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MORTARS

Historic mortars and restoration mortars

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Dry-stone wall; Wanla, Ladakh, India

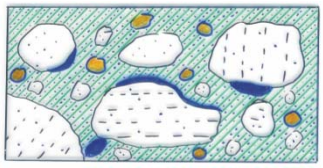
Boulder masonry, around 450 AD,
St. Stephan, Chur, GR

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

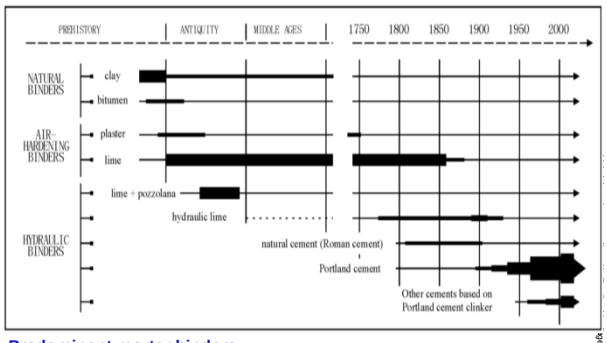
Air = pore space

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, etc.



Predominant mortar binders

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

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

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)

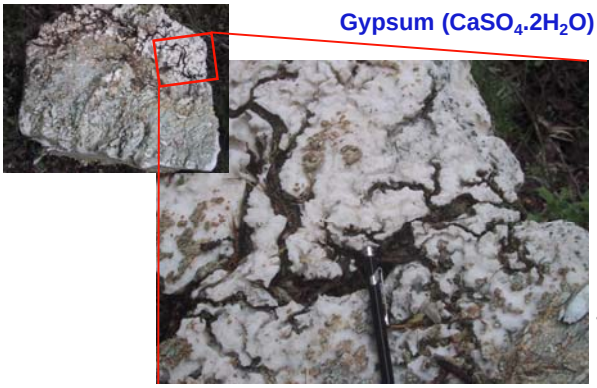
Building material composed of sand (0.63 -2mm), silt (2 – 63 µm), manure and clay (about 40-40-10-10%)

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 ($CaSO_4.2H_2O$)



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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

$CaSO_4 \rightarrow CaO + SO_3\uparrow$

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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

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

Quicklime (lime, burnt lime; CaO)

Addition of water = slaking

Video on slaking under : http://www.youtube.com/watch?v=UXO0l5_4Eqw ; 12.10.2015

Video on dry slaking under : https://www.youtube.com/watch?v=4ZhRKfaU3Es ; 12.10.2015

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!

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.

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

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)

Pozzolanic mortars

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

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

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

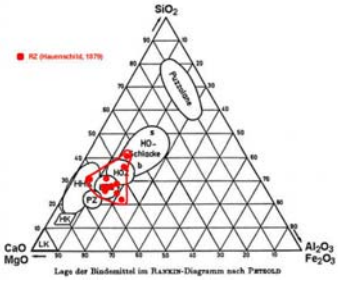
All information, photographs and graphics used in the following slides on Roman cement, private communication by:

Prof. Johannes Weber, Universität für Angewandte Kunst Wien

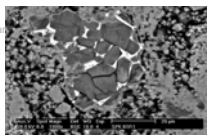
Marl

Fine grained sedimentary rock containing a mixture of lime and clay

$CaCO_3$ | SiO_2 Al_2O_3 Fe_2O_3



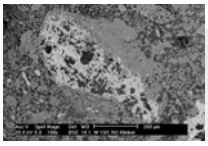
Portland cement



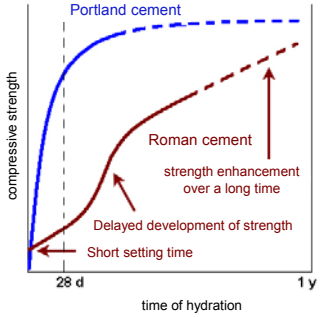
Lime-stone + clay $\xrightarrow{1400\,^\circ C}$ PC clinker:
$C_3S + C_2S + C_3A + C_4AF$

Marl $\xrightarrow{< 1100\,^\circ C}$ RZ-"clinker":
~~C_3S~~ + C_2S + ~~C_3A~~ + ~~C_4AF~~ +
non crystalline mixed phases

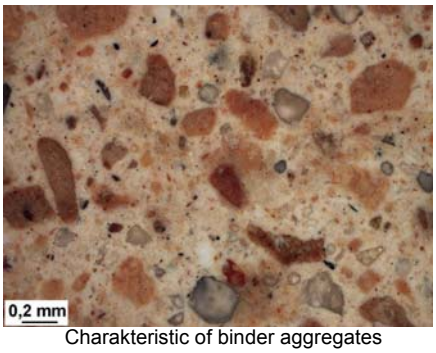
Roman cement



Development of strength



Cross section of a Roman cement mortar seen through a microscope



Charakteristic of binder aggregates

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%

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.

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 ; 25.9.2015

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

Buildings constructed only out of mortars s.l.

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

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 25.9.2015

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 ; 25.9.2015

http://upload.wikimedia.org/wikipedia/commons/9/96/Rotunda_Pantheon.jpg ; 25.9.2015

http://upload.wikimedia.org/wikipedia/commons/thumb/7/76/Dome-of-Pantheon_Rome.JPG/800px-Dome-of-Pantheon_Rome.JPG ; 25.9.2015

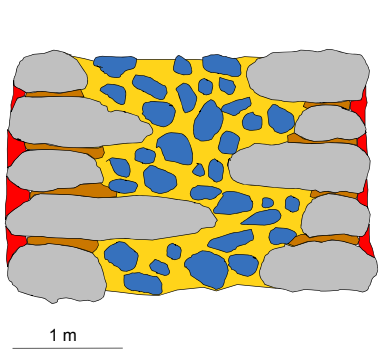
Conservation Sc

24.3.2004

Wuennewil, FR, church
Rammed concrete ca. 1932 (béton non armé)

Constructions out of stones and mortar

Mixed pebble and mud and mud brick wall



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

Materials and conservation of built cultural heritage – mortars /49

Meiringen, BE, Resti,14.10.08,
Rough stone masonry

Materials and conservation of built cultural heritage – mortars /50

Sils im Domleschg, Campi,2.6.04

Materials and conservation of built cultural heritage – mortars /51

bedding mortars

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

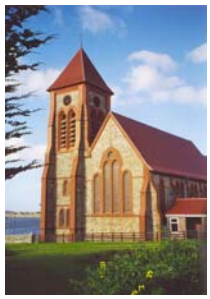
Mortar dominated wall from Läufelfingen/BL
ruined castle , 20. century

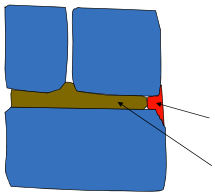
Opus spicatum, (herringbone pattern)
Freudenberg, Bad Ragaz SG

Boulder masonry,
Bossonens, FR

Stone walls: jointing mortars

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





Créteil, église,
24.9.2014

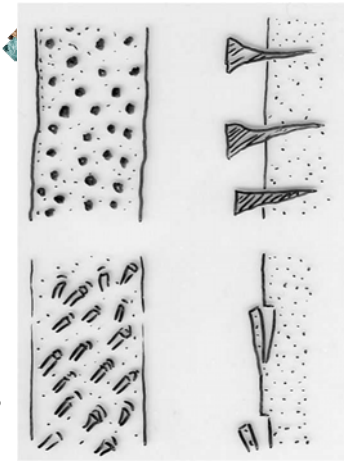

Dolomitic lime mortars
San Gaidenzio, Casaccia GR

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

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

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

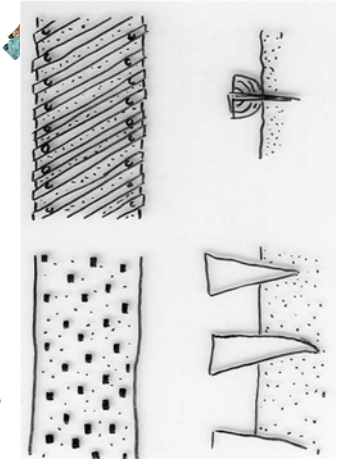
overhead Andreas Arnold



Drawing Andreas Arnold

Iron nails with big heads

Cuts

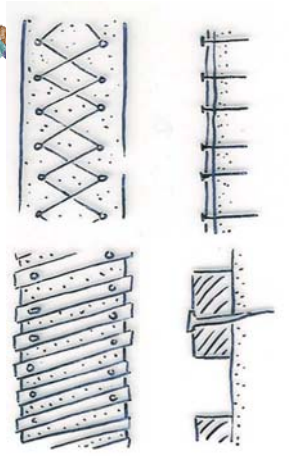


Drawing Andreas Arnold

Half branches

Wooden spigots

(out of hard wood from branches)

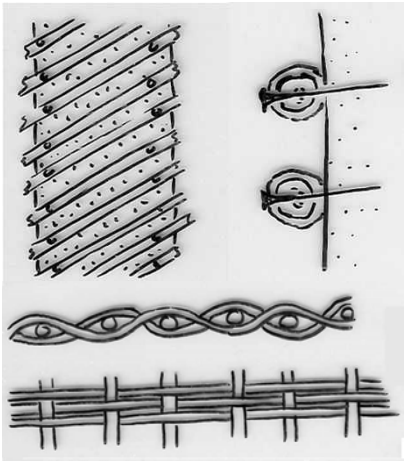


Drawing Andreas Arnold

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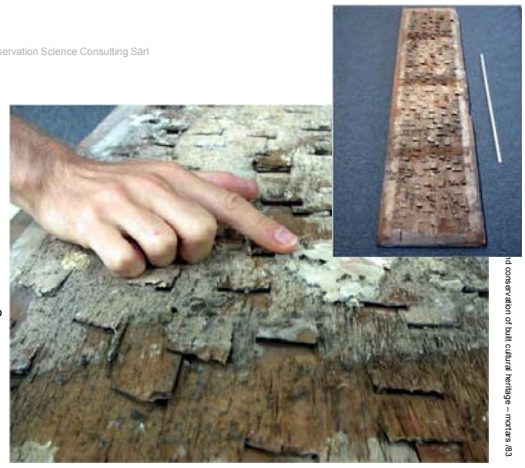
Haus zum Vergnügen Basel
Wall board, cut with an axe 15.Jh

Photos Andreas Küng



Malta, Valetta, St. Johns Co-Cathedral

ZH, Winterthur, Mörsburg, 21.5.2013

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School, Surcuolm, GR

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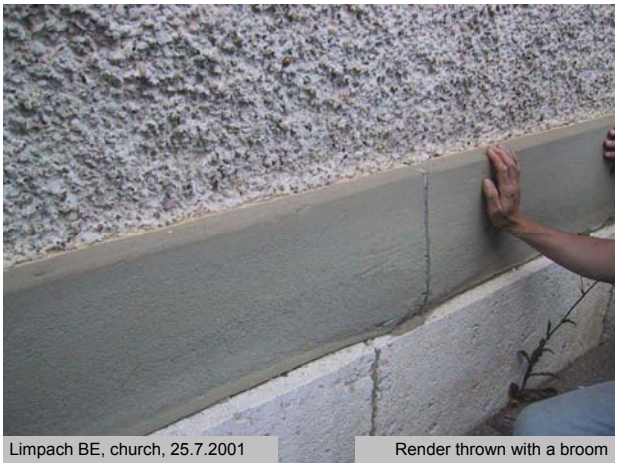
Berne, Zieglerspital, decorative render

Verena Church, Zurzach, AG



Limpach BE, church, 25.7.2001 Render thrown with a broom

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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

Zürich, Affolterm

Ittingen TG, Chartreuse, church
4.5.2003

Zürich, Altstetterstr.119

Zürich Seebach, School

Mortar with applications

Sgraffito

Wanla, Ladakh, North India

wall painting support

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

Scagliola

Gypsum plaster, glue, pigments

Palais fédéral, Berne

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

Roman cement
Photos Johanes Weber, Wien

Mosaic
other works of art

Münsingen BE, Roman mosaic

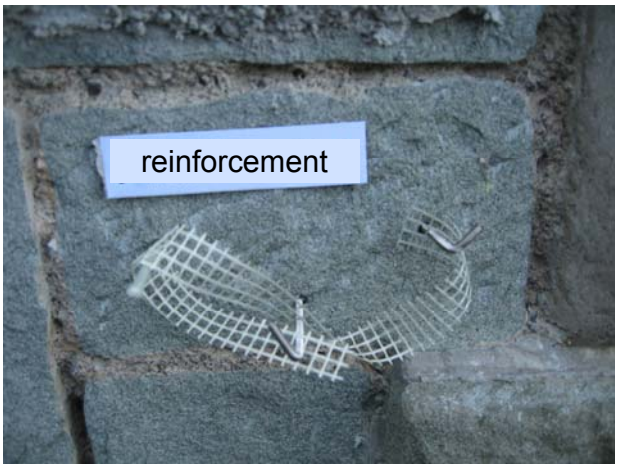
Evang. Lutherian
church, Zürich

Sculpture by Alicia Penalba, Uni St. Gallen 12.12.2002

repair material
- for stones
- for renders

grouts

Bern, Bärenplatz, repair mortar



Repair mortar;
ground layer

finish

Brienz GR, ruined castle Belfort

Palas-north wall, bordar repair of plaster; 3.6.02

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