A method to recreate historic mortars applied at Norrlanda church on the Island of Gotland, Sweden

Kristin Balksten
Department of Chemical and Biological Engineering, Environmental Inorganic Chemistry, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden, kristin.balksten@hgo.se

Britt-Marie Steenari
Department of Chemical and Biological Engineering, Environmental Inorganic Chemistry, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden, bms@chalmers.se

SUMMARY: In the process of restoring a lime plaster on an old building, a lot of knowledge is needed in order to make the new plaster similar to and compatible with the old one. This work was carried out with the aim to create a method which makes it possible to recreate historic mortars. There are two important steps in the method: i) a practical data base consisting of mortars made with the application of local materials, known craftsmanship and the variation of a number of parameters was produced; ii) a combination of field studies and material analysis methods was used to investigate the structure and properties of the historic mortar.

By combining field studies with microscopic studies of mortars in SEM and thin section specimens it was found to be possible to compare historic lime plaster surfaces and new reference surfaces of lime plaster on both a macroscopic and a microscopic scale. Microscopic studies using SEM give information about the type of slaked lime used in the mortar, as well in the reference as in the old mortars. Investigations of thin section specimens in an optical microscope give information about the type of lime and sand used, the mixing ratio, the working technique, the resulting pore structure of the mortar etc. In field studies old plaster surfaces and newly made reference surfaces are compared. It gives knowledge about how the mortars were built up and worked on, which tools that might have been used, how it was lime washed etc. The combination of those studies makes it possible to create restoration mortars with lime slaked as the historic lime, sand with similar particle size distribution curve and mineral composition, similar mixing ratio and pore structure. It is also possible to build up the new plaster in the same way as originally concerning layers and working technique, with similar tools and lime wash with recipes similar to historic ones.

The use of the method is illustrated in a case study of the plaster restoration on the medieval church Norrlanda on Gotland, carried out in the summer of 2006.

KEY-WORDS: craftsmanship, earth slaked lime, historic lime mortars, SEM, thin section

1. RESEARCH AIM

In the process of maintaining and restoring historic buildings it is recommended to choose materials and methods that are as close as possible to the original of the building [1]. In order to make a new mortar similar to a historic lime mortar, knowledge is needed about the original type of binders, the lime slaking technique, the properties of the aggregates, and the mixing ratios used. There is also a need for knowledge about how the mortars and plasters were made, i.e. the craftsmanship of the time when the original plaster was applied.

The research aim of the present work was to develop and implement a method to recreate historic mortars. The method consists of two major steps:

i) A reference database consisting of a large number of reference mortar surfaces reflecting the influence of different parameters, such as quicklime slaking method, aggregate particle size distribution and after treatment of the plaster, influence the properties of the plaster.

ii) An investigation of remaining historic mortars on the object to be restored.

The use of the method is illustrated in a case study of the Norrlanda church carried out in the summer of 2006. This investigation is a part of a research program focused on the Gotlandic churches and their lime plaster problems [2].

2. INTRODUCTION

According to the Venice Charter, restoration should aim “to preserve and reveal the aesthetic and historic value of the monument and is based on respect for original material and authentic documents” [1]. The implication of this when restoring the plaster of a historical building is that materials and methods should be chosen with regard to authenticity and compatibility as well as technical properties. In Sweden, the common practice has been to try to recreate existing historic plasters when restoring a building. In most cases this practice has been based on insufficient data and a more systematic approach is needed.

Many types of historic mortars and their properties have been investigated by research groups during the last years [3-25]. However, none of the investigations have been presented as a part of recreating historic mortars.

Generally, the methods that have been used for investigations of historic mortars have been wet chemical elemental analysis methods, X-ray powder diffraction (XRD) or petrological examinations, microscopy studies of polished thin sectioned mortar specimens, investigations using scanning electron microscopy in combination with element identification by X-ray fluorescence spectroscopy (SEM-EDX) and examination of written material about the building in question. From optical microscopy analyses of thin section specimens and investigations using SEM-EDX it is possible to get information about the composition and particle size of the binder and the aggregates, as well as the porosity of the mortar.

Additional, in situ studies of the old lime plaster surfaces can give indications of how the plasters were built up, i.e. how many layers of plaster that was applied, if any reinforcement such as fibrous material was used, if any paint or lime wash was applied on the surface etc. In many cases tool marks can be found and these give information about the way the plaster was put on to the masonry and how the surface was treated during the hardening process.

This paper describes the development and testing of a method to recreate historic mortars. The method is based on microscopy investigations in combination with field studies and comparisons with a database containing reference materials made for the local environment where the plaster is to be applied.

3. MATERIALS AND METHODS

By comparing remaining historic mortars and plasters to the reference material, both in situ and in light microscope and scanning electron microscope (SEM) it is possible to understand how to make restoration mortars similar to the old ones.

3.1. Reference materials

From year 2002 to 2005, a reference material consisting of a large number of lime mortar surfaces has been produced in order to study the influence of the main variables involved [26]. The reference materials reflect the local variations in material composition as well as application and surface treatment methods. Well experienced local craftsmen were consulted and involved in the production of the reference materials. The main variables of the reference surfaces are:

- lime putty made with different traditional slaking techniques
- aggregates with different particle size distributions
- different mixing ratios between lime, sand and water
- different mixer types and mixing times for making mortars
- influence of the underlying material and its suction capacity
- working techniques and working time for making different surface textures on the hardening plaster
- application of lime wash made with different recipes and applied on different times in relation to when the lime plasters were made.

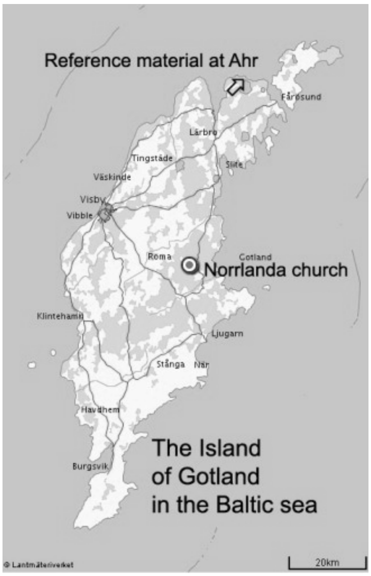

Figure 1: Marked in the map of Gotland is Norrlanda church where the case study took place and Ahr where the reference material is situated in a rough climate.

The reference surfaces are applied on an old lime stone building located in Ahr on the northern point of the island of Gotland, see map (figure 1). Approximately 150 reference surfaces have been made and their properties have been and are being documented. The reference samples have been investigated by using thin section samples made for studies in a polarization light microscope and by measurements of density, open and total porosity and capillary water suction. This made it possible to describe the compactness, homogeneity and pore structures of the corresponding materials.

In a previous study the same reference samples have been used to identify the reasons why the mortars may have different durability when exposed to frost-thaw cycles [27].

3.2. Historic mortars

During their history, many of the Gotlandic medieval churches were gradually rebuilt from Romanesque churches to Gothic churches (figure 2). Since parts of the outer walls were included in the new structures during this process, it is often possible to find well preserved medieval lime plaster surfaces on the attics; with lime wash, tool marks and other relevant information.

Figure 2: Medieval church building history illustrated in three examples; 1) completely Romanesque, 2) Romanesque nave with Gothic choir and semi-Gothic tower and 3) Gothic nave and choir to a Romanesque tower. They are from left Fardhem, Garda and Norrlanda churches and are all part of the bigger research project about lime plasters.

In this paper the mortars of Norrlanda church will be discussed as a case study. The mortars were studied from two main perspectives: i) identification of the materials and compositions used in their production, and, ii) identification of the methods used by the craftsmen carrying out the original plastering. As described in the introduction, a thorough investigation of a historic mortar can give information about the lime slaking technique used, the mixing ratio between binder and sand, use of additives, the mineralogy and particle size of the sand, the number and thickness of plaster layers, the use of lime wash, the shape of some tools used etc.

3.3. Investigation methods – Microscopic studies

Mortar samples were studied using Scanning Electron Microscopy (SEM). The microscope used is a Quanta 200 SEM FEG from FEI. It is equipped with a Schottky field emission gun (FEG) for optimal spatial resolution. The samples were mounted on a carbon adhesive tape without further treatment.

SEM was used to study the pore structure, the sand particles and the structure of the particles in the lime itself, both in putty and in carbonated lime plaster samples [28]. The SEM photographs show the lime mortars in magnifications of 2 500-25 000 times.

Optical microscopy studies of thin section mortar specimens were used to obtain information about the type of binder, the pore structure, the mixing ratio, the minerals and grain sizes of the sand particles etc. [29; 30].

Thin section specimens were prepared from both historic mortars and mortars produced in this study. An UV-fluorescent epoxy was used in a vacuum impregnation of the samples before they were polished down to a thickness of ca 3μm and studied in an Olympus BH-2 polarization microscope. The magnification of the pictures shown here is 20 times.

4. RESULTS AND DISCUSSION

4.1. Reference mortars

None of the reference mortars made during 2002-2005 showed any signs of frost damage due to the rough climate with many frost-thaw cycles. Thus, from these observations it was not possible to exclude any set of parameters from further considerations. (For future purposes, the reference surfaces will be observed over a longer period.) A selected number of the reference surfaces were chosen for closer investigations and thin sections were made from most of them.

The following text presents some interesting examples from the reference material that has been of importance for recreating the historic mortars of Norrlanda church.

The electron micrographs showed that the particle structure in the lime depends on the slaking techniques [29; 31]. Figures 3a, 3b, 4a and 4b illustrate the different structures of wet slaked and earth slaked lime. The sand particles are in both cases imbedded in lime. The particles in the earth slaked lime are organized in a very porous structure while the particles in the wet slaked lime are organized in a slightly more compact structure. The earth slaked lime in figure 3b has a structure similar to the lime in the historic mortars in figure 3c and d.

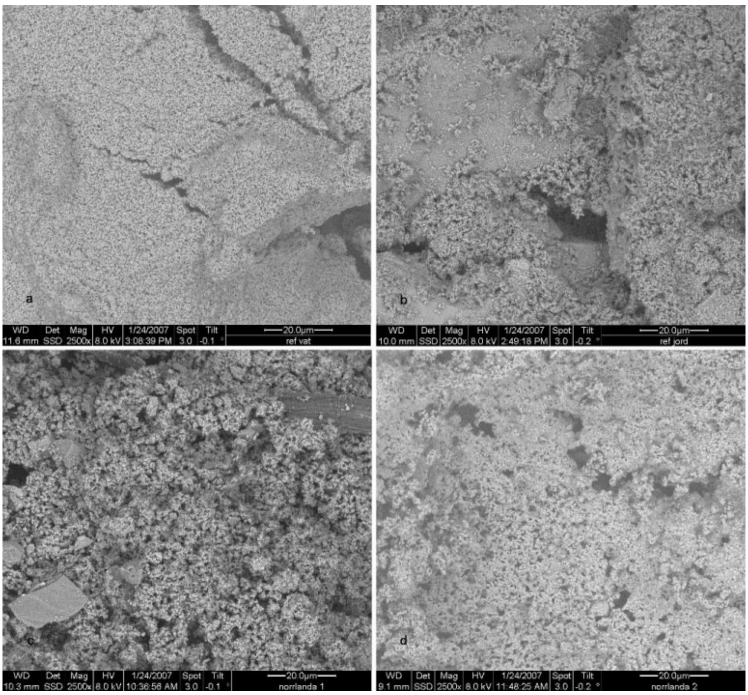

Figure 3: SEM of two reference mortars of a) wet slaked lime and b) earth slaked lime compared to two historic mortars from Norrlanda church in c) and d). The earth slaked lime in b) has a porous structure similar to the lime in the historic mortars in c) and d).

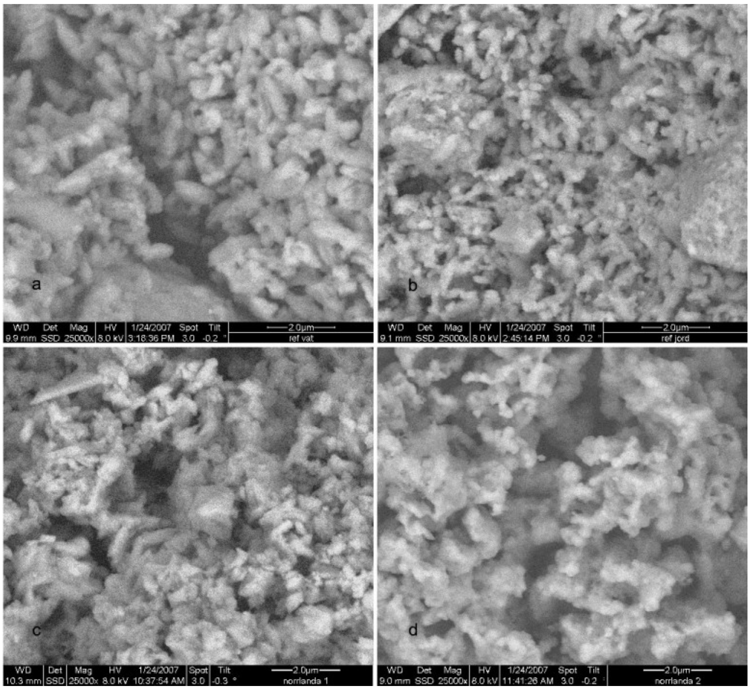

Figure 4: SEM of the lime in two reference mortars of a) wet slaked lime and b) earth slaked lime compared to the lime in two historic mortars from Norrlanda church in c) and d).

The results from optical microscopy showed as well that there are significant differences between the reference mortars. Figure 5 shows mortars from lime produced with the different slaking techniques; earth slaking [31], wet slaking and dry slaking. The mixing ratio was 1:2 by volume and all other parameters were the same in the mortar preparation. The different kinds of lime give mortars with different homogeneity and pore structure, visible in the optical microscopy.

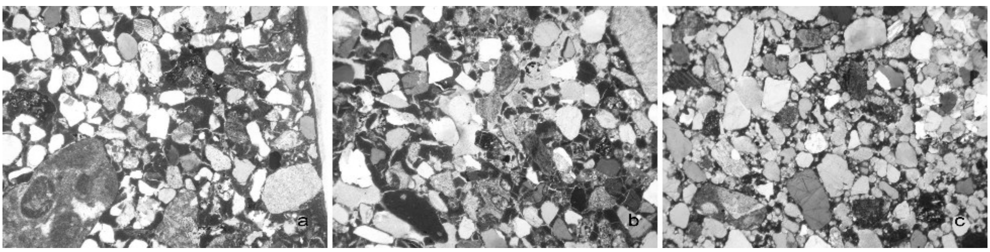

Figure 5: Examples from the reference material: A comparison of a) earth slaked, b) wet slaked and c) dry slaked lime in mortars with mixing ration 1:2 by volume. The width of each thin section is equivalent to 4.5 mm.

Figure 6 shows mortars made with varying mixing ratio (1:1, 1:2 and 1:3 by volume) between lime putty and sand. The mixing ratio has an influence on the compactness and pore structure of the mortar. In this case, a mixing ratio of 1:1 gives a mortar most similar to the historic mortars.

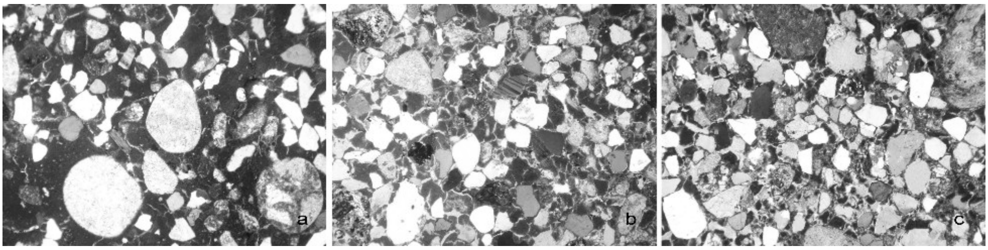

Figure 6: Examples from the reference material: A comparison of mixing ratios. The mixing ratios in those lime mortars varies from a) to c) with 1:1, 1:2 and 1:3 by volume made of lime putty and sand. The width of each thin section is equivalent to 4.5 mm.

Figure 7 shows examples of materials where the mortar surfaces have been worked on in different stages of drying. Figure 7 comes from a study of the influence of working the surface in different time and intensity with a tool in order to make the mortar more homogeneous and compact [26]. The mortar in figure 7a was worked upon when it was still wet and that in figure 7b when it had set for some time and just started to dry. The results showed that when the wet surface is worked upon at an early stage, the lime is transported to the plaster surface and a sandy layer without binder is created between this lime rich layer and the inner parts of the mortar. If the mortar is allowed to set before the surface structuring is made, the lime-rich surface layer is firmly attached to the mortar as shown in figure 7b. By looking at the historic lime mortars in the case study, one can draw the conclusion that this practice was known by the craftsmen and that the plasters were worked on after the mortar had set.

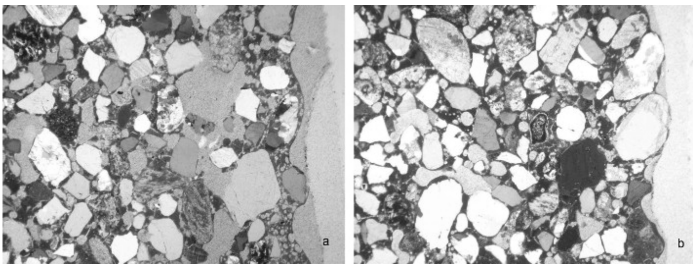

Figure 7: Examples from the reference material: A comparison of lime mortars worked on in different grades of drying: a) is worked on when it is still wet and very soft while b) is worked on after the mortars have started to dry out and just stiffened up. The mortar is mixed 1:2 by volume and the mortars in both examples are coming from the exact same mix, from the exact same bucket. The width of each thin section is equivalent to 4.5 mm.

Another interesting observation noticed in the production of the reference surfaces is how drying cracks occur. Mixing ratio, water content and thickness of the mortar layer all influence the appearance of drying cracks.

4.2. Historic mortars from Norrlanda church

Due to the different building times of the choir and the nave of the church, it is believed that the lime plaster which still remains on the west façade of the choir on the attic is from approximately the year 1300 [32] (figure 8a and b). The lime plaster is made from 1-2 layers of a lime rich, cream white mortar. It is a relatively thin lime plaster that follows the structure of the stone wall which makes its appearance smooth but lively. Some drying cracks are visible. The tool that has been used to finish the surface must have had a rounded shape which made it possible to follow the wall structure.

On the south façade of the tower some old (possibly original) layers of lime plaster were found (when the lime plaster of poor quality was taken down during the summer of 2006) (figure 8c). These plaster layers are even thinner than the one found in the attic and they are not as smooth. Drying cracks are visible here as well. The surfaces are covered with a lime rich lime wash in 1-2 layers allowing the drying cracks to be filled up with lime.

The historic mortars from the attic in Norrlanda church are all very lime rich and the mixing ratio varies a little, 2:1 to1:1 by volume as found in the microscopy investigation (figure 9). The mortars are all compact, but they contain a few round air pores. Occasionally lumps of unwhipped lime, typically 1-5 mm like the one visible on the left side of figure 9b were found. Looking back at the reference surfaces this is typical of mortars using earth slaked lime.

The SEM photos of lime mortars (figure 3c and d), show the adhesion between lime and sand particles and how the sand particles are embedded by lime. The second set of SEM pictures (figure 4c and d) shows the lime in the mortars in a larger magnification. This allowed a closer study of the particle structure of the lime and it can be seen that the historic lime is closely resembles the earth slaked lime in figure 3b and 4b.

Figure 8: Medieval lime plaster from approx year 1300 at Norrlanda church. The plaster surface exists in the attic and it has been preserved due to a rebuilding, first of the choir (around year 1300) and then the nave in the middle of the 14th century [13]. The first two pictures (a) and (b) are from the attic. The third picture (c) show a lime plaster surface still remaining outdoors on the south façade. It is a thin layer similar to the layer in the attic. It was covered by thick lime wash.

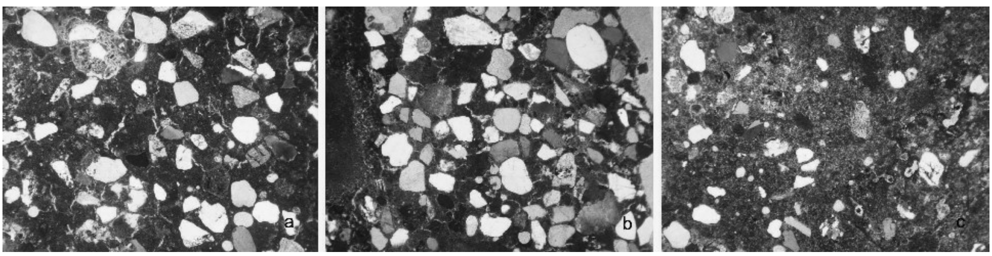

Figure 9: a) to c) Examples from the historic mortars: This is three examples of thin sections of historic mortars from Norrlanda church. The width of each thin section is equivalent to 4.5 mm. Those lime mortars from Norrlanda church are coming from the attic, from joints and plaster surfaces. b) A plaster surface at the attic who has remained when the church transform from Romanesque to Gothic [13]. Notice to the left in that picture where there is a big lime lump from unwhipped lime.

4.3. Restoration mortars

The recipe for the restoration mortar for Norrlanda church was chosen based on comparisons between the reference materials and the samples of historic mortars taken from the church. This mortar was then used for the re-plastering of the south façade of the church tower. In order to make a restoration with a realistic budget it was decided to use commercially available lime and sand rather than trying to produce authentic raw materials for each building.

Thus, the restoration mortars were made using earth slaked lime putty (figure 10) and sand in a mixing ratio 1:1 by volume. The lime was produced by placing traditionally burned lime stones [33] in the ground for 5-10 years, where it was slowly slaked by the humidity in the soil. The sand used was natural sand from Gotland with grain size 0-3 mm (figure 11). This sand is the commercially available sand for mixing mortars on Gotland and earlier investigations have shown it to be very close to the sand in the historic mortars shown in figure 9 a and b.

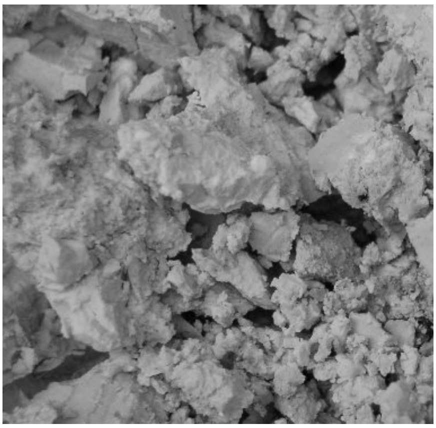

Figure 10 Earth slaked lime putty used for restoration mortars. Here you see the consistency of the lime before it has been whipped.

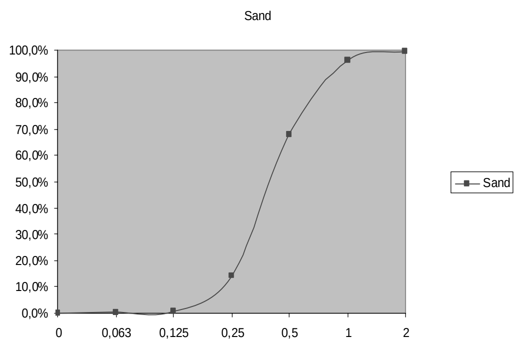

Figure 11: Sand curve for sand used in restoration mortars.

The consistency of the mortars was made sticky, but rather dry, in order to avoid too many drying cracks. It was applied on the wall by a trowel and it was pressed, not thrown, on to the wall (figure 12b). After the mortar had set it was made smooth with the edge of the trowel (figure 12a). By working the surface after the mortar had set, it was possible to close the drying cracks and to make a smooth surface without a lime film. According to established craftsmanship and earlier observations, such a surface is needed in order for the lime wash to attach well. The lime wash was made of wet slaked lime putty and water in the relation 1:2 by volume. It was applied in three layers until it covered the lime plaster surface completely. The lime wash application was carried out during two days, starting the day after the plaster work was completed.

Figure 12: a) The lime rich mortar can be pressed on to the wall. b) After it has set the surface is worked on with the side of a trowel.

When re-plastering the south façade of the tower of the church the aim was to create a plaster with properties and composition close to the historic plaster. A photo of a thin section of the chosen restoration mortar is shown in figure 13. It is a well mixed mortar with air pores and small drying cracks very similar to one of the historic mortars of the church (figure 9b). The lime lump in the top of the picture is an unwhipped particle typical of earth slaked lime, similar to the lime particles found in the historic mortars. Figure 14 shows the finished lime plaster surface that follows the structure of the limestone wall in the same way as the original plaster did. The status of the new plaster will be monitored during the coming years.

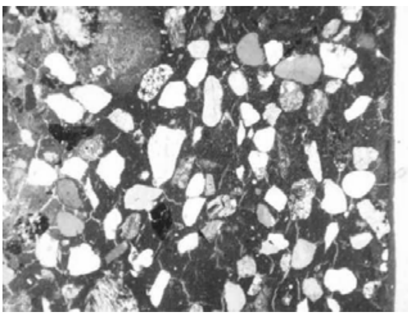

Figure 13: Restoration mortar chosen at Norrlanda church: earth slaked lime and sand, 1:1 by volume.

Figure 14: The finished new made lime plaster surface is following the structure of the lime stone wall like the old ones are. a) To the right, under the lower skylight, are approx two square meters of old mortar covered only with lime wash. b) A close up of the new lime plaster covering Norrlanda church from summer 2006 and forward.

5. CONCLUSIONS

A method to recreate historic lime mortars was developed and verified in a case study. It can be concluded that by comparing historic mortars with reference mortars using microscopy methods in combination with field studies it is possible to make restoration mortars similar to historic ones. With the combination of a scientific analysis and practical experiences from craftsmen it was possible to determine not only of what the mortars were made but also how they were made.

The example of Norrlanda church has shown the method to be useful in a practical context and the result is a plaster that correlates well with the original plaster both regarding appearance and microscopic structure. In this case the method resulted in a mortar with a composition and pore structure that ought to provide good technical properties and durability [27].

In order to use this method, a large number of reference mortar surfaces have to be made based on the local, traditional variations in mortars and plasters. Furthermore, application of the method requires a team with expert knowledge in both microscopic investigations and the whole practical process from mixing mortars to making lime plasters.

Further studies will aim to verify the general applicability of this method, based on a number of case studies in different geographic regions. During 2007 the tower of Örgryte old church in Gothenburg and Fleringe church on Gotland will be replastered using this method.

6. ACKNOWLEDGEMENTS

This work has been funded by The Knowledge Foundation, Sweden, and a consortium consisting of Samfälligheten Gotlands kyrkor, Byggnadshyttan på Gotland, Cementa Research AB, MPI, Svenska kyrkans församlingsförbund and Nordkalk.

Special thanks are directed to Tor Broström, University College of Gotland and all the craftsmen at Gotland especially the brothers Kenth and Curth Klasén who have spent many hours discussing, experimenting and working with lime together with Kristin Balksten.

Bibliographic references

[1] ICOMOS homepage of Venice Charter, http://www.icomos.org/venice_charter.html (2007-02-21):

[2] BALKSTEN, K. Kalkputs. *Porstrukturens betydelse för beständighet.* Licentiate thesis. Chalmers University of Technology, Sweden, 2005.

[3]ALVAREZ, J.I., NAVARRO, I., *Tower of Pamplona's San Cernin church*. Cement and Concrete Research 30 (2000) pp 1413-1419.

[4] BENEDETTI, D., VALETTI, S., BONTEMPI, E., PICCIOLO, C., DEPERO, L.E. *Study of ancient mortars from the Roman Villa of Pollio Felice in Sorrento (Naples).* Applied Physics A 79 (2004) pp 341-345.

[5]BIANCHINI, G., MARROCCHINO, E., VACCARO, C. *Chemical and mineralogical characterization of historic mortars in Ferrara (northeast Italy).* Cement and Concrete Research 34 (2004) pp 1471-1475.

[6] BISCONTIN, G., BIRELLI, M. P., ZENDRI, E. *Characterization of binder employed in the manufacture of Venetian historical mortars.* Journal of Cultural Heritage 3 (2002) pp 31-37.

[7] BRUNO, P., CALABRESE, D., DI PIERRO, M., GENGA, A., LAGANARA, C., MANIGRASSI, D.A.P., TRAINI A. and UBBRÌACO, P. *Chemical–physical and mineralogical investigation on ancient mortars from the archaeological site of Monte Sannace (Bari – Southern Italy).* Thermochimica Acta, 418 (2004) pp 131-141.

[8] CAZALLO, O., RODRIGUEZ-NAVARRO, C., SEBASTIAN, E., CULTRONE, G. and DE LA TORRE, M.J. *Aging of lime putty: Effects of traditional lime mortar carbonation.* Journal of the American Ceramic Society 83 (2000) pp 1070-1076.

[9] DEGRYSE, P., ELSEN J. and WAELKENS M. *Study of ancient mortars from Sagalassos (Turkey) in view of their conservation.* Cement and Concrete Research 32 (2002) pp 1457-1463.

[10] ELERT, K., RODRIGUEZ-NAVARRO, C., SEBASTIAN PARDO, E., HANSEN, E., CAZALLO, O. *Lime mortars for the conservation of historic buildings*, Studies in Conservation 47 (2002) pp 62-75.

[11] Elsen, J., Brutsaert, A., Deckers, M., Brulet, R. *Microscopical study of ancient mortars from Tournai (Belgium).* Materials Characterization 53 (2004) pp 289-294.

[12] ELSEN, J. *Microscopy of historic mortars – a review.* Cement and Concrete Research 36 (2006) pp 1416-1424.

[13] GENESTAR, C., PONS, C. *Ancient covering plaster mortars from several convents and Islamic and Gothic palaces in Palma de Mallorca (Spain).* Analytical characterization. Journal of Cultural Heritage 4 (2003) pp 291-298.

[14] HEINEMEIER, J., JUNGER, H., LINDROOS, A., RINGBOM, Å., VON KONOW, T. and RUD, N. *AMS 14C dating of lime mortar.* Nuclear Instruments and Methods in Physics Research B 123 (1997) pp 487-495.

[15] HENRIQUES, F.A. *Replacement mortars in conservation: an overview,* Proceedings of the 10th International Congress on Deterioration and Conservation of Stone, ICOMOS, Stockholm, 2004, pp 973-984.

[16] HUGHES, J., CUTHBERT, S. *The petrography and microstructure of medieval lime mortars from west of Scotland: Implications for the formulation of repair and replacement mortars.* Materials and Structures 33 (2000) pp 594-600.

[17] MARINONI, N., PAVESE, A., FOI M. and TROMBINO L. *Characterization of mortar morphology in thin sections by digital image processing.* Cement and Concrete Research 35 (2005) pp 1613-1619.

[18] MERTENS G. and ELSEN J. *Use of computer assisted image analysis for the determination of the grain-size distribution of sands used in mortars*. Cement and Concrete Research 36 (2006) pp 1453-1459.

[19] MIRIELLO D. and CRISCI G.M. *Image analysis and flatbed scanners. A visual procedure in order to study the macro-porosity of the archaeological and historical mortars.* Journal of Cultural Heritage 7 (2006) pp 186-192.

[20] MONTOYA, C., LANAS, J., ARANDIGOYEN, GARCIA CASADO, P.J., ALVAREZ, J.I. *Mineralogical, chemical and thermal characterizations of ancient mortars of the church of Santa Maria de Irache Monastery (Navarra, Spain).* Materials and Structures 37 (2004) pp 433-439.

[21] MOROPOULOU, A., BAKOLAS, A., BISBIKOU, K. *Investigation of the technology of historic mortars.* Journal of Cultural Heritage 1 (2000) pp 45-58.

[22] MUGNAINI, S., BAGNOLI, A., BENSI, P., DROGHINI, F., SCALA, A., GUASPARRI, G. *Thirteenth century wall paintings under the Siena Cathedral (Italy). Mineralogical and petrographic study of materials, paining techniques and state of conservation.* Journal of Cultural Heritage 7(2006) pp 171-185.

[23] PAPAYIANNI, I. *Design and manufacture of repair mortars for interventions on monuments and historical buildings,* Proceedings of the International RILEM-workshop "Repair mortars for historic masonry", Delft, Unedited pre-prints. Delft, Holland, 2005.

[24] RAMPAZZI, L., POZZI, A., SANSONETTI, A., TONIOLO L., and GIUSSANI, B. *A chemometric approach to the characterization of historical mortars.* Cement and Concrete Research 36 (2006) pp 1108-1114.

[25] RODRIGUEZ-NAVARRO, C., HANSEN, E. and GINELL, W.S. *Calcium hydroxide crystal evolution upon aging of lime putty.* Journal of the American Ceramic Society 81 (1998) pp 3032-3034.

[26] BALKSTEN, K., KLASÉN, K. *The influence of craftsmanship on the inner structures of lime plasters.* Proceedings of the International RILEM Workshop Repair Mortars for Historic Masonry. Unedited pre-prints. Delft, Holland, 2005, pp 9-16.

[27] BALKSTEN, K., MAGNUSSON, S. (2004) *The pore structure in lime plaster as a key to understanding moisture transportation properties and frost damages.* Proceedings of the 10th International Congress on the Deterioration and Conservation of Stone, ICOMOS, Stockholm, Sweden, 2004, pp 1033-1040.

[28] HANSON, C., THELIANDER, H. *Properties and quality of lime. Part 1. The influence of conditions during reburning.* Nordic Pulp & Paper Research Journal 3 (1994) pp 161-166.

[29] HIDEMARK, O., HOLMSTRÖM, I. *Kalkputs 2. Historia och teknik – redovisning av kunskaper och forskningsbehov*. Riksantikvarieämbetet, Stockholm, 1984.

[30] VON KONOW, T. *Restaurering och reparation med puts- och murbruk.* Åbo akademi, Åbo, 1997.

[31] BALKSTEN, K., STEENARI, B-M. *Evaluation of the effect of the slaking method on the particle size and structure of lime putty.* Submitted to HMC08.

[32] LAGERLÖF, E., SVAHNSTRÖM, G. *Gotlands kyrkor.* Rabén & Sjögren, Stockholm, 1966.

[33]LISINSKI, J. Gotlandskalk. *Beskrivning av traditionell kalktillverkning i Hejnum-Djupkvior.* Riksantikvarieämbetet, Stockholm, 1987.