# The Use of Mortar Dating in Archaeological Studies of Classical and Medieval Structures

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There are many anonymous buildings dating from the Classical and Medieval periods where their date of construction cannot be confirmed by written sources or artefacts such as coins.

Mortar is different from other dateable materials in that it is abundant during the construction process. Mortar dating - if successful - could provide an important chronological key in archaeology. Since 1994 the interdisciplinary *International Mortar Dating Project* has been devoted to developing a method of dating lime mortar and concrete-like materials. <sup>14</sup>C has been analyzed in mortars from Medieval churches in the Åland Islands in the archipelago between Finland and Sweden and also from Classical Archaeology (i.e. ancient buildings in Italy, Spain and Portugal from the time of the Roman Empire and from Medieval structures in Rome itself).

The methodological development of this technique has been both complicated and time consuming, and is therefore best illustrated by a chronological account of our work. The methodological principles have been known since the 1960s (Labeyrie and Delibrias 1964), but many factors have stopped its use in practice including carbon forms influencing the results. However, testing mortar during the 1980s in the ruins of the Franciscan convent of Kökar (in the outer Åland archipelago) was sufficiently encouraging for us to continue refining the method within the *Project of the Åland Churches* that started in 1990. In the beginning the <sup>14</sup>C dating was done with a conventional radiocarbon counting technique that involved using large one kilogram samples; but in 1994 this was replaced by analysis performed by the AMS (Accelerator Mass Spectrometer) (Heinemeier et al. 1997). This was an important improvement that allowed the dating of much smaller samples that are easier to prepare and analyze.

We will describe how the Åland project of dating Medieval mortars soon spread into the world of Classical Archaeology, and how it was gradually implemented for different types of mortars from different parts of the Roman Empire. The project is directed from Åbo Akademi University in Finland while the <sup>14</sup>C AMS analysis is performed in the Accelerator Laboratory at Aarhus University in Denmark. The team has expertise in Classical Archaeology (both for Rome and the Iberian Peninsula) and recently the Radiocarbon Accelerator Unit at Oxford University has joined our team.

# THE PRINCIPLE OF MORTAR DATING AND THE PREPARATION PROCEDURES

The principle behind mortar dating is straightforward (Van Strydonck and Dupas 1991, Hale et. al. 2003; Lindroos 2005). At the time of hardening the mortar absorbs  $CO_2$  from the atmosphere, and

thereafter it can be subjected to normal  ${}^{14}C$  dating analysis like organic materials such as shells, corals and young limestone etc. (fig. 1).



Figure 1. The principle of mortar dating. The chemistry of the hardening process involves carbon dioxide from the atmosphere being absorbed into the mortar (Hale *et al.* 2003)

The results given as <sup>14</sup>C ages BP (Before Present = AD 1950) have to be converted to calendar years by means of a complex calibration curve that varies over time according to atmospheric <sup>14</sup>C levels. The precision of the method varies depending on where the BP results intersect with the calibration curve. For example, Medieval Scandinavian mortars are often disturbed by irregularities in the curve during the 14<sup>th</sup> century. But where the calibration curve falls steeply the results can be surprisingly precise. While it can be difficult to yield exact dates with <sup>14</sup>C analysis, it is frequently possible to place the mortar within the right century. This is useful in situations such as Åland where the chronology has always been open to speculation.

Sampling has to be done carefully and one handful of mortar is usually enough. The mortar should preferably be taken from a place where it has hardened quickly and the sample chosen with the help of archaeological expertise (to avoid selecting mortar from a subsequent repair). The sample is then immediately tested in the field for alkalinity with the use of phenolphthalein.

This method of dating mortar has been known in theory since the 1960s (Labeyrie & Delibrias 1964), but contamination from unburned fossil limestone and re-crystallization of the mortar prevented experimental development of the method. To achieve accurate dating of the mortar the preparation process in the laboratory has to be meticulous, involving mineralogical and chemical analysis of the readily soluble component to determine the hydraulic index (Van Strydonck *et al.* 1986).

The sample preparation procedure starts with mechanical separation whereby the mortar is carefully crushed and wet sieved to select a suitable grain size. Through experience we have learnt that the optimal grain size varies depending on sample type, but is usually between 30 and 150  $\mu$ m. The material is further checked for unburned fossil limestone with cathodoluminescence microscopy

(Lindroos 2005, pp. 8-11). During the preparation for <sup>14</sup>C AMS-analysis further chemical separation is allowed to take place (e.g. the samples are dissolved in chilled phosphoric acid in vacuum kept in an ice bath). The reaction with the acid creates a flow of carbon dioxide gas that is interrupted at different stages and separate fractions are collected for dating and stable isotope analyses.

The goal of the <sup>14</sup>C AMS-analysis is to date the mortar itself rather than the organic materials enclosed in the mortar (e.g. charcoal, splints of wood and leaves etc.). However, any organic material found embedded in the mortar is also separately dated to double check the results of the mortar dating. We have observed that charcoals reflect the so-called "old wood effect" in that they provide inconsistent results on dates.

Initially only two carbon dioxide fractions were dated per sample, approximately 15% and 85% of the collected reaction. This was on the assumption that porous mortar carbonate would dissolve more quickly than unburned fossil limestone, resulting in the first fraction being free from this kind of contamination. The second fraction would most probably include the contaminant and therefore yield results too ancient (Baxter and Walton, 1970; Folk & Valastro, 1976).

# MORTARS DATED IN TWO FRACTIONS

## The churches of the Åland Islands

The reason for using this technique on the churches from the Åland Islands was an urgent need to accurately date these buildings. For a long time the chronology of the Åland churches has been subject to much controversy due to a lack of contemporary written sources. During the Middle Ages there were thirteen mortared stone churches and chapels on the islands, that both formed a surprisingly heterogeneous group in the immediate vicinity but were distinct from other churches in the surrounding area. Archaeological excavations failed to solve the problem of dating and this led to many speculative opinions with wide variations in date depending on the authority cited. The Project of the Åland Churches was initiated to help solve this puzzle and from the beginning involved an interdisciplinary approach making use of different types of scientific dating. At first the problem seemed simple and straightforward: dendrochronology was the obvious answer and a programme was started to count tree rings on the wood in the churches. However, the results of this testing were disappointing. Dendrochronological analysis could not date the initial building construction in any of the Åland churches as the naves were all roofed at a later date. (however this technique did successfully date the church towers which were built subsequent to the roofing of the naves; this information added to an understanding of the chronology of the churches). It was therefore the case that mortar dating was the only option to establish the date of construction of the churches.

Four Medieval churches in the Åland Islands - those of Hammarland, Eckerö, Saltvik and the tower of Jomala - were the first to be dated through <sup>14</sup>C AMS analysis in two fractions. The results of the

first fraction did indeed seem to prove the theory - they were void of contamination and showed that initial church building began on the Islands towards the end of the 13<sup>th</sup> century (fig. 2). This unanimous chronology for the mother churches is surprising because no other evidence suggested a simultaneous building programme. On the contrary, the Åland churches are all very different from each other, both in size and plan, and to some extent in building technique. However, they do have unifying features including the use of the local red granite as the main building material, vaulting in field stones, framed windows and portals with local Ordovician limestone (the churches also avoid the use of brick). In the case of Jomala church, the first fractions from five samples from the tower suggest the calibrated time span AD 1279-1291, corroborating satisfactorily with the dendrochronological analysis, which yields AD 1281 for the same structure. So the use of mortar dating appeared to be validated on the Åland Islands.



Figure 2. Statistical results from mortar analysis in two CO<sub>2</sub> fractions from three churches on the Åland Islands. The first fractions suggest a building period towards the end of the 13<sup>th</sup> Century.

#### Torre de Palma, Vaiamonte, Portugal

Torre de Palma - a Roman villa in the eastern part of Portugal - provided the first test of the technique when applied to a building dating from Classical times. The villa is situated close to the Spanish border and was one of the largest farms, or *latifundias*, in the Iberian Peninsula during the Roman period. Apart from the initial atrium house, the villa included two baths, vast surrounding

living quarters with stables and wine/olive presses, all suggesting a horse-breeding farm with a variety of other farming activities. Although sampling was carried out all over the site in 1997-2000, the adjoining basilica initially was the main focus of our interest. The basilica was erected in adobe but had a well-preserved mortared stone foundation that was still visible. The basilica has an unusual plan that is rectangular with a nave and two aisles and double apses (one in each end of the rectangle). Another rectangle was added towards the west and included yet another building with two apses (Maloney & Hale 1996).

Mortar used on the periphery of the Roman Empire is not hydraulic and chemically it resembles the Medieval mortars found on the Åland Islands. It is very different from the Roman pozzolana mortar described below. High quality marble - probably from the quarries in nearby Estramoz - provided pure raw material for the mortar limes. Thirteen samples were analyzed in two fractions from the walls of the initial basilica. Ten of them yielded the same results from their first fractions. Calibrated results suggest that the basilica was erected in AD 535-600, probably by the Visigoths (Maloney, 2000) (fig. 3).

![](_page_4_Figure_2.jpeg)

Figure 3. Plan and calibrated results from the double-apse Basilica of Torre de Palma, Portugal (Maloney 2000, Aarhus)

The second fractions of several of the samples produced dates close to those of the first fractions. The only exception was from a font in the southern sacristy, beautifully lined with hard mortar mixed with crushed bricks whose first fraction yielded results far too young. The same puzzling effect was later observed with all the waterproof constructions in the villa.

Work at Torre de Palma showed that the mortar dating techniques could usefully be applied to buildings from Classical times. Sensible results were obtained from all the different buildings in the villa area from the Classical period. But yet again there was no opportunity to compare the results with other data. Because of this the mortar dating technique did not establish itself with a wider audience.

### **Classical mortars from Rome**

To validate the technique it was necessary to apply it to buildings in Rome where the dates of the structures are well known. However, this approach presented other challenges. Roman Pozzolana is hydraulic with an entirely different chemistry to that which we had previously studied. Pozzolana mortar is the key to Roman architecture as one of the techniques that revolutionised Roman architecture. Pozzolana mortar is generally known to harden under water without the necessity to react with atmospheric carbon dioxide (Blake 1968, pp. 312-318). Because of hydraulic Pozzolana the Romans were free to mould any variety of vaults, domes and cupolas (Lancaster 2005, pp.1-21), thus creating the strong constructions that we still know today.

![](_page_5_Picture_3.jpeg)

Figure 4. Ancient Rome: Trajan's Market with Trajan's Forum in the foreground and the Medieval tower of Torre delle Milizie in the background (photo Åsa Ringbom)

1998-99 signalled the beginning of mortar analysis of ancient Roman Pozzolana concrete, but since the principle behind the dating method is based on analyzing the carbon dioxide absorbed in the hardening process, we did not expect encouraging results. The area in Rome selected for sampling by Lynne Lancaster (a member of our team) included Trajan's Forum, Trajan's Market and the Basilica Ulpia (fig. 4). This area is known for the high quality of mortars used from the Trajanic period. Sampling was supervised by Janet DeLaine and was also done in Ostia on structures dating from the reigns of Trajan and Hadrian. In both localities we had an opportunity to start testing the method on firmly dated mortars of an entirely new chemistry. Initially the sampling result in very confusing results. Samples taken in 1999 were separated in three fractions (the ideal aimed at was 30%, 30% and 40% of the total dissolution process). Of these fractions 1 and 2 were usually dated. The dates suggested by the first fractions were extremely uneven and far too recent compared to the actual date known from written sources and brick stamps. However, after this initial disappointment we soon realized that the second fractions yielded dates close to the expected age, which was the reign of Trajan (AD 98-117) (**fig. 5**).

![](_page_6_Figure_1.jpeg)

#### Rome samples, final results (January 2001) (Rome 20, deep samples and crushed tile not shown)

Figure 5. Results from Rome and Ostia - BP and calibrated. Joint calibration of the second fractions, united by an almost horizontal line in black, yield the age of 65 AD-125 at a confidence of 68.2% (Aarhus)

#### Medieval mortars from Rome

During our first sampling tour in Rome in 1998 samples were not only taken from buildings belonging to the Classical period but also from Medieval structures; at this stage the samples were separated in two  $CO_2$  fractions only. This time the first fractions appeared to give reasonable results. For example, the church of Santo Urbano (recently uncovered in the excavations of the Via dei Fori Imperiali) obviously belongs to the Romanesque period. The first fraction from a Carolingian structure in the Forum of Nerva intersected with the calibration curve during the end of the 8<sup>th</sup> century, and three samples from the Torre delle Milizie produced differing dates for the first fractions, but indicated a construction date for the tower of the 13<sup>th</sup> Century (table 1) (see fig. 12).

Table 1. <sup>14</sup>C dates and  $\delta^{13}$ C values for Medieval mortars from Rome. St Urbano: on top of Trajan's Forum. Carolingian construction: on top of Nerva's Forum. Torre delle Milizie: behind Trajan's Market.

Sample	Carbon yield and			
	fraction size (F)	$^{14}C$ age BP $\delta^{13}C$		Calibrated age
St Urbano	3.5%			
AAR-4797.1	0.25 (per 12s)	920±30	-9.9	AD 1060-1135
AAR-4797.2	0.75 (per 22min)	1060±35	-9.9	AD 960-1020
Carolingian				
Structure	2.8%			
AAR-4802.1	0.47 (per 7s)	1250±25	-16.1	AD 695-780
AAR-4802.2	0.53 (per 40min)	3520±50	-6.4	BC 1880-1790
Torre delle				
Milizie	4.6%			
AAR-4798.1	0.23 (per 10s)	835±30	-10.6	AD 1190-1255
AAR-4798.2	0.77 (per 34 min)	3575±50	-3.4	BC 2010-1830
	4.2%			
AAR-4799.1	0.31 (per 12s)	585±25	-11.1	AD 1330-1395
AAR-4799.2	0.69 (per 29min)	1205±45	-7.7	AD 780-810
	3.6%			
AAR-4800.1	0.26 (per 15s)	750±35	-14.3	AD 1260-1285
AAR-4800.2	0.74 (per 17min)	885±45	-8.3	AD 1040-1220

These Medieval Roman mortars still include Pozzolana, and their chronology is less well known. Yet there has to be an explanation for first fractions in this case to yield reasonable results. Could the hydraulic character of the mortars explain the difference? It was now necessary to establish the hydraulic index of each sample (Van Strydonck *et al.* 1986, Van Strydonck and Dupas 1991). Our

chemical analyses has revealed a corroboration between a low hydraulic index and a reasonable age for the first fractions, but this was not so obvious for all the Medieval mortars in Rome. At first sight, the results from the Medieval buildings seemed rather confusing. Although the first fractions yielded plausible results, they were not always congruent, and the second fractions occasionally proved to be unreasonably old.

Surveying our general results we gradually became aware of a statistical pattern. For non hydraulic mortars the first fractions seemed to come close to the expected age. This interpretation, of course, was emphasized if several samples from the same building unit yielded the same result with the first fraction. If, in addition to this, both fractions from one individual sample coincided then it provided additional support for relying on the result from the first fraction. The basilica in Torre de Palma fulfilled both these criteria.

With hydraulic mortars, both with ancient Roman Pozzolanas and maybe also with mortars made hydraulic by adding crushed bricks into the aggregate, the first  $CO_2$  fraction generally yielded results far too uneven and too recent. However, in these cases the second fraction (see **fig. 5**) came close to the expected age. This knowledge was invaluable for a deeper understanding of the process of mortar dating and it inspired the application of new routines.

# INTRODUCTION OF ANALYSIS IN SEVERAL FRACTIONS FOR MORTARS FROM CLASSICAL ANTIQUITY

The experience from Rome which showed the second fraction produced dates close to the expected age indicated the need to focus on the dissolution process and the necessity of learning how to recognize the right age in anonymous samples. Thus in 2002 a decision was made that, to achieve the right age using the mortar dating technique, the samples should be dated in at least five fractions that ideally consist of 20% of the total dissolution process (**fig. 6**). This was required to create a profile (e.g. fig. 8) for additional information and to get more data for modelling the effects of the contaminants.

When several fractions tend to yield the same age the plateau of the profile normally coincides with the expected age. These profiles were introduced both for the Classical period and for Medieval structures.

By way of example we considered Santa Costanza - one of the best-preserved structures in Rome from the  $4^{th}$  Century AD – which has a somewhat enigmatic background. The original function of this cylindrical building attached to the horse shoe shaped Basilica of Sant'Agnese is unknown and so is the date of its construction. The building has usually been seen as a mausoleum built by and for Constantina (daughter of Constantine the Great) while she was residing in Rome between marriages and is thought to have been built sometime between AD 330 and 337. However,

excavations performed by Dr. David Stanley at the joint between the cylindrical structure and the horse shoe shaped Basilica revealed that the latter originally was joined to a triconch construction under the present building of Santa Costanza. Consequently, Santa Costanza is a later addition to the Basilica. The chemical composition of the mortars from these two building units is also entirely different from each other (Materiali e tecniche... 2001, catalogue 2, pp. 207-209, and catalogue 11, pp. 240-241). Stanley dated Santa Costanza to the second half of the fourth Century (Stanley 1993) for which controversial view he has met harsh criticism (Rasch 2000, pp. 155-156). One sample collected from restoration works in Santa Costanza was first analyzed in two CO<sub>2</sub> fractions, with the typical result: the second fraction came close to the estimated age, or  $1710 \pm 50$  BP (calibrated AD 260-410). Renewed analyses in three fractions fitted in with the earlier results and together they provided a profile for which the radiocarbon age of  $1690 \pm 35$  BP is defined by a horizontal level or plateau. This result supports Stanley's point of view (Ringbom 2003). However, the result from only one sample run in several fractions from two different chemical separations of the same grain size is obviously not sufficient. One completely new series of analysis in four fractions (performed at the Oxford Radiocarbon Accelerator Unit) confirmed the earlier result from the AMS Laboratory at Aarhus. A combined profile, with a plateau spanning three fractions yields a radiocarbon age of  $1697 \pm 19$  BP, or after calibration AD 260-280 (5,8 %) and AD 330-390 (64,4 %) (fig. 7).

![](_page_9_Figure_1.jpeg)

Figure 6. Chemical separation of mortar in five CO<sub>2</sub> fractions (i.e. increments) (sketched by Alf Lindroos)

Extending the plateau to the last fraction does not make a great difference to the final result. The age  $1710\pm17$  BP suggests a building period between AD 260-280 and AD 320-390. Repeated analysis of one sample has not finally resolved the enigmatic question of the date of construction. To determine the time of construction we therefore needed to analyze more samples in the future, both from Santa Costanza and from the original Basilica of Sant'Agnese.

![](_page_10_Figure_0.jpeg)

Figure 7. Profile from Santa Costanza and calibrated results: analysis initially performed at the AMS-laboratory (Aarhus, and later confirmed by the Radiocarbon Accelerator Unit, Oxford)

One of the first samples from Rome taken in 1998 from Basilica Ulpia (built by Trajan 106-112 AD) had initially been chemically collected into only two  $CO_2$  fractions. To begin with the result was seen as a failure. However, the date of the second fraction was more or less as expected, and it therefore seemed like a good case to double check with a profile consisting of five successive fractions. This time the result was convincing. We received a regular profile (**fig. 8**) with a horizontal plateau at the known age of  $1873\pm18$  BP, which after calibration gives a date of AD 80-140.

The Amphitheatre at Merida Augusta, a town in western Spain founded by Emperor Augustus for his retired soldiers, is marked by the same kind of ambiguity concerning the date of construction as Santa Costanza. According to an inscription found in the Amphitheatre it was erected in 7 BC. However, the work of Pedro Mateos Cruz (archaeologist and head of the National Museum of Roman Art in Merida) suggests that the construction of the amphitheatre belongs to the Flavian era or AD 69-96. In this case the mortar is very hard and concrete-like and it has also been claimed to be hydraulic in character (Cruz 1999, p. 39). The mineralogy is most extraordinary in that it has a dominating magnesium rich component. An age profile from the Amphitheatre, based on eight

fractions reaches a plateau at the Flavian period ( $1944\pm27$  BP, or AD 25-85 at 58,8 % and, AD 100-120 at 9,4%). In a case like this plenty of re-crystallizations influenced the early part of the profile. Chemical analysis shows that this mortar is not hydraulic. Even so, a plateau is not reached until the later fractions (**fig. 9**).

![](_page_11_Figure_1.jpeg)

Figure 8. Basilica Ulpia, Trajan's Forum. Results from the first analysis in two CO<sub>2</sub> fractions later confirmed by a profile created by five successive fractions (Aarhus)

![](_page_12_Figure_0.jpeg)

Figure 9. The Amphitheatre at Merida Augusta, Spain (Ringbom *et al.* 2003). Profile created by results from eight successive CO<sub>2</sub> fractions from the same sample analyzed on two different occasions (Aarhus)

# ANALYSIS IN FIVE FRACTIONS OF MEDIEVAL MORTAR

These profiles from the Classical period were by comparison very informative. Our more complex chemical separation of the samples into five  $CO_2$  fractions is a step in the right direction. The profile thus created illustrates the dissolution process. The first part of the profile which tends to be too recent reveals the influence of re-crystallization or alkaline features, whereas the last part of the profile (which normally turns out to be too ancient) shows the influence of fossil unburned limestone dissolving at a slower rate than the mortar.

Based on this work it seemed important to introduce analysis in five fractions to the Medieval mortar from the Åland Islands. The same procedure was consequently followed in the church of

Sund, which had never been archaeologically excavated and where there were no additional means of dating from coins or artefacts. The church has a rectangular plan and is vaulted in two naves, with many details in the architecture and the wall paintings pointing towards a Gotland influence. The church was burned several times, which made dendrochronological analysis of the building constructions irrelevant.

In total five samples from the nave in Sund were analysed in five fractions. Two samples were taken from the walls, one from a cavity in the wall (017) and one at socle level (014). The age profiles reach a plateau within the same time span calibrated to AD 1240-95. Two additional samples (025 and 026) from the vault show atypical profiles with a sharp decrease in the radiocarbon age towards the end. Even if we cannot fully understand the irregularity of these profiles from the vault, the results of the plateaux seem to support the results from the nave (fig. 10).

![](_page_13_Figure_2.jpeg)

Figure 10. The church of Sund, Åland. Five profiles from the nave of the church suggest a building date at the second half of the 13<sup>th</sup> Century (Aarhus. Photo Åsa Ringbom)

In the case of Sund an interesting chronological feedback is provided by a gigantic crucifix, measuring more than 5 m in height, and architecturally perfectly fitted in the vaulted interior (Ringbom & Remmer 2005, pp. 167-177). This crucifix is the largest to be found in a parish church north of the Alps, and it is therefore unlikely to have belonged to any possible smaller wooden predecessor. Dendrochronological analysis of the crucifix performed by Peter Klein from the Institute of Wood Biology, Hamburg University, Germany, suggests a cutting of the oak for the corpus in northern Germany some time between AD 1236 and 1246 (fig. 11).

![](_page_14_Picture_1.jpeg)

Figure 11. The crucifix in Sund, originally a ring-crucifix of Gotland type. Dendrochronological analysis shows that the oak of the body of Christ was felled between 1236 and 1246 (photo Åsa Ringbom)

Therefore, for the church of Sund - which is representative of Medieval mortar from Scandinavia - the plateaux of the profiles seems to yield the right result. Why not the first fractions, as was the case earlier, when Åland mortars were analyzed in two fractions? The samples from Sund are slightly more hydraulic than other mortars from the Åland Islands and - more importantly - most of them showed the presence of readily soluble young and minor carbonate phases affecting the first fractions. In this case re-crystallization has been identified microscopically and the results of the first fractions were different for all samples from the same building phase. The only place in the respective profiles where the ages are concordant, and which represents the bulk of the samples, is the horizontal level. The supporting date of the crucifix was also significant for the interpretation.

Similarly, when a sample from Torre delle Milizie which had previously been analysed in two  $CO_2$  fractions in Aarhus (as described above) was analysed in five fractions in Oxford, the profile confirmed the estimated date of construction as some time towards the end of the 13<sup>th</sup> century and also demonstrated the extreme level of contamination of the successive fractions (**fig. 12**).

![](_page_15_Figure_1.jpeg)

Figure 12. Earlier samples of mortar from Torre delle Milizie analyzed in Aarhus in two CO<sub>2</sub> fractions. The date to the 13<sup>th</sup> Century is confirmed by a profile of five successive fractions of sample Rome 007 (Oxford)

![](_page_15_Figure_3.jpeg)

Figure 13. The church of Hammarland, Åland. Earlier results analyzed in two CO<sub>2</sub> fractions confirmed by profiles: the building of the nave took place during the last quarter of the 13<sup>th</sup> Century (Aarhus)

#### Checking earlier results from Åland

The interpretation of the profiles from the church in Sund (cf. **fig. 10**) demonstrated an urgent need to return to our earlier results from Åland. It was vital to know what sort of profiles would emerge from samples of those non-hydraulic Medieval mortars analyzed earlier and how they were to be interpreted. The results of profiles from Hammarland (**fig. 13**) and Eckerö (**fig. 14**) were reassuring: the first fractions of the profile tended to yield the same age as the initial, whereas a plateaux was hard to find. This is because readily soluble Åland limestone is abundant in the aggregates. One of our first improvements of the method when we adopted AMS analysis was to minimize the size of the first  $CO_2$  fraction. The new results from the profiles confirmed that this was the right approach.

![](_page_16_Figure_2.jpeg)

Figure 14. The church of Eckerö, Åland. Earlier results analyzed in two CO<sub>2</sub> fractions double checked and verified (Aarhus)

#### CHALLENGES IN THE FUTURE

The first big challenge - to identify, separate, and minimize contaminating fossil limestone in the samples prepared - now seems feasible even though the mechanical separation could still be improved. The second big challenge was to date hydraulic Roman Pozzolana mortar. When analysing samples separated in only two  $CO_2$  fractions we found that the expected age was reached with the second fraction. Corroboration was provided from dates firmly known from brick stamps and other historical sources. In order to improve the resolution of the chemical separation, dating in five successive  $CO_2$  fractions from each sample was introduced. These <sup>14</sup>C age-profiles are more informative and enable mathematical modelling of contamination and re-crystallization.

The third big challenge lies ahead in the future. This will be to find a precise way to interpret the profiles correctly, or rather, to find out when the results of the first  $CO_2$  fractions are relevant for the dating, and when we should rely on the plateau in the profile for the right age. We already know that the interpretation depends on the character and the quality of the mortar, but we believe that we can see a statistic pattern: with non hydraulic mortars usually the first fraction counts, whereas hydraulic pozzolana mortars reveal the right age at the plateau of the profile. When on occasions profiles from less hydraulic mortars result in distinct plateaux, these tend to reveal the right age. However, here the nature of the first fraction is the real key: it shows whether the mortar has been subject to re-crystallization or not. The identification of the re-crystallizations is therefore crucial to our continued research.

It is clear that further work needs to be done on refining the method. But it is important to test the limits for the implementation of mortar dating, i.e. different kinds of mortars, from different parts of the world, and from different chronologies. In future we intend focusing on establishing the correct building chronology for the Åland churches.

#### ACKNOWLEGDEMENTS

Lynne Lancaster, The University of Ohio, Athens, Ohio The Foundation of Åbo Akademi University The Finnish Society of Sciences and Letters The County Government of the Åland Islands The Danish Research Council of Natural Science

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