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MORTARS

Historic mortars and restoration mortars

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Dry-stone wall; Wanla, Ladakh

Boulder masonry, around 450 AD,
St. Stephan, Chur, GR

Definition

A mortar is a mixture of binder, aggregate, additives and water, which is applied as a soft, ductile mass and which hardens to a stiff, rigid material.

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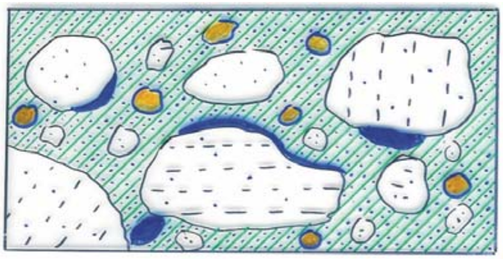
Mortar = binder
+ aggregate
+ water
+ air
+ additives



Sketch Andreas Arnold

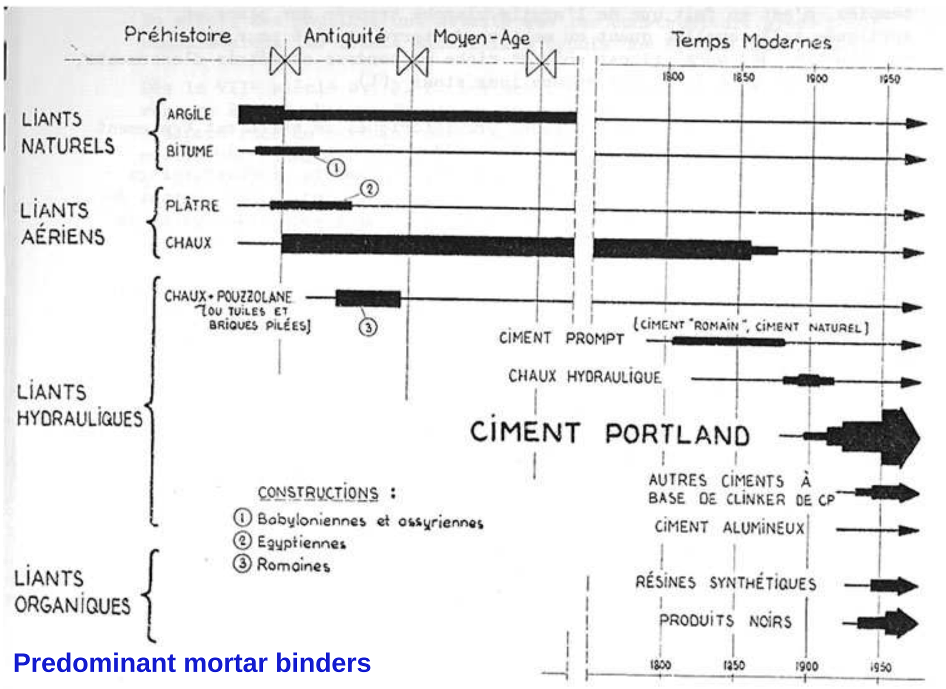
Binder = (mineral) glue

Water = reaction partner + adjustment of workability

Aggregate = framework, (theoretically) inert

Air = pore space

Additive = give the mortar certain properties, consistency, workability, enhancing or retarding of setting and hardening reaction, etc.



Predominant mortar binders

from Delisle, J.P., Furlan, V. (1977)

Mortar properties (1/2)

A Chemical properties

A1 **while applying:**
strong alkalinity – tools necessary; can cause a problem to some original materials
water soluble parts in the original materials - can be mobilized (e.g. during wetting for preparing the support)

A2 **while setting**
Chemical reactions between new and original mortars – e.g. original gypsum mortars and ordinary Portland cement mortars - formation of Ettringite and other expansive minerals

A3 **properties after setting**
repair materials with water soluble constituents – e.g. salts in cement materials

A4 **weathering properties**
Chemical reactivity of repair mortars as similar as possible to original materials

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Mortar properties (2/2)

B Physical properties

Necessary properties strongly dependent on the use of the mortar

B1 **while applying:**
Workability; fluidity; smoothness; early compressive strength; adhesive strength;

B2 **while setting**
Shrinking; expanding; compressive and adhesive strength;

B3 **properties after setting**
water vapour permeability; capillary water uptake; hygric, hydric and thermal expansion; frost resistance; adhesion; compressive and tensile strength
Structure; colour; possibilities to be painted or treated otherwise

B4 **weathering properties**
Change of physical mortar properties during exposure

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Mortars are used for e.g.:
- pisé building, compressed concrete, reinforced concrete
- Stone walls: bedding mortars, jointing mortars
- plasters / renders
- support for wall paintings
- floors
- ceilings
- stucco, scagliolia
- stone imitate with or without reworking by stonemasons
- mosaic
- works of art
- casting mortars
- repair material for stones or renders
- grouts

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Buildings constructed only out of mortars s.l.

- pisé building
- rammed earth
- compressed concrete
- reinforced concrete

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Basgo, Ladakh castle built out of rammed earth (pisé)

3.8.2010

Rammed earth construction Vietnam (2005)
from: http://en.wikipedia.org/wiki/Rammed_earth ; 30.09.2013

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Yemen, Sana'a
many-storeyed tower-houses built of rammed earth (pisé)

Image from: http://commons.wikimedia.org/wiki/File:Sanaa,_Yemen_view.jpg ; last visited 30.9.2013

Pantheon, Rome, between 118 and 125 AD

Compressed pozzolanic mortars

http://upload.wikimedia.org/wikipedia/commons/thumb/2/2a/Einblick_Panorama_Pantheon_Rom.jpg/800px-Einblick_Panorama_Pantheon_Rom.jpg ; 30.9.2013

http://upload.wikimedia.org/wikipedia/commons/9/9e/Rome_Pantheon.jpg ; 30.9.2013

http://upload.wikimedia.org/wikipedia/commons/thumb/7/76/Dome_of_Pantheon_Rome.JPG/800px-Dome_of_Pantheon_Rome.JPG ; 30.9.2013

Pozzolana (latent hydraulic materials)

Principle

Extraction of natural (or artificial) SiO_2-rich and reactive material – grinding - mixing with lime – mixing with aggregate and water – hydraulic setting

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Natural raw materials

Pyroclastic volcanic deposits
Pozzolana (Italy), Trass (Germany), Santorin earth (Greece)

Diatomaceous earths (kieselgurs / terre d'infusoires)
Moler earth (islands Fur and Mors, Denmark)
TripoliteDakine (Tripolis, Libya)

Other sedimentary depositions and rocks
Gaize (Marne, Ardennes, Meuse; France), fine grained sedimentary rock containing colloidal silicate (opal)

Artificial raw materials

Brick dust (low burning temperature), to some extent blast furnace slag (scories de haut fourneau)

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Pozzolanic mortars

Binder = pozzolanic material and lime
Water
Aggregate = sand
Additions = fibers, hair, etc.

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Wuennewil, FR, church

Rammed concrete ca. 1932 (béton non armé)

24.3.2004

Hydraulic lime, portland cement

Principle, hydraulic lime

Extraction of natural stones (limestone, siliceous limestone, marl, clay) – burning (1000 to 1200° C) – slaking of CaO – grinding - mixing with aggregate and water – hydraulic setting

Principle, portland cement

Extraction of raw materials (limestone, clay, sand, iron ore;) – grinding and mixing of raw materials in precise proportions, homogenising of the mixture - burning to clinker (1450° C) – adding additions and grinding – mixing with aggregate and water – hydraulic setting

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Hydraulic lime

Lime stone and clay

Burning temperature 1000° C to 1200° C

Main clinker composition :

Belite	Di-calcium silicate	$2CaO.SiO_2$	C2S
	Tri-calcium aluminate	$3CaO.Al_2O_3$	C3A
	Calcium oxide	CaO	C

Portland cement

Lime stone, clay, sand, iron ore (mix allowing no free CaO to be formed!)

Burning temperature until about 1450° C

Main clinker composition (% = average mixture):

Alite	Tri-calcium silicate	$3CaO.SiO_2$	C3S	60%
Belite	Di-calcium silicate	$2CaO.SiO_2$	C2S	16%
	Tri-calcium aluminate	$3CaO.Al_2O_3$	C3A	11%
	Tetra-calcium aluminate ferrite	$4CaO.Al_2O_3.Fe_2O_3$	C4AF	8%

Setting of clinker phases

Hydration of the silicates:

C3S: $2(3CaO.SiO_2) + 6H_2O \rightarrow [3CaO.2SiO_2.3H_2O] + 3Ca(OH)_2$

C2S: $2(2CaO.SiO_2) + 4H_2O \rightarrow [3CaO.2SiO_2.3H_2O] + 1Ca(OH)_2$

Alite and belite → formation of colloidal CSH and hydrated lime

Hydration of the aluminates and ferrites:

C3A: $3CaO.Al_2O_3 + Ca(OH)_2 + 12H_2O \rightarrow 4CaO.Al_2O_3.13H_2O$

Very fast reaction, slowed down by gypsum, forming ettringite $[(CaO)_6(Al_2O_3)(SO_4)_3.32H_2O]$ on the surface of the aluminates

C4AF: $4CaO.Al_2O_3.Fe_2O_3 + 4Ca(OH)_2 + xH_2O \rightarrow 2x4CaO.Al_2O_3.Fe_2O_3.\ xH_2O$

Ferrites and aluminates react with the calcium hydroxides produced during hydration of the silicates.

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compressive strength

strongly influenced by amount of water used; highest strength at w/c = 0.3 (**w**ater to **c**ement, in volume parts)

Surplus of lime in initial mixture → free CaO

because of the high temperature burning of cement, this CaO is formed by coarse crystals and hence reacts very slowly with water → expansion during setting or later

Gypsum/sulfates present outside the cement reacts with C3A to ettringite → enormous volume increase, structural problems

Alkalis

on average cement contains 0,8% alkalis (Na_2O and K_2O)

→ soluble salts causing serious deteriorations of historic buildings

Damage after portland cement injection in Schloss Wiehe (D)

Images from: http://www.schloss-wiehe.de/schadensgeschichte.html ; 30.9.2013

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Hydraulic lime, portland cement

Binder = cement clinker, hydraulic lime
Water = precise, optimal amounts
Aggregate = suitable sand
Additions = diverse (liquidifiers, frost resistance inhancer, etc.)

Constructions out of stones and mortar

Loam (terre glaise)

Building material composed of sand (0.63 -2mm), silt (2 – 63 µm), manure and clay (about 40-40-10-10%)

Binder = clay minerals (drying = setting)
Water = the more water used the bigger the shrinking
Aggregate = sand, silt, straw, etc. → reduce shrinking
Additions = liquid manure, brine → reduce shrinking

Adobe (brique en pisé)

Air dried bricks formed out of loam

Mixed pebble and mud and mud brick wall

Lime

Principle

Extraction of natural stone (Limestone, marble; mainly $CaCO_3$) – burning – slaking – mixing with aggregate and water – air setting = hardening – lime ($CaCO_3$) mortar

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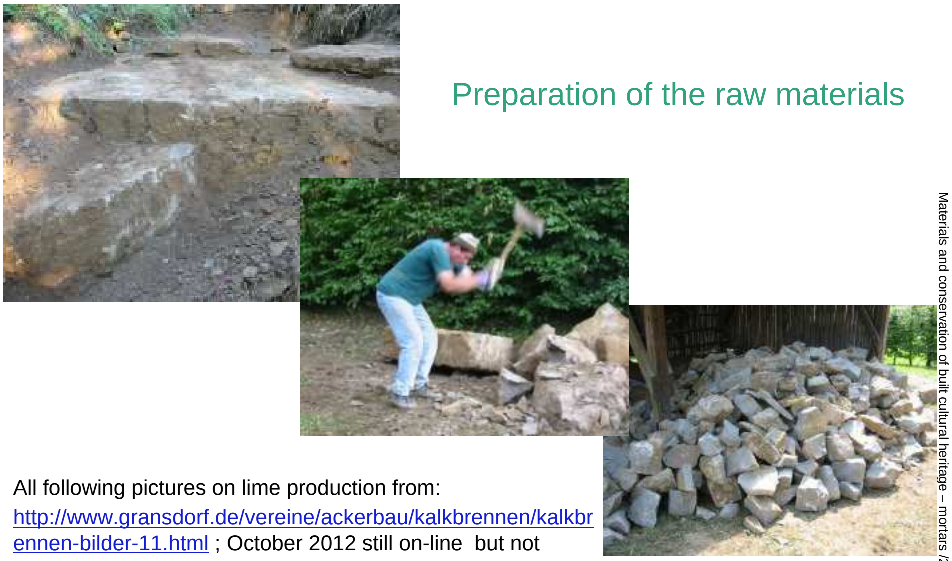
Preparation of the raw materials



All following pictures on lime production from:
http://www.gransdorf.de/vereine/ackerbau/kalkbrennen/kalkbrennen-bilder-11.html ; October 2012 still on-line but not anymore 30.9.2013

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Filling of the kiln

Collecting the fuel

Initial burning phase

Ignition at 20:15

A few hours after ignition the stones begin to dehydrate (black smoke)

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next morning dehydration nearly complete; clay covering is applied

clay layer is nearly dry, but black fumes can still be seen

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after about 35 hours: White between covering stones

flames come through the cover

after about 45 hours

Colour of embers (braise) shows high temperature

total firing time was 68 hours

After firing visible volume reduction

Burning

Lime (900 to 1000° C): $CaCO_3 \rightarrow CaO + CO_2\uparrow$

Factors influencing the properties of the burnt lime

- type of lime stone used
- dimension of the stones used for burning
- type of kiln
- type of fuel
- duration of burning
- temperature of burning

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Quicklime (lime, burnt lime; CaO)

Addition of water = slaking

Video on slaking under : http://www.youtube.com/watch?v=UXO0l5_4Eqw ; 30.9.2013

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Slaking of quicklime (extinction de la chaux vive)

$CaO + xH_2O \rightarrow Ca(OH)_2 + (x-1)H_2O$

Highly exothermal reaction; very quick (hence the name) and leading to a very noticeable temperature rise (boiling)

Addition of the soichiometrically needed amount of water plus the water evaporating during the process – powder of hydrated lime (chaux en poudre ou chaux hydratée)

Slaking with an excess of water and curing over years under water but protected from frost action in a pit – lime putty (chaux en pâte)

„Dry“ slaking – diverse possibilities, e.g. mixing with sand and water and immediate (sometimes still warm) use

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Lime mortar

Binder = lime

Water = little water → setting without fissures

Aggregate = sand

Additions = casein, animal hair, plant fibers, pigments, etc.

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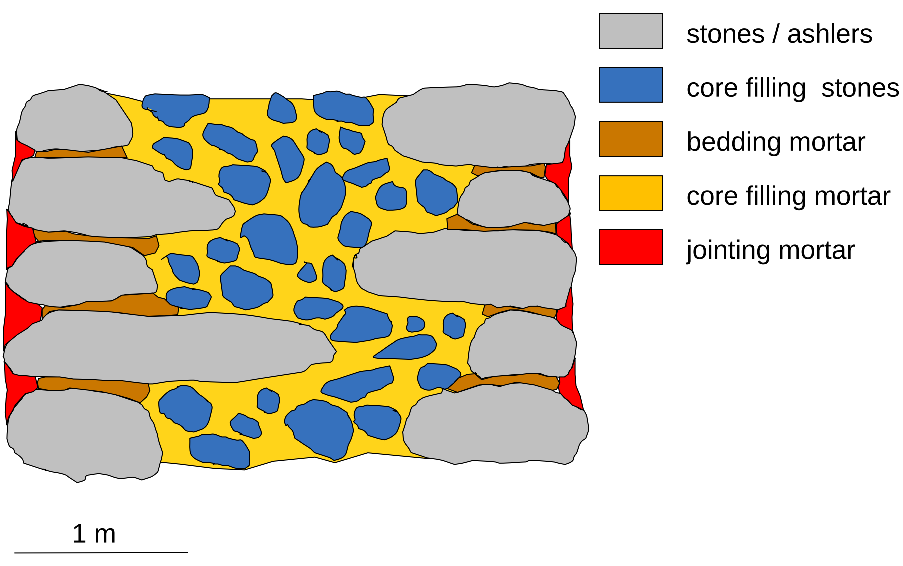

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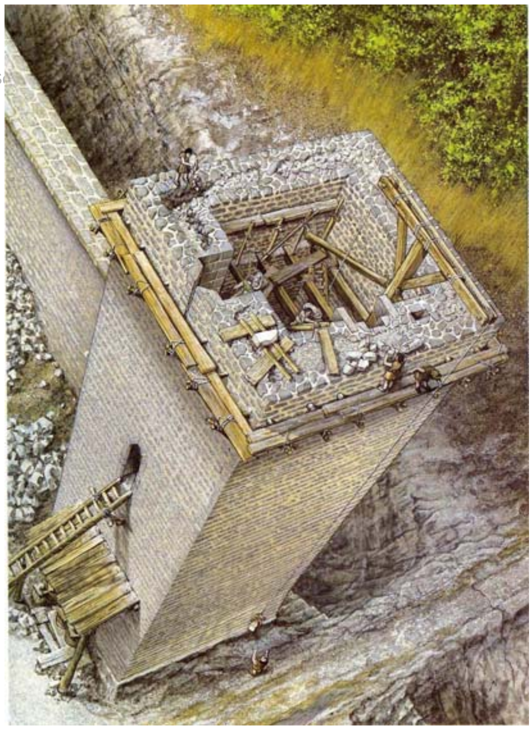
Boxler, H. and J. Müller (1991). "Burgenland Schweiz. Bau und Alltag." 2. Auflage. Verlag AARE Solothurn.



Meiringen, BE, Resti,14.10.08,
Rough stone masonry

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Sils im Domleschg, Campi,2.6.04

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bedding mortars

Loam as bedding mortar
India, Ladakh, Wanla, 23.7.2010


Zillis, GR, St. Martins church,
Romanesque wall


Fribourg, FR, city wall,29.5.08,
Ashlar masonry

Mortar dominated wall from Läufelfingen/BL
ruined castle , 20. century

Opus spicatum, (herringbone pattern)
Freudenberg, Bad Ragaz SG

Boulder masonry, Bossonens, FR

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Stone walls: jointing mortars

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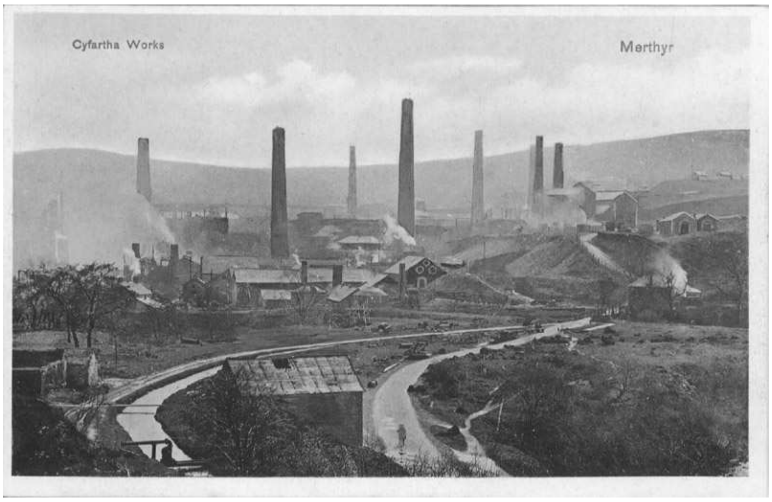
Cyfarthfa Ironworks, Merthyr Tydfil, GB
Iron production started 1765,
Closed 1919.



Info and photo from: http://www.alangeorge.co.uk/Images_A-H/CyfarthaWorks_web.jpg ; 30.9.2013

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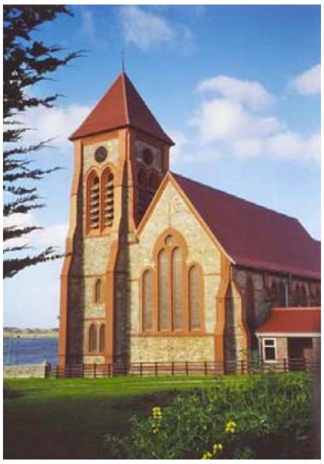
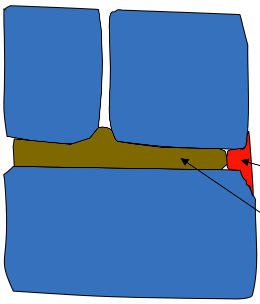
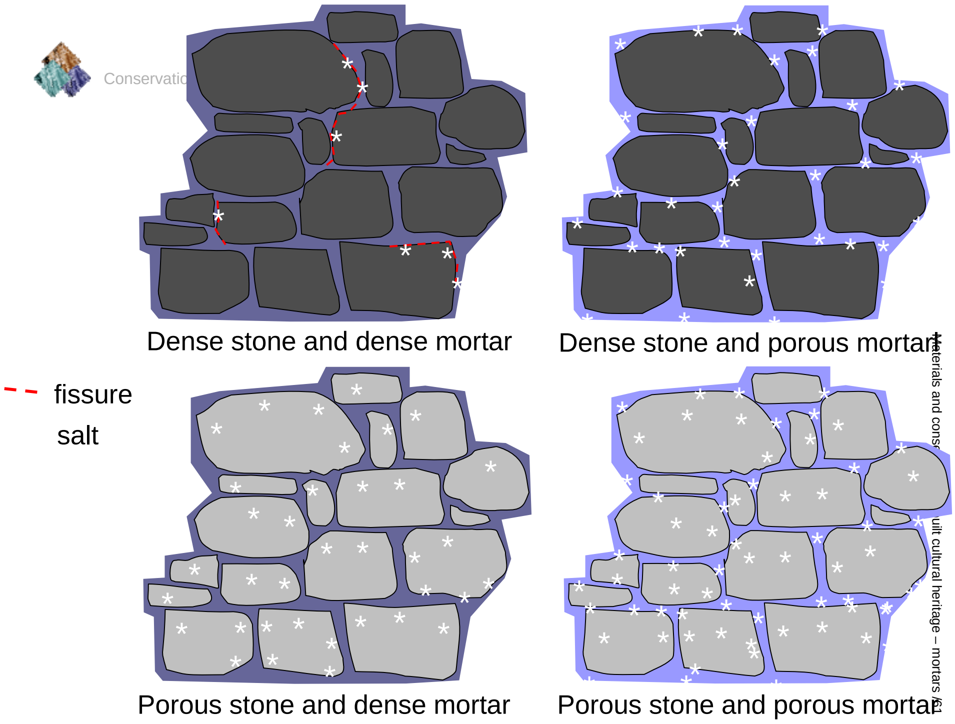
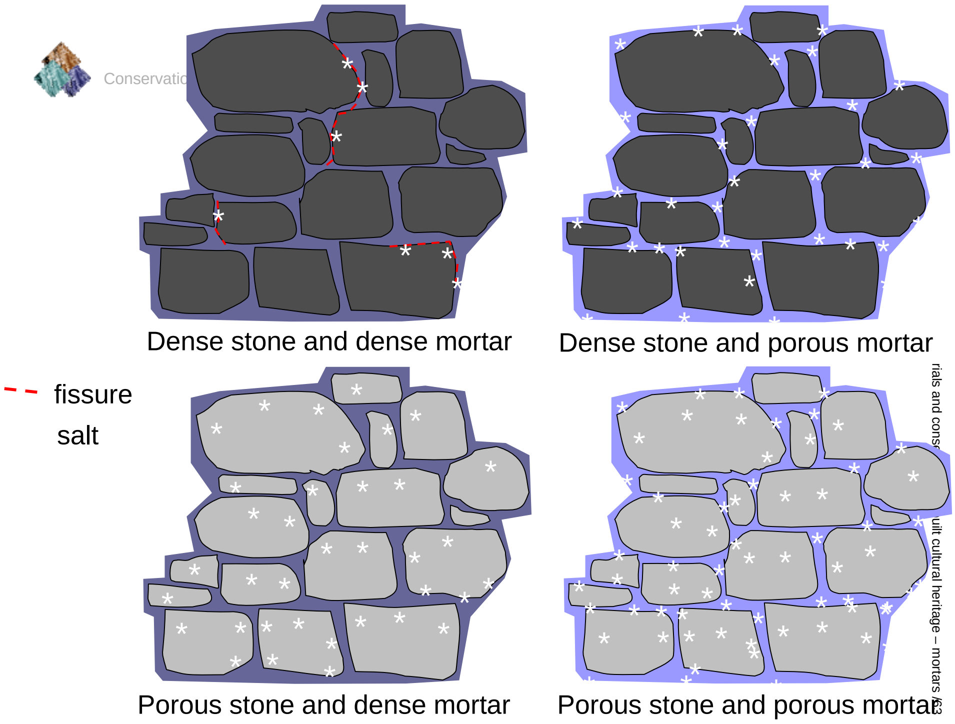
Christchurch Cathedral, Stanley, Falkland islands
Photo from:
http://de.wikipedia.org/wiki/Falklandinseln#Geschichte






Dense stone and dense mortar
Dense stone and porous mortar
fissure
salt
Porous stone and dense mortar
Porous stone and porous mortar


Dense stone and dense mortar
Dense stone and porous mortar
fissure
salt
Porous stone and dense mortar
Porous stone and porous mortar


Example
Ruined castle of Läufelfingen, BL

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Dolomitic lime mortars
San Gaidenzio, Casaccia GR

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Burning

Dolomite (700 to 1000° C): $CaMg(CO_3)_2 \rightarrow CaO + MgO + 2CO_2\uparrow$

Factors influencing the properties of the burnt lime

- type of lime stone used
- dimension of the stones used for burning
- type of kiln
- type of fuel
- duration of burning
- temperature of burning

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Slaking of dolomitic lime

„dry“:

$$xCaO + xMgO + 2xH_2O \rightarrow xCa(OH)_2 + (x\text{-}y)Mg(OH)_2 + yMgO + yH_2O$$

In a pit:

$$CaO + MgO + xH_2O \rightarrow Ca(OH)_2 + Mg(OH)_2 + (x\text{-}2)H_2O$$

Mg-Phases are separated from $Ca(OH)_2$– pure lime-putty!

Possible setting products of dolomitic lime binder

Portlandite	$Ca(OH)_2$
Calcite	$CaCO_3$
Aragonite	$CaCO_3$
Dolomite	$CaMg(CO_3)_2$
Periclase	MgO
Brucite	$Mg(OH)_2$
Magnesite	$MgCO_3$
Nesquehonite	$MgCO_3.3H_2O$
Lansfordite	$MgCO_3.5H_2O$
Artinite	$MgCO_3.Mg(OH)_2.3H_2O$
Hydromagnesite	$3MgCO_3.Mg(OH)_2.3H_2O$

Summary of chemical reactions for dolomitic lime

Burning

Dolomite (700 to 1000° C): $CaMg(CO_3)_2 \rightarrow CaO + MgO + 2CO_2\uparrow$

Slaking

Dolomitic lime:

„dry": $xCaO + xMgO + 2xH_2O \rightarrow xCa(OH)_2 + (x\text{-}y)Mg(OH)_2 + yMgO + yH_2O$

In a pit: $CaO + MgO + xH_2O \rightarrow Ca(OH)_2 + Mg(OH)_2 + (x\text{-}2)H_2O$

$Ca(OH)_2$ is separated from the Mg-Phases – $Ca(OH)_2$-putty!

Setting

Lime: $Ca(OH)_2 + CO_2 + H_2O \rightarrow CaCO_3 + 2H_2O$

Mg-Phases:

$xMg(OH)_2 + yMgO + pCO_2 + qH_2O \rightarrow$

$aMg(OH)_2 + bMgO + cMgCO_3.nH_2O$ + d-MgHydrCarb

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Lime or dolomitic lime mortar

Binder = lime and Mg hydroxides, hydrogencarbonates and carbonates

Water = little water → setting without fissures

Aggregate = sand

Additions = casein, animal hair, plant fibers, pigments, etc.

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Decorative wall coverings
• plasters / renders
• sgrafitto
• support for wall paintings


Paspels, GR, ruined castle, Alt Sins
19.3.06; pietra rasa

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Brienz, GR, ruined castle Belfort, 13th century render on the west wall of the „Palas“

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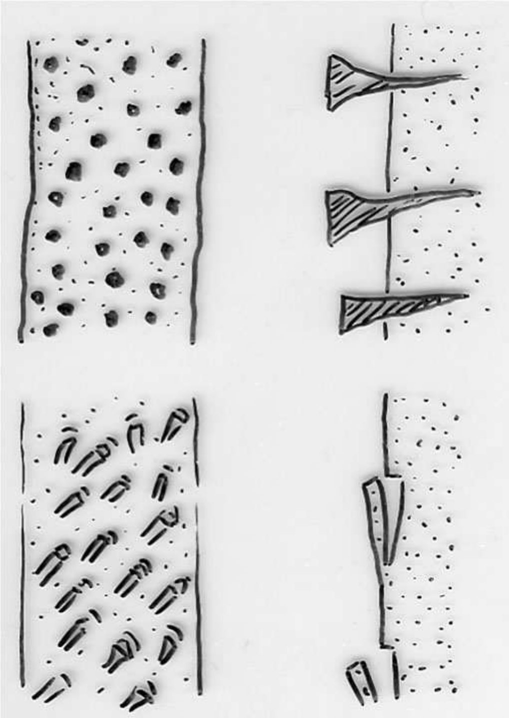
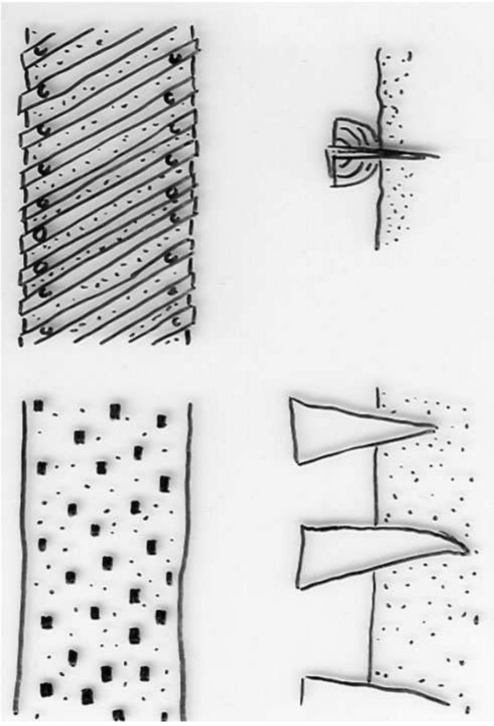
overhead Andreas Arnold



Drawing Andreas Arnold

Iron nails with big heads

Cuts

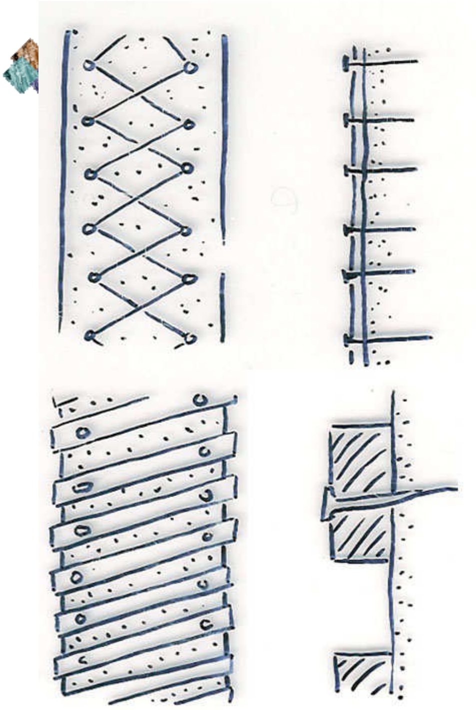


Drawing Andreas Arnold

Half branches

Wooden spigots

(out of hard wood from branches)

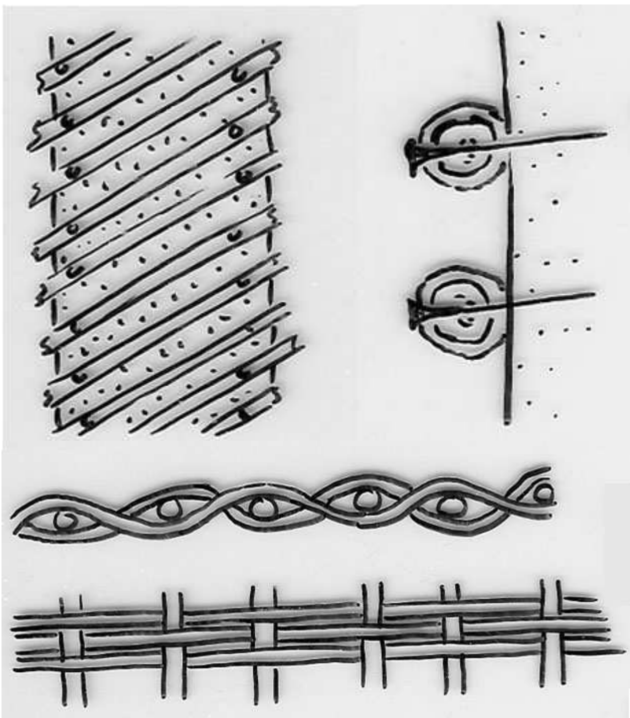


Drawing Andreas Arnold

Nails with wire
mainly 18^{th} – 19^{th} century
from 19^{th} on increasingly wire tacks

Wooden slats and
forged nails

more recent times tacks



Reed

Wattle (treillis)
Schilf

Drawings Andreas Arnold

Malans, GR

Kuessnacht, SZ

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Haus zum Vergnügen Basel
Wall board, cut with an axe 15.Jh

Photos Andreas Küng

Malta, Valetta, St. Johns Co-Cathedral

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School, Surcuolm, GR

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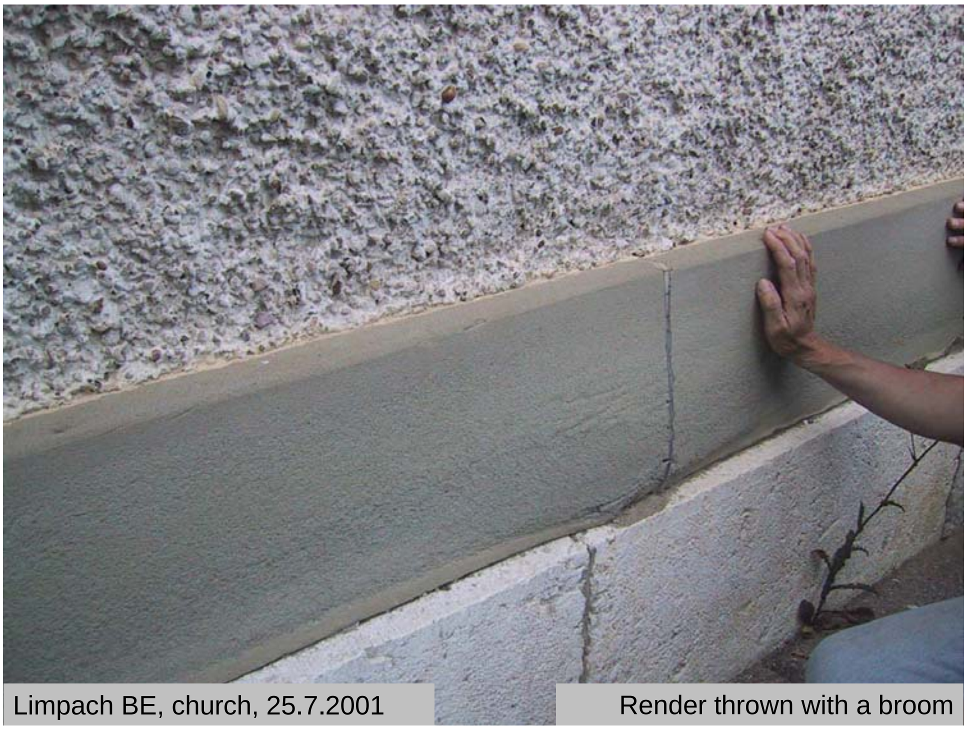
Berne, Zieglerspital, decorative render


Verena Church, Zurzach, AG


Limpach BE, church, 25.7.2001

Render thrown with a broom

Machine to apply a „Worms“ render

Foto:
Gipsergeschäft Kradolfer GmbH, Abt. Restaurierung, Wilerstrasse 22, 8570 Weinfelden

Küsnacht ZH, Höchhus, 2.7.2001

Render surface worked with a sack

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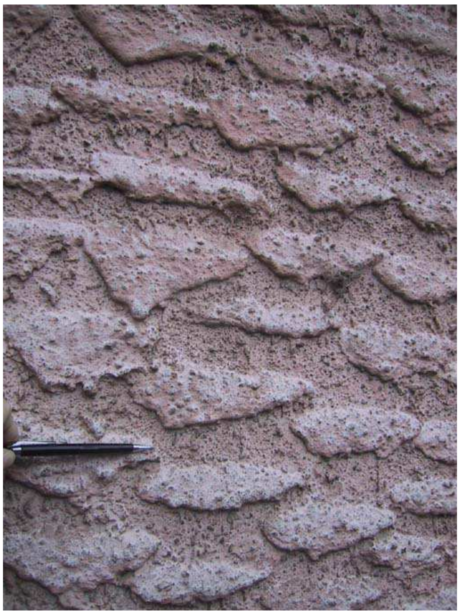

Küssnacht, SZ

Chur, GR

6.3.2004

Conserv

Ittingen TG, Chartreuse, church
4.5.2003

Zürich, Altstetterstr.119

Zürich Seebach, School


Mortar with applications

Sgraffito

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Wanla, Ladakh, North India

wall painting support

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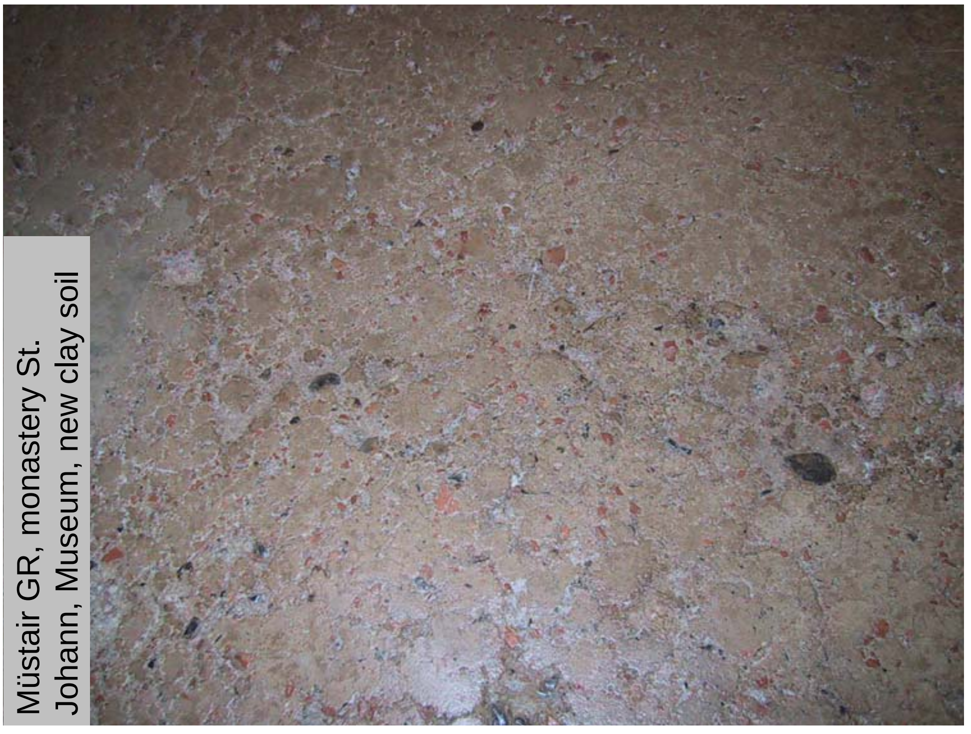
floors


Bischofszell TG, bridge over the Thur, 1487, carriageway


Müstair GR, monastery St. Johann, Museum, new clay soil

stone imitate
- with or
- without reworking by stonemasons
- castings

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Scagliola

Gypsum plaster, glue, pigments

Palais fédéral, Berne

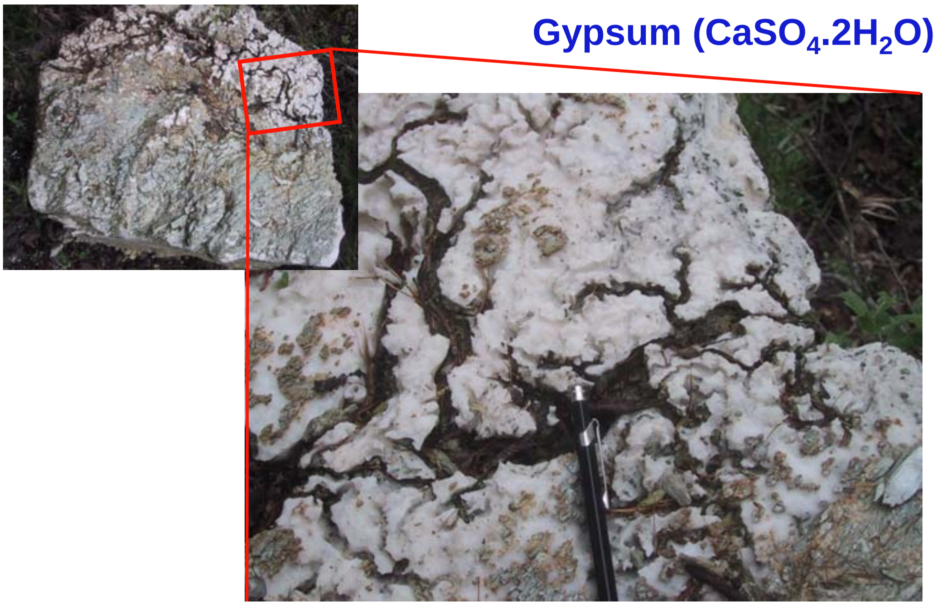
Gypsum

Principle

A) Extraction of natural stone (gypsum, $CaSO_4.2H_2O$) – burning – mixing with water – crystallization = hardening - gypsum

B) Extraction of natural stone (anhydrite, $CaSO_4$) – mixing with water and other ingredients – crystallization = hardening - gypsum

Gypsum ($CaSO_4.2H_2O$)



Gypsum burning

Heating to 65 to 110° C (Bassanite, plaster of Paris)

$CaSO_4.2H_2O \rightarrow CaSO_4.\ ½H_2O + 1½\ H_2O\uparrow$

- under atmospheric pressure = β-Halfhydrate
- under pressure in an autoclave = α-Halfhydrate

	α-Halfhydrate	β-Halfhydrate
Porosity of burnt material	non-porous	porous
water needed for setting	less	more
setting	slow	quick
compressive strength of set material	high	low
tensile strength of set material	high	low

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Heating to 180 - 240° C

→ Anhydrite III (Halfanydrite) ~ 1% H_2O (scarcely soluble)

Heating to 240 - 600° C

→ Anhydrite II no remaining water (= dead-burned gypsum)

Heating to > 600° C (mostly 900 - 1100° C)

Some of the anhydrite is transformed to lime

$CaSO_4 \rightarrow CaO + SO_3\uparrow$

Common properties of all gypsum or anhydrite binders:

- setting by (re-)crystallization of gypsum
- expand during setting (no setting fissures; need no aggregate)
- somewhat water soluble

Use of gypsum or anhydrite binders

Low temperature gypsum

Plastering, stucco, scagliola (faux „marbre“, Stuckmarmor)

High temperature gypsum

Flooring-plasters – usually with waterproof coating

Gypsum / anhydrite mortars

Binder = gypsum, anhydrite

Water = amount no problem;
no stirring allowed after setting has started

Aggregate = none necessary

Additions = animal glue, alum, wine, pigments, etc.

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Luzern, former Hotel Beaurivage; stone casts dating from ca. 1910

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Roman cement

Principle, roman cement

Extraction of natural stones (Marl = lime-rich mudstone) – burning (below 1100° C) – grinding - mixing with aggregate and water – hydraulic setting

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Roman cements

- Lime free hydraulic binders

  unlike hydraulic lime they contain **no** free lime

- Natural cements

  Burnt from a natural raw material - Marl

- Low temperature Cements

  Burnt at temperatures below sintering

All information, photographs and graphics used in the following slides on Roman cement, private communication by:

Prof. Johannes Weber, Universität für Angewandte Kunst Wien

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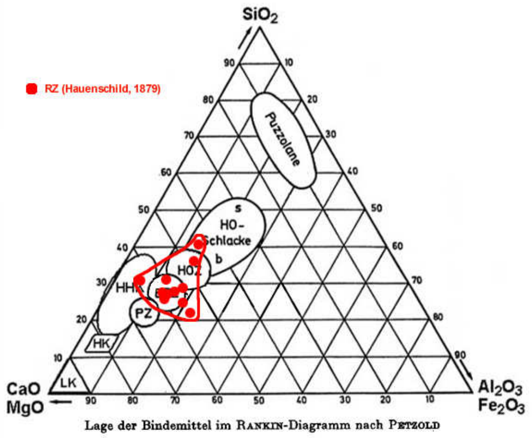
Marl

Fine grained sedimentary rock containing a mixture of lime and clay

$CaCO_3$	SiO_2, Al_2O_3, Fe_2O_3



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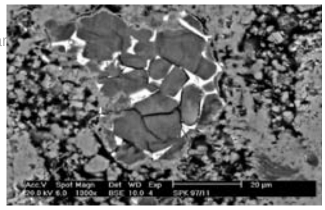
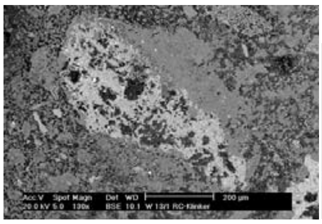


Portland cement

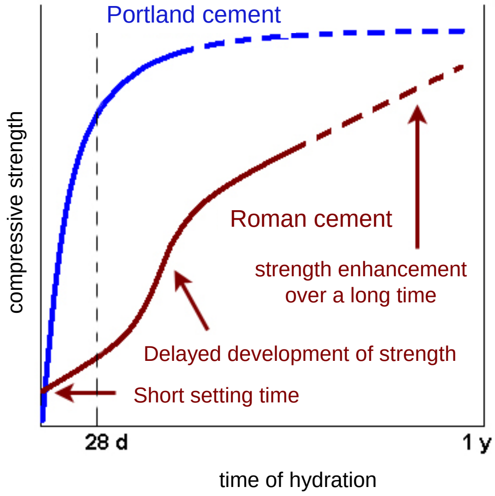
Lime-stone + clay —1400 °C→ PC clinker: **C_3S** + C_2S + C_3A + C_4AF

Marl —< 1100 °C→ RZ-“clinker“: ~~C_3S~~ + **C_2S** + ~~C_3A~~ + ~~C_4AF~~ + **non crystalline mixed phases**

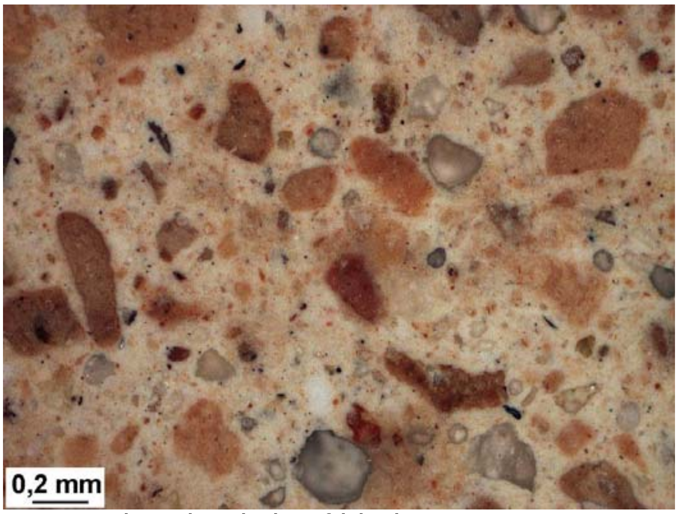
Roman cement



Development of strength



Cross section of a Roman cement mortar seen through a microscope



Charakteristic of binder aggregates

Roman cement
Photos Johanes Weber, Wien

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Mosaic
other works of art

Münsingen BE, Roman mosaic

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Evang. Lutheran church, Zürich

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Sculpture by Alicia Penalba, Uni St. Gallen

12.12.2002

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repair material
• for stones
• for renders

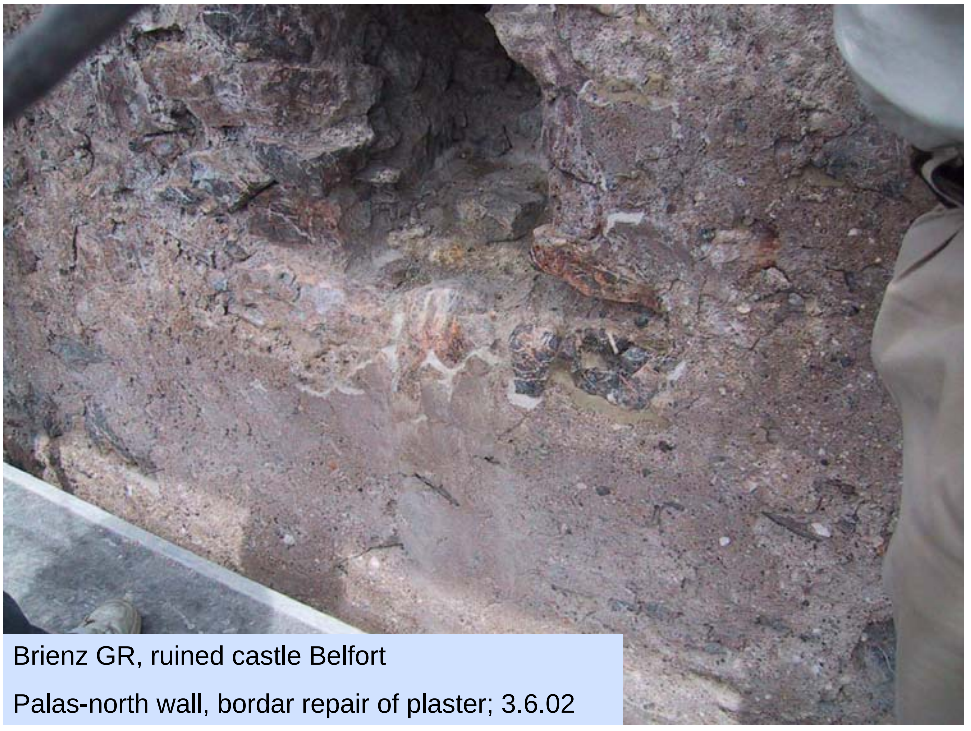
grouts

Bern, Bärenplatz, repair mortar


reinforcement


Repair mortar;
ground layer


finish



Brienz GR, ruined castle Belfort

Palas-north wall, bordar repair of plaster; 3.6.02

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