SUB-HYDRAULIC BINDERS IN HISTORICAL MORTARS

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Abstract

The present nomenclature for pure lime binders and hydraulic binders is adapted to modern materials. A large proportion of historical mortars fall in the category of non-hydraulic mortars, although their functional properties often reflect a significant content of hydraulic components in the binder. It would be misleading to regard these mortars as pure lime mortars, although they generally do not harden under water. The hardening of these mortars occurs largely through carbonation, but the hydraulic components in the binder give additional hardening through hydration. This results in a mortar with higher final strength and generally lower porosity. The colour of these mortars is mostly white with warm yellow or grey tones due to the presence of iron and manganese. In the discussion of properties of historical mortars these mortars have been overlooked. It is the opinion of the authors that this is an important group of mortars that requires special attention and to some extent provides an opportunity to use more durable mortars in applications that are exposed to severe climatic conditions. These properties are often attributed to mortars with a chemical composition of 0.15 to 0.30 using the cementation index described by Boynton. This compares with a binder of the composition CL 90-95 following the European norm EN 459-1 for building limes.

1 Introduction

The present nomenclature for pure lime binders and hydraulic binders intended for use in masonry mortars and renders is tailored to the materials available on the market today. This is true both for the present standards, such as the EN 459-1 (1) European Normative for building limes, and for the various procedures used to calculate the cement index and classify binders. The European normative defines pure lime binder, CL 90, as lime with more than 90 weight percent of CaO + MgO on a loss free basis (free and bound water and CO_2 are not included in the calculation), and with a MgO content of less than 5 weight per cent and a CO2 value of less than 4 weight percent. ASTM C207 Hydrated Lime For Masonry Purposes (2) and C 1489 Lime Putty For Structural Purposes (3). (2) requires a minimum of 92 weight percent of CaO and MgO, and a maximum of 5 weight percent CO2. Interestingly, ASTM C5, which was first developed in 1915 and still in use, specifies a maximum of 5 weight percent oxides of silica, alumina and iron and a maximum of 3 weight percent of CO_2. In the classification used by Boynton (4) based on Eckel (5) the cement index is defined as:

$$CI = \frac{2.8 * SiO2 + 1.1Al2O3 + 0.7Fe2O3}{CaO + 1.4MgO}$$

The CI lower limit for the least hydraulic binders, classified as feebly hydraulic, is 0.30. The calculated cementation index, CI, compares chemically with the composition of a lime-cement mix with that proportion of cement. The lower limit for feebly hydraulic lime and the CL 90 limit therefore compare chemically with a lime-cement mix having 30 weight per cent of cement or a 1 volume lime to 0.26 volume cement mix. The comparison with a lime-cement mix is included only to provide an illustration of how hydraulic these mortars are and is not an example of a mortar with similar functional properties!

It follows from this that the existing classifications do not distinguish between different types of historical mortars and provide an insufficient basis for the choice of restoration mortars. It is therefore the intention of the authors to draw the attention to binders and mortars that are intermediate between high-purity lime mortars and those defined as hydraulic according to the modern classification. The existence of these mortars has been recognised by Vicat in the 19^{th} century (in 6). In the discussion of properties of historical mortars this important group of sub-hydraulic mortars has been overlooked. Although these mortars harden mainly through carbonation and generally do not harden under water, it would be misleading to regard these mortars as pure lime mortars when compared with contemporary pure lime mortars. In this context we may compare with lime-cement mortars and note that also a mortar with 65 weight per cent of cement carbonates. It is also important to be able to identify pure lime mortars, in a restricted sense, which is a type of mortar that has been in use for a very long time.

The present paper has its origin in a Scandinavian context but the observations have a more general application (e.g. 7). The time period covered by the analysed mortars that are discussed here extends from about 1000 to 1850. Binders with a stronger hydraulic effect were introduced in the latter part of this time period. An early example is Parkers patent on a Roman cement from 1796. These more highly hydraulic binders were primarily intended for special structures, where the strength and hydraulic properties were important, for example in canal locks, and were not primarily used for house building. Hausmann's large-scale alteration of the layout of Paris that began in 1853 heralded a new era in the European building process with its dramatic increase in scale, the increased transport capacity and the industrialisation of lime and cement production. The use of binders with a higher hydraulic content became increasingly common for house building from this time onwards. But these binders and mortars are outside the scope of the present paper. A large proportion of historical mortars produced prior to 1850 fall in the category of non-hydraulic mortars according to both the European norm and the classification used by Boynton, although their functional properties largely reflect the significant content of hydraulic components (e.g. 8).

2 Chemical composition and microstructure

The binders and mortars discussed in this paper have a lower content of hydraulic components than feebly hydraulic binders (3). Modern classifications, such as those used by EN 459-1 and Boynton, do not identify these as a group, although mortars of this type are widespread and commonly found in historical buildings. As an indication of how common these binders were, the results of analysis of acid-soluble CaO and SiO_2 in 25 mortars from different structures, located mainly in Sweden, are presented in Table 1. The dates of construction ranged from 1100 AD to 1860 AD. The chemical compositions are the content of acid-soluble components in analysed mortars. The analyses were performed according to NT BUILD 436 (9). The samples were taken from render and joint and grout mortars in masonry. The results gave an average CI calculated using the formula given by Boynton, but only taking CaO and SiO_2 into consideration gave an average CI of 0.10 and a maximum value of 0.22, while seven of the samples had a CI over 0.15. A cementation index of 0.1 compares, as pointed out above, chemically with a lime-cement mix with 10 weight per cent cement. A CI of 0.22 compares chemically with a lime-cement mix with 20 weight percent cement. This can also be compared with the results of Schäfer and Hilsdorf (10). It is important to point out the difference between the composition obtained from an analysis of a hardened mortar and the analysis of a binder. The mortar may change its composition with time due to leaching. The analysis may be disturbed by acid soluble components in the aggregate or the presence of pozzolanas in the mortar. Furthermore, the components SiO_2, Fe_2O_3 and Al_2O_3 in the mortar are frequently difficult to analyse.

A comparison of historic Swedish limestone quarries shows that the limestone formations contained beds that are both low and high in hydraulic components. The latter would result in hydraulic lime in a modern sense, but it was not used in historic times. The lime produced for historic lime mortars from these quarries were generally pure lime or the sub-hydraulic type discussed in the present paper (11). Production of hydraulic binders in Sweden commenced in the late 18th century. Prior to this the layers of limestone that were rich in hydraulic components were selectively avoided when quarrying limestone for lime production or the limestone were burned at a low temperature short time in order to avoid the formation of hydraulic minerals. Limestone with a higher hydraulic content was considered to be difficult to control in the burning and slaking process. This observation is in agreement with written reports from that time. Carl von Linné writes in his account of a journey in southeastern Sweden in 1741 that limestone that hardened when water was added during slaking was not used for lime burning.

These historical mortars differ also in other respects, such as their homogeneity, low aggregate content and low air content, with poorly distributed, large air voids. These properties were probably an undesired effect of the difficulties in mixing the mortars and were often less pronounced in prominent and prestigious buildings where the building process was probably more strictly controlled. These differences were not related to the chemical composition of the binder.

3 Chemical composition of sub-hydraulic binders

It is not useful to define sub-hydraulic binders and mortars based on the functional properties of the historic mortars, such as strength, as these may have changed significantly with time and the present properties are likely to be different to when they were new. It is not possible to define them based on mix proportions or mixing characteristics. The property that these mortars have in common is the low, but significant, content of hydraulic components. However, due to the variability of historic mortars, the presence of pozzolanic additives and the difficulties in mortar analysis hydraulic components cannot be used as clear definition.

Table 1. Chemical composition and CI of mortars that were analysed by both chemical and microscopical analysis. In those cases where the mortars contained calcite in the aggregate, the content of acid-soluble calcite was corrected using the method described in the RILEM method COM-C1 (12). The CI was calculated using the equation given by Boynton, with the exception that only calcium oxide and silicon dioxide were taken into consideration. CI = 2.8*weight per cent SiO_2/ weight per cent CaO.

Structure	Built	Locality	Render/Masonry	CaO	SiO_2	Loi975	CI
Church	1800	Sweden	Render/Masonry	24.8	1.5	24.8	0.17
Church	1750	Sweden	Render	21.3	0.6	21.3	0.08
Church	1750	Sweden	Render	7.4	0.5	8.5	0.19
Church	1150	Sweden	Grout	15.0	0.5	19.1	0.09
Church	1500	Sweden	Render	24.5	1.1	26.2	0.13
Church	1150	Sweden	Masonry	18.3	0.4	22.1	0.06
Church	1860	Sweden	Render	17.7	0.3	21.7	0.05
Church	1300	Sweden	Render	38.6	0.5	21.7	0.04
Church		Sweden		39.2	0.3	41.6	0.02
Church	1100	Sweden	Masonry	23.4	1.4	17.2	0.17
Church	1550	Sweden	Masonry	21.4	0.6	21.4	0.08
Church	1500	Sweden	Render	20.3	1.2	20.3	0.17
Church	1150	Sweden	Render	16.5	0.4	16.5	0.07
Church	1150	Sweden	Render	18.2	0.3	18.2	0.05
Castle	1500	Sweden	Masonry	24.0	1.4	21.6	0.16
Castle	1500	Sweden	Masonry	18.2	0.6	15.9	0.09

Church	1500	Estonia	Render	19.7	0.8	17	0.11
Bridge	1500	Bosnia	Grout	17.6	0.4	43.2	0.06
Church	1500	Estonia	Render	20.4	1.0	17.6	0.14
Fortification	1688	Sweden	Masonry	25.3	0.5	23.7	0.06
Industry		Sweden	Render	17.6	0.4	14.3	0.06
Castle	1600	Sweden	Masonry	23.1	1.1	20.2	0.13
Official building		Sweden	Render	7.5	0.6	6.2	0.22
Monastery	1180	Sweden	Grout	14.6	0.9	15.1	0.17
Mosque	1500	Kosovo	Masonry	47	0.6	39	0.04

4 Influence on functional properties

As the term sub-hydraulic implies, it refers to mortars that do not harden under water. The hardening process occurs largely through carbonation, although the hydraulic components in the binder do give additional hardening through hydration. This gives a hardened mortar that generally has higher final strength and lower porosity. The colour of these mortars is mostly white, with warm yellow or grey tones due to the presence of iron and manganese. There is a general trend for these mortars to become darker with increasing hydraulic content. The reason for this is that in most limestones there is an increase in the content of chromatophores such as iron and manganese as the content of hydraulic components increases. This is not, however, always true and a moderately hydraulic limestone may well be as light as a pure lime mortar.

5 Repair requirements

Sub-hydraulic mortars provide a good substrate both for pure lime mortars and feebly hydraulic mortars. Although sub-hydraulic mortars provide a good substrate for pure lime mortars and lime wash, the ability to use mortars that compare better in terms of their technical properties with this group of historical mortars may be advantageous in some cases. It is important that the properties of the restoration mortar, such as strength and porosity, compare well with those of the original mortar in order to obtain good adhesion and retain the moisture transport properties of the structure (13). Other aspects of compatibility are also likely to be improved if the repair material has properties that closely resemble the substrate.

Sub-hydraulic mortars have largely been used in the same type of applications as pure lime mortars. However, in situations where both types of mortars have been available, have they often been used in different applications. This approach can also be applied in restoration. The restoration of Borgholm Castle in southeastern Sweden can be used as an example of how a division between different lime mortars can be applied in practice. This castle was built and rebuilt in several stages between the 13th and 18th centuries. The masonry mortars were made using lime produced from the local Öland limestone, giving slightly hydraulic mortars. For applications where a white render was desired for aesthetic reasons, lime imported from the nearby island Gotland was used where possible. For the current restoration of the castle a lime kiln has been built on the site to produce a sub-hydraulic mortar from the local limestone (14). This mortar has the durability needed for the wall crests overlooking the Baltic Sea. It should be pointed out that it is not the aim, nor even possible, to produce identical mortars as those used originally.

The colour of mortars used in the restoration of masonry and renders are important for the visual impression of a monument. In historical times sub-hydraulic mortars were applied both as render and as a lime wash that gave a slightly yellow and grey shade of white. The resemblance of the lime wash to a watercolour finish gave a different impression to a bright, uniformly white surface

These are examples that demonstrate the need for this type of mortar in restoration applications where it has been used previously. There is probably no mortar available on the market today that compares with the technical and aesthetic properties of these mortars. New production is needed to produce binders that have these properties and offer consistent quality at a price that is competitive on the market. Local production, as at Borgholm Castle, can only be used on projects with considerable resources, where this approach can be used for several purposes including production, demonstration and tourism.

5 Discussion and conclusions

The aim of this paper has been to identify the existence of sub-hydraulic binders in historic mortars. It is the authors' opinion that the hydraulic properties of these mortars are significant from the antiquarian viewpoint and that they should be distinguished from pure lime mortars. Microscopical and chemical analysis has shown that this is an important group of historical mortars with aesthetic and technical properties that differ from pure lime mortars. This requires special attention, and to some extent provides opportunities for the use of mortars that fulfil requirements for durability in situations that are exposed to severe climatic conditions. The identification of sub-hydraulic lime mortars as a specific group of mortar also provides a more restricted application of the term pure lime mortars as an added benefit.

The identification of sub-hydraulic mortars as a separate type of lime mortar is not only a question of definitions, but also about practice. Sub-hydraulic mortars may be applied in the restoration of historic monuments where these have been applied previously. It is not possible today to produce mortars with properties identical to the historical mortars. It is important independent of type that the binders have consistent properties so that the quality of restoration work can be assured.

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