Roman cements - key materials of the built heritage of the nineteenth century

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1. Introduction

Highly hydraulic binders, known as natural or Roman cements, were key materials for the economic and easy manufacture of stuccoes for the exterior of buildings during the nineteenth and early twentieth centuries. Roman cements were produced by burning naturally occurring deposits of calcium carbonate rich in clay minerals. They were distinguished from other hydraulic binders principally by a very short setting time, agreeable texture and colour, little shrinkage on setting and excellent weather-resistance. They were first produced in England in 1796 when James Parker patented a cement known as Parker’s or Roman cement (Parker 1796). The material was obtained by firing clay-bearing calcareous nodules found in the London clay beds on the Isle of Sheppey, England. Despite implied links to the Roman binders, Parker’s ‘Roman cement’ was a true hydraulic cement very different from the hydraulic binders used by the Romans in which pozzolanic materials, not cementitious in themselves, had combined with lime in the presence of water to form insoluble compounds possessing cementing properties. The Roman cement mortars were mainly used in construction where masonry was subjected to moisture and high levels of strength and durability were needed.

The manufacturing of Roman cement developed in mainland Europe after 1850. In contrast to England, where cements were largely produced from the nodules, marls were the usual source.
Despite this difference, the term ‘Roman cement’ and its translation into various national languages was widely used to describe natural cements from both sources. Roman cement mortars were highly recommended in contemporary technical literature and textbooks for stuccoists as being ideal for plastering applications (particularly run mouldings and castings). They were used on a massive scale for economic and easy manufacture of ornaments and renders for the exterior of buildings in the period of European Historicism and Art Nouveau (19th/early 20th century). Roman cement is now often referred to as the exterior equivalent of gypsum plaster as it offered the same speed of set and manipulation as gypsum yet could withstand exterior conditions very effectively. The unique properties of this particular binder and the specialised methods of its usage enabled craftsmen to develop a stylistic language of architectural decoration which today determines the aesthetic appearance of central areas in most European cities.

In the UK, the use of Roman cements gradually declined in the latter half of the nineteenth century, being displaced by the newer Portland cement which came to dominate the market. In contrast, it is known from contemporary sources that - e.g. in the Austro-Hungarian Empire of 1887 - the amount of Roman cement produced was five times higher than that of either Portland cement or hydraulic lime (Tarnawski 1887). In the years following World War I, the dominance of the newer Portland cement on the market and modern functional architecture, with its total absence of ornament, brought a quick decline in the production and use of Roman cements. The lack of appropriate binding materials - matching those available to the craftsmen of the nineteenth century - has for a long time deprived architects and conservators of the original historic technology for the repair and conservation of such objects. A further problem was an absence of any broader information on the material characteristics, ageing behaviour and adequate technologies for protection and restoration, which resulted in little understanding for the necessity for well-designed, high-quality interventions. Although there exists a range of historic literature and archival sources describing raw materials, manufacturing process, composition of mortars as well as application and craft techniques (e.g. Vicat 1828, 1837, Pasley 1830, Austrian Standard 1878, Tarnawski 1887, Eckel 1905, Bohnagen 1914), the quality of this literature is inconsistent due to the changing regional markets and scientific approach and methodology during the period in question i.e. late 18th to early 20th centuries. Only relatively recently, with growing interest in European art of the late 19th/early 20th centuries, have attempts been undertaken to investigate these historic renders and to develop strategies and adequate measures for their conservation. The RENDEC project (1997-1999) provided ample information on historic cements and mortars used in Central Europe in the
period around 1900 (Decorated Renders 1999). Cailleux et al. (2006) evaluated properties, microstructure and deterioration mechanisms of historic concretes produced with the use of natural cements from the French Rhône-Alpes region. The French natural cement Prompt is still produced by Vicat by burning marl deposits at Chartreuse in the Rhône Alps at moderate temperatures and is the only natural cement produced in Europe. Peconi et al. (2005) provided information on petrographical, mineralogical and chemical characteristics of the ‘artificial stones’ used to decorate palaces in Florence in the nineteenth and twentieth centuries. All materials investigated were hydraulic mortars and the use of natural cements to produce the decorations can be inferred from the presence of unhydrated di-calcium silicate (belite) identified in some samples. Varas et al. (2005) characterised hydraulic mortars manufactured with the use of Spanish natural cements at the end of the nineteenth century. The ROCEM project, supported by the European Commission as part of its 5th Framework Programme, has extensively investigated historic renders based on Roman cements and has re-established this historic material and technology to the conservation practice (Weber et al. 2007; Hughes et al. 2007a, 2007b, 2007c, 2008a, 2008b; Tislova et al. 2008; Vyskocilova et al 2007). The aim of the present publication is to provide information on Roman cements, awaken interest in this unique material and technology and help conservation authorities and practitioners to plan and carry out restoration of historic Roman cement stuccoes to new high standards.

2. What is Roman cement?

Roman cements were produced from marls - limestones containing clay – frequently sourced in the form of cement-stones embedded in clay or shale deposits. This natural combination of calcareous and argillaceous matter required only moderate calcination(800 - 1200°C) - below the sintering temperature - and subsequent grinding to produce a binder of remarkable strength and durability. The success of the cement synthesis at low temperatures resulted from the natural intimate mixture of lime and clay (source of silica, alumina and iron oxide) in the marl, which could not be attained in any man-made mixture. Roman cements can be placed between hydraulic limes and Portland cements in the sequence of binders shown in Figure 2. They differ from hydraulic limes in that they are not high in free lime and therefore require grinding rather than slaking. They differ from the Portland cements by the different chemistry resulting from considerably lower calcination temperatures. While $\text{C}_2\text{S}$
(dicalcium silicate, belite) is the major hydraulic phase in Roman cements, \(C_3S\) (tricalcium silicate, alite) is the major phase in ordinary Portland cement.

The Austrian Standard of 1878, modified in 1890, provides a contemporary definition of Roman cements: ‘Roman cements are products obtained from argillaceous marlstones by burning below the sintering temperature. They do not slake in contact with water and must therefore be ground to a floury fineness.’ It specifies the range of setting times which facilitated the choice of a suitable material for a given decorative task: ‘Roman cements bind fast, medium and slow. By fast binding cements one should understand those which with no addition of sand start to harden within 7 minutes from the moment water is added. Roman cement is considered a slow binding variety if hardening starts later than after 15 minutes’. Other features specified by the standards are: volume consistency under water and in air, fineness of grinding, as well as tensile and compressive strengths for various cements and ages, as given in Table 1.

3. Raw materials and the production of Roman cements

Suitable marlstones, which were exploited for Roman cements, could be found in different geologic formations: the best known English Roman cements were made by calcining Septarian nodules from the Eocene London clays or from the Jurassic and Cretaceous formations along the coastlines. In continental Europe, deposits of stratified marls were mined in France, especially in the Jurassic areas of Burgundy and the Cretaceous region near Grenoble. The marls quarried in the Eastern Alps were of Jurassic, Cretaceous or Eocene age, such as in the Bergamo area in northern Italy, in Tyrol, the area near Salzburg and in the area west and south of Vienna. Other important sites of production were situated mainly in the Swiss Pre-alps, in Southern Germany, Bohemia and Galicia, today’s Southern Poland.

The marlstone was crushed to small, fist sized fragments and mostly fired in shaft kilns – an early example is shown in Figure 3. The exact type and size of those kilns varied, but with growing industrialisation during the nineteenth century an increasing number of big factories were running batteries of kilns for the production of Roman cement. The usual fuel was coal, coke, wood or turf. The calcination temperatures had to be high enough to largely enable the decomposition of calcite, but on the other hand low enough to prevent sintering. Under such conditions, different degrees of calcination were likely to occur even within one batch.
Unable to slake in contact with water, caused by its lack of free lime, the calcined material, the Roman cement ‘clinker’, had to be ground to a fine powder. Then it was packed usually into 250 kg barrels or 60 kg sacks and shipped by rail or river.

4. Historic Roman cement mortars

During the ROCEM project, a number of historic buildings across Europe, rendered and decorated with Roman cement mortars, were investigated (Weber et al. 2007). They covered a long period of the nineteenth and early twentieth centuries. The samples of mortars collected were representative of different modes of application, from cast ornaments to in-situ applied renders and hand-run elements. The most evident observation was the generally excellent state of preservation of the investigated elements.

**Aggregate**: A striking observation was a wide range of aggregate content: for cast and hand-run mortars the aggregate contents were low - typically 20 - 25%, for renders and especially pointing mortars the proportion was higher - generally 40 - 50%. The results match the recipes for mortar mixtures given in the handbooks of the nineteenth century. A wide range of mineralogical materials were used as aggregate, which reflected local geological conditions.

**Hydrated binder**: The microstructure of the Roman cement pastes shows a very fine ‘groundmass’ encapsulating a significant amount of unhydrated remnants of original cements; in some cast mortars their amount can even outmatch the inert aggregate. Incompletely hydrated grains of C$_2$S – a principal compound of Roman cements - are most frequent, as well as gehlenite (C$_2$AS), rankinite (C$_3$S$_2$), wollastonite (CS) and a number of solid solutions in the system SiO$_2$-CaO-Al$_2$O$_3$-Fe$_2$O$_3$. A thorough investigation by means of SEM/EDX permitted the classification of the unhydrated cement grains into three major groups: overfired, well fired and underfired. The different degree of calcination within the same batch of the raw material was the result of its natural inhomogeneity as well as temperature gradients within a kiln. The remnants are of significant importance for the mortar properties, as they act as aggregates strongly bound to the surrounding hydrated matrix of the cement. Their maximum grain size is around 1 mm, an indication that historic Roman cements were ground quite coarsely. The historic Roman cements mortars are usually strongly carbonated.

**Layer structure**: The plain renders varied in thickness between 2 - 50 mm. As a result of the low shrinkage on setting, it was possible to apply Roman cement mortars much thicker in comparison to lime coats which did not exceed 10 - 12 mm. The renders could consist of a single
render coat applied directly to a solid masonry background or be a sandwich structure in which the render coat was followed by the second coat providing a final level surface. Also, run mouldings and castings usually had finer outer layers and a coarse interior core.

There is well documented evidence that early English Roman cement stuccoes were coloured by limewashes and later by oil paints, sometimes to imitate the colour of Bath stone. The post-1850 Roman cement stuccoes in Central Europe were usually unpainted, and Roman cement wash, composed of the cement diluted in water, was a universal technique for finishing them.

**Porosity:** A distinctive feature of most historic Roman cement mortars is their high porosity accessible to water (30 - 40 % by volume), combined with generally high mechanical strength and excellent durability. Mercury porosimetry has revealed two principal categories of pores. The finest pores with the pore diameter below 0.2 µm are present within very well-hydrated mature Roman cement matrix. Larger pores with the diameters of around 1 µm are characteristic of mortars strongly exposed to air in which the hydration process was interrupted by the evaporation of water.

**Physico-mechanical parameters:** Historic Roman cement mortars show high strengths and moduli of elasticity, but at the same time they are highly porous and accessible to water. They can thus be regarded as strong, brittle and porous materials. The addition of lime, quite common for renders but never for architectural castings, significantly decreases the strength at increased elasticity, porosity, water absorption and vapour permeability (see Table 2).

### 5. Conservation problems

Roman cement stuccoes are generally very durable. Fine surface cracks, forming an irregular network not related to building features, are a distinct characteristic of all Roman cement renders and architectural castings. They are caused by normal drying shrinkage and usually do not lead to damage. Only rarely can they widen if the stucco is exposed to the severe impact of rain water, especially at the top of buildings. Very exposed Roman cement surfaces can suffer from erosion of their close compact structure. Wider cracks with displacements can also appear as the result of structural movements which cannot be accommodated by rather hard and stiff Roman cement stucco. Hollow sounding areas, indicative of a loss of bond, are common but lead, exceptionally, to losses only when water is freely admitted and trapped between the stucco and the wall.
An improper maintenance, making the stuccoes vulnerable to chronic excessive dampness, is a far more frequent cause of failure. In the upper parts of the facades the source of dampness can be damaged or ineffective exterior drainage systems leading to rain water leaks. In the area at ground-level, ineffective drainage and waterproofing of the foundation walls can lead to the intrusion of moisture and destruction of the renders of the façade, mainly due to transmission and crystallization of salts.

The main conservation problem, however, is the later repair and renovation measures irreversibly altering the original surfaces. Few materials have been so little appreciated and treated as Roman cement stuccoes. Years of neglect, the accumulations of paint layers or sprayed cement coatings, damaging cleaning and patchy repairs with improper materials adversely affect and aesthetically degrade a substantial part of the nineteenth and early twentieth century built heritage. Original renders and decorative castings are often removed when in poor condition rather then conserved or replaced. Once removed or irreversibly coated, the important information on past aesthetic concepts, technology and building skills is lost for good. Therefore, the unaltered Roman cement facades, preserving their original colour and architectural surface in an undisturbed state, are rare in spite of the fact that the technique was used on a massive scale during the period of rapid urban growth in Europe. Efforts must be maintained to understand, respect and sustain this relatively modern architecture by a careful evaluation and conservation.

6. Calcination of Roman cements

**History**: It is generally agreed that the calcination of marls to produce Roman cements should be conducted at ‘low’ temperatures and that over-burning produces an inferior product (e.g. Eckel, 1905). However, even Eckel, in his definitive English language text, suggests that this may be between 900 – 1200°C. Historic texts frequently refer to the observation that the best cements often contained a small amount of calcite which had not been de-carbonated during the firing process. The period of calcination has been variously reported as lying between 30 – 72 hours but this would include the heating, soaking and cooling cycles. Pasley (1830) suggested a period of 2 – 3 hours at red heat would be sufficient.

**Cement formation on heating**: Calcination of various marls in a laboratory kiln has revealed the important reactions which take place during production: the decomposition of calcite to lime, the dehydration and decomposition of clay minerals to amorphous aluminosilicates and the reaction of lime with quartz and clay mineral decomposition products to give dicalcium silicate –
belite as a mixture of two structural modifications $\alpha'$ and $\beta$ and, at higher temperatures, calcium aluminosilicate - gehlenite. As the calcination is increased, the calcite, quartz and amorphous contents decrease; the free lime increases to a maximum before decreasing; the gehlenite increases; the total belites increase but with $\alpha'$-belite dominating at low temperatures before transforming to $\beta$-belite with an increase in temperature (Hughes et al. 2007, 2008a, 2008b). The cements are therefore very sensitive to calcination temperature and yield best strengths at relatively low temperatures. The optimum cements are associated with the maximum $\alpha'$-belite content, a high amorphous phase together with a residual calcite content indicating incomplete calcination. It is clear that the historic descriptions of quality cements have been confirmed by present-day investigations: the best cements do indeed retain a proportion of calcite and over-burning yields inferior cements.

7. Hydration, strength development, porosity

Typical water/cement ratios used in mortar and paste formulations are in the range of 0.65 – 1.0. The hydration and strength development of Roman cement proceed according to a two-step mechanism:

Step 1 – Roman cement pastes harden within a few minutes after the rapid initial set. Six-hour strength values of up to 4 MPa are obtained. Early strength development was found to correlate with the formation of crystalline calcium aluminum oxide carbonate (or carbonate hydroxide) hydrates (C-A-H) (Vyskocilova et al. 2007). The workable time may be considerably extended by admixing small amounts of appropriate retarders like citric acid and potassium citrate (Hughes et al. 2008b).

Step 2 – After a varying dormant period, depending on the type of Roman cement, further strength development leads to high final strength values – after 1 year compressive strengths exceeding 20MPa were measured using small cylinders of cement paste, height : diameter ratio 1:1. Further strength development proceeded due to the hydration of belite, $\alpha'$-belite being more reactive than $\beta$-belite, yielding calcium silicate hydrates – the C-S-H gel. Late strength development continues over several years and may lead to high final strength values: in 100 year old historic Roman cement mortars, compressive strength values up to 50 MPa were measured (see Note on Table 2).

The pastes of the rapid-hardening Roman cements showed a characteristic development of the pore structure with the time of hydration (Tislova et al. 2008, Vyskocilova et al. 2007). Mercury
intrusion porosimetry revealed generally a unimodal distribution of pore sizes. However, the ‘threshold’ pore width, corresponding to the minimum pore dimension of the porous structure, decreases considerably with increasing curing time. At early ages, a relatively open pore structure is produced by the quick growth of the C-A-H phases in the pastes with the threshold pore diameter between 0.2-0.8 µm. The initial open structure remains unchanged during the dormant period of the paste which can extend up to several weeks. Only then does the threshold pore width shift to smaller values concentrated around 0.02 µm, which is the result of filling larger pores by the formation of the C-S-H gel.

The evolution of the pore structure correlates well with the development of the specific surface area which is determined by water vapour adsorption. In the case of the Roman cements, surface area of the early structure produced by the quick growth of the C-A-H phases does not exceed approximately 20 m²/g. Formation of the C-S-H gel brings about an increase of the surface area up to 120 m²/g, the value being approximately proportional to the amount of the C-S-H gel formed.

8. Restoration of Roman cement – Roman cement for restoration

Casting architectural decorative details

Historically, Roman cements were widely used for the mass-production of cast decorative elements in large numbers and at reasonable costs. Roman cement mortars had the advantage of being more durable in outdoor exposures than gypsum stuccos and far less expensive than terracotta or zinc plate.

Originally, the castings were produced in elastic moulds made of animal glue; despite the use of oil as an isolating medium, they were very sensitive to the prolonged action of moisture. The typically rapid setting of Roman cement mortars allowed for a quick removal of the casts and enabled therefore the repeated use of the moulds. In order to reduce their weight the casts were normally hollow and were fixed to the masonry on wrought iron nails. By their typically pinky-brown to dark brown colour, Roman cements resembled burnt clay, and this is probably why cast Roman cement elements were frequently left unpainted, though the decorative elements could be integrated into a more elaborated colour concept of the façade by painting them.

In accordance with examinations of historic Roman cement mortars, the cement to aggregate ratio should be at least 2:1 by volume, for example 3:1 is perfectly acceptable. So the mixture
must be much richer in cement than mortars for rendering. The aggregate can be quite coarse, with the maximum grain size reaching even 1 cm; but well rounded gravel should be preferred to ensure good flowing properties. A good consistency is obtained with a water to cement ratio of 0.65 at which exact copies, free of voids, can be produced even for casts rich in fine details. Due to an extreme sensitivity of fresh Roman cements to moisture, absolutely dry aggregates (sands) should be used. This is an important prerequisite to obtain the highest possible early strength. After the mortar has been poured into the mould, the exothermic reactions should produce a temperature increase in the cast of up to around 40 °C within several minutes. Under such conditions, the cast elements can be removed from the mould after about 30 min. The final strength of Roman cement mortars develops over a prolonged period of time; therefore storage of castings at humid conditions, favouring the progress of cement hydration, is essential. Citric acid can be used to retard setting and extend the workable time to at least several minutes. The dosage should be 0.2 – 0.5% in water, which corresponds to 0.13 – 0.32% related to the weight of the cement.

Rendering and run work

The grand stuccoes of the nineteenth century always contained linear or oval mouldings, like cornices, obtained by applying in situ the mortar and repeatedly passing a profile over them. Renders, usually rusticated or lined out with false joints, were used to imitate stone details and textures. It was usual to produce the stuccoes in two or more coats, the inner coat being a coarse-grained ‘core’ on which a fine-grained thinner finish layer was applied. Roman cement was a preferred material to execute the stuccoes due to its quick setting which facilitated progress of the process.

The mortar design for the in situ stucco work differs from that for casting described above. The mortars should obviously contain a larger proportion of the aggregate filler; for the base coat the optimum cement to aggregate ratio is 1:1.5 by volume, for the finish coat 1:1. The aggregates are commonly sands, quite coarse for the base coat (grain sizes up to 4 mm but concentrated around 0.25 mm), finer for the finish layer. A good consistency is obtained with a water to cement ratio of about 0.6.

The workable time has to be considerably extended for the in situ work. Therefore, the retarder (citric acid) should be added at the concentration of 0.5% in water, which corresponded to 0.3% of the weight of the cement. The workable time is then around 30 min which is sufficient for an experienced practitioner to render several square metres. The surface can be worked to produce the required texture or a close polished finish within an additional 1 hour or so.
Prior to the application, the surface must be well wetted not to take water from the stucco mass. As observed many times for historic renders, Roman cement mortars can be applied as a single coat in an astonishing range of thicknesses from 3 to 60 mm.

**Restoration of Roman cement stuccoes**

Nineteenth and early twentieth century buildings deserve the same good conservation approach as objects from earlier periods. Unfortunately, they have long been undervalued as purely utilitarian constructions and therefore have been vulnerable to frequent renovation and redecoration measures which would have had little concern for the requirements of good conservation. The proper remedial strategy for Roman cement stuccoes must take into consideration several aspects:

**Cleaning and uncovering:** First of all it should be recalled that paint layers need not affect the original building materials adversely as long as they are in a good state of preservation. The decision to remove paints or to clean surfaces is therefore frequently an aesthetic rather than technical question.

There is no basis for the frequently encountered concern that façade materials can be damaged by cleaning with the use of water. The close, sound surface of Roman cement stuccoes, especially of cast elements, has a relatively low water absorption capacity. On the other hand, these are highly porous in their bulk and quickly release the absorbed water. Thus, the removal of polymer-bound paints is best performed by using superheated water systems, while mineral paints and surface coatings require a low pressure abrasive cleaning by a swirling action of a mixture of air, water and fine mineral powder. Stubborn residues require hand cleaning with the use of fine mechanical tools. In such cases, full cleaning of a façade is not feasible, at least on economic grounds, and the façade is usually overpainted.

**Grouting and injection of cracks:** the network of fine cracks, so characteristic of Roman cement stuccoes, usually does not pose any threat. The same is true of the frequent hollow spaces between the render and the masonry. However, when it is necessary to stabilise the detached areas, grouting can be carried out using a mixture of Roman cement with water to the required consistency, possibly with the addition of a surfactant. After flushing out the void with water, the grout is introduced. Cleaned and dampened cracks can be also effectively filled and stabilised by a Roman cement-water grout. Unlike synthetic resins, however, it will not glue together loose fragments.

**Repair of damages:** the repair mortar should be designed to match the colour and texture of the host material. A range of aggregates must therefore be first tested in terms of grading,
composition and amount. The composition can be varied with cement content in the range 1 to 3 parts by volume which would produce mortars of a required strength compatible with the original stucco. Surfaces of a repaired cavity should be painted with slurry of mortar to achieve a good adhesion of the repair. If necessary, a dispersion of polymers commonly used in restoration, can be used for the same purpose. The repair should be kept moist for a period of time to assist proper hardening. Due to its high water retention within the fresh mortar and the capacity to continue hardening at elevated relative humidity, self-desiccation of Roman cement mortars is unlikely to occur.

**Surface coatings:** Where the stucco was originally coloured to imitate stonework, the colour is to be applied to a cleaned and repaired surface. The paint treatment should produce a translucent coating of high durability and the colour should be matched to surviving original examples. Unpainted Roman cement façades can be coated with a thin layer of Roman cement wash, if an aesthetic re-integration of stained and eroded surfaces is necessary.

9. Conclusions

The principal achievement of conservation science in the last 10 years is re-establishing the use of Roman cements in conservation practice. With the ready availability of Roman cements the family of historic hydraulic binders, necessary for the appropriate conservation of the built heritage of the nineteenth and twentieth centuries, is now complete; we no longer need to turn to substitutes for help. It can be hoped that use of Roman cement based mortars and washes in the restoration of historic buildings of the period will meet with a growing acceptance on the grounds of performance of these unique binders:

- They are an authentic historic material and technology compatible with the original stuccoes.
- Roman cements extend the range of natural historic binders of varying hydraulicity available for conservation practice - lime→hydraulic lime→natural cement.
- They optimally match the colours and textures of the historic host materials.
- They are universal binders enabling restorers to produce a range of decorative elements on the facades of buildings from architectural castings to plain renders.
- They are pure salt-free material.
- They can be applied in thick layers due to low shrinkage.
- The Roman cement mortars combine high strength with high porosity which assures good transport of water and water vapour.
- The historic Roman cement stuccoes and renders of a wide range of aggregate content exhibit excellent durability.
References


Bohnagen A (1914) Der Stukkateur und Gipser. Leipzig, Reprinted Verlag Leipzig, Holzmunden


Decorated Renders around 1900 in Europe: Technological Studies and Principles of Conservation and Restoration. EU-Rendec, Bundesdenkmalamt, Arbeitshefte zur Baudenkmalflege, Kartause Mauerbach, Verein Förderung der Baudenkmalpflege, Mauerbach, 1999


Parker J (1796) A certain Cement or Terras to be used in Aquatic and other Buildings and Stucco Work. British Patent 2120, dated 27 July 1796 to James Parker of Northfleet

Pasley CW (1830) Observations, deduced from experiment, upon the natural water cements of England, and on the artificial cements, that may be used as substitutes for them. Printed by authority, at the Establishment for Field Instruction


Tarnawski A (1887) Kalk, Gyps, Cementkalk und Portland-Cement in Österreich-Ungarn. Selbstverlag, Wien


Vicat LJ (1828), Résumé des connaissances positives actuelles sur les qualités, le choix et la convenance réciproque des matériaux propres à la fabrication des mortiers et ciments calcaires. Paris


Fig. 1. Former warehouse of the Court Theatres, 1873, by Gottfried Semper and Carl Hasenauer, Lehargasse 6-8, Vienna. An exquisite facade combining brick, stone and Roman cement renders preserved in the authentic, naturally aged state.
ARTIFICIALLY MIXED RAW MATERIALS

ca. 75% lime + 25% clay

fired above 1400°C (vitrification)

- ground
- typically mixed with gypsum

PORTLAND CEMENT

NATURAL RAW MATERIALS

pure lime
(<10% clay)

low clay content
(10 - 25% clay)

high clay content
(> 25% clay)

fired between 800 and 1200°C

- slaked
- ground

mixed with natural or synthetic puzzolans

AIR LIME
HYDRAULIC LIME
TRASS-LIME
TRASS-CEMENT

ROMAN CEMENT
Fig. 3. Production began in this shaft kiln in 1811 which is located in Sandsend, near Whitby, England. The shed at the rear is where barrels used for transportation were manufactured.
Fig. 4. A remnant of the original Roman cement showing a hydrated ring around an unhydrated core
Fig. 5. Cross-section of a typical Roman cement cast element with a very low amount of aggregate including some coarse-grain gravel; the surface zone is coloured by residues of glue or oil coming from a mould or an isolating medium
Fig. 6. Typical irregular network of fine shrinkage cracks characteristic of Roman cement renders
Fig. 7. A Roman cement casting disfigured by a thick coating of a cement spray, removed mechanically from a part of the element
Fig. 8. Change of composition of a Roman cement with temperature – the main components of the optimum material are $\alpha'$ – belite, amorphous phase and smaller amount of undecomposed calcite
Fig. 9. Typical strength development assessed for two types of Roman cements (cement 1 – no dormant period, cement 2 – high early strength, extended dormant period)
Fig. 10. Evolution of the pore-structure of a Roman cement paste during hydration: the initial open structure remains unchanged during the dormant period after which the threshold pore width shifts to smaller values due to blocking of pores by the formation of the C-S-H gel.
Fig. 11. Stripping existing modern masonry paint with the use of superheated water
Fig. 12. Repair of damages
<table>
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<th>Age</th>
<th>Tensile strength [N/mm²]</th>
<th>Compressive strength [N/mm²]</th>
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<td>Roman cement</td>
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<td>Quick ≤ 15 min</td>
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Table 2 Compilation of physical and mechanical values assessed for historic Roman cement mortars. N.B. the compressive strengths were established from samples prepared to a size of 40 x 40 x 20 mm and the values should be appropriately factored in order to yield comparisons with values obtained from conventional cylinders or cubes.

<table>
<thead>
<tr>
<th>Historic Roman cement stuccoes</th>
<th>Compression strength [MPa]</th>
<th>Tensile strength [MPa]</th>
<th>Modulus of elasticity [kN/mm²]</th>
<th>Bulk density [g/cm³]</th>
<th>Water-accessible porosity [vol. %]</th>
<th>Water absorption coefficient [kg/m²h⁰.₅]</th>
<th>Water vapour permeability 10⁻¹⁰ [kg/m²sPa]</th>
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</thead>
<tbody>
<tr>
<td>Render (with lime)</td>
<td>11</td>
<td>0.6</td>
<td>5.4</td>
<td>1.43</td>
<td>39</td>
<td>23</td>
<td>11</td>
</tr>
<tr>
<td>Render (pure RC)</td>
<td>38 ± 19</td>
<td>1.6 ± 0.8</td>
<td>21 ± 10</td>
<td>1.7 ± 0.04</td>
<td>28 ± 9</td>
<td>9 ± 4</td>
<td>4</td>
</tr>
<tr>
<td>Casting</td>
<td>44 ± 7</td>
<td>2.1 ± 1.5</td>
<td>17 ± 1</td>
<td>1.64 ± 0.02</td>
<td>31 ± 1</td>
<td>7 ± 0.5</td>
<td>3</td>
</tr>
</tbody>
</table>