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MORTARS

Historic mortars and restoration mortars

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Dry-stone wall; Wanla, Ladakh, India

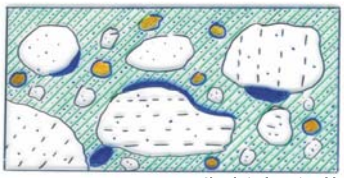
Boulder masonry, around 450 AD,
St. Stephan, Chur, GR

ca. 30 cm

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.

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.

Classification of mortars

- according to their use:
bedding mortar, jointing mortar, plaster, render, wall painting support, stucco, grout, repair mortar for stones, stone imitation etc.

- according to their predominant binder:
Clay, lime, pozzolan, hydraulic lime, cement, gypsum, etc.

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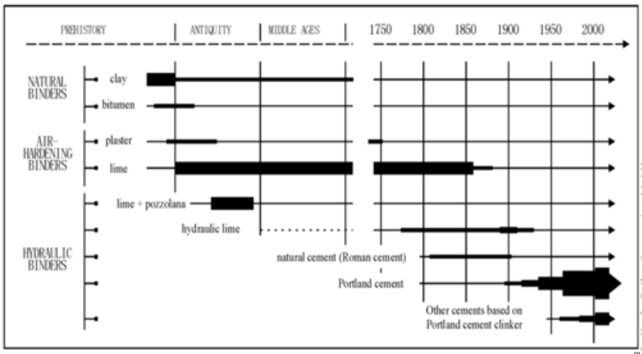

Predominant mortar binders

From: Elsen et al (2010) adapted after Delisle, J.P., Furlan, V. (1977)

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Binders	Raw material
Bitumen / asphalt	Natural deposit (later: Chemical processing)
Loam	Natural deposit
Gypsum	Natural deposit
Lime	Natural deposit
Dolomitic lime	Natural deposit
Pozzolan	Natural deposit / artificial mix of natural deposits
Hydraulic lime	Natural deposit / artificial mix of natural deposits
Roman cement / natural cement	Natural deposit
Portland cement	Artificial mix of natural deposits
Water glass	Chemical processing
Sorel cement / magnesia binder	Chemical processing
Epoxy / other synthetic material	Chemical industry

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Bitumen / Asphalt

mixture of organic liquids that are highly viscous, black, sticky and composed primarily of highly condensed polycyclic aromatic hydrocarbons.

Image: Asfalt rodzimy Słowacja.jpg

Binder = bitumen

Aggregate = e.g. gravel → compressive strength, less susceptible to heat deformation

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

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

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

Historically: Stucco, sculptures, renders

Modern: Flooring-plasters

Statue of Charlemagne, St. John convent, Müstair, GR

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.

Lime ($CaCO_3$)

Burning

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

after about 45 hours

Colour of embers (braise) shows high temperature

total firing time was 68 hours

After firing visible volume reduction

Film on lime burning (in German but with instructive pictures)
https://www.youtube.com/watch?v=WxTAam-FN8A ; 23.9.2016

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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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Quicklime (lime, burnt lime; CaO)

Addition of water = slaking

Video on slaking under : http://www.youtube.com/watch?v=UXO0I5_4Eqw ; 23.9.2016

Video on dry slaking under : https://www.youtube.com/watch?v=4ZhRKfaU3Es ; 23.9.2016

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Dolomitic lime

Burning

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

Slaking of dolomitic lime

„dry“:

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

In a pit:

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

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


Dolomitic lime mortars
San Gaidenzio, Casaccia GR

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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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Pozzolan (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

Pozzolan (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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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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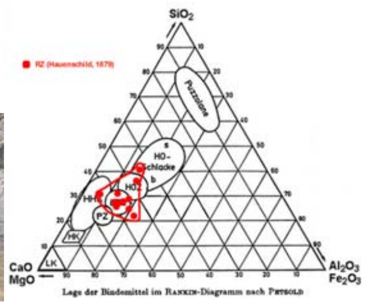
Infos and images by:

Prof. Johannes Weber, Universität für Angewandte Kunst, Wien

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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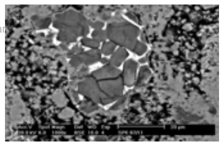
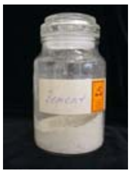


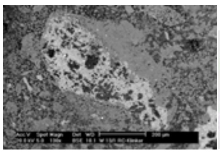


Portland cement

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



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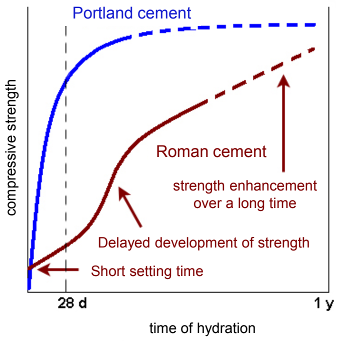
Development of strength



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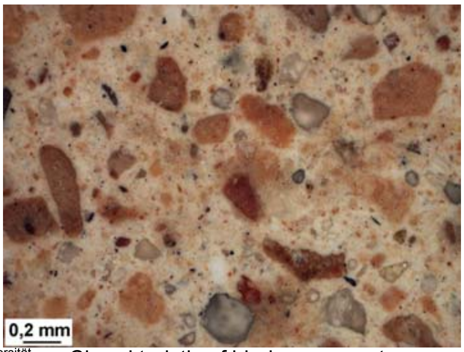
Cross section of a Roman cement mortar seen through a microscope



Charakteristic of binder aggregates

Infos and images by:

Prof. Johannes Weber, Universität für Angewandte Kunst, Wien

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

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%

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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 ; 23.9.2016

Degradation of Bernese sandstone by salts from concrete

Efflorescence of thermonatrite ($Na_2CO_3.H_2O$)

CH, BE, Bern, Altenberg, wall at the river Aare, 30.1.2008

Hydraulic lime, portland cement

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

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 ; 25.09.2015

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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 23.9.2016

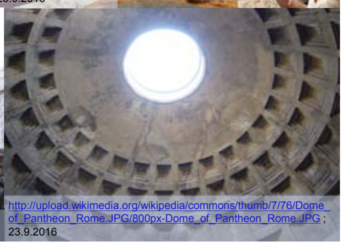
Materials and conservation of built cultural heritage – mortars

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 ; 23.9.2016

http://upload.wikimedia.org/wikipedia/commons/9/9e/Rome_Pantheon.jpg ; 23.9.2016



http://upload.wikimedia.org/wikipedia/commons/thumb/7/76/Dome_of_Pantheon_Rome.JPG/800px-Dome_of_Pantheon_Rome.JPG ; 23.9.2016

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Wuennewil, FR, church

Rammed concrete ca. 1932 (béton non armé)

24.3.2004

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Constructions out of stones and mortar

Mixed pebble and mud and mud brick wall

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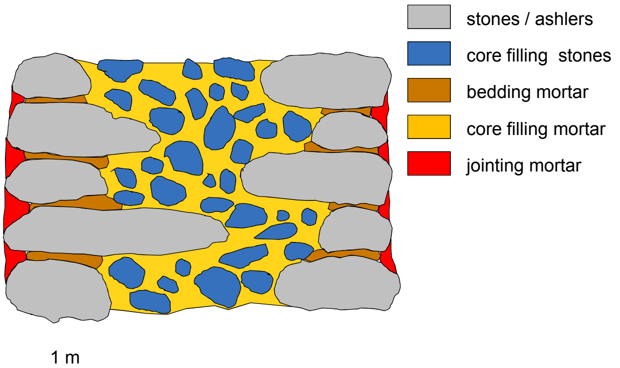

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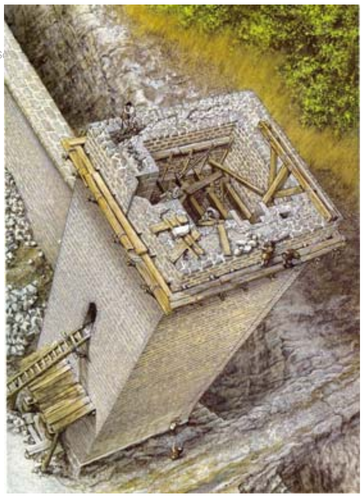

Meiringen, BE, Resti,14.10.08,
Rough stone masonry

Sils im Domleschg, Campi,2.6.04

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bedding mortars

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Loam as bedding mortar
India, Ladakh, Wanla, 23.7.2010

Zillis, GR, St. Martin church,
Romanesque wall


Fribourg, FR, city wall,29.5.08,
Ashlar masonry

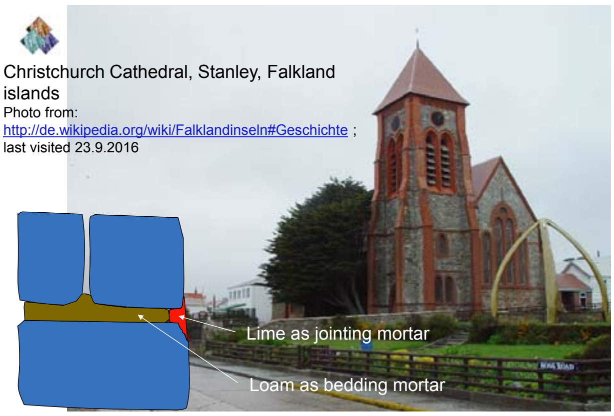

Mortar dominated wall from Läufelfingen/BL
ruined castle , 20. century


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

Boulder masonry,
Bossonens, FR

Stone walls:
jointing mortars

Christchurch Cathedral, Stanley, Falkland islands
Photo from:
http://de.wikipedia.org/wiki/Falklandinseln#Geschichte ;
last visited 23.9.2016



Type of construction often used also in Europe until medieval time!

Créteil, église,
24.9.2014

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

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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

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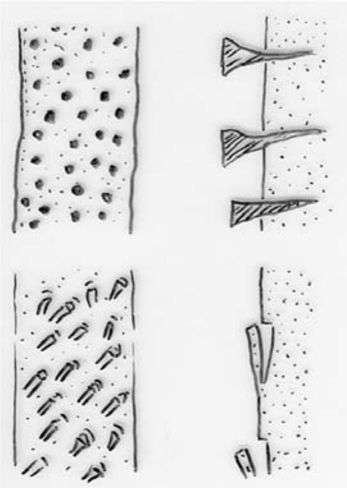

Iron nails with big heads

Cuts

Drawing Andreas Arnold

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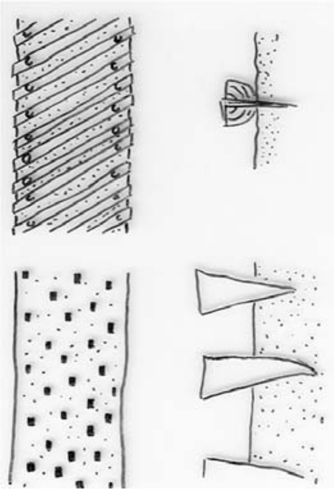
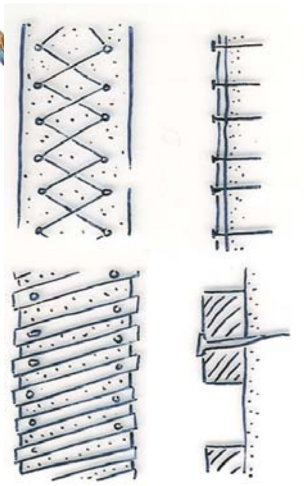


Drawing Andreas Arnold

Half branches

Wooden spigots

(out of hard wood from branches)

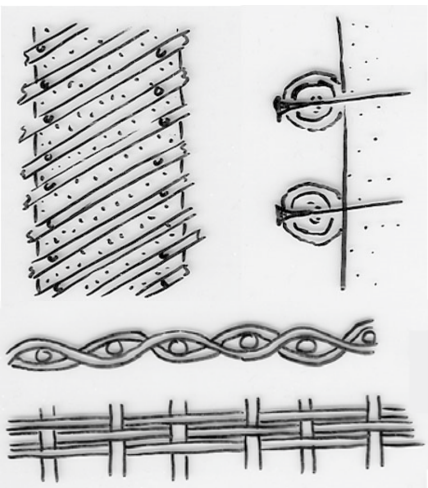


Drawing Andreas Arnold

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

Wooden slats and forged nails

more recent times tacks



Reed

Wattle (treillis)
Schilf

Drawings Andreas Arnold


Malans, GR

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Küssnacht, SZ

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

Photos Andreas Küng

nd conservation of built cultural heritage – mortars /81

Malta, Valetta, St. Johns Co-Cathedral

ZH, Winterthur, Mörsburg, 21.5.2013

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School, Surcuolm, GR

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Berne, Zieglerspital, decorative render

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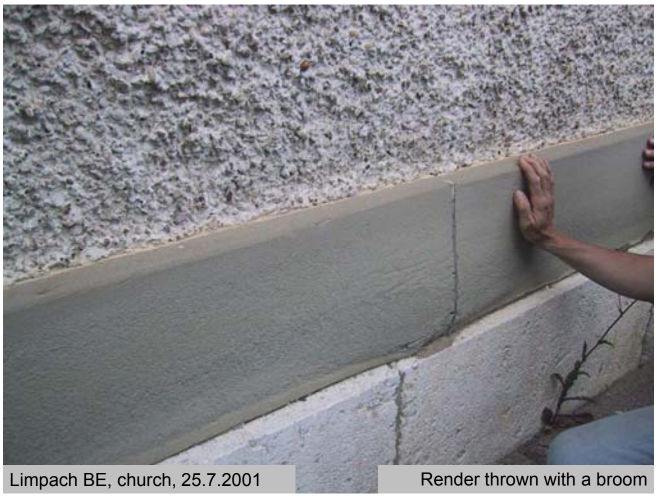
Verena Church, Zurzach, AG



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

Küssnacht, SZ

Chur, GR 6.3.2004 s /91

Zürich, Affolterm

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Stone imitation

Ittingen TG, Chartreuse, church
4.5.2003

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Zürich, Altstetterstr.119

Zürich Seebach, School

Mortar with applications

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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

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

Scagliola

Gypsum plaster, glue, pigments

Palais fédéral, Berne

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

Roman cement
Photos Johanes Weber, Wien

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Mosaic
other works of art

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Münsingen BE, Roman mosaic

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Evang. Lutheran church, Zürich

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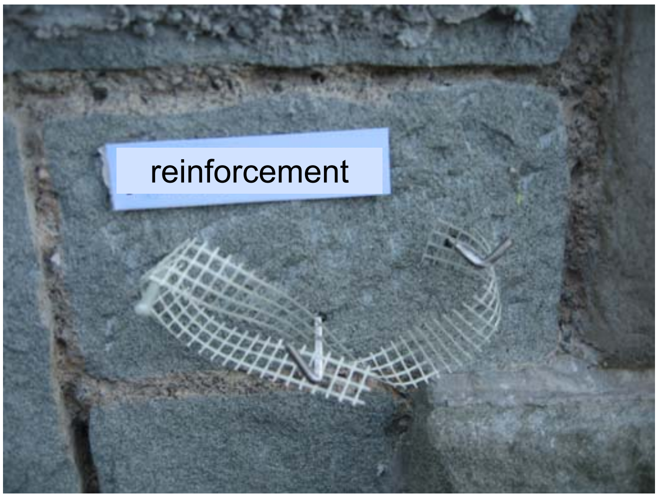
Sculpture by Alicia Penalba, Uni St. Gallen

12.12.2002

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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