7 days	Compressive strength MPa – Standard strength – 28 days	Compressive strength MPa – Standard strength – 28 days	Initial setting time minut	Soundness (expansion) mm
32,5 N	-	≥ 16,0	≥ 32,5	≤ 52,5	≥ 75	≤ 10
32,5 R	≥ 10,0	-				
42,5 N	≥ 10,0	-	≥ 42,5	≤ 62,5	≥ 60	
42,5 R	≥ 20,0	-				
52,5 N	≥ 20,0	-	≥ 52,5	-	≥ 45	
52,5 R	≥ 30,0	-				

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Civilcrete

general purpose cement

Civilcrete complies with the chemical and physical requirements of SANS 50197 (EN197) for a Class IV 32,5R cement.

PHYSICAL PROPERTIES

Property	Civilcrete*	EN Spec. requirement
2 day *Compressive strength*	16,0 MPa	≥ 10,0 MPa
7 day *Compressive strength*	26,8 MPa	—
28 day *Compressive strength*	43,5 MPa	≥ 32,5 MPa
Initial set	197 minutes	≥ 75 minutes
Soundness	1,0 mm	≤ 10 mm

**Average test results*

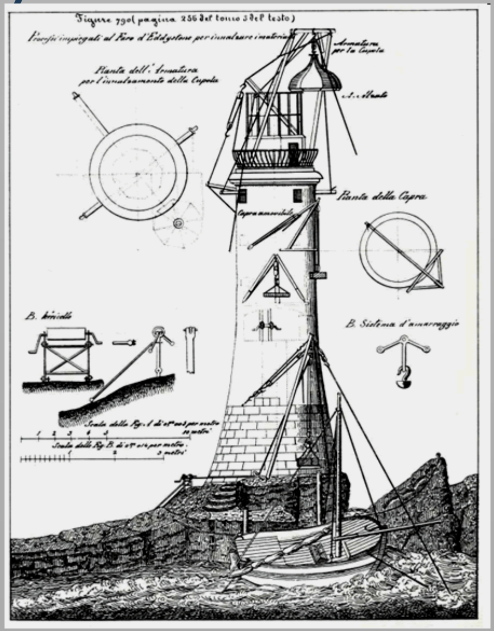
Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Hydraulic lime

- used by the Romans (100 B.C.)
  - (Plinus, Vitruvius)

  „Opus caementicium“
- forgotten in the middle age
- discovered again in the 18th century by burning **limestone containing clays**
  - 1756 – John Smeaton
  - 1796 - „roman cement“ (James Parker)
  - Louis Joseph Vicat



Eddystone Lighthouse

Hydraulic lime

Raw material:

- **argillaceaous** (= containing clays) **limestones** → **natural hydraulic lime** (NHL)
- **quick lime** (burned limestone) + **pozzolanic** materials → **hydraulic lime** (HL)

Pozzolanic materials (pozzolans):

- consist mainly from reactive silica (SiO_2) and alumina (Al_2O_3)
- when finely ground and in the presence of water, they react with dissolved $Ca(OH)_2$
- volcanic ash, fly ash, silica fume, high-reactivity metakaolin, ground granulated blast furnace slag

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Hydraulic lime manufacture

Natural hydraulic lime (NHL):

- burning of raw materials at the temperature **under 1250 °C**
- slaking (only when HM > 3)

Hydraulic lime (HL):

- grinding of quicklime together with pozollans

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Hydraulic lime

- **in contrast to portland cement has higher amount of the free CaO and no alite (C_3S)** → lower strength than cement

According the degree of hydraulicity (hydraulic modulus):

- **feebly hydraulic lime** (HM 6 - 9) - need slaking
- **moderately hydraulic lime** (HM 3 - 6) – need slaking
- **eminently hydraulic lime** (HM 1,7 - 3) – does not need slaking

Natural hydraulic lime - EN 459

Type	**SO_3** (mass %)	**Free lime** (mass %)	**Strength after 28 days** [MPa]
NHL 1	≤ 2	≥ 50	≥ 0,5 - ≤ 3
NHL 2	≤ 2	≥ 40	≥ 2 - ≤ 7
NHL 3,5	≤ 2	≥ 25	≥ 3,5 - ≤ 10
NHL 5	≤ 2	≥ 15	≥ 5 - ≤ 15

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering

Hydraulic lime use

- **monuments renovations**
  - better breathing of walls
  - moisture can evaporate
  - mortars and renders do not set too hard
  - expansion joints can often be avoided
  - reduced condensation
  - no salt staining

Using of cement with old bricks

Department of Materials Engineering and Chemistry
Faculty of Civil Engineering