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Isotope Technologies Applied to the Analysis of Ancient Roman Mortars

Results of the CRAFT Project EVK4 CT-2001-30004

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FOREWORD I

By Mr Janez Potočnik. EU Commissioner for science and research

Dear readers,

I knew that we had a great deal to learn from the Romans, but reading this enlightening booklet I realised that there is so much more to discover than I imagined!

The "self-healing mortars" used in ancient Roman buildings are a surprising example. But much more than that. This research project shows the fascinating variety of research. It shows that we can turn research into technological advances. And it is yet again proof that small and medium-sized enterprises (SMEs) are crucial for Europe's competitiveness: that they are very dynamic, and also very varied. This allows them to respond rapidly to the opportunities of changing markets. I am fully aware that this is not an easy task.

I am therefore happy that the Commission supported this project, through its research programmes and specific initiatives - in particular, the 'City of Tomorrow and Cultural Heritage' key action of the Fifth Framework Programme for Research. Our overall goal is to reinforce the scientific and technical basis for protecting and rehabilitating European cultural heritage.

This publication outlines the successful research of a consortium of SME partners and Research Institutes into the properties of ancient Roman mortars. The new processes and materials will be registered in European Patents allowing the SMEs to produce specialised mortars for use in the restoration and preservation of ancient buildings and monuments.

I do hope that the ingenuity and perseverance of our researchers combined with funds from the EU will lead to many more success stories like this one.

FOREWORD II

By Mrs Cristina Gutiérrez-Cortines, Member of the European Parliament

It is an honour for me to write the preamble for such a research work, one that can be an example of how cultural issues, integrated into social and human sciences can be the basis of technical research. In doing so we are creating an association among the sciences that goes further than the mere interdisciplinary collaboration.

After having worked for more than three decades on the conservation of cultural heritage, I recognise the lack of technical knowledge on materials and techniques that were used in the past. We usually know a lot about the history of the monuments and archaeological sites, however very few know about their composition, behaviour of the materials, or their specific needs.

The development of a systematic and scientific research that supports knowledge and compatible solutions for the old architecture is important and necessary for those, who are responsible for the management and restoration of the cultural heritage. It is the lack of knowledge of old techniques and materials which leads to poor restoration and in many cases is not always compatible with the old original structure. Methods that frequently have provoked real harm to the original work, have disfigured the image, and have generated strong visual impacts.

I appreciate the initiative and the strength carried out by this group of researchers. The science and the instruments of analysis development in work of this kind are indispensable contributions that will have immediate practical use, helping in a direct way scholars from the past and those who have made decisions for the restoration. These updated technologies from this interdisciplinary team, will help us undertake the study of the buildings and archaeological sites with more objective methods.

It is necessary to congratulate the authors and the institutions for the work done, and DG Research FP5 programme 'City of Tomorrow and Cultural Heritage' for the publication of this project. This publication will provide professionals and cultural heritage managers new knowledge that opens the door to ecological and sustainable solutions.

Cristina Gutiérrez -Cortines. Prof. Dr. History of Art

Acknowledgements

"In a world given over to globalization, local heritage and culture gives a much needed security to people's sense of identity and their communities ability to recognize themselves"
Gianfranco Berbenni, OFM Cap

The idea of the ITER project was born in 1996 in Rome by a small group of interdisciplinary thinkers and SME managers guided by the Franciscan monk Padre Gianfranco Berbenni, founder of the not for profit MultiUniversus Foundation and currently president of InGentibus Foundation e.V.[1]

ITER has demonstrated that one of the keys to success has not only been the cooperation among research and industry, but also the involvement of 3 stakeholders and a business SME during all phases of the project including the phase of fundamental research.
The successful cooperation consisted on solid team work and trust which was built throughout the project. Sharing interdisciplinary expertise and knowledge among the partners- particularly among the Antiquities Authorities stakeholders- contributed to the solidarity of the team.

We, the SME partners Hydroisotop, Servin, Krusemark and FUTUREtec, together with the research institutes IFE – Institute for Energy Technology and CNR – Consiglio Nazionale delle Ricerche 'Gino Bozza, would like to convey our deep gratitude to

- our Project Officer at the European Commission Mr. Brian Brown,
- the former Head of Unit there, Mr. David Miles,
- Mr. Cyril Silver, formerly officer at the European Commission,
- Mr Klaus Seyfried, currently vice president of InGentibus e.V.,
- Ms Johanna Leissner, Project Officer at the European Commission

all of whom played a vital role at various stages in the life of this project and without whom we could not have fulfilled our role in this challenging project.

[1] http://www.ingentibus.org

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General Introduction

Learning from Roman Mortars

Roman buildings were made to last. One of the key reasons for their longevity is the quality of the mortar used in their construction. The best Roman mortars are durable, strong and resistant to water and environmental conditions.

The goal of the ITER project was to understand how the Romans prepared their mortars to enable them to remain so durable. Roman mortars can remain effective for up to at least 2,000 years, while modern mortars are often in need of restoration after merely 50 years. In addition to helping reproduce ancient mortars, a better understanding of Roman mortars could therefore also aid in developing better modern mortars.

The ITER consortium consisted of four SMEs and two RTD performers. In addition, three antiquities authorities were subcontracted to the project. Fostering effective co-operation with a multidisciplinary approach, for instance, between experts conducting mineralogical and isotopic analysis of ancient building techniques and knowledgeable specialists working in the protection of cultural heritage and ICT, was a key factor to the success of this CRAFT project.

Isotopes and Archaeology

The analysis of isotopes in mortar had not been done prior to the ITER project. This innovative isotope technology was conducted alongside traditional analytical techniques, to examine samples of Roman mortar from three major archaeological sites, with the help of the relevant antiquities authorities. The sites, representing different climatic and environmental conditions, were in Germany (Colonia Ulpia Traiana, Xanten), Italy (Villa Traiana, Rome), and Israel (Caesarea Maritima).

The small and medium seized enterprises (SMEs) Hydroisotop (Germany) and Servin (Italy) conducted light isotope analysis, along with providing expertise on sampling procedures and data interpretation, while the mortar producer Krusemark (Germany), supplier of mortar to archaeological and conservation bodies for use in heritage projects, as well as to the building trade generally, prepared mortar prototypes.

The RTD performers provided dedicated research facilities, which were beyond the means of the individual SMEs. The Institute for Energy Technology (Norway) analysed heavy isotopes and light isotopes, while CNR (Italy) conducted the mineralogical analysis. The results, together with historical and bibliographical information, were stored in an internet database. FUTUREtec (Germany) constructed the database with Servin, developed an ITER co-operative working tool, and oversaw intellectual property rights issues relating to the project.

All elements in nature consist of different isotopes, which are atoms of an element with same number of protons but different numbers of neutrons in their nucleus.

Isotope technologies analyse differences in the ratios of isotopes in selected elements. In the mortar samples, isotopes of carbon (C), strontium (Sr), oxygen (O) and lead (Pb) were measured, along with sulphur (S) and nitrogen (N). This yielded important new information on the origin and composition of building materials, mortar preparation methods, building techniques, and how environmental factors affect mortars over time.

Self-healing Mortars

The Romans knew what they were doing when it came to producing mortar.
Roman building technology is based on a variety of mortar assemblages depending on the function of the building materials. Although mortar from around the former Roman Empire varies in composition due to differences in local materials (e.g. sand and limestone), distinct similarities in the ratios of components and preparation technique were observed at the three sites.

The most important finding of the ITER project was to show that part of the lime component in Roman mortar can remain reactive for hundreds and, in some cases, thousands of years. This is due to its encapsulation within lime nodules. While the outer surface becomes calcified, sealing off the mortar inside, the core retains small nodules of reactive lime. If the mortar becomes cracked and carbon dioxide enters the core, the reactive lime crystallises to form calcite. This acts to rebind the mortar. The encapsulation of part of the binder in nodules is therefore an important part of the preparation technique. This property can explain the durability of Roman mortars.

Conserving the past, building for the future

The ITER partners established models of Roman mortar composition and preparation technique. From this, Krusemark produced mortar prototypes at the laboratory level.

Mortar prototypes, together with the mortar database, will form the basis of authentic mortars for the accurate conservation of ancient buildings and artefacts. They will also lead to the production of new mortars with improved durability for use in modern buildings. The knowledge gained from the study of bedding mortars in Roman cisterns, for example, may lead to new mortars with enhanced hydraulic performance.

The methods of mortar analysis and preparation developed during the ITER project are being protected by the participating SMEs. This will enhance their prestige and increase their potential markets. Other spin-offs arising from ITER methodologies include the monitoring of materials in buildings and the assessment of air pollution that better distinguishes its impacts from that of intrinsic deterioration due to construction and materials.

The project may have a widespread impact: In the future, the methodologies could help to monitor the state of cultural heritage on a European level and provide, among others, dedicated IT tools for decision-makers.

1. The Vision of Re-designing Ancient Mortars

The EU-CRAFT project ITER – Isotope Technologies Applied to the Analysis of Ancient Roman Mortars – started in April 2002 and ended in June 2004. The motivation of the consortium was to introduce new technologies to the analysis of Roman Mortars, reconstruct the original technology, and rediscover the composition of building materials that in some cases have remained intact for approximately 2.000 years.

Since it has been clearly documented that some Roman buildings are more resistant than many modern ones, the mortars have been sampled from ancient constructions, which were produced during the best developing period of Roman age. Because Roman mortars were made from materials found in different places, it was necessary to sample and study the mortars from different parts of the former Roman Empire to assess their raw materials, climatic conditions, environmental factors, and degree of conservation.

The analytical approaches were based on the combination of:

1. The analysis of isotopes in mortars as an innovative technique. The results of such analyses were expected to improve the knowledge on the origins of high resistant ancient mortars and to give more precise basic information on their preparation such as mixing techniques and burning temperatures.

2. The physico-chemical and morphological characterisation of mortars (mineralogy, physical parameters, trace elements analysis, bulk chemical analyses, electron microscopy, I.R. and U.V. Spectroscopy). In view of a basic approach to isotope analysis, it was necessary to use traditional techniques such as complementary sources of information and references.

Isotope technology offers additional information on the formation of mineralogical compounds that give the stability to Roman mortars. The results of the sampling and analysis have led to a new approach for the production of prototypes, which can also be applied to future projects in the field of Buildings Preservation and Restoration.

Demonstrating the validity of isotope technology in analysis of mortars and building materials, was one of our goals

Another goal of the consortium was to create a database of mortar characteristics based on the analytical data that was collected. This database has been the crux for production and testing of prototype mortars, as well as the basis for an internet based information system, which is open to all partners. There background data and results of the project are collected and accessible.

1.1 The Problem

Roman mortars and plasters have characteristics that have enabled them to survive for thousands of years and retain their major characteristics of strength, hardness and resistance to water; modern mortars or plasters that are commercially available do not have these characteristics.

A systematic method for design and reproduction of these mortars has two major advantages:

1. Improvement in the repair and maintenance of Roman structures throughout Europe and the Middle East, which are an essential part of our cultural heritage. The same approach could be adopted for the analysis of other building materials used in

mediaeval, renaissance and more recent periods. That way the restoration of these structures can also become more authentic.

2. Improvement of modern mortars and plasters with characteristics superior to those currently available.

Traditional analysis methods have proven to be insufficient for solving the riddle of Roman mortars. One reason for this is that geochemical and mineralogical methods work on chemical evidence, but do not provide reconstruction processes that have consumed the reacting material, such as organic matter. Further, an origin assignment based on chemical properties of mortars often is ambiguous and therefore complementary methods are required to yield information on processes, as well as the origin of material.

1.2 Objectives

The main objectives of the ITER project have been to:

1. Demonstrate the scientific validity of isotopic analytical investigations and methodologies on ancient Roman mortars to better understand why they are so resistant to physico-chemical alteration.
2. Create a database of mortar characteristics based on the collection of all analytical data concerning isotopic technologies complementary to traditional analysis, with the aim to enable the reproduction of mortars for authentic preservation and restoration of ancient buildings and artefacts.

Secondary objectives have been to steer project activities towards results and products that are amenable to dissemination and further development. These were:

- To test isotopic analytical methodologies compared to the traditional methods, for the identification of the provenance, decay, and the conservation processes of ancient mortars
- To develop new technologies and methodologies in the field of isotopic analyses and collect them in a database, in order to disseminate the identification of the special characteristics of materials in ancient structures
- To produce mortar prototypes at laboratory level based on the knowledge and data gained during the project and for testing / confirmation of the research results.
- Further improvement of the investigation methodologies and technologies, which will be offered to industry and archaeologists, in order to preserve of our cultural heritage. The results and database are of importance to industrial applications in terms of quality improvement of mortars.

1.3 The Consortium

The ITER consortium consisted of a core group of:

- Four (4) Small and Medium Enterprises – Hydroisotop, FUTUREtec, Servin, and Krusemark.
- Two (2) research institutes -IFE – Institute for Energy Technology (Norway) and Consiglio Nazionale delle Ricerche "Gino Bozza" (Italy).
- Three (3) antiquities authorities (Jerusalem - Israel, Roma - Italy, Xanten – Germany).

The SMEs and research institutes complementary covered the areas of geochemical and isotopic analysis, information technology, and mortar production / design.

HYDROISOTOP specialises in the measurement and interpretation of natural isotope contents in connection with chemical and mineralogical investigations. The company's role in the project was the measurement, comparison test of the different laboratories, examination, and interpretation of analytical data.

FUTUREtec is a well-established SME operating in the fields of information, communication technologies, and technology transfer of research results at international level. They are specialized in the development of databases, interactive portals and software. The company's role in the project was to develop the internet based ITER database, the co-operative working tool and to lead the dissemination and exploitation activities.

KRUSEMARK deals with the development, production, and distribution of dry mortars. The company has specialised in the production of rendering mortars (undercoat mortars, one-coat-mortars, lightweight-mortars and coloured mortars, with decorative function), damp-proofing mortars and renovation mortars and special mortar systems for the restoration of natural stones, as well as coating mortars to produce copies and pointing mortars. Krusemarks role in the project was the development of the ITER dry mortar prototypes, exploitation and dissemination among the existing customers and interested institutions.

SERVIN - Servizi Integrati Gestionali Ambientali - works on the application of environmental knowledge: from natural resources research and exploitation, to site remediation, project management, and environmental assessment evaluation. It has strong links with major Italian scientific institutions such as the Universities of Turin, Bologna, Rome, Venice, Milan, and European laboratories in France and Germany. Its role in the project was the technical co-ordination of the sampling campaign and the database development and dissemination.

The ICVBC CNR "Gino Bozza" is a branch of the Istituto per la Conservazione e la Valorizzazione dei Beni Culturali (Institute for the Conservation of Cultural Properties) belonging to Consiglio Nazionale delle Ricerche (Italian Research Council). The aim of ICVBC CNR "Gino Bozza" is the conservation of works of art through the application of scientific methods for the knowledge of ancient materials and techniques and for the identification of the causes of decay. The objective is to provide a technical support for the conservators and for the restorers. The research activity covers the field of stone material, including mortar, plaster and brick. The ICVBC CNR "Gino Bozza" is also involved in the draft of standard methods of scientific analyses in the field of stone material conservation. As a prime RTD performer ICVBC CNR "Gino Bozza" is leading in the field of mortar analysis.

IFE – Institute for Energy Technology (IFE) - is an independent foundation established in 1948 with departments at Kjeller and Halden. The Institute carries out long-term research such as basic research in physics with a focus on projects that have a significant impact on industrial innovation and technology renewal. IFE has special expertise in isotopic analysis techniques applied in many industrial areas.

The interaction between Research Institutes and SMEs in this project provided an opportunity to address a technically demanding subject material requiring interdisciplinary efforts on different institutional levels.

Fostering effective interdisciplinary co-operation was a key factor to the success of this CRAFT project.

1.4 Contribution to EU Policies

ITER's major aim has been to make a substantial and innovative contribution to the protection, conservation and enhancement of the European cultural heritage.

The European Commission is not only a political and economic organisation. Its overall objectives and policies are related beyond all other considerations to the improvement of the quality of life of its citizens. The preservation and availability to the public of that part of our cultural heritage, which is embodied in ancient buildings and artefacts is an essential element in those aspects of the quality of life which are cultural and not merely economic. Thus this project has supported strongly the EU policy on the protection, conservation and enhancement of the European cultural heritage.

Increasingly, the public demand is for authenticity. People like to know that a Roman building, for example, is either in its original form or, where restored, is as near as science and engineering can make it, identical to its structure in Roman times.

This project has been devoted to that objective. Isotopic techniques will enable mortar, and eventually, other building materials to be traced back to their sources so that duplication of the materials used by the Romans can be assured. That makes an important contribution to the execution of EU policies related to the European Cultural Heritage.

There is a further EU policy which has been and is directly supported by this project. That is the policy for the promotion of Tourism. Europe is the richest area of the world in ancient, medieval, renaissance and more recent works of distinction in art and architecture. People travel within Europe and from the rest of the world to Europe to see these structures and artefacts. This project will make it easier to keep such monuments in good repair, will help retain their integrity and authenticity, and will make their continuing availability to the public more certain. This will encourage further tourism and thus contribute to the objectives of EU policy related to tourism.

Two other aspects are important. First, the results of the ITER project make an important contribution to the conservation of ancient towns, which otherwise might be irreparably damaged and thus, contribute to EU social policies which call for the preservation of life, as it has been lived for centuries, in our diverse forms of towns and villages and thus stem some of the unhealthy population movement from villages and small towns to the big cities. Secondly, the results will be applicable also to restoration work in an authentic manner carried out on more modern buildings and the results based on the performance of Roman mortars should assist in increasing the longevity of more modern structures and their resistance against water (e.g. Venice) and earthquakes.

It is also important, in addition, to note that this project has been driven by small and medium-seized enterprises (SMEs). It has fulfilled the needs of SMEs and it has encouraged international co-operation between them. Thus it has added its small contribution to the EU policy of encouraging SMEs and their co-operation between themselves and with technology providers.

2. The Riddle of Roman Mortars

2.1 What we know

Ancient Greek and Latin Authors wrote about lime preparation and the mix of *Pulvis Puteolanus* (a volcanic powder from 'Campi Flegrei' area, near Naples) to make a very strong mortar. The most valuable text on the original Roman recipes is the treatise *De Architectura* (Ten books of architecture) written by Vitruvius in the last decades of the 1st century B.C. The second book is devoted to the description of building materials where chapter 4, 5 and 6 describe the components of the mortar and are closely related to our field of interest.

The words of Vitruvius are very clear and we have verified in many cases the correspondence between Vitruvius' recipes and the real composition of Roman mortars pointed out by mineralogical and chemical analyses. *English translation by Frank Granger – Loeb Classical Library, Harvard University Press, 1934.*

> *"Chapter IV - ON SAND*
> *1. …in rubble structures we must first inquire about the sand, that it be suitable for mixing material into mortar, and without the admixture of earth. Now the kinds of quarried sand are these: black, white, red, and from lignite. Of these, that which makes a noise when rubbed in the hand will be best; but that which is earthy will not have a like roughness. Also, if it is covered up in a white cloth, and afterwards shaken up or beaten, and does not foul it, and the earth does not settle therein, it will be sui.*
> *2. But if there are no sand-pits whence it may be dug, then it must be sifted out from the river bed or from gravel, not less also from the sea-shore. But such sand has these faults in buildings: it dries with difficulty, nor does the wall allow itself to be loaded continuously without interruptions for rest, nor does it allow of vaulting. But in the case of sea sand, when plastered surfaces are laid upon walls, the walls discharge the salt of the sands and are broken up.*
> *3. But quarry sand quickly dries in buildings, and the surface lasts; and it admits of vaulting, but only that which is fresh from the pit. For if after being taken out it lies too long, it is weathered by the sun and the moon and the hoar frost, and is dissolved and becomes earthy. Thus when it is thrown into the rubble, it cannot bind together the rough stones, but these collapse and the loads give way which the walls cannot maintain. But while fresh pit sand has such virtues in buildings, it is not useful in plaster work; because owing to its richness, the lime when mingled with straw cannot, because of its strength, dry without cracks. But river sand because of its fineness (like that from Signia [a town of Latium]), when it is worked over with polishing tools, acquires solidity in the plaster."*

> *"Chapter V - ON LIME*
> *1. After furnishing an account of the supply of sand, we must next be careful about lime, to burn it out of white stone or lava; the lime which shall be out of thick and harder stone will be useful in the main structure; that which shall be of porous material, in plaster work. When it is slaked, then let it be mingled with the sand in such a way that if it is pit sand, three of sand and one of lime is poured in; but if the sand is from the river or sea, two of sand and one of lime is thrown together. For in this way there will be the right proportion of the mixture and blending. Also in the case of river or sea sand, if anyone adds crushed and sifted potsherds in the proportion of one to three, he will produce a blending of material which is better for use.*
> *2. And so when lime receives water and sand and then strengthens the structure, the following seems to be the cause: just as other bodies, so also stones are blended of the elements. And those which have more air are soft; more water, are pliant from the moisture; more earth, are hard; more fire, are more fragile. Therefore if stones of this last quality are crushed before they are burnt, and mixed with sand, and thrown into the*

work, they do not become solid, nor can they hold the building together. But when they are thrown into the kiln, they are seized by the violent heat of the fire and lose the virtue of their former solidity. Their strength is burnt out and exhausted and they are left with open and empty pores.
3. Therefore when the moisture which is in the body of that stone, and the air, are burnt out and removed, and the stone retains the remaining latent heat, on being plunged into water (before it recovers power from fire), the moisture penetrates into the open pores, and it seethes and thus, being cooled again, it rejects the heat from the substance of the lime. Thus, moreover, whatever weight the stone possesses when it is thrown into the kiln, it cannot answer to that when it is taken out ; but when it is weighed, the bulk remaining the same, it is found to lose about one-third of its weight when the moisture is burnt out. Therefore, when the pores and attenuations of the lime are open, it catches up into itself the mixture of the sand; thus it coheres and, as it dries, joins with the rubble and produces solid walling."

"Chapter VI- ON POZZOLANA
1. There is also a kind of powder which, by nature, produces wonderful results. It is found in the neighbourhood of Baiae [on the bay of Naples] and in the lands of the municipalities round Mount Vesuvius. This being mixed with lime and rubble, not only furnishes strength to other buildings, but also, when piers are built in the sea, they set under water. Now this seems to happen for this reason: that under these mountainous regions there are both hot earth and many springs. And these would not be unless deep down they had huge blazing fires of sulphur, alum or pitch. Therefore the fire and vapour of flame within, flowing through the cracks, makes that earth light. And the tufa which is found to come up there is free from moisture. Therefore, when three substances formed in like manner by the violence of fire come into one mixture, they suddenly take up water and cohere together. They are quickly hardened by the moisture and made solid, and can be dissolved neither by the waves nor the power of water.
2. But that there are fervent heats in these districts may be proved by this circumstance. In the hills of Baiae which belong to Cumae [north of Baiae] sites are excavated for sweating-rooms. In this hot vapour rising deep down perforates the soil by the violence of its heat, and passing through it rises in these places, and so produces striking advantages in sweating-rooms. Not less also let it be recorded, that heats in antiquity grew and abounded under Mount Vesuvius, and thence belched forth flame round the country. And therefore now that which is called "sponge-stone" or Pompeian pumice seems to be brought to this general quality from another kind of stone when it is subjected to heat.
3. But that kind of sponge stone which is taken thence is not found in all places, only round Etna and on the hills of Mysia (..), and if there are in any other places properties of that kind. If, therefore, in these places there are found hot springs, and in all excavations, warm vapours, and if the very places are related by the ancients to have had fires ranging over the fields, it seems to be certain that by the violence of fire, moisture has been removed from the tufa and earth just as from lime in kilns. 4. Therefore, when unlike and unequal substances are caught together and brought into one nature, the hot desiccation, suddenly saturated with water, seethes together with the latent heat in the bodies affected, and causes them to combine vehemently and to gain rapidly a strong solidity. (...)"

The great number of translations in different European languages up to the first decades of 19th century testifies the importance of Vitruvius' treatise. Medieval and modern Authors on art and architecture always investigated the Roman mortar in order to make mortar with the same characteristics of strength. Authors report the recipes for making different kinds of mortar with lime and pozzolana and try to explain the mechanism of lime setting. It is very useful to understand the raw material used and the curing of the mixture before the use even if the recipes seem to be reported, in some cases, without a direct experience of the mortar making.

The problem of the Roman mortars is well pointed out by Rondelet's 'Traité de l'art de bâtir' (Paris, 1802; Tome 1, Livre 2, Section 2, Article 4, 283-284): the conclusions is remarkable!

“Du mortier des Romains:
Je ne pense pas, comme plusieurs auteurs l’ont prétendu, que les anciens Romains aient eu une méthode de faire le mortier, différente de celle que l’on pratique encore aujourd’hui à Rome et dans toute l’Italie, ainsi que dans plusieurs autres pays. Il est certain que malgré la décadence des arts qui a suivi celle de l’Empire romain, on n’a pas discontinué de bâtir jusqu'à nos jours; on a pu perdre, pendant plusieurs siècles, le goût de la bonne architecture, parce qu’elle demande des études et des connaissances aux-quelles les révolutions causées par l’invasion des peuples du nord ne permit pas de se livrer: mais quant au procédés de l’art de bâtir , qui sont à la portée des ouvriers ordinaires, il faut croire qu’ils ont été transmis jusqu’à nous, tels qu’ils se pratiquaient du temps des anciens Romains. Cette question m’ayant paru une des plus importantes de l’art de bâtir, j’ai examiné avec soin les restes des anciens édifices tant de Rome que de l’Italie et de la France bâtis par les anciens Romains, et j’ai reconnu, en comparant les mortiers employés à leur construction avec ceux des édifices construits depuis dans les mêmes pays, qu’au bout d’un certain temps il parvenaient à une dureté égale. On voit par plusieurs parties des constructions de Saint Pierre de Rome, qui sont en briques apparentes, que le mortier qui les unit est aussi dur que celui des édifices antiques, tels que le Panthéon d’Agrippa, le temple de la Paix, et plusieurs fragments qui sont de la plus haute antiquité.
L’excellence qu’on attribue au mortier des anciens Romains, provient autant des bonnes qualités e la chaux et du sable qu’ils y employaient, que de l’attention qu’ils avaient de le bien broyer, afin de faciliter l’union et la mélange exact de ces matières. Je me suis assuré, par plusieurs essais, que plus le mortier est broyé, plus il acquiert de consistance, et plus il durcit promptement. Avec de la chaux ordinaire de Paris, et du sable moyennement gros, je suis parvenu à faire des briques en mortier qui, au bout de dix-huit mois, avaient acquis presqu’autant de dureté et de consistance que le mortier des Romains. (...)”

2.2 What we investigated

In spite of existing knowledge on the type of ingredients, little was known about the processing of the material, how regional sources of material affected quality, and what organic or other minor additives improved the hardening process.

Isotope methods provide analytical data on:

- The process of hardening of lime/mortar can be quantified and measured with the ^{14}C technique as the carbon dioxide needed for the reaction represents a chronometer that starts decaying as soon as the mineralogical reaction of calcification takes place.
- The ^{13}C and ^{18}O signature of calcite reveals information about the source of carbon, even if the original product was consumed in the reaction.
- Regional sources can be identified based on Sr, Pb and other isotopic fingerprints.

3 The Methodology: Isotope Techniques on Solid Phases

3.1 Sampling Technique

The sampling strategy has been defined as a procedure with four objective steps:

1. Identify the best possible characterisation of the sample site regarding the differentiation of building materials and techniques (see chapter 4). In this phase it is important to differentiate the used mortars based on knowledge of the function of the building/wall, its inner structure and possible changes. It also includes the consideration of the environment of the sampling site (traffic / weather and different exposures / previous restoration measures etc.).
2. Sample with the aim of minimizing the impact on the building / wall and optimising the reliability / reproducibility of the sample assuring that the mineralogical and isotope analysis can be reproduced.
3. Analyse the chemical, mineralogical and isotopic characterization to further understand the building techniques.
4. Identify processes of weathering, self-healing by re-crystallization, gas diffusion, and decomposition of materials in order to use this information in making a better mortar prototype.

The institutes (IFE and CNR) have specified their needs on the mortars to be analysed where small samples of about 100 g were sufficient. CNR worked on cores using mineralogical techniques where one inch coring was proposed with sample splitting: 2 for mineralogy and 2 for isotopes and with 1 sample of each stored.

The final sampling procedures and specifications applied in Arcinazzo (Rome) have been defined as follows:

- The drilling equipment is a portable wall-driller, equipped with an iron diamond sampler (Figure 1);
- The sampler has a diameter of 2 cm and a length of 50 cm;
- Drilling is done by dry drilling, in order to avoid the contamination produced by the cooling liquid (usually water). An attempt to use gaseous nitrogen as cooling liquid was made, but it was observed that the phase of extracting the sample from the core-sampler gives no guarantee of avoiding contamination.

These sampling procedures have also been applied in the two other sites, Xanten and Caesarea Maritima.

Surface material may be strongly altered, thus one should drill cores as long as possible to obtain unaltered material. After drilling, the samples are split into subsections along the core and put into sealed plastic bags where analysis of the light stable isotopes requires 5 g of material. The amount of material needed for analysis of the heavier stable isotopes is difficult to specify since we cannot predict isotope concentrations.

A good run is depending on the concentration of Pb and Sr in the sample where 0.5 μg of purified Sr or Pb is sufficient for duplicate analysis. After chemical dissolution and ion exchange, the Pb and Sr fractions are analysed on a TIMS (Thermion Ion Mass Spectrometer) for the isotope ratios.

Figure 1 *Sampling in Xanten, with a portable wall-driller, equipped with an iron diamond*

3.2 Isotope Methods Applied to Mortars

3.2.1 Carbon Isotopes

Carbon is an abundant element in the universe and forms the basis of life on Earth. Consequently, it is prevalent in the biosphere, crust and mantle of the Earth, hydrosphere, and atmosphere. Carbon occurs in a reduced form in organic compounds and coal, in an oxidized state such as carbon dioxide, as carbonate ions in aqueous solutions, and as carbonate minerals. In addition, it is found as a native element in the form of graphite and diamond.

Carbon has 2 stable isotopes, ^{12}C and ^{13}C (98.89% and 1.11% respectively) as well as a radioactive ^{14}C, which occurs in nature due to its formation in the upper atmosphere by a reaction on stable ^{14}N. The stable carbon isotopes are fractionated by a variety of natural processes, including photosynthesis and isotope exchange reactions among carbon compounds. Photosynthesis leads to enrichment of ^{12}C in biologically synthesized organic compounds. On the other hand, isotope exchange reactions between CO_2 gas and aqueous carbonate species tend to enrich carbonates in ^{13}C. As a result, the isotopic abundance of ^{13}C in terrestrial carbon varies by approximately 10 percent.

The isotopic composition of carbon $^{13}C/^{12}C$ is expressed in terms of the delta notation, $\delta^{13}C$, also used for oxygen. The reference standard is CO_2 gas obtained by reacting $CaCO_3$ carbonate samples, originally belemnites of the Peedee Formation (PDB standard), with 100% phosphoric acid at 25°C. A calibration standard, NBS-19, is used which has been compared to PDB where carbon is analysed as CO_2 gas using mass spectrometers. .

The isotopic composition of calcium carbonate precipitated from aqueous solutions is controlled by several factors, including:

1. The $\delta^{13}C$ value of CO_2 gas in equilibrium with carbonate and bicarbonate ions in solution;

2. Fractionation of carbon isotopes between CO_2 gas, the carbonate and bicarbonate ions in the solution, and solid calcium carbonate;
3. The temperature of isotopic equilibration;
4. The hydrogen ion activity (pH) and other chemical properties of the system that have an effect on the abundance of carbonate and bicarbonate ions in the system.

The $\delta^{13}C$ values of carbonate rocks of marine origin are virtually constant and have values close to zero on the PDB scale.

3.2.2 Lead Isotopes

The element lead occurs in nature with four Pb-isotopes with approximately the following distribution: ^{204}Pb 1.4%, ^{206}Pb 24.1%, ^{207}Pb 22.1% and ^{208}Pb 52.4%. The ratio between the different lead isotopes varies in different geological systems due to the formation of ^{206}Pb and ^{207}Pb when ^{238}U and ^{235}U, respectively, decays while ^{208}Pb is a product of the radioactive decay of ^{232}Th. ^{204}Pb is the only isotope of lead which gets no addition from radioactive decay and thus its abundance in the Earth's crust is not changing with time.

Lead is widely distributed throughout the Earth and occurs not only as the radiogenic daughter of uranium (U) and thorium (Th) but also forms its own minerals from which U and Th are excluded. Therefore, the isotopic composition of Pb varies between limits from the highly radiogenic Pb in very old U, Th-bearing minerals to the common Pb in galena (PbS) and other minerals that have low U/Pb and Th/Pb ratios.

Lead is also a trace element in rocks where its isotopic composition contains a record of the chemical environments in which the Pb resided. Each environment has different U/Pb and Th/Pb ratios that affect the isotopic evolution of Pb. The U/Pb and Th/Pb ratios are altered by magma generation, fractionation, hydrothermal and metamorphic processes, weathering, and other low temperature processes at the Earth's surface. The isotopic composition of a particular sample of Pb may be modified both by decay of U and Th and by mixing with Pb having different isotope composition. As a result, the isotopic compositions of Pb in rocks and ore deposits display complex patterns of variation that reflect their particular geologic histories.

Uranium and thorium have similar chemical properties and can substitute extensively for each other. However, under oxidizing conditions, U forms the uranyl ion that in turn forms compounds that are soluble in water. Therefore, U is a mobile element under oxidizing conditions and is separated from Th whose compounds are generally insoluble in water. The U enrichment of carbonate rocks results from the fact that U occurs in the oceans as uranyl ion that co-precipitates with calcium carbonate, while Th is associated primarily with water insoluble sediment.

3.2.3 Strontium Isotopes

Strontium (Sr) has four naturally occurring isotopes, with the approximately following distribution: ^{84}Sr 0.56%, ^{86}Sr 9.87%, ^{87}Sr 7.04% and ^{88}Sr 82.53%. All these isotopes are stable, but ^{87}Sr gets a contribution from the decay of ^{87}Rb. The isotopic abundances of Sr isotopes are thus variable because of the formation of radiogenic ^{87}Sr by the decay of naturally occurring ^{87}Rb. For this reason, the precise isotopic composition of Sr in a rock or mineral that contains Rb depends on the age and Rb/Sr ratio of that rock. The ability of strontium to replace calcium to a large degree in minerals and biogenic material allows it to be a tracer for processes and transport in the environment.

The isotopic composition of Sr in circulation in the hydrosphere depends on the $^{87}Sr/^{86}Sr$ ratios of the rocks that interact with water at or near the surface of the earth. Isotopic homogenization of Sr released into solution occurs by mixing during transport until it arrives in the oceans or in a closed basin on the continents. From there the Sr re-enters the rock cycle primarily by co-precipitation with calcium carbonate. The $^{87}Sr/^{86}Sr$ ratios of marine carbonate minerals are assumed to be identical to those of seawater at the time of deposition, provided that they have not been altered during diagenesis. The sedimentary carbonate and evaporated rocks of the world have therefore preserved a record of the changing isotope composition in the oceans and on the continents throughout time.

The isotopic signature of Sr will thus be unique for every carbonate and yield information about its source and time of formation, and later super-position due to atmospheric and hydrologic conditions.

3.2.4 Analytical Procedures

The mortar samples were disintegrated and slightly ground in an agate mortar, which was washed with 3 M HCl and rinsed with de-ionized water between samples.

For Sr and Pb analyses, samples of about 40 to 50 mg, were transferred over into 2 ml plastic tubes and added ultra clean HCl drop-wise with increasing concentration until no more reaction was observed. The samples were then centrifuged, the clear solution pipetted off and transferred into new clean 2 ml plastic tubes and taken to dryness on a hotplate at about 90°C. After evaporation was completed the residues were taken up in 200 µl 3 M HNO_3 of ultra clean quality and centrifuged. The solution was sucked off and the plastic tube rinsed with ultra clean water before the sample was transferred back into the tube prior to the ion exchange.

A modification of the ion extraction chromatographic method described by Horwitz et al. (1992; 1994) was used. The ion exchange columns were packed with crown ether resin (Eichrom SR-B50-S, 50–100 µm) that was changed between every new set of samples. The empty columns were rinsed with 3 M HNO_3 and ultra-clean water before new crown ether resin was loaded. After loading, the columns were cleaned with ultra-clean water and ammonium carbonate solution. The samples, dissolved in 200 µl 3 M HNO_3, were sucked onto the six parallel ion-exchange columns with the help of a peristaltic pump after they had been activated before hand with 3 M HNO_3.

Most other elements were washed out with 3 M HNO_3 while Sr and Pb were trapped on the columns. Strontium was then eluted with ultra-clean water and lastly Pb with diluted ammonium carbonate solution. The samples were taken to dryness and were ready for mass spectrometric analysis.

For ^{13}C and $\delta^{18}O$ isotope analysis the sample (about 1 mg) was transferred to a 10 ml vacutainer, put in a temperature controlled Aluminium block and flushed with He for 5 min. Then 0.1 ml 100% H_3PO_4 was added and the reaction controlled at 25.0 °C for 2 hours. The produced CO_2 gas (calcite fraction) was then flushed out with He flow on to a Poraplot Q GC column and analysed directly on a Finnigan MAT DeltaXP, Isotope Ratio Mass Spectrometer.

3.2.5 Mass Spectrometry

Two rhenium filaments are needed for the analyses of Sr, one on which the sample is loaded (evaporation filament) and one for monitoring the ionisation (ionisation filament). For Pb only one rhenium filament is needed. The rhenium filaments are welded onto a sample holder that is changed for every new sample. Before use, the rhenium ribbons on the sample holders are out-gassed under vacuum. The filaments are then screwed onto a turret taking 12 samples and one standard.

The Sr samples are dissolved in 1 µl 10% HNO_3, applied onto the evaporation filament and taken to dryness. For analyses of Pb 2 µl of Merck silicagel is first applied to the sample filament and then taken to dryness. Then the sample is dissolved in 1 µl H_3PO_4 and loaded onto the silicagel and taken to dryness.

The total blank of Sr and Pb for the separation procedure was less than 100 pg, resulting in a blank of less than 2ng/g sample. The mass spectrometric analyses were performed on a Finnigan MAT 261 mass spectrometer with double rhenium filaments for Sr and single rhenium filaments for Pb. The isotopic ratios of Pb were corrected for mass fractionation by repeated analyses of the NBS 981 Pb standard and Sr by the NBS 987 Sr standard. The isotopic ratios for $^{13}C/^{12}C$ and $^{18}O/^{16}O$ were analysed on a Finnigan MAT DeltaXP, IRMS and calibrated versus NBS-18 and NBS-19.

References

Horwitz, E.P., Chiarizia, R. and Dietz, M.L., 1992. A novel strontium-selective extraction chromatographic resin. Solvent Extraction and Ion Exchange 10, 313–336.

Horwitz, E.P., Dietz, M.L., Rhoads, S., Felinto, C., Gale, N.H. and Houghton, J., 1994. A lead-selective extraction chromatographic resin and its application to the isolation of lead from geological samples. Analytica Chimica Acta 292, 263–273.

4 The Description of the Sites and the ITER Database

4.1 Villa Traiana (Arcinazzo Romano, Italy)

The Aniene river valley stretches from the centre of Tivoli (about 30 km East of Rome) to Subiaco (about 60 km). Aniene River, called *Anio* by the Romans, flows in a valley run through *via Tiburtina Valeria* and *via Sublancensis*. The valley is surrounded by the calcareous slopes of Monti Tiburtini, Prenestini, Lucretili, and Simbruini.

The Aniene valley is flanked by Jurassic limestone outcrops and Miocene marly-limestone outcrops. Marly-limestone formation is constituted by:

- Thin bedded cherts with cherty limestone intercalations (Monti Tiburtini on the right bank).
- Fine grained limestone (called Majolica) with chert and calcite layers.
- Detritic limestone with marly intercalations. North from Tivoli, at some distance from the Aniene valley, white limestone.
- Outcrop (Sterparo – Lecinone group, lower Lias): they are well bedded, sub-crystalline or brecciated and suited for making lime. The zone near the river, in the segment where the valley is wider (between Castel Madama and Vicovaro and along the Empolitana valley).
- Outcrops of tufas and pozzolana (volcanic sediments, middle Pleistocene) and conglomerates.
- Near S. Cosimato (Vicovaro) banks of travertine.
- Outcrop belonging to the palaeoAniene; travertines were used in Roman times.
- Recent alluvial deposits together with clay deposits are found near the river and their tributaries (Empolitana, Licinese near Licenza).

The territory provided the raw materials for building mortar preparation where quarry activities are documented by wall remains and quarry traces such as*lapidicinae* in the open air and underground. Ancient quarries were located near the trade routes and areas of quality stone: it is important to note that modern quarry activities are often situated on ancient sites.

The importance of the Aniene Valley is witnessed by the agriculture, animal farming, passage of main roads (*via Valeria* and *via Sublacensis*), presence of aqueducts and imperial villas. The description of these elements is made via the examination of archaeological remains and leads to a specific theme: the local preparation of mortars.
The agriculture was based on the *villae rusticae* (farms) for soil cultivation, animal farming, and wood exploitation. The location is on the mountain slopes were soils are fruitful, wood is adequate, and roads are near such that trade was facilitated. The location on the slopes needed the construction of artificial terraces (*substructiones*) to create the level on which the villa was built.

Today the architectural remains are not visible, but different kinds of artificial terraces are still visible. This is a good sample of Roman masonry and it is possible to follow the evolution of the Roman mortar from the first construction of the villas (2nd century BC) to the last period of activity (5th century AD). Roman masonries were always restored, rebuilt, or adapted with the superimposition of different structures.

The masonries show the typical structures of the Roman architecture: *opus siliceum* (the so-called 3rd and 4th mode after Lugli classification) was made by local limestone; *opus* *quadratum* was more rare and was made by tufa or travertine; *opus caementicium* was covered by various kind of veneer: irregular shaped stone (*opus incertum*), pyramidal shaped stone (*opus reticulatum*), brick (*opus latericium*), a mix of brick and stone (*opus mixtum*), brick and stone in parallel rows (*opus vittatum*).

All the masonries used local stone in order to limit the transportation costs and different masonries show different kinds of mortar (not only in buildings of different time).

Aqueducts are important examples of Roman masonries since the frequent restoration works maintained the efficiency of the water pipes and are well documented by literature, as well as epigraphic remains. Skilled workers carried out the works on the aqueducts and their masonries were made with a better quality than the local examples: this is very important in the mortar studies on the aqueducts and roads.

The first villa was donated by Mecenas (or by Augustus) to the poet Horace (32 BC). The villa is located in the Licinese valley and was improved during the Flavii and later.

The villa of the emperor Nero (*Sublaqueum*) was built before 60 BC and transformed by Benedictine monks in the early years of 6th century AD.

The third villa was built by Emperor Trajan near Arcinazzo Romano (Monti Affilani) between 105 and 110 AD and was preceded by another construction (100 AD). All these villas are good examples to study the ancient Roman mortars (Figure 2) since the year of construction is known and the raw material certainly comes from local quarries.

Figure 2 *Villa Traiana and Arcinazzo Romano (Photo: Q. Berti)*

4.1.1 Site Characterization

New excavations (since 1999) unearthed the entire lower foundation of the villa and a number of mortar samples, corresponding to the different building phases (100-115 AD) became available. There are the bearing structures of the present-day villa, terraces, and porticoes, rooms of the west block and reinforcements of the same structures. Deep excavations showed an older villa (100-105 AD) where the differences of the building times are witnessed by *fistulae aquariae* made by lead and marked by the imperial seal that helps to establish a precise chronology.

Walls show the characters of the Trajan period: *opus mixtum* (*reticulatum* and brick), *opus latericium* and, for the first time, *opus vittatum* (small block of stone and brick). In fact a late building period (4th-5th century AD) may also be considered, but the Trajan period is certainly documented. The stone elements of the *opus reticulatum* (*cubilia*) or the *opus listatum* were made by limestone or by the so-called “Cardellino” a local soft travertine.

Characteristics of the mortars are quite different from the Nero villa. Here we found a lower quality due to the components and the production process.

The pozzolana fraction is poor and the aggregate is made by abundant river sand and stone scales (Cardellino). The raw material for the binder is a local grey limestone with calcite or cherty veins easy to cleave. The burning and the slaking were badly performed leaving lumps in the mortar; poor mixing caused cavities and low fluidity where the result was a low structural resistance. Due to this fact the terraces had to be reinforced during the same building phase when the foundations fell down.

The short time and the budget constraints probably were the reasons for the lack of quality in an imperial building. The time restrictions forced the use of local material and reduced the time for lime making. Bricks were made with local clay and the low quality of the products prevented their reuse in the restoration works. Bricks show *signa* made by fingers as in the local product made on the yard; there is no evidence of *figulinae* usually used in imperial buildings.

The comparison between different periods shows a moderate percentage of pozzolana in the mortars of the villa instead the use of river sand in some terracing restorations. Plasters to fix the marble slabs to the walls follow the same recipe. The same workers that made the bedding mortars probably fixed the marble slabs. A whole sector of the villa’s yard has a low standard of building quality compared to the perfection of the marble veneers, of the opera sectilia with coloured marbles, of the stuccoes and wall paintings: ancient yards were subdivided according to the workers duty. The older villa seems not to be affected by the time shortage and the low budget: the villa remains unfinished and covered by the new building. The *opus caementicium* is more resistant with a well-prepared mortar of the same components.

Late additions, as the stairway in the central part of the low terrace show a mix with a high percentage of earthy fraction and low cohesion and resistance. This result shows the deterioration of the preparation processes during the time, but also the local climate (low temperatures) is responsible to the mortar decomposition.

4.1.2 Building Materials

The raw materials required for constructing good mortar were present in the Aniene valley including limestone to make the binder, pozzolana, and river sand to make the aggregate. The use of these materials has been indicated by remains of quarry works, kilns, since ancient times.

The lime (calx cocta) comes from the burning of limestone and was made using kilns set up in the same quarry area. The quarry sites were scattered and the limestone outcrops are spread along the mountain slopes where stones were collected directly. In the quarries ancient or modern cuts are quite invisible due to the presence of alluvial deposits and vegetation. Kilns are clearly visible as big rounded cavities dug in the ground and surrounded by limestone blocks where a mouth was present in order to ignite the fires and to take the lime after the burning.

Woodpiles were set on the ground and covered by a great quantity of limestone pieces. The kiln shape remained unchanged during the century as described by Cato (*De agri cult*ura 38, 1-4), where the dimensions consisted of a diameter of 10 *pedes* (3 meters) and height of 20 *pedes* (6 meters).

These kilns were found scattered along the valley with a concentration on the western slope of Monte Lecinone (near the road) and above San Polo dei Cavalieri. Roman kilns are mainly located in the valley near the building yards while medieval kilns are located on the top of the mountains according to the growth of the *Castra* (fortified villages).

The lime production was devoted to the trade of Rome and Tivoli because the limestone outcrops on Monti Tiburtini are suitable for preparation of bedding and plastering lime. The lime is subdivided into two different classes:

- Fat lime (*calx pingius*) from pure and hard limestone that is good for bedding or plastering due to its fast setting nature.
- Slim lime (*calx macra*) from impure and thin-bedded limestone used for plastering.

The lime of low quality was produced from soft (easy to cut) calcareous deposits of the ancient flow of the Aniene River and the presence of pits useful to the hydration of burnt lime (*calx viva*) is not witnessed in the Aniene valley.

Sand (*sabulum, rena*) come from the banks of Anienen River: this sand is rare and mainly composed of granules, which is why the Roman mortars of Aniene valley were made using pozzolana instead of sand. Sand used in the great buildings probably come from abroad. The pozzolana (*pulvis puteolanus*) takes its name from the volcanic region near Pozzuoli (Naples). Big outcrops are present in the neighbourhood of Rome coming from the activity of the so-called Vulcano Laziale. Limited outcrops are present in the Aniene Valley also (Castel Madama) on the Valeria (near Vicovaro and San Cosimato): this is a good quality black pozzolana (together with beds of lapilli, slags and ejecta), used in Roman times.

Mortar types

Two kinds of mix were used in Roman times, a mix of:

- Lime and sand (materia ex calce et harena)
- Lime and pozzolana (materia ex calce et pulvere Puteolano).

The different proportion of components helps to distinguish two kinds of mortars: fat mortar and slim mortar. The use of each mix is linked to the availability of the raw materials where the use of pozzolana was prevailing (Table 1).

The proportion of sand is reported by {Vitruvius De arch. 2, 5, 1} and {Pliny, Nat. hist. 36, 175} as one part lime and two to three parts of river or marine sand; yielding approximately 25-33% lime. The quarry sand is pure, without earthy fractions, and was suitable to avoid wall crumbling and the amount of lime gives compactness to the masonry. Pliny reports that the destruction of many buildings in Rome was caused by the low amount of lime used by builders in order to have a low cost.

Figure 3 *Sampling in Arcinazzo Romano, Villa Traiana*

A great number of mortar samples examined in the Aniene valley and in the surrounding territories (Preneste, Tivoli and Sabina) shows the almost exclusive use of pozzolana instead of sand in mortar preparation. There are two reasons:

- Low quantity of sand available in the Aniene valley.
- Suitability of the hydraulic mortars based on pozzolana to the climate conditions of the valley.

The use of pozzolana reduces the damage caused by frost and the high humidity. The mix lime-pozzolana can be used in the early spring and in the late autumn giving a good resistance to the works. Present-day experience only allows for masonry works between March and mid October. The use of fat lime produces a true hydraulic mortar useful to works in special conditions (bridges, piers, etc.) and has a faster setting during rainy days. These characters were enhanced in public buildings (i.e. aqueducts) where a rapid quality construction at low cost was needed.

4.1.3 Sample Location

The Villa Traiana close to Rome was chosen as the first of three sites for sampling. During the first sampling campaign on October 14th 2002 in Arcinazzo the sampling protocol was tested and applied in the field. The sampling technique - coring with a hand-held driller of up to one (1) inch diameter – proved to be applicable. The option of using nitrogen as cooling medium and at the same time as gas atmosphere in order to avoid secondary reactions during the sampling, e.g. with CO2, was discarded as a result of this sampling campaign. Although the application of nitrogen during the drilling was possible with the available core driller, it was very difficult to be applied in the field.

As a result of the sampling in Rome, a routine procedure was established for the other sites.

A total of 12 cores have been taken from the excavation site of Villa Traiana. The walls were described in detail and mapped in order to show the exact location of the sample. The location is important for several reasons:

- There are several generations of walls and repairs that need to be identified and distinguished.
- The walls have different functions and may have been constructed with different materials or techniques.
- The building was buried by sediments/soil for a long period of time. Within the soil zone high CO2 concentrations and shallow groundwater may have caused an exchange of ^{13}C isotopes with the building material. These effects may differ drastically depending on the exact location of the wall.

The exact location of the samples and depth of the cores was mapped to build background information for the interpretation of results at a later stage (Tables 1- 2; Figures 4 - 8). The hardening of lime depends on the diffusion of carbon dioxide into the building material and pockets of wet lime were found in building with Roman mortars. This suggests the diffusion process being slowed down by intact walls where cracks would allow faster diffusion of atmospheric carbon dioxide and a 'healing' effect. The correlation between depth and isotope data, especially ^{13}C allows us to identify these effects.

As a result of the first sampling, the consortium has learned about the importance of environmental impacts on the sampling location: The quality of the mortar and the impact of secondary processes (weathering) varied significantly between different walls of the same building and different phases of the construction.

Table 1 Coring of walls according to Figures 4 to 8

Wall	Core	Samples (thickness in cm)								Depth (cm)
		from	to	from	to	from	To	from	to	
A	1									28
	2	0	6	6	11	11	18			18
B	1									
	2									16
D	1									18
	2									
E	1	0	5	5	9	9	14			14
F	1	0	11	11	17	17	23	23	27	27
	2	0	7	7	16	16	19	19	25	25
G	1	0	6	6	15	15	17	17	19	19
	2	0	10	10	20	20	28			28
	3	0	7	7	12	12	20	20	24	24
H	1	0	11	11	17	17	20			20
	2	0	7	7	16	16	19			19

Overall view of the Villa Traiana Sampling Site, Sala del Triclino.

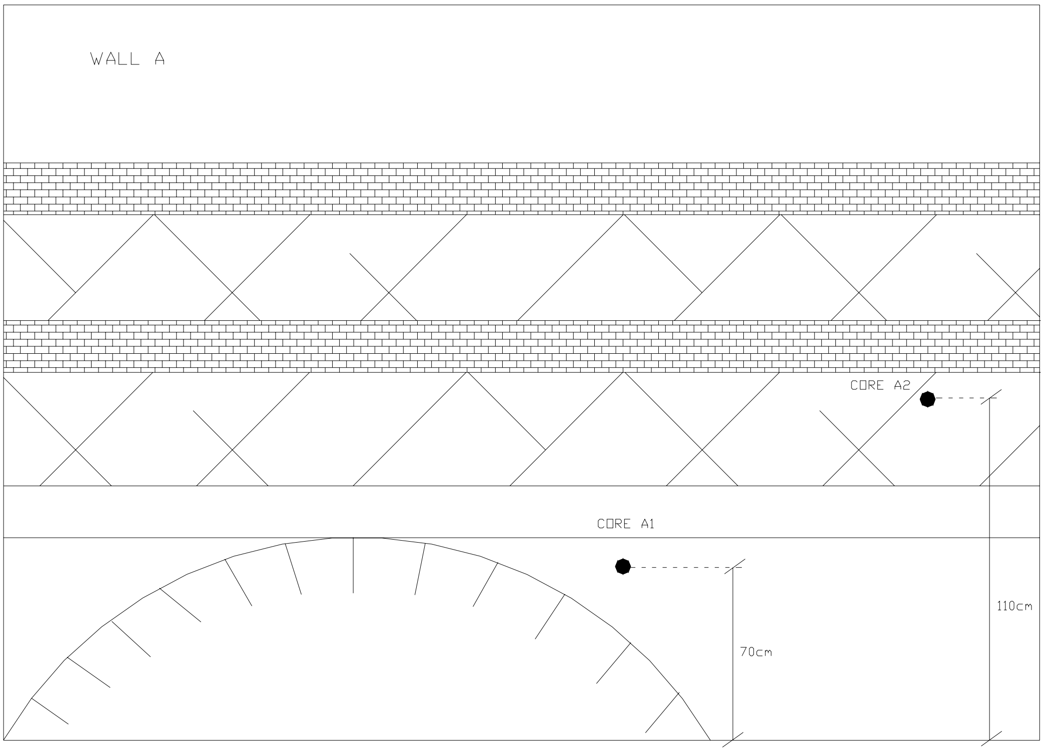

Figure 4 *"Sala del Triclinio" plant, Wall A view*

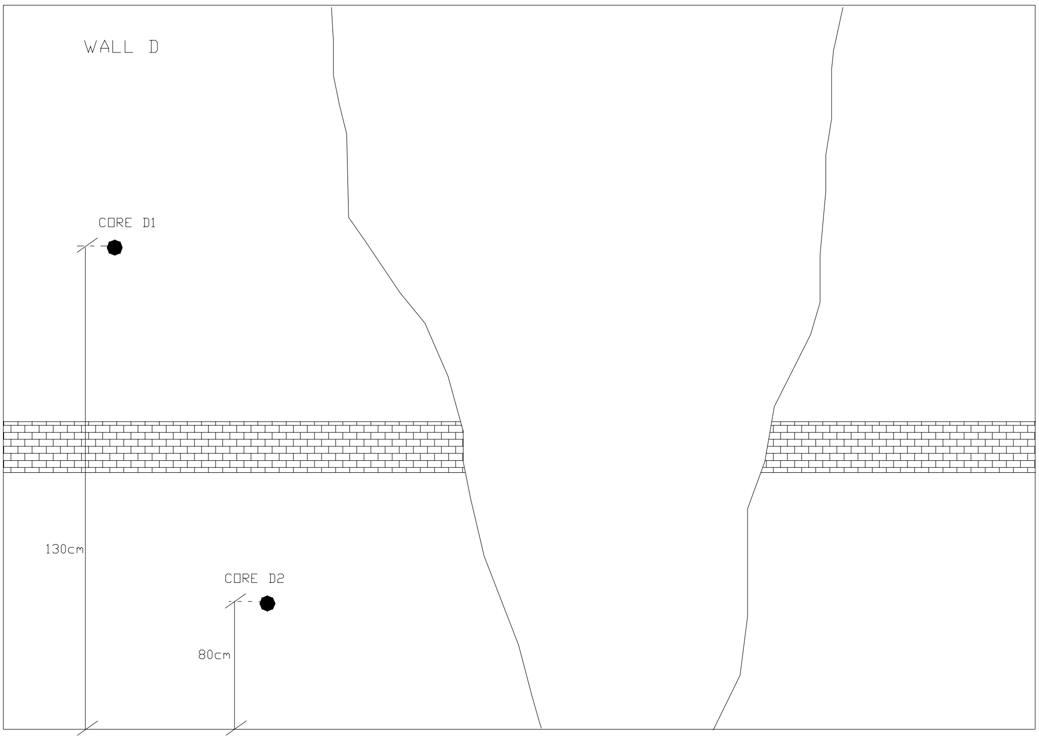

Figure 5 *Wall D view*

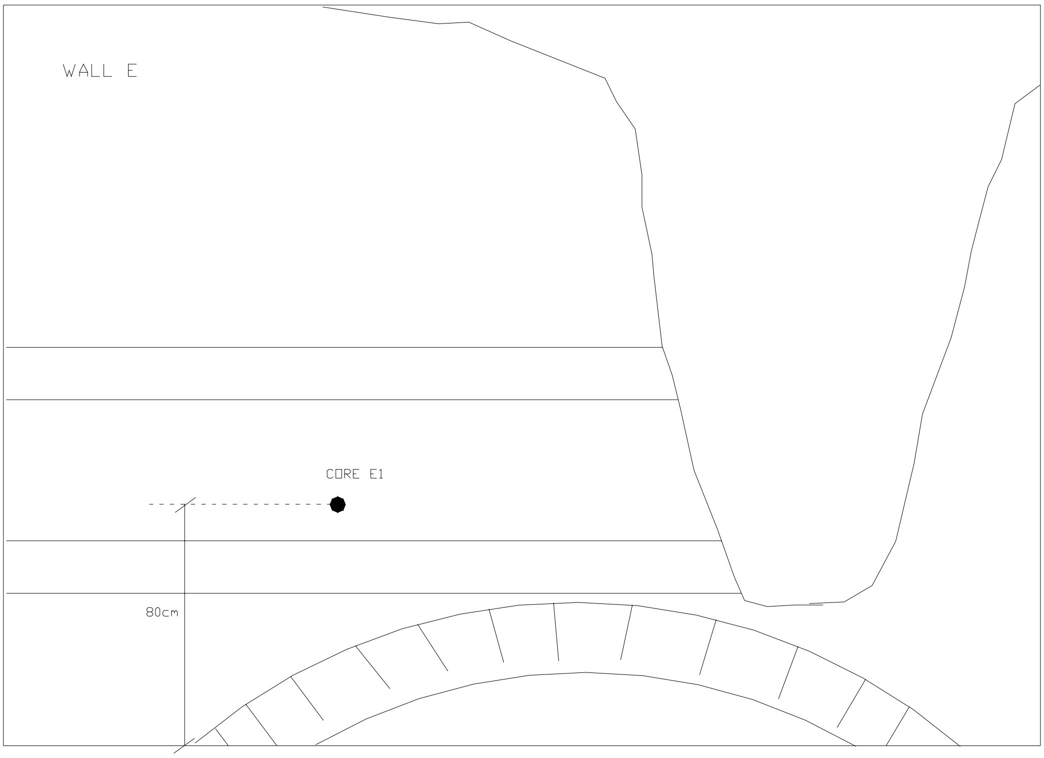

Figure 6 *Wall D view, Wall E view*

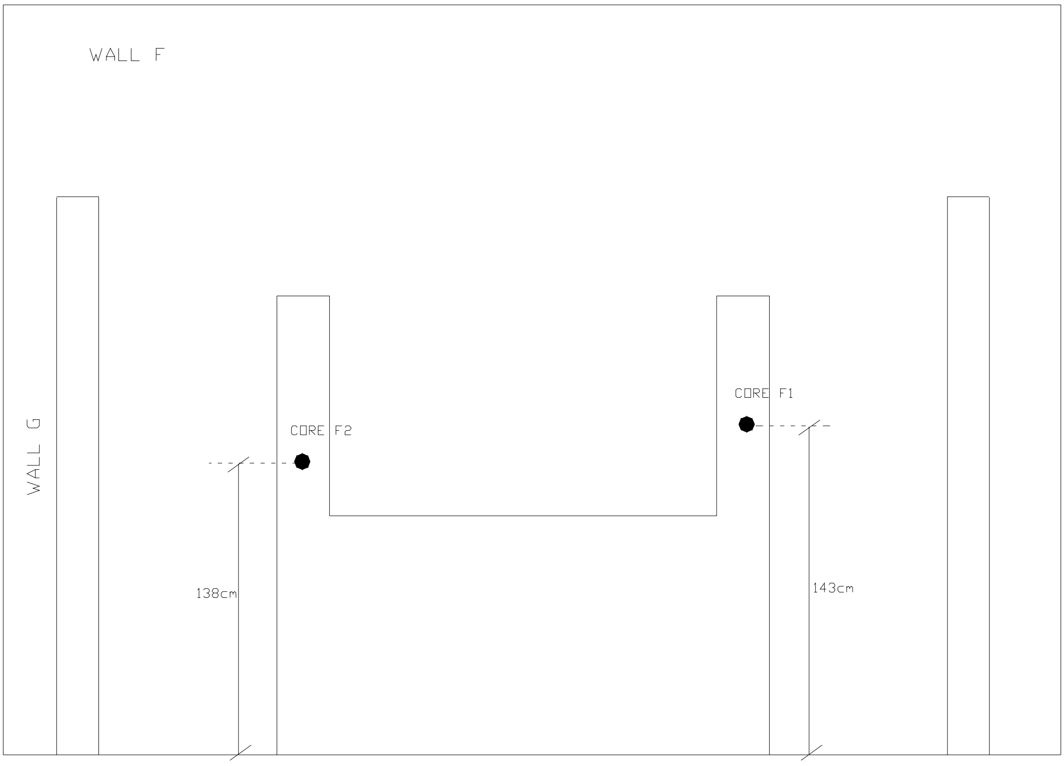

Figure 7 *Wall F and wall G view*

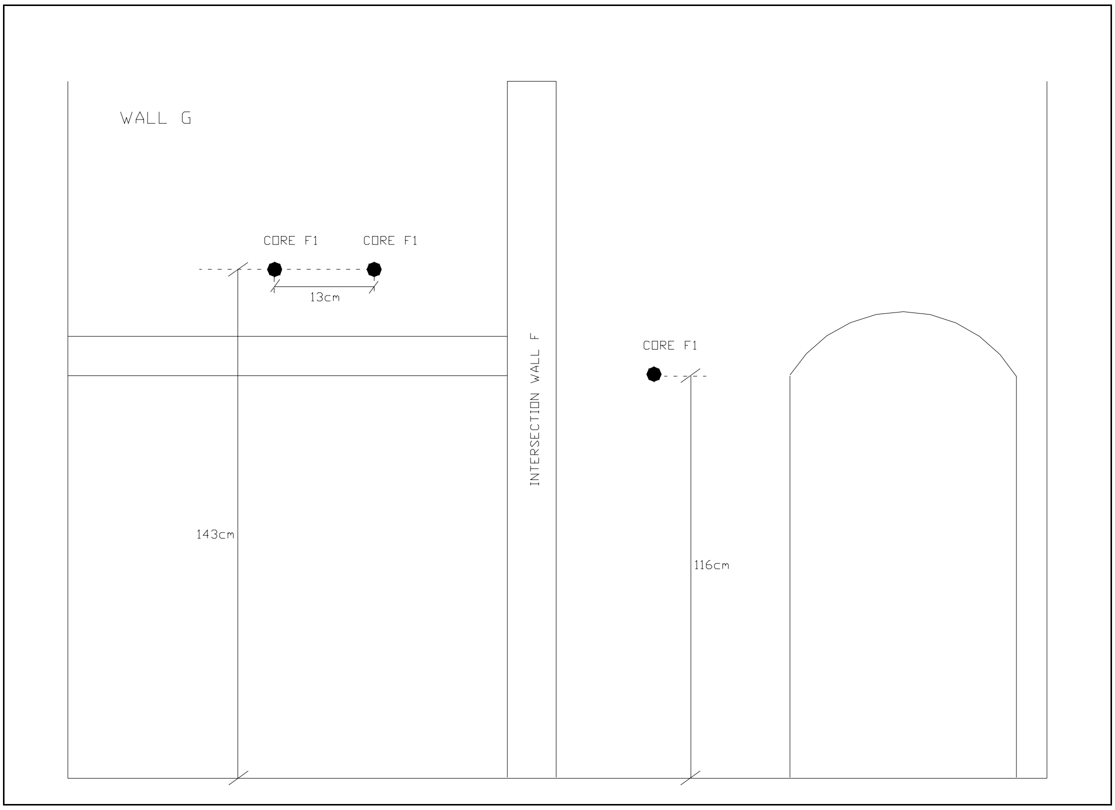

Figure 8 *Wall F view, Wall G view*

Table 2 Description (color and texture) of the samples from Villa Traiana

NUM.	TIPOLOGY	PHOTO	DESCRIPTION	LOCATION
D1	Bedding mortar	5440-41-74	Grey, dark grains, strong	2nd room East triclinium West wall
D2	Bedding mortar	5442-43-75	Grey, dark grains, strong	2nd room East triclinium West wall
A1	Bedding mortar Op. reticul. (down)	5448-49		2nd room East triclinium North wall
A2	Bedding mortar Op. vittatum (up)	5448-49-73	Grey, dark grains, strong	2nd room East triclinium North wall (opposite sample E1)
E1	Bedding mortar Op. vittatum (up)	5460-61-76	Whitish, dark grains, white lumps, strong	3rd room East triclinium South wall (opposite sample A2)
F1	Bedding mortar	5462-63-77	1st: grey, arenaceous, white lumps, strong. 2nd: brown, concretions, dark grains, crumbly	Triclinium East pilaster
F2	Bedding mortar	5464-65-78	Grey, arenaceous, white lumps, crushed brick, crumbly	Triclinium West pilaster
G1	Bedding mortar	5468-69-79	Grey, dark grains, white lumps, strong	Triclinium West wall
G2-3	Bedding mortar	5466-67-80	Whitish, dark grains, white lumps, concretions, crumbly	Triclinium West wall
H1	Bedding mortar	5470-81	Grey, dark grains, strong	Nymphæum West wall
	Plaster	5483-84	Three layers, white painted layer on the surface	Allochthonous
	Plaster	5485	Two layers, red painted layer on the surface; white lumps and coarse grains size in the inner layer	Allochthonous
WMG	Bedding mortar	5471-72-82	Grey, arenaceous, crumbly	Wall

4.2 Colonia Ulpia Traiana (Xanten, Germany)

The site of the Roman Colonia Ulpia Traiana (CUT) is located immediately north of modern Xanten in North Rhine-Westphalia, Germany; close to the Dutch border at the banks of the river Rhine. The CUT was a major city in the Roman province of Germania Inferior (Lower Germany), second only to the Colonia Claudia Ara Agrippinensium (Cologne where the Rhine formed the borderline of the Roman Empire.

The CUT is a listed monument its eastern part and the town baths in the western part form the modern Archaeological Park Xanten (APX). The ground of the western part is to a large extent in the ownership of the APX and let to local farmers for agricultural purposes. The remaining plots of land are gradually being purchased with funds from the government of North Rhine-Westphalia. A national road which is intersecting the area of the Roman town to date will be relocated allowing to unify both areas of the town and to form a single archaeological park of 0,73 square kilometres in near future.
The Landschaftsverband Rheinland operates both the Archaeological Park Xanten and the museum in the town centre as an institution to research and to present the Roman past to a

wider public. Combined museum and park attract some 350.000 visitors a year and are one of the most visited archaeological sites in Germany.

Figure 9 *Protection shelter at the town baths. Sampling in Xanten,*

Roman activities in the area of Xanten started at the time of Augustus. The first military fortress Vetera I was built on top of the Fürstenberg some three kilometres south of the CUT. The location was well chosen since the Fürstenberg rises some 50 meters above the plains of the Rhine valley though Tacitus has criticised the location and the defensive systems [TACITUS, HISTORIAE, LIBER IV, 23]. The military camp served as a base for the attempted conquest of Germany to the east of the Rhine. After the defeat in the Teutoburg Forest in AD 9 the Romans retreated and the Rhine became the empires permanent border for the next 250 years. Vetera I was destroyed during the revolt of the native Batavian tribes in AD 69 / 70. A new fortress, Vetera II was built some two kilometres to the east where this camp accommodated Roman troops from 70 AD to 270 AD.

At the site of the Colonia Ulpia Traiana a small civilian settlement began to grow being located at a branch of the meandering Rhine that probably served as a natural harbour for both the military camp on top of the Fürstenberg and the civil settlement. The legal status of this earlier settlement is not clear to date and research on the pre-colonia period still continues. The inhabitants were traders, craftsmen and farmers where the interaction between the local residents and the soldiers at Vetera is still to be researched.

The civilian settlement was granted the rank of a Colonia by the emperor Trajan at about 100 AD and the town formed the centre of an extensive tract of surrounding land. Some 10.000 people lived within the walls on an area encompassing 73 ha where:

- Veterans of a reallocated legion received parcels of land thus forming an economically potent stratum of the population;
- The inhabitants also comprised Romanised Gauls and Germans.

The Colonia Ulpia Traiana featured all elements of a planned Roman city: organised infrastructure with conduit, sewers and a street grid, temples, forum, an amphitheatre, walls, and gates. Its public buildings emphasised it as belonging to the Roman Empire and at the same time they underlined the high status of the city.

Some of the existing living-quarters of the pre-colonia settlement were retained and incorporated in the new town. Other parts of the earlier settlement were demolished to provide the space for large communal buildings. The graves lay along the road that connected the CUT with Colonia Ulpia Noviomagus (Nimeguen) in the north and Colonia Claudia Ara Agrippinensium (Cologne) in the south.

Franks raided the Colonia Ulpia Traiana in 276 and ended the town's period of prosperity. A smaller, heavily fortified town for civilians and soldiers was erected later in its centre utilising materials of demolished buildings. With the rise of Christianity the centre of settlement activities shifted to south. The so-called grave of St. Victor, a Christian martyr, became the nucleus of medieval Xanten; the name Xanten derived from ad sanctos (at the saints). The crumbling buildings of the Roman city served as a quarry: all suitable material was used for construction of the medieval churches and houses in the town of Xanten or was sold. The Roman city vanished from the surface and was gradually turned into farmland. Thus, the CUT is the only known example of a continental Roman city north of the Alps that was not covered by later building activities.

In 1819 Phillip Houben, a local advocate, started excavations in the area of the CUT where he found a collection of curiosities and antiquities that he presented in a small private exhibition open to the public. Houben published a history of the CUT in 1839, which also included 48 large colour plates with drawings of the gems, coins, vessels, tools and skeletons found.

In 1877 citizens of Xanten founded the Niederrheinischer Altertumsverein (Lower Rhine Antiquities Society) and started to examine the area of the former Roman city. While some of the methods employed seem to be quite barbaric in our times it was the first systematic research in the CUT. In 1933 the amphitheatre of the town was excavated as part of a job creation scheme. Excavations conducted by the Rheinische Landesmuseum Bonn und the direction of v. Petrikovits also exposed parts of the Roman harbour and the harbour temple in 1934 / 35.

Xanten was heavily destroyed in WW II. As part of the reconstruction process in the 1950s it was decided by the town council to create an industrial estate at the area of the former CUT. Thus, the predominantly agricultural region at the lower Rhine should receive economic impulses for further development. At the area of the town baths a concrete pre-fab factory was planned. Since there was no sufficient conservation legislation for North Rhine-Westphalia at this time, there was no legal way to prevent building activities and the destruction of the Roman remains.

The cost of excavation of all areas prior to the construction of factories and houses was prohibitive. Thus only limited emergency excavation work was executed. In 1957 H. Hinz started an emergency excavation of the town baths that continued even when building works had started. This work showed in a dramatic way the loss of archaeological remains as a result of the industrial scheme.

An alternative concept was presented in 1973 when the Land North Rhine-Westphalia, the town of Xanten and the Landschaftsverband Rheinland agreed to purchase the ground of the Colonia Ulpia Traiana from various owners and to create the Archaeological Park at Xanten (APX). In 1977 the first part of the park was opened to the public. At this time no proper conservation legislation existed in North Rhine-Westphalia. It was only in 1980 that the government adopted an up-to-date conservation legislation that allowed the protection of archaeological sites from further destruction. Subsequently, on 5th of July 1984 the site of the CUT became a listed monument.

The main objective of the APX is to prevent further building activities in the area of the Roman town to avoid the loss of archaeological data. In order to compensate for the loss of a planned and partially executed industrial area with potential jobs and demonstrate why a considerable amount of public funding is used to purchase land. The results of excavation activities are disseminated to the general public where he methods employed to communicate archaeology ranges from reconstructions to protection shelters and from information panels to guided tours. Today, the park attracts more than 300.000 visitors a year and is one of the most visited archaeological sites in Germany. It has become a staple in the economy of Xanten employing 49 full time and another 30 part time.

4.2.1 Site Characterization

The site of the Colonia Ulpia Traiana is located in the lower Rhine valley some 100 kilometres north of Cologne. It is about 1.140 kilometres from the origins of the river in the Swiss Alps to Xanten and the river continues for another 180 kilometres to the North Sea. There are numerous tributaries such as the Neckar, the Main, the Lahn and the Moselle. Thus, aggregate from various sources were transported to the lower Rhine area where it formed deposit.

The general features of the landscape were formed in the last glacial period but due to the meandering river it was only in about 1800 that the area got its present shape. For example, the site of the hill that used to accommodate the military camp Vetera II in Roman times has completely vanished. It was eroded by the Rhine changing the riverbed and there is a dead channel at the location of Vetera II.

In Roman times the water table of the Rhine was at about 15.80 metres above sea level that was clearly visible at the Roman piers excavated by v. Petrikovits in 1934. Today the water table of the river is at just above 14 metres above sea level. The water table of the river changes considerably in relation to droughts and flood periods. While flooding had existed in Roman times it may not have had the same amplitude since the Rhine was meandering and offered wide flood plains. Intelligently the CUT was located on a low ridge running north-south a few meters higher than the surrounding area, thus CUT is still above the water in the case of flooding.

The altitude of the flat valley plains is at about 21 metres above sea level. The river flat is bordered by glacial moraines on either side that reach heights of up to 80 metres. Both valley and moraines consist of sediments, gravel, clay and sand (KLOSTERMANN 1986). There is a general decline from the moraines in the west towards the river. Below surface the groundwater flows constantly from the surrounding hills towards the river.

Climatic conditions

Traces of pollen and other plant remains excavated from different strata suggest that the climatic conditions of the area have only slightly changed. It is generally assumed that the temperature was slightly higher in the Iron ages declining gradually towards late antiquity. In early medieval times the temperature was slightly lower than present.

It has been suggested that in Roman times the meadows close to the river were used for cattle since they were prone to annual flooding. The plains of the flat valley were used for agriculture where wheat and barley were staples in the diet. Remains of figs, chickpeas, garlic and vine may be an indicator for trade rather than Mediterranean climatic conditions in the lower Rhine valley in Roman times.

The data for the present climatic conditions are delivered from the station at Kleve, some 20 kilometres north west of Xanten (Station Kleve, 46 m above sea level, 51°46'N, 6°06'E). The average temperature for the years 1971 – 2000 is just below 10°C with an average rainfall of 760 mm. Sub zero temperature in winter is limited to short periods.

The area of the CUT was used as a quarry to exploit stone material for building purposes in an area where there is no natural source of stone. After exploitation, the area close to the medieval centre of the city was used intensively for agricultural purposes. The local farmers knew it as "stony ground". Thus, the farmers employed horse drawn ploughs even after WW II not ploughing more than 20 centimetres. Going any deeper would lift numerous stones to the surface of the farmland. This prevented further loss of archaeology.

Since farmers have used the area an unknown amount of fertiliser may have been employed. It can be anticipated that a large amount of manure was spread in the area. However, since the area of the CUT was less suitable for ploughing, it was predominantly used for grazing and the production of hay. The decision to turn the area into an industrial estate was taken in 1950's and the area of the town baths was one of the first areas to be built on. The land was bought from farmers before the widespread use of nitrogen fertiliser became common. Other parts of the CUT remained farmland and nitrogen fertilizer was in use until the official listing of the site in 1984 and the use of commercial fertilizer became illegal.

War damage

Unexploded ordnances can still be found in the excavation process. The shelling harmed the archaeological site in two ways:

- The impact of shells and explosions resulted in physical force on the subterranean structures. The circular structures of bomb impact can still be traced in magnetometer measurements.
- Chemical elements left after explosion and leaking from unexploded ordnances creates a hostile environment for the survival of archaeological remains.

Modern tourism and vandalism

The archaeological remains of CUT are presented to the public in the Archaeological Park Xanten. While most remains are covered with protection shelters and conserved to the state of art they are threatened by vandalism and tourism. The annual 300.000 visitors harm the ancient fabric and even more damage is caused by deliberate destruction. A large percentage of the visitors are school classes with children being careless to outright aggressive against foreign property. A sincere understanding of the values of original fabric does not exist and teachers are powerless and / or unwilling to control the pupils when they enter the park. Due to financial limitations there are not a sufficient number of guardians and various schemes have been proposed to reduce the impact of vandalism but none of them has been successful. Exposing the ruins requires regular maintenance but even the cleaning of walls and floors as well as the conservation and repair work interfere with the original fabric.

4.2.2 Building Materials

The Colonia Ulpia Traiana was located in the sediment area of the lower Rhine valley, thus there are no exploitable natural resources of stone and the range of building materials locally available was limited to clay, sand, gravel, and pebbles. Furthermore, the area around the Colonia was covered with shrubs and low forests at the beginning of the first century AD hence the timber suitable available for building purposes was limited.

All materials not available locally had to be transported to the site at considerable expense and in Roman times this meant shipping materials down river. Thus the majority of the sources for building materials used in the CUT can be found along the rivers Rhine, Moselle, and Main.

- Timber of substantial size for the construction of the harbour came from the Main area.
- Sandstone for the harbour temple was quarried in Lothringia and grauwacke (a particular type of Sandstone) came from Lindlar.
- The tuffa for the city walls and basalt came from a volcanic area close to Koblenz. Limestone for architectural details and for the production of lime came from Wülfrath and Iversheim.

All sites named above have in common, that they are located close to the River Rhine and its tributaries. The Roman army introduced the production of bricks and tiles from local clay and kilns of a Roman military production plant were excavated about 1 km south of the Colonia.

The latest period of the military camp Castra Vetera I was built of stone, brick and tiles. The private houses in the early settlement were predominantly built in rammed earth or timber framing, filling the panels with wattle and daub. The tiles and stones of the destroyed military camp were reused for foundations. These buildings were covered with thatch or shingles. In the Colonia period local residents preferred local materials and most of the private buildings were erected in the same way - rammed earth walls or timber framing covered with tiles and slate. By contrast, the public buildings were made of stone.

4.2.3 Location of Samples

The Samples from Xanten (Table 3) were taken in January 2003 (in sub zero temperature). They were taken on different walls of the town baths (Grosse Thermen) as this structure was chosen as most suitable of all buildings of the CUT since both its history of construction and use and of excavation and restoration is well documented.

The town baths in Xanten represent the classical linear type of Roman baths with the apodyterium (Changing rooms) on the southern side are followed by the frigidarium (cold bath). There were two tepidarii (lukewarm baths) and a caldarium (hot baths). Suditarii (sweat rooms) and a palaestra (sport grounds) complete the structure that covers the entire insula measuring 108 by 107 metres. The state of the material was found to be excellent leading to a much better understanding of the isotope profiles from the well preserved site. Samples were taken at different depths with a core driller and sent to the laboratories at CNR and IFE. The samples were located and assigned to different types of mortar and different wall functions in order to improve the accuracy of the evaluation.

In the excavation of the town baths, oak foundation piles were exposed which allowed for dendrochronological dating. The trees were cut at 125 +/- 5 AD dating the construction of the town baths in the reign of Emperor Hadrian. The town baths were built some 30 years after the Trajan has granted the title of a Colonia. There were some earlier structures in this area that were demolished to allow for the construction of the baths.

The town baths were discovered in 1879 when members of the Niederrheinischer Altertumsverein discovered large masonry structures by poking the ground with metal poles. The first excavation started immediately after discovery and in 1880 the first report was published in Bonner Jahrbücher, a respect journal on antiquities (AUS'M WEERTH 1880). A sketch drawing in the report clearly shows the outlines of the basilica thermarum (Apodyterium) but Aus'm Weerth fails to identify the building as the town baths. He suggested the structure could have been the central building of a military camp.

H. Hinz resumed excavations at the town baths, prior to the construction of a concrete plant. From 1957 to 1963 numerous trenches were excavated exposing the full size and quality of the site and the excavation work even continued while the building works had started at other parts of the area. At least, the Roman bath was recorded and photographed before it was covered with modern structures. The dramatic situation of the emergency excavation triggered the establishment of the archaeological park in 1973.

Figure 10 *Sampling in Xanten*

In 1984 the concrete plant was relocated to a new industrial area to the West of Xanten. The existing structures on the site of the town baths were demolished and the Roman remains excavated once again. A few parts of the ancient structures were destroyed completely by the construction of the modern foundations but other parts survived remarkably well. Parts that have not been exposed by Hinz were excavated for the first time.

From 1997 to 1999 a modern steel and glass protection shelter was built on site to protect the exposed walls from the Roman period. This shelter reconstructs the form of the Roman bath while it uses modern materials: a red tin roof resembles the clay tiles and glass panels with white dots give an impression of the plastered walls. An elevated steel walkway at the original Roman floor level gives access to the rooms. The original foundation walls survived up to floor height. Some parts of the walls were restored with similar stone and modern lime mortar (samples 1 and 2)

Table 3 Description of samples from Xanten

ITER-ID	Type	Date	Cut	Floor	Location-ID	Description
X1A Modern	Mortar	31.01.2002	Area S2	from M34	44155	silty, fine material with several core pieces
X1B Modern	Mortar	31.01.2002	-	-	-	silty, fine material with several core pieces
X2A	Mortar	31.01.2003	Area S3	from M31	44156	mortar with fine sand, grey
X2B	Mortar	31.01.2003	-	-	-	mortar, fine with small stones, grey/dark
X3	Mortar	31.01.2003	Area Pr. (east)		44157	fine, white/brown and little reddish
X3B	Mortar	31.01.2003	-	-	-	mortar, brown/grey, fine with small pieces
X4	Mortar	31.01.2003	Area Pr. (east)	from M37	44158	mortar, sandy coarse, reddish
X4B	Mortar	31.01.2003	-	-	-	sandy, white/brown/reddish with core pieces
X5	Mortar	31.01.2003	Area Pr. (east)	from M70	44159	sandy, white/brown/reddish
X5B	Mortar	31.01.2002	-	-	-	silty material, reddish, sandy
X6	Mortar	31.01.2003	Area T2	from M83	44160	fine material, brown/reddish
X6B	Mortar	31.01.2003	-	-	-	fine material, brown(greyish), no coarse/sand fraction
X7	Mortar	31.01.2003	Area T2		44161	reddish, sandy material with piece 3-4 cm
X8	Mortar	31.01.2003	Area C	from M83	44162	fine material, white/brown with piece 3-4 cm
X8B	Mortar	31.01.2003	-	-	-	mortar fine
X9	Mortar	31.01.2003	Area T2	from M83	44163	mortar, coarse with piece of mortar (3-4 cm)
X10	Mortar	31.01.2003	Area T2	from M83	44164	coarse sand, stones and mortar, piece 3-4 cm
X11	Mortar	31.01.2003	Area C	from M100	44165	coarse material, stones, sand, little mortar
X12	Mortar	31.01.2003	Area C	from M100	44166	coarse material stones, little mortar
X13	Mortar	31.01.2003	Area C	from M100	44167	pieces of coarse material

4.3 Caesarea Maritima (Israel)

Caesarea is a large site, comprising about 235 acres within its semicircular perimeter wall. The entire site is under the jurisdiction of the Carmel Coast Regional Council (CCRC). Part of the site, within the Byzantine wall was declared a National Park in 1968 under the Law of National Parks & Nature Reserves (1968). The entire site was declared an Antiquities Area under the Law of Antiquities (1964). The area declared a National Park is managed by the Authority for Nature and National Parks (ACNNP) under the Ministry of the Environment.

The average annual number of day-visitors in Caesarea over the last five years is 522,000 and including night-visitors the estimated average figure is approximately 670,000. There has not been any significant trend of growth or decline in the visitor flow since the beach and restaurants are freely open to the public after official "closing time" of the National Park ticket offices.

The average annual number of visitors at the Sdot Yam and Hana Senesh museums is about 15,000 to 20,000 (for each museum).

Figure 11 Caesarea Maritima, Israel (Photo: N. Davidov)

Caesarea is located on the Sharon coast, about midway between Haifa and Tel Aviv. Herods the Great named the port city to honour his patron, the emperor Caesar Augustus. A Phoenician port town, Straton's Tower, existed earlier in the site. The town flourished in the third century BCE and especially in the later second century BCE, when the local tyrant, Zoilos held it against the expanding Jewish Kingdom, perhaps fortifying it with the "city wall of Straton's Tower" mentioned in a Rabbinic source (Tosefta Shevi'it IV, 11). The town finally passed to Alexander Jannaeus in about 100 BCE. During forty years of Hashmonean rule, Straton's Tower probably acquired a Jewish population. The town was in a state of decay when Octavian, the future Caesar Augustus, restored it to the Jewish state in 31 BCE.

Between 22 and 10/9 BCE, Herod built Caesarea on the site of Straton's Tower. Josephus praises the King's lavish construction, which included a theatre and an Amphitheatre, a royal palace, the marketplace (agora), streets on a grid plan, and especially the harbour. Above the old main harbour of Straton's Tower and just to the east, he created a spacious temple platform. Upon this platform he erected a temple dedicated to the goddess Roma and to the deified Emperor Augustus. Nevertheless, Caesarea became a typical Greek city-state (polis) of the Hellenistic age, ruled by a city council and magistrates under a resident royal general.

When the Romans annexed Judea to the empire in 6 CE, they made Caesarea the headquarters of the provincial governor and his administration. The city remained the capital of Judea, later called Palaestina, until the end of classical antiquity. In 66 CE, on the eve of the First Jewish Revolt against Rome, the pagan majority massacred most of the Caesarea's Jews. In the second and third centuries, the city continued to profit from links with the Roman emperors.

The virtual extinction of the Jewish community in 66 apparently implicated most Christians as well, and it is from the later second century that there is a renewed record of a Christian church, with its own bishop. In the same period, Jews resettled in Caesarea, attracted by economic advantages.

By 250 in the town and villages of Caesarea's countryside, the population was heavily Jewish and Samaritan. With the advent of the Christian Roman Empire (fourth-seventh centuries), Caesarea's population and economy expanded, as in the rest of Palestine. A new fortification wall enclosed far more urban space. In this period Caesarea remained a metropolis, or provincial capital. Planed as a three-year project for 50 employees and extended over six years and up to 180 employees in 1994-5. The excavations were shared by the Israel Antiquities Authority and Haifa University, and also supported delegations from the USA (the Caesarea Combined Excavations, and the University of Pennsylvania).

The excavations at the Southwest Zone solved one of the enigmas of Herod's city mentioned by the historian Josephus. Josephus wrote that the public buildings of Herod's city consisted of a theatre and an amphitheatre constructed "by the sea south of the harbour". No amphitheatre had been observed at the above location, prior to the recent project, despite the accurate geographical description. A long U shaped building (about 315X68 m), with tiers on the long and circular sides was uncovered along the modern beach since the third month of the recent excavations.

While the excavations advanced it became clear that the building functioned as a Roman circus (hippodrome in Greek), possessing a barrier along the arena (spina in Latin), and starting gates (carceres in Latin) on the north end. The circus was constructed in Herod's day and was activated for the first time during Caesarea's inaugurations on 10 BCE. A study of historical records revealed that those writing Greek — such as the works of Josephus and Strabo — used the term 'amphitheatre' as synonymous to 'hippodrome'.

The recently discovered chariot course facility is named now “Herod’s circus” to distinguish from the eastern hippodrome known as such for more than 120 years. Herod’s circus functioned till the middle of the 2nd c CE, and then replaced by a larger facility at the East Zone of the city (i.e. the Eastern Hippodrome). The south third of Herod’s circus was converted to a Roman amphitheatre for gladiator combats (munera) and wild beast’s games (Venationes), which functioned till the end of the 3rd c CE. The area south of Herod’s circus to the southern city-wall, and west of the theatre compound to the sea, was occupied by governor’s campus.

The excavations uncovered the governor palace and some offices and chambers of officials employed by the Provincia Judea / Palestina. The huge size of the palace, as well as the Latin inscriptions engraved into marble and granite pedestals or written on mosaic floors, confirmed the identification. A typical Italian cemetery, possibly for the families of governor’s staff, was found outside the south city-wall. The Governor’s palace was abandoned at about the turn of the 3rd c CE, and ordinary buildings replaced it. The insulae east of Herod’s circus were developed for habitation one generation after Herod’s death.

A partly excavated large mansion, which occupied the entire W2S3 insula, may serve as an example for rich family home of the 1st -2nd c CE Caesarea. The mansion consisted of two courtyards surrounded by rooms, typical to the contemporary Mediterranean architecture (likewise the governor’s palace, but half size).

A public bathhouse was constructed in the 4th CE over the remains of the Roman mansion and Herod’s circus at the south half of W2S3 insula, and functioned to the end of the Byzantine City. The bath consisted of a summer unit (with an open frigidarium), a winter unit (with a roofed one), and a palestra for public meetings. The large public building that occupied the W2S2 insula had a two stories west flank supported by a battery of long vaults (possibly magazines, the northern one was converted to a Mitraeum in the 3rd-4th c CE). The plan of the building, as well as inscriptions carved in stone, or written on mosaic floors, indicated the building functioned as the praetorium in the Byzantine period.

The area north and south of the public bath was occupied by several storerooms, including more than 25 compartments of typical subterranean bins, dated to the Byzantine period. A splendid Byzantine palace, which occupied the south third of W2S4 insula, also owned a lower terrace with an irrigated garden facing the beach. The southwest Zone was deserted after the Arab conquest of 640 CE, and its buildings were recycled either at Caesarea or exported by land and sea routs. The recent excavations suggest that the theatre compound be transformed into a citadel after the Arab conquest, not earlier.

The excavations at the Temple platform revealed the foundations of the pagan temple built by Herod in honour of Augustus and Rome. The Herodian platform was expanded 21 m westward, by a battery of vaults, at the end of the 3rd / beginning of 4th CE. The platform remained the main religious centre of Caesarea despite the change from paganism, Christianity, a Moslem mosque after 640 CE, and a Latin church when the Crusaders conquered Caesarea on 1101 CE.

The harbour west of the Temple platform has been partly silted since the late Roman period. The fortified Moslem town that emerged out of the ruins of the Byzantine city in the 8th-9th CE, as well as the Crusader town, extended eastward into the silted harbour. Several houses of the mediaeval town, each owing a private well and a cesspit were uncovered in the silted harbour.

The Crusader town was conquered and deliberately destroyed by the Mamluks on 1265 CE.

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4.3.1 Site Characterisation

Ancient writers described natural disaster, but those literary accounts should be attempted with great caution. In absence of other information, however, such texts are useful, but should never be considered definitive and archaeological data when available, can provide more reliable indicators.

The following list, compiled from previous catalogues, indicates the seismic events at Caesarea described by ancient writers:

- 92 BC Destruction of coastal cities in Israel by seaquake *
- 115 AD (December 13) Destruction of Caesarea by seaquake *
- 130 AD Strong earthquake damaged Caesarea
- 363 AD Destruction of Apollonia (20 Km. South of Caesarea) by earthquake
- 551 AD (July 9) A great seaquake hit the coast from Tripoli to Caesarea. Sea receded for two miles.*
- 1114 AD seaquake damaged coastal cities *
- 1170 AD (June 29) disastrous earthquake damage and loss of life. Caesarea was damaged.
- \1303 AD (August 8) Damage in Palestinian coastal cities *
- 1752 AD Destructive earthquake along the coast of Palestine
- 1856 AD (October 30) seaquake at Haifa (20 Km. North of Caesarea)*
- 1940 AD (January 27) earthquake at Haifa
- 1951 AD (January 30) earthquake felt throughout Israel. Epicentre probably off the coast of Tel-Aviv.
- 1957 AD (July 18) off the coast of Sidon. Felt from Jaffa to Tripoli
- 1984 AD (August 24) Felt in many places in north-western Israel. Epicentre 30 Km southeast of Haifa.

** The asterisks indicate the ambiguity of the events*

Slope failures along the Mediterranean cliffs of Israel are directly related to the lithology and position of exposure of the rock unit in the cliff face. The destructive processes affecting the coastal cliffs of Israel are seen as time depend processes acting in two independent zones, at the top and bottom of the cliffs.

At the top of the cliff these processes are classed as short- term phenomena that may be seen as seasonal changes or those initiated by man. At the bottom of the cliff these processes are classed as long-term phenomena where several climatic seasons to a number of years may pass between events.

These processes mainly depend on abrasive action of waves and, to a lesser extent, on wind. Wave action is a major factor in moving material along the beaches. Undercutting and abrasion, which mainly occurs during major storms, may intensify movements in places where waves reach the base of the cliff. Hamra (clay) slopes deform by flowing and piping of clay material, particularly at the base unit, at the end of winter when the water content reaches a maximum. During summer this process may continue, due to the irrigation and watering of gardens at the top of the cliff. Circular slides are common cover the Kurkar (sand stone) slopes with loose Hamra, sand and toppled blocks of the overlying hard calcarenite. The frequency of this event depends on the intensity of the winter season. Most slide material found at the base of the cliffs is seen to have originated from the higher parts. Stability and recession of the coastal cliffs can be greatly increased by controlling top cliff processes that are intensified by infiltration of domestic water and construction near the cliff edge.

Climatic Phenomena

A typical Mediterranean climate of a winter rainy season, from October to March and a hot dry summer from April to September affect the coastal area. The relative humidity is generally higher along the coast than inland. Winter is dominated by cyclones that move eastwards from the coast with winds between SW and NW of a velocity of up to 80 Km/h. The south-western winter winds generate waves from 5-7 m high and have the greatest effect on the beaches and cliffs. Spring and autumn are quieter transitional seasons with light variable winds. Light winds occur during the summer.

Typical temperatures range from 12-14 °C in January to 24-26°C in August, and may occasionally reach as high as 42 °C during the hottest summer days. Average annual rainfall ranges from 500–800 mm.

The atmospheric condition of the site is the main cause of deterioration of the materials. Since the excavation, when the materials are exposed to UV light, humidity, and environment a deterioration process is starting. The aerosols from the sea cause the salt efflorescence and consequently the encrustation of the antiquities. The wind from the sea causes also the erosion of the Kurkar stones and the other materials. The rain during the winter causes a serious destruction of the mosaics and favors the grout of vegetation that damages the mosaics pavements and the frescoes.

The high humidity of the site is a serious problem for the antiquities. A monitoring system that was installed on the wall paintings at the Hippodrome revealed a relative humidity higher than 70%. At the end it was necessary to remove the monitoring because the instruments couldn't resist to the environment conditions of the site. The humidity and the erosion cause also damage to the building's stones, the consequence is that the static condition of many complexes isn't stable.

Vegetation

A biological research was done from 1998 to January 2000. Some strains of fungi were identified during the research in the Hippodrome, Roman Villa, Nympheum, and Big Palestra in Caesarea. They belong to the following: Trichoderma, Aspergillus, Phoma, Alternaria, Ulocladium, Curvularia, Biporalis, Penicillium, Fusarium, Cladosporium, Phialophora, Papulaspora, Botrytis, Mortierella, Paecilomyces. Trichoderma, Aspergillus, Alternaria, Ulocladium, Penicillium are predominant strains of fungi during all phases of identification.

Even though they are heterotrophic organisms, fungi have often been isolated from weathered stones, especially in tropical areas. While the inorganic composition of stone does not offer a favourable substrate for the growth of these organisms, organic residues of various origins are nearly always present on stone and mural paintings, and this factor aids the growth of fungi.

The vital activity of fungi is more active during rain-seasons. Twenty five strains of higher plants were identified during the research in Caesarea: Parietaria lusitanica, Valantia hispida, Chrysanthemum coronarium, Launaea tenuiloba, Mesembryanthemum crystallinum, Picris damascena, Lolium rigidum, Medicago litoralis, Avena sterilis, Withania somnifera, Echium glomeratum, Nicotiana glauca, Convolvulus arvensis, Cakile maritima, Glaucium flavum, Lotus palustris, Papaver syriacum, Leontodon laciniatus, Anthemis palestina, Reichardia tingitana, Trifolium purpureum, Atriplix semibaccata, Tamarix, Alhagi maurorum, Cynodon dactylon.

The Alhagi maurorum is the predominant strain of higher plants today. In the cases of higher plants at the sites, a problem arises from the expansion of the roots system, which sometimes extends itself many meters both in depth and laterally. This can be dangerous for wall structures if the higher plants are too close to them. In some cases such as the vegetation that covers the structures is an important cause of deterioration and can produce collapses, the detachment of frescoes, damage to walls, etc. The growth of plants on mosaics causes the detachment of tessellatum from the bedding layer, the disintegration of the bedding layer, and the loss of tesserae.

Pollution

The conclusions of the researches of the "Cities Union for the Environment" (that is an association of eighteen settlements of the Caesarea area, that works for the environment) are that the main cause of pollution of the area are the soot of the cars, the chemical materials from the Electricity Station of Hadera and from the industrial area of Haifa, that is the biggest in the north of the Country. The industrial areas of Caesarea, Or Akiva, Hadera etc. that are close to the site do not influence the environment.

Caesarea is located close to the main highway No. 2 and the old road No. 4 between metropolitan Tel Aviv and metropolitan Haifa. These roads have interchanges and exits to Caesarea, and consequently the site is highly accessible from south, east and north (as well as by boats from the west). The vicinity to the highway is one of the causes of pollution of the site.

The areas that are situated at the east side of the Electricity Station of Hadera are directly affected by its pollution. The Alexander River that is close to the Station was cleaned in its lower part, and all the fishes of the upper part died as a consequence of the high pollution of the water. In an air photograph of the site of 1995 it's appear that all the refuse of the Sdot Yam glue factory were throw in the sea.

The pH value for the rainwater ranged from 3.9 to 9. About 65 % of the rain water in north Israel is considered to acid. The rain represents air masses that will be transported further eastward toward the Israeli coast, and the relatively low pH suggests that generally the acidity is imported to our coast rather than contributed from local anthropogenic (Cd, Cu, Pb, Zn) sources. Positive relationships were observed between silicic acid concentration and pH in rainwater. No correlation was found between nutrient concentrations and sodium and chloride concentrations, indicating that their source is non – marine. While the marine components in rainwater over Israel have concentration similar to worldwide coastal areas, pH, Ca and SO_4, concentrations were found to be relatively high. Na, Ca, Cl, SO_4 and HCO_3 dominate the chemical composition of rainwater in central Israel.

4.3.2 Building Materials

Kurkar is a type of sandstone derived from sediments typically found along the Mediterranean coast of Israel. These stones were use in Caesarea for the building. The composition of kurkar consists of silt and finely graded quartz sand transported by the Nile to the sea, and possibly also airborne dust from the Sinai Peninsula. The precipitation of natural cement from water acts with these sediments by thoroughly coating the individual grains and cementing them into solid rock. The sedimentary components and cement of the rock's makeup determine the texture, shape and strength of kurkar (Table 4).

4.3.3 Sampling

The 3rd sampling location was in Caesarea. Due to the vicinity to the coast, this location helped to show the impact of environmental factors on the geochemical signature of the mortar and the isotopic fingerprint (Figure 12).

Table 4 Samples taken in Caesarea

num.	tipology	photo	description	location	period
1.AB	building mortar from wall	404	white, strong	Building,south east of circus	I AD
2.AB	building mortar from wall	404	white, strong	Building,south east of circus	I AD
3.AB	building mortar from wall foundations	407	gray,crumbling	Foundations,south of the theater	2 AD
4.AB	building mortar from wall foundations	407	gray,crumbling	Foundations,south of the theater	2 AD
5.AB	building mortar from tomb	408	white,medium strong	Cemetery,south of the theater	2 AD
6.AB	building mortar from wall	411	white,medium strong	City wall,south of the theater	1 BC
7.AB	building mortar from wall of tower	413	white,medium strong	Round tower,south of the theater	1 BC
8.AB	building mortar from wall of tower	415	white	Square tower,south of the theater	1 AD
9	NOT PERFORMED				
10.AB	building mortar from wall	417	white	Port vaults,north	1 BC
11.AB	building mortar from wall	419	A - red,B - white	Port vaults,north	3-4 AD
12.AB	building mortar from staircase	421	gray with shells	Monumental staircase,Port vaults	3-4 AD
13.A	plaster and rendering mortar	423	gray with shells	Channel,Port	1 BC
14.A	plaster and rendering mortar	425	gray with shells	Channel,Port	1 BC
15.AB	building mortar from wall	427	whitish	Vault No1,Port vaults,south wall	1 BC
16.AB	building mortar from wall	429	whitish	Vault No1,Port vaults,north wall	3-4 AD
17.AB	building mortar from wall	618	gray	Circus,South,supporting wall	1 AD
18.AB	building mortar from wall	620	gray	Circus,South,supporting wall	1 AD
19.AB	building mortar from wall	621,622	gray	Circus,South,Hippodrom wall	1 BC
20.A	building mortar from foundations	623,625	gray	Circus,South, Metha Prima	1-2 AD
21.A	building mortar from foundations	626,627	gray	Circus,South, Metha Seconda	1-2 AD
22A	building mortar from wall	628,629	white	Circus easthern wall,Vomitorium	1 AD
23AB	building mortar from wall	630,631	white	Circus easthern wall,Vomitorium	1 AD
24A	building mortar from wall	633,634	gray	CircusI,Vomitorium supporting wall	1 AD
25A	building mortar from wall	635,636	gray,covered white plaster	CircusI,Vomitorium supporting wall	1 AD
26.AB	plaster , rendering mortar,rubble	637,638	gray,covered gray plaster	Bet Hanania,Aqueduct A,chanel	1 AD
27.AB	building mortar from wall	639,640	gray, coarse	Bet Hanania,Aqueduct A,wall	1 AD
28.AB	plaster , rendering mortar,rubble	641,642	gray,covered gray plaster	Bet Hanania,Aqueduct B,chanel	2 AD
29.AB	building mortar from wall	643,644	gray, coarse	Bet Hanania,Aqueduct B,wall	2 AD
30.AB	plaster , rendering mortar,rubble	645	gray,covered gray plaster	Bet Hanania,by-pass,chanel	4-5 AD
31.AB	building mortar from the dam	647,648	gray,covered white plaster	Crocodile creek dam	4 AD
32.XY	building mortar from the dam	649,650	and 670,gray	Crocodile creek dam	4 AD
33.AB	building mortar from aqueduct	657,659	gray,plaster and rubble	Entrance of the aqueduct in city	1-4 AD
34.AB	building mortar from aqueduct	660	gray,coarse	Entrance of the aqueduct in city	1-4 AD
35.AB	building mortar from aqueduct	662,665	gray,coarse	Entrance of the aqueduct in city	1-4 AD

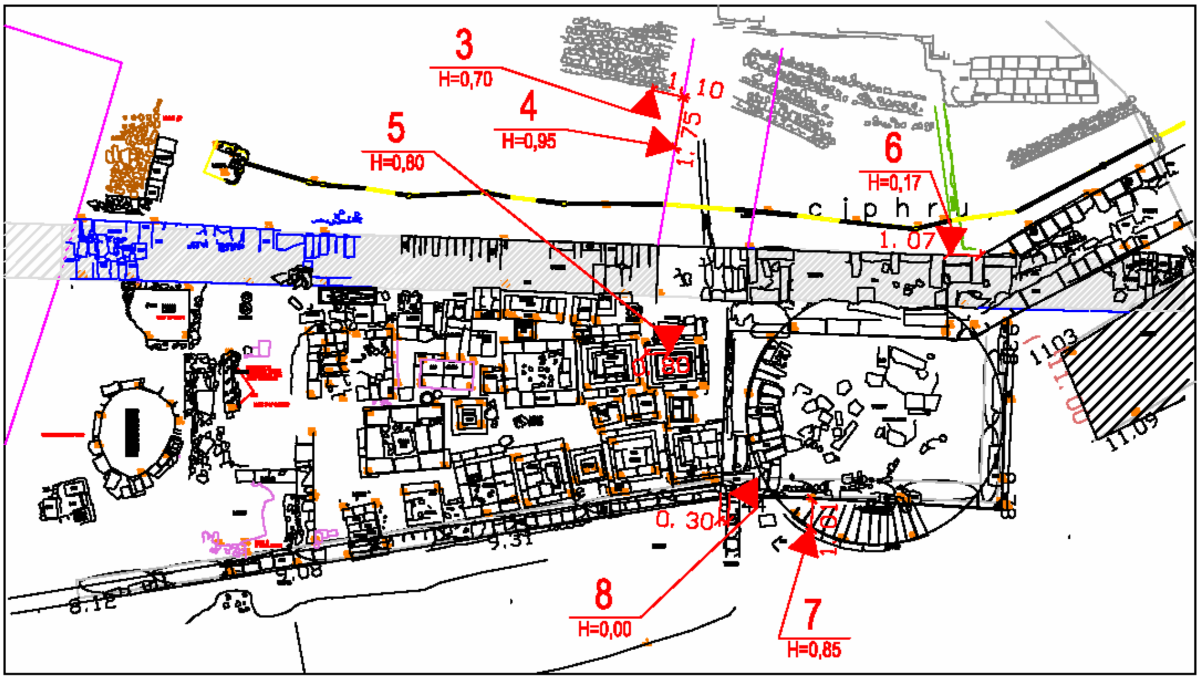

Figure 12 *Sampling area in Caesarea*

4.4 The ITER Database

One of the major results of ITER is the database, which is an integral part of the Interactive web portal: http://www.iter-eu.com.

The portal has been developed as a communication tool with forum, file archive and database. It has been designed for two major purposes:

- To provide an open work space for all project partners (restricted area);
- To provide a first platform for the final phase of dissemination of results (public area).

It is structured with:
- A graphic presentation of the project, used as a shell to contain main project documents (e.g. work plan, scientific contents, partner's skills and profiles);
- A forum management system, that allows easy data exchange and facilitates communications within the partners;
- A link to the ITER database system that is the product and final recipient of all bibliographical and experimental data.

A common information and data structure has been developed in correspondence to the data structure of the ITER database. The main idea behind this information concept was to structure the information collected within ITER according to the objectives of the project and based on the main parameters of the investigation.

The data collection was defined as an instrument to reach the long-term objective of developing mortars for the conservation of archaeological sites with original material having similar properties to the original Roman mortars and of defining parameters of similarity between ancient and recent mortars.

The data collection was conceived in view of:

- Developing a monitoring method based on process understanding;
- Searching for original materials and classes of materials used in the construction process;
- Taking into account possible external environmental factors that affect the actual properties of mortars;
- Taking into account the different types of mortar used in the construction process depending on the function of the building and the wall (mosaic, static element) within the sampling process.

4.4.1 ITER Database Structure

The structure of data collection is based on the description of classes of data: sites, monuments, cores and sampling parameters (Figure 13).

A site can contain different monuments, which is further subdivided into structural elements with archaeological indices -walls, floors, pillars etc. for identification.

A site has a series of environmental properties that are important for the study of weathering effects: mean annual rainfall, distance from the sea (concentration of salts in rainfall), temperature, altitude, land use; for example specification of the impact of traffic for the application of lead isotopes.

A monument is linked to a site. However, a monument has a specific age, coordinates and unique identifiers. The monument is described within a text file in order to accommodate information for which it is difficult to develop a data structure.

Cores are the units of the sampling procedure. They are linked to the analytical data that is also identified by sampling campaigns. Every core has a depth stratigraphy of the core. That allows further differentiation. The analytical data is linked to samples.

The data structure also needs to accommodate different components; materials and sources of building material that are linked to analytical results. Building materials from the vicinity of sites or known sources of building material will also be sampled within the project. The matrix of analytical results from sources and components of building material versus cores from the archaeological monuments can be used to derive the mixture of components and to infer the building technique.

The database represents a knowledge base where relevant information is stored and linked to the datasets.

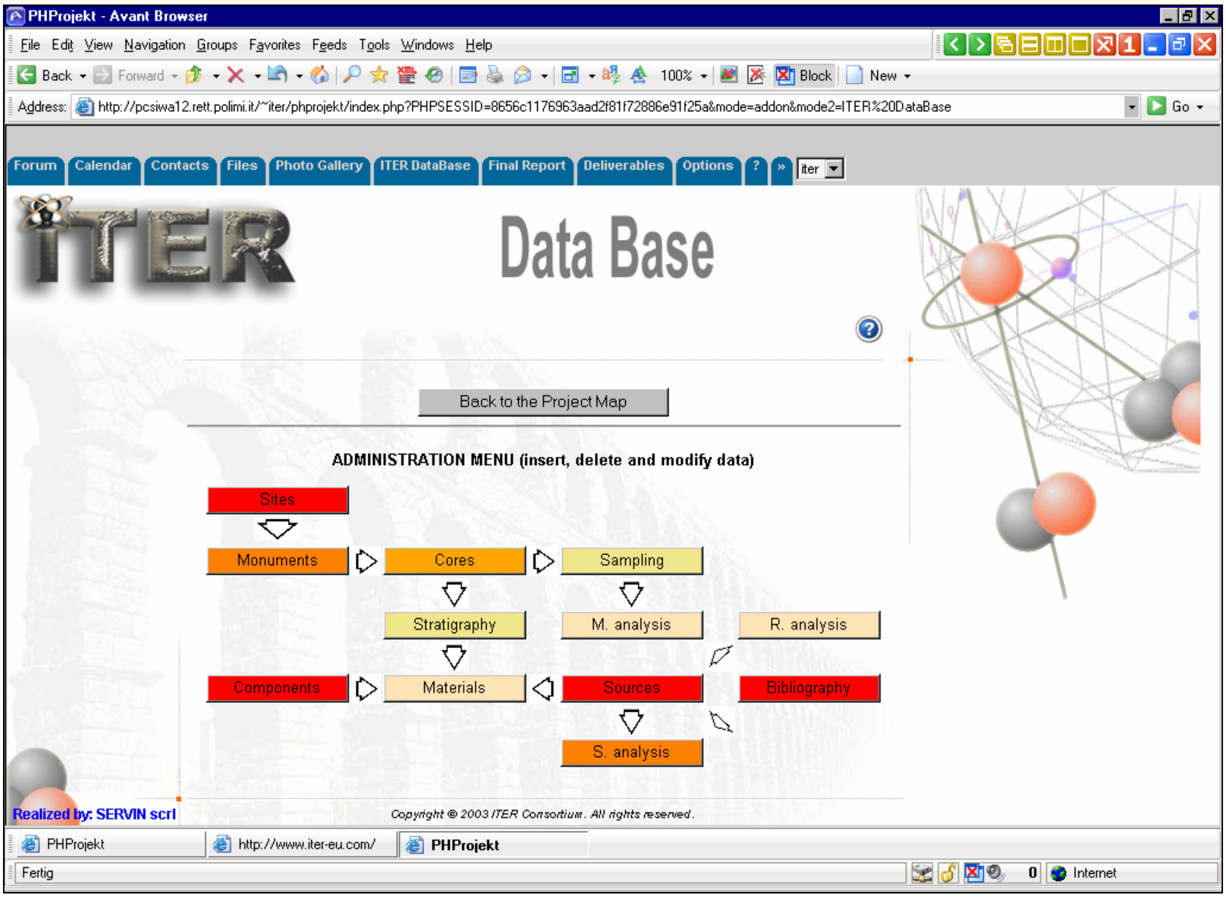

Figure 13 *The screenshot showing the structure of data collection and implementation as an internet database*

4.4.2 Technological Implementation

An important part of the work has been the development of the internet-based database tool, as integral part of the ITER web portal, with the goal to permit to all partners, researchers, as well as registered users to retrieve on line all scientific data, documents and images gathered during the course of the project.

The ITER Database tool is based on Open Source environment with a PHP front-end interface and MySQL back-end database.

Physically, it is allocated on a Solaris machine at the Gino Bozza research centre of Consiglio Nazionale delle Ricerche, Milan.

5 Analysis of Data

5.1 Mineralogical Analysis

After a visual analysis and preliminary descriptions, samples were:

- Subdivided for thin sections preparation and for XRD analysis.
- Petrography analyses were performed using a polarizing microscope.
- X-ray diffraction analyses were performed on powdered samples.
- SEM analyses on cross sections on the same sample used for thin section.
- Grain size was measured on the thin section and reports the maximum length of the clasts; the coarser aggregate is excluded.
- Binder-aggregate ratio is measured in volume and may be different from the original one because of the small mortar portion examined and because of the transformation occurred during the period of burial.

5.1.1 Villa Traiana

The mortars taken at Villa Traiana are always bedding mortars. The binder material was identified as pure calcite (from slaked lime); there is no evidence of the presence of silicon in the binder fraction. The presence of magnesium in the binder fraction seems to be linked to the use of magnesian limestone to make lime. Geological formations outcropping near the villa (Monti Attilani) are Rudist limestone together with dolomite intercalations (Cretaceous) and Briozoan limestone (Miocene).

The aggregates are composed of always silica-poor alkalic igneous rock, with leucite, pyroxene (diopside and augite), muscovite as the most common minerals. The sorting is bad; crystal grain size 0,2-3,0 mm; rock fragment grain size 2-10 mm; brick fragment grain size >10 mm; white lumps of 2-8 mm.

The binder-aggregate ratio (in volume) is always 3 parts binder and 2 parts aggregate. Leucite crystals are clearly surrounded by a rim. The rim presents the bright interference colours of calcite. Microchemical examinations allow distinguishing two different kinds of rims: one is composed by calcium and it’s surrounded by another rim composed by silicon and aluminium; the second one is made by Silicon and Aluminium only, with very low evidence of the presence of calcium.

There is evidence of the presence of phosphorous; this element is linked to the calcium in well circumscribed areas; it’s possible to identify the mineral apatite (calcium phosphate).

The apatite is a common mineral in volcanic sediments as “Pozzolana” employed in the mortars. Sulphur shows a widespread diffusion in the samples; it is not possible to determine the presence of a specific mineral containing this element. Needle like crystals, with the presence of silicon and aluminium, are also present in the samples.

The source of raw material for the aggregate is a pyroclastic deposit (called Pozzolana) from Lazio volcanic districts. The southernmost district, called Vulcano laziale (about 30 km South-West from Arcinazzo Romano), featured three phases with many cycles; during the second cycle of the first phase (about 600-500,000 years) the amount of pyroclastic deposit was very large and covered about 80 square kilometres around the crater. Pyroclastic material is called “Pozzolana rossa” o “Pozzolana di San Paolo”.

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5.1.2 Xanten

The mortars sampled at Colonia Ulpia Traiana are always bedding mortars; only one sample is a plaster.

The colour is almost always pale in mass (binder), sometimes pinkish (#17).
The binder composition is always calcite (from slaked lime): the lime is always pure lime and there is no evidence of the presence of silicon; magnesium also is scattered without a concentration in the binder fraction.

The aggregate composition is: quartz crystals, metamorphic rock fragments, sandstone fragments; crushed brick. Minerals component are: quartz, feldspar, calcite. The sorting is always bad; crystal grain size is 0.2-3.0 mm, rock fragment grain size 1-7 mm, brick fragment grain size 3-6 mm.

The binder-aggregate ratio (in volume) is almost always 3 parts binder, 1 part aggregate. There is low evidence of the presence of phosphorous and sulphur; these elements are diffused and not linked to the presence of minerals.

The source of raw material for the binder is supposed to be local limestone and the raw material for the aggregate is local river sand.

The mortar used as plaster (sample #X4) is rather reddish in colour. Binder composition is always calcite (from slaked lime). Aggregate composition is crushed brick and quartz crystals. Iron is diffused in the brick used as aggregate. The sorting is very bad together with irregulr grain size: brick fragment 0.3-4.0 mm.

The binder-aggregate ratio (in volume) is: 3 parts binder, 2 parts aggregate.

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5.1.3 Caesarea

Different kinds of mortar with different purposes were sampled: bedding mortar, rendering mortar, plaster.

Bedding mortars are referred to:
1st century b.C. - masonry (samples #1,2,16)
1st century b.C. - city wall (#6)
1st century b.C. - masonry (#11)
1st century b.C. - masonry (#17,25)
1st century b.C. - foundation (#20)
1st century AD - foundation (#21)
1st century AD - aqueduct (#35)
2nd century AD - aqueduct (#29)
2nd century AD - dam, two mortars at different depth (#32x,32y)

The colour of the mortar is pale brown, reddish or black.
The binder composition is: gypsum (from calcined mineral) (samples #1,2,16); calcite (from slaked lime) (samples #6,11,17,20,21,25,29,32). Rod shaped calcium bearing crystals (about 100 μm) are present in cavities. Some cavities are filled by crystals; others show a crystal growth only around the edges. The morphology of the crystal, observed in cross section by optical microscopy, shows small sized crystals around the edge of the cavity and a crystal size increase moving away from the edge. This kind of morphology is quite similar to the morphology of calcium carbonate crystals that occur in rock veins originated by the precipitation of calcium carbonate from waters filling cracks that are present in a rock bed (i. e. limestone).
The aggregate composition is: quartz crystals (#1,2); sand (quartz, feldspar, metamorphic rocks) (#6,21,32x); calcareous sand (quartz, sandstones cemented by calcite, fragments of seashells) (#17,20,25,29,32y); crushed brick (#11,31,35) or without aggregate (#16).
Mineral components are: quartz, calcite, silicates.
Organic material is: ash (burnt wood)(#17,35).
The sorting is different: good with grain size 0.2-1.0 mm (#1,2); medium with grain size 0.2-5.0 mm (#6,11,17,20,21,25,29,32).
The binder-aggregate ratio (in volume) is: almost always 3 parts binder, 1 part aggregate.
The source of raw material for the binder is local gypsum bearing rock or local limestone.
The source of raw material for the aggregate is local sand from marine shorelines.

Rendering mortars of the aqueduct water pipe are referred to:
1st century b.C. (#13)
1st century b.C. (#14)
1st century AD (#26)
1st century AD (#33,34)
2nd century AD (#28a,28b,30)
The colour of the mortar is pale brown.
The binder composition is: calcite (from slaked lime); there is evidence of the presence of magnesium and of silicon witnessing the use of hydraulic lime; the presence of sulphur is very low and this element is diffused and not linked to the presence of minerals.
The aggregate is: sand with different composition: quartz, feldspar and metamorphic rocks (#13,14,28a,34); limestone fragments with quartz, sandstones cemented by calcite and fragments of seashells (#28b,30,33); crushed brick (#26,28a,30,33,34).
Mineral components are: quartz, calcite, silicates.

Organic material is: ash (burnt wood)(#30,33),
The sorting is: bad with the grain size 0.2 - 5 mm,
The binder-aggregate ratio (in volume) is: almost always 3 parts binder, 1 part aggregate,
The source of raw material for the binder are local limestone and marls.
The source of raw material for the aggregate is local sand from marine shorelines.
Plaster mortar is reported to 2nd century AD (#31)
The mortar is made by two superimposed layers, grey to white in colour.
Inner Layer
The binder composition is: calcite (from slaked lime).
The aggregate composition is: brick, calcitic powder (quartz, calcite crystals), volcanic rock fragments. There is evidence of the presence of phosphorous; this element is linked to the calcium in well circumscribed areas; it's possible to identify the mineral apatite; apatite is a common mineral in volcanic rocks.
The sorting is: medium with the grain size 0.4 - 1.4 mm.
The binder-aggregate ratio (in volume) is: 1 parts binder, 1 part aggregate.
Source of raw material for the binder are local limestone (?).
Source of raw material for the aggregate are crushed brick and calcite.
Outer layer
The binder composition is: calcite (from slaked lime).
The aggregate composition is: quartz only.
The sorting is: good with grain size 0.8 mm.
The binder-aggregate ratio (in volume) is: 3 parts binder, 1 part aggregate.

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5.2 Isotope Analysis

The samples taken at the three sites were sent to IFE (Norway) for isotope analysis of the light stable isotopes and of the heavy isotopes. The results are presented in the following chapters.

5.2.1 Villa Traiana

The location of the Villa Traiana site is on a slope and before being uncovered this site had been penetrated by groundwater solutions and rainwater for many centuries. This situation has most certainly initiated exchange processes between ground water, soil and mortar / masonry that may lead to different degrees which have equilibrated the isotope ratios in the mortar. The limestone bedrock of Monti Affilani outcrops a few hundred metres up the slope behind Villa Traiana but at a higher altitude. Monti Affilani is,composed of a Miocene Bryozoan limestone in its lower part and a Cretaceous Rudist limestone making up the upper part. The lime stones have probably been quarried in order to supply the raw material for the binder in the mortar and the masonry. The $^{87}Sr/^{86}Sr$ value for the lower limestone is 0.70868 and corresponds to an age of about 17 million years (McArthur et al. 2001) that corresponds to Middle Miocene as pointed out above.

The $^{87}Sr/^{86}Sr$ value for the limestone of 0.70868 is similar to the Sr value of sample WMG, 0.70870 (Figure 14). This latter sample is a strongly deteriorated mortar from the more basal parts of the building structure and has been altered into sandy clay. The sample was chosen in order to have an end member of weathering and deterioration, or a worst case. However, the similarity between those two Sr values most probably depends on the weathering of the Limestone Mountain, transport down the slope, and following impact on and exchange with the WMG mortar. An outer mortar sample (taken with hammer, at drill-core F) gave an 87Sr/86Sr value of 0.70931. This sample, looking seemingly quite intact in hand specimen, was taken at a higher level in the building and thus probably not so affected by groundwater but more from rainwater. Rainwater can be assumed to have a Sr ratio of above 0.710, a figure that would increase the Sr value from that of the limestone/WMG of about 0.70868 up to 0.70931 for the mortar.

In two diagrams where $^{87}Sr/^{86}Sr$ and $\delta^{13}C$, respectively, are plotted versus drill-core depth, core E:1 seems to be the least altered. Its outermost part (0-5 cm) has a $\delta^{13}C$ value of about –6.62 and an $^{87}Sr/^{86}Sr$ value of 0.70905. Further inwards the core (5-9 cm and 9-14 cm) the $\delta^{13}C$ value increases to about +2 (2.14 and 1.83, respectively) similar to the fresh limestone value of +1.06. Core E:1 thus seems not to have been altered to greater degree but preserved an original $\delta^{13}C$ signature. The $^{87}Sr/^{86}Sr$ values (mean 0.70780) are moreover much lower than for the bedrock sample of 0.70868. The inner $^{87}Sr/^{86}Sr$ values of about 0.70780 on the other hand corresponds to an age of about 65 Ma (McArthur et al. 2001) or upper Cretaceous which is the time of formation of the upper parts of Monti Affilani.

The answer is found in Ancient Authors. Vitruvius wrote about two kinds of stone used for lime making: "the lime which shall be out of thick and harder stone will be useful in the main structures; the lime which shall be out of porous material will be useful in plaster work" (*De Architectura* book 2 chapter 5): this is the case of the Villa Traiana with hard limestone used for lime to make main structures. Moreover, according to Vitruvius and Pliny (*Natural History* book 36, chapter 53), the stone to be used for lime were collected along the rivers rather than in a quarry: in the case of Villa Traiana the Roman architects should have used stones coming from surrounding slopes without distinction between Miocene or Cretaceous limestone.

What we see from the $^{87}Sr/^{86}Sr$ ratios is the use of limestone from the two different available sources; from the Miocene limestone 17 million years old and from the Upper Cretaceous limestone aged 65 million years.

Core A:2 implies a greater depth of weathering from its $\delta^{13}C$ -values which inwards the core increases towards positive values. The same trend is true also for core H:1 that starts at a $\delta^{13}C$ -ratio of about –20 but ends up at about –1.57 versus depth. Core G:2 has the same trend. The only core that deviates is F:1 that shows decreasing ratios. From the $\delta^{13}C$ versus depth diagram it seems that the cores emanate from a $\delta^{13}C$ interval in their outer parts between –7 to –20. Taking into account that the $\delta^{13}C$ -ratio for CO_2 in air is about –7 and that the value for biologic overgrowth is about –23 this is reasonable for the outermost part of the cores being in contact with the atmosphere, rain and biological species. The weathering and alteration naturally decreases with depth.

It is also a trend that the cores A:2 and E:1 from the "innermost" structures have less negative carbon values than the "outer" cores G:2 and H:1 that could imply a greater influence of biologic material with low isotope ratios on the latter cores.

In the $\delta^{13}C$ versus $\delta^{18}O$ -diagram the samples yield more distinct trends (Figure 15). The bedrock limestone is the only sample with both positive $\delta^{13}C$ and $\delta^{18}O$ -values and the drill-core samples show a conical spread emanating from the bedrock value. One path ends with $\delta^{13}C$ -values of about –20 and $\delta^{18}O$ -values of about –10. The other path ends with $\delta^{13}C$ -values of about –13 but similar $\delta^{18}O$ -values of about –10. Considering the limestone $\delta^{13}C$-value of about +1 the very light values of down to –20 for the cored mortar H:1 must depend on reactions in the material or input of biologic material. More original and less altered material having less negative isotope ratios are found in the upper right part of the diagram.

An investigation of mortar from 14 Scandinavian churches aged between 1050 and 1990 yielded $\delta^{13}C$ -values about –10 to –15 (unpublished results) similar to this investigation. An explanation could be reactions within the mortar during carbonisation e.g. with organic/biologic matter which have common values between –20 to –25. A well-known fact is that the Romans mixed the mortar with animal hair, charcoal, snails, blood and whatever, as reported by Pliny "Maltha is prepared from fresh lime, a lump of which is slaked in wine and then pounded together with pork fats and figs, both of which are softening agents" (*Natural History* book 36, chapter 58).

In the $^{206}Pb/^{207}Pb$ vs. $^{208}Pb/^{206}Pb$ diagram most samples gather about 1.20 for the $^{206}Pb/^{207}Pb$ ratio but with a large spread for the $^{208}Pb/^{206}Pb$ ratio (Figure 16). Strongly deviating is the bedrock limestone value of 1.23 and 2.00, respectively. Most samples follow a parabolic trend from which F:1 deviates with almost constant $^{206}Pb/^{207}Pb$ ratios but a spread between 2.075 to 2.085 in $^{208}Pb/^{206}Pb$ ratios. H:1 may be part of the F:1 trend.

The WMG sample, a completely deteriorated mortar, has a $^{206}Pb/^{207}Pb$ ratio of about 1.20 indicating lead contribution from the bedrock, with a value of about 1.23, from solutions coming downhill and penetrating the structure. A $^{206}Pb/^{207}Pb$ ratio of about 1.20 is also an expected natural value which also most of the samples gather about. The WMG sample, moreover, has similar $^{87}Sr/^{86}Sr$ value as the bedrock that depends on a contribution from this source just as for the Pb.

The mortar sample on the other hand being from an upper part of the structure has the lowest $^{206}Pb/^{207}Pb$ value of 1.19 indicating a contribution from industry and traffic with values between 1.15 and 1.18 and traffic values of below 1.10, respectively.

The outermost sample from core E:1, 0-5 cm, which implied a contamination of its Sr ratio may also have suffered a lowering of its $^{206}Pb/^{207}Pb$ ratio due to environmental pollution. The slab of mortar, which acts as an outer drill-core sample, yields an even lower Pb ratio pointing towards anthropogenic contamination. From the $^{206}Pb/^{207}Pb$ ratio versus depth diagram it is apparent how the outermost samples have suffered the impact from air-transported pollutants like traffic Pb and industry. In the case of the mortar sample and the outer part of core E:1 this is also sustained by the increased Sr ratios towards that of rainwater.

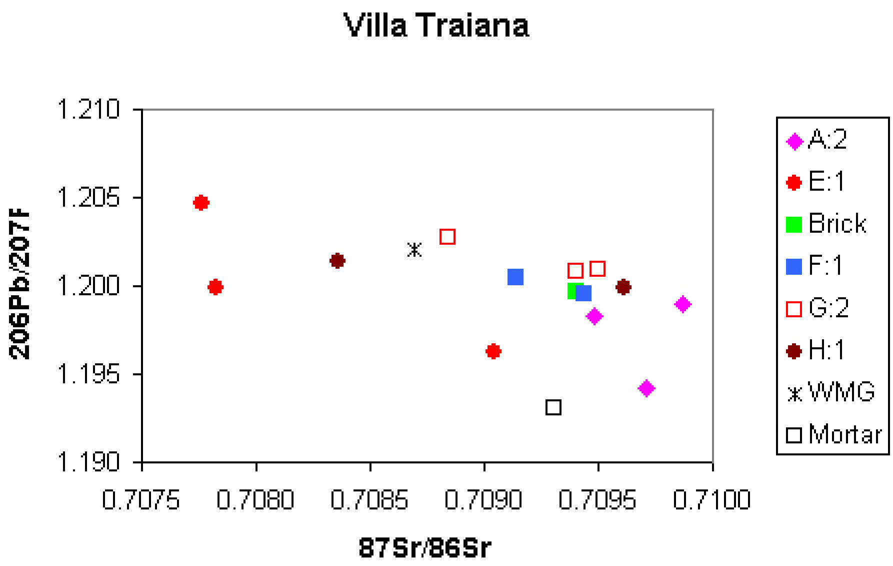

Figure 14 *206Pb/207Pb versus 87Sr/86Sr ratios for Villa Traiana*

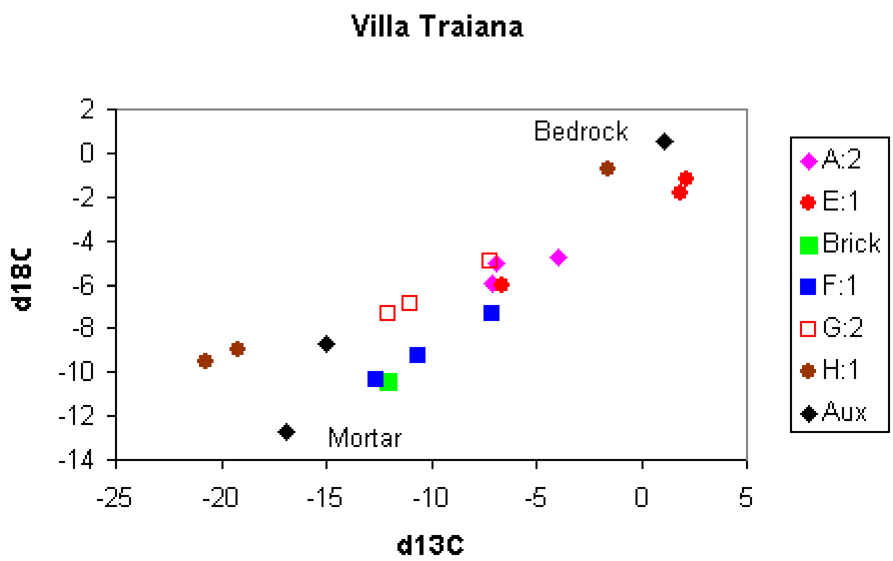

Figure 15 *$\delta^{18}O$ versus $\delta^{13}C$ values for Villa Traiana*

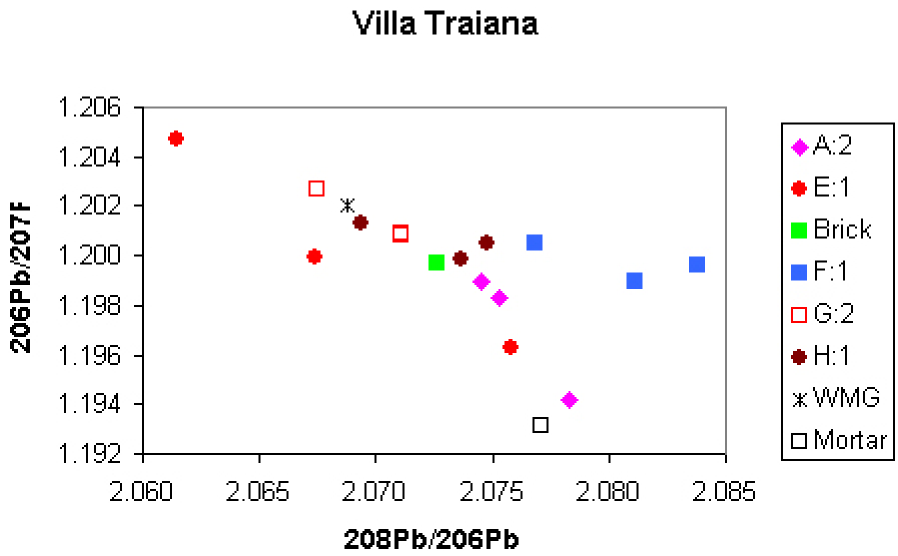

Figure 16 *206Pb/207Pb versus 208Pb/206Pb ratios for Villa Traiana*

5.2.2 Xanten

The Xanten site was buried for many centuries before being excavated but the building structures were never below the groundwater level. Thus there has not been a severe isotopic exchange between the mortar and the soil solutions. However, a certain impact from rainwater solutions penetrating the soil cover from above and later on also air pollution has to be taken into account. The drill-core samples from Xanten were taken in two steps, as outer cores, the outside plus a few centimetres, and inner cores, a following number of centimetres inwards.

In the diagram $^{206}Pb/^{207}Pb$ ratios versus outer/inner cores, there is a tendency that the outer parts, old or new core, have a lower Pb value. This is probably due to impact of air pollution and exchange with traffic Pb ($^{206}Pb/^{207}Pb$ about 1.10) and industrial Pb (about 1.16) in the air. The same tendency but more strongly accentuated can be seen in the $^{206}Pb/^{207}Pb$ versus $^{208}Pb/^{206}Pb$ ratios where all the outer cores (except one) have the lower values (Figure 17). This exchange with the atmosphere ^{13}C values where the outer parts have higher $\delta^{13}C$ values can also be seen in the positive values indicating exchange with the atmosphere (about –7). The inner parts have more negative values probably due to organic matter, possibly from the production of the mortar as addition of different organic matter was common.

The $^{87}Sr/^{86}Sr$ ratio for the Wulfrath limestone of 0.71032, considered the raw material for the binder, is rather high and indicates that it is not of purely marine origin (Figure 18). This value, however, is in the middle of the obtained Sr values while the modern mortars have low $\delta^{13}C$ versus $^{87}Sr/^{86}Sr$ values. There is also a certain clustering of results in the ^{18}O-$\delta^{13}C$ values between –15 to –28 and $\delta^{18}O$ diagram with very negative δ values between –5 to –20 (Figure 19). The Wulfrath limestone itself has a normal ^{18}O value of –9.6 and a $\delta^{13}C$ of +3.5.

One of the modern mortars, outer part of core 2, yields an anomalous $^{206}Pb/^{207}Pb$ ratio of 1.23 in contrast with its inner part of 1.19, which is a more normal value. The cause for this anomalous value is unknown and traffic and industrial Pb can be ruled out since they would lower the Pb ratio.

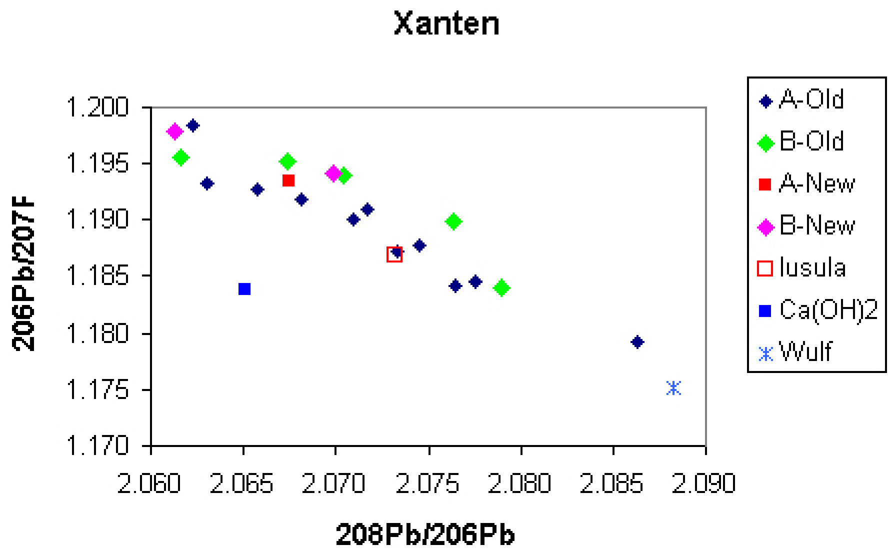

Figure 17 *206Pb/207Pb versus 208Pb/206Pb ratios for Xanten*

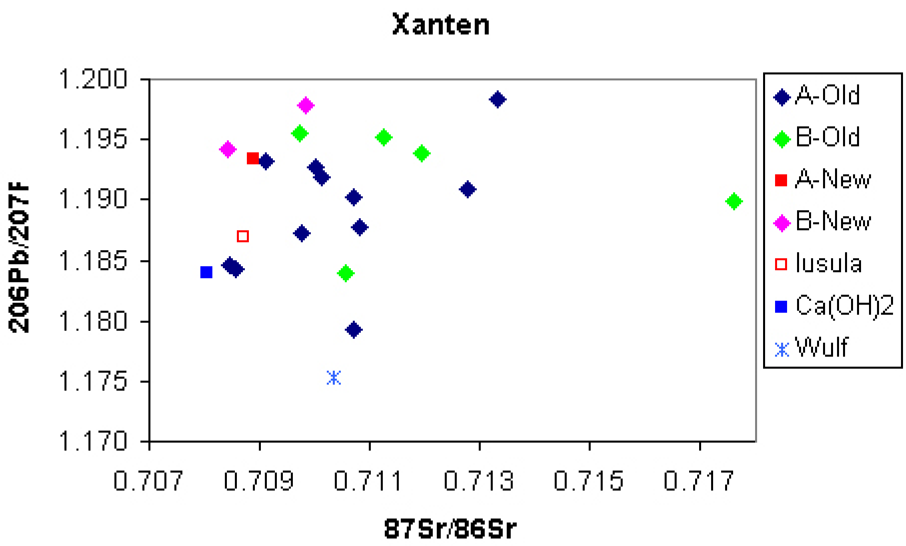

Figure 18 *206Pb/207Pb versus 87Sr/86Sr ratios for Xanten*

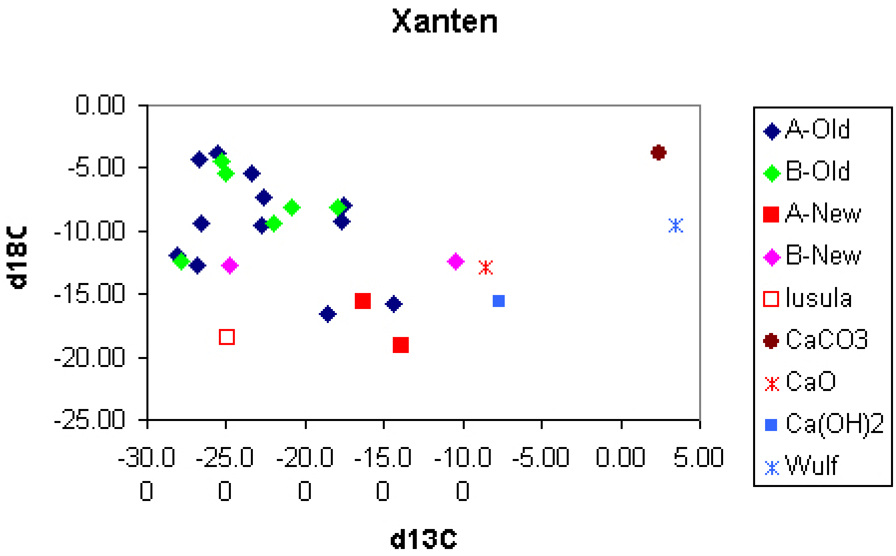

Figure 19 *$\delta^{18}O$ versus $\delta^{13}C$ values for Xanten*

5.2.3 Caesarea

The Caesarea site, with its location right at the waterside, has been exposed for over 2 thousand years with salt-spray from the Mediterranean. The influence of the see is considerable especially during wintertime with heavy storms and strong winds generating up to 5-7 metre high waves. The aerosols from the sea cause salt efflorescence and deterioration of the building materials due to crystallization of salts. This is an ongoing process with alternating crystallization, dissolution, re-crystallization, dissolution etc. After the decline and demolition of Caesarea the land has been used for agriculture up to recent times. Before excavation the site was covered by sea sand in the form of sand dunes while the upper layer and the ground inlands consisted by cultivated soil.

The sampling was made mainly by taking drill-core samples that were split in an outer (0-10 cm) and an inner part (10-20 cm). Plotted in $^{206}Pb/^{207}Pb$ versus $^{208}Pb/^{206}Pb$ and $^{206}Pb/^{207}Pb$ versus $^{87}Sr/^{86}Sr$ diagrams there is no trend when it comes to outer and inner parts of the cores but the sample results are quite evenly mixed. Another picture emerges however, when the mortar samples are plotted according to building time. In the $^{206}Pb/^{207}Pb$ versus $^{208}Pb/^{206}Pb$ diagram the samples from 1 BC show a much larger spread than the samples from 1 AD while the samples from 2 AD plot within a very restricted area (Figure 20).

In the $^{206}Pb/^{207}Pb$ versus $^{87}Sr/^{86}Sr$ diagram the spread is also very mixed in the outer core/inner core diagram but quite different in the diagram based on building time. The samples from 1 BC show a larger spread than the 1 AD samples but have similar $^{87}Sr/^{86}Sr$ ratios while the samples from 2 AD have markedly lower Sr ratios more similar to the limestone possibly being the base for the lime production. The $^{87}Sr/^{86}Sr$ ratios for the samples from 1 BC and 1 AD are moreover similar to the value for seawater (Figure 21). This value is reasonable taking into account the vicinity to the sea and the impact of sea-spray. On the other hand do the samples from 2 AD not seem to have been so strongly affected since they plot in between the values of seawater and the limestone values. This observation leads to an interesting question: is the decreasing spread in isotope values over time an indication of the development of a better and more resistant mortar? Especially taking into account the limited spread and less impact of seawater spray on the 2 AD mortar.

In the ^{18}O diagram the outer and inner cores have $\delta^{13}C$ versus $\delta^{18}O$ between –5 to –20 but when plotted versus time we get the same picture as for Sr and Pb; the spread for 1 BC is larger than the spread in 1 AD which is larger than the spread in 2 AD (Figure 22). The spread is also cone-like emanating from the limestone samples that have ^{18}O values. A trend is also that the 1 BC samples spread evenly within the cone while the 1 AD and 2 AD samples mainly plot along an axis within the centre of the cone. This cone-like spread of ^{18}O values for the mortar is also similar to the spread in Villa Traiana.

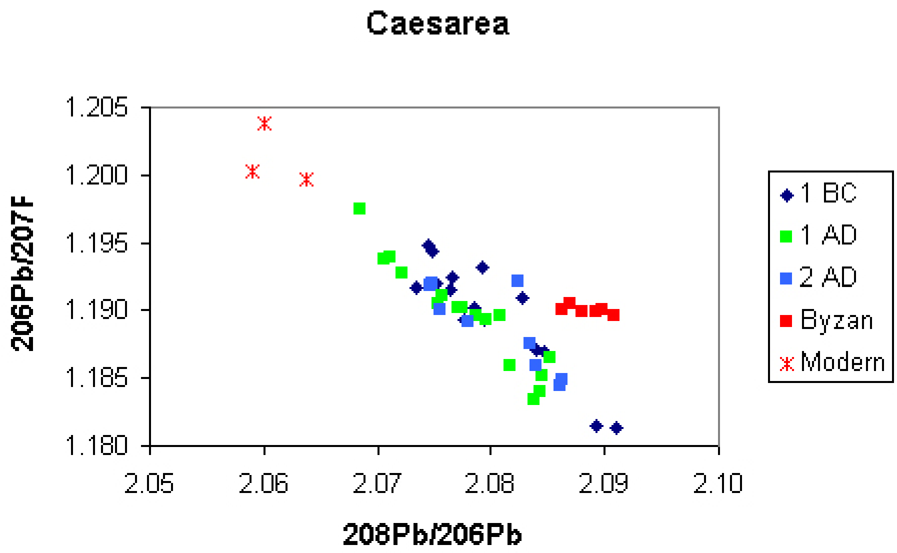

Figure 20 *206Pb/207Pb versus 208Pb/206Pb ratios for Caesarea*

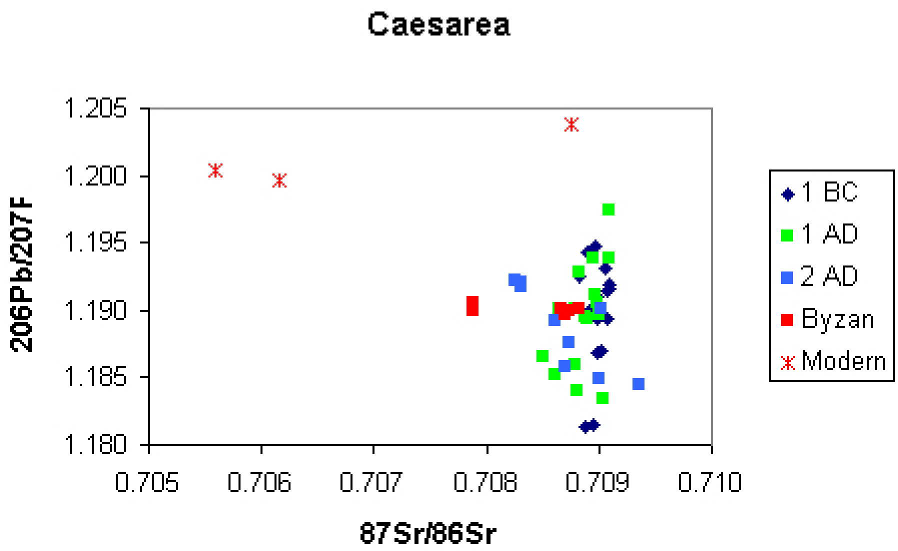

Figure 21 *206Pb/207Pb versus 87Sr/86Sr ratios for Caesarea*

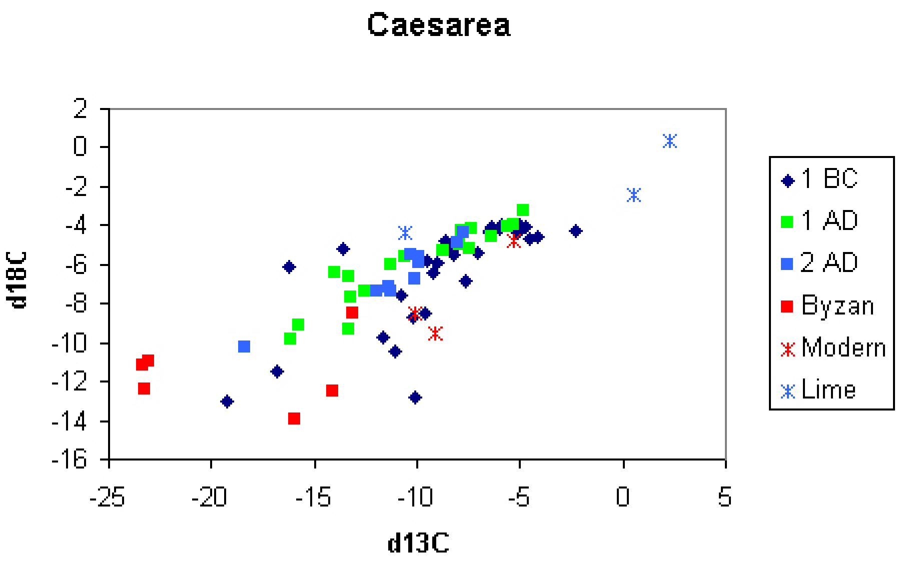

Figure 22 *$\delta^{18}O$ versus $\delta^{13}C$ values for Caesarea*

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5.3 Discussion of Isotope Data

The search for reasons why Roman mortars exhibit special properties has been based on three major assumptions:

- The combination of the major components binder aggregate was different from the modern ratio.
- Special ingredients or minor components, which provide a longer durability to Roman mortars, might have been used.
- The production techniques were different, thus causing different physical properties that can not be detected chemically.
- In some cases organic material might have been added in order to create an inner source of CO_2

The consortium has reviewed the existing literature on mortars and has analyzed mortar samples from three different sites; Xanten (Germany), Caesarea (Israel) and Villa Traiana (Italy) in order to study which of these three possible changes contribute to the characteristics of Roman mortars. Isotope techniques have been used. The stable isotopes ^{13}C and ^{18}O as well as the ^{34}S and ^{15}N values might give insight to the type of materials used and the source of additives.

The carbon data from Villa Traiana is very negative and mostly far below -7, which is the value for CO_2 in air. A significant depth variation exists for all samples. The variations' range is between the end members of – in this case – a bedrock slab with a ^{13}C value of +1.06 ‰ and a mortar slab with a light composition. Some samples have very light isotopic compositions for carbon-13. This indicates that beyond source and material properties, there are other processes related to:

- Reaction grades of lime / carbonate.
- Diffusion of CO_2.
- Weathering or isotope exchange with ambient water and CO_2 that affects the isotope composition. This is an important result because it shows that some isotopes (in this case ^{13}C and ^{18}O) indicate variations that are not directly visible with other mineralogical techniques. These variations are indicators of processes that can indicate key processing techniques or additives that have been consumed in the reaction process.

The hypothesis has been raised and discussed that organic additives may have been used to introduce a source of CO_2 into the building material, enhancing the hardening of the mortar (or the formation of calcite). Some data indicate the contribution of carbon from organic sources. However, it is very interesting to note that G. Åberg (IFE) found similar depth-isotope patterns in a series of mortars from Medieval and recent buildings. This point to a depth-pattern due to a gradual carbonatisation process rather than to isotope signatures related to material sources.

The data gave first evidence that the carbonatisation process – the transformation of lime to calcite – may be traced through the isotope signature in mortars. This can be a key to the understanding of the time scale of the lime-carbonate reaction. This reaction is also related to material properties such as the tendency to close cracks and self-healing. Hence, it can help to explain some properties of Roman mortars.

The secondary re-carbonatisation and exchange with carbon isotopes from the environment is observed in villa Traiana. There the exchange of carbon isotopes occurs between the soil, atmosphere and the groundwater during the burial of the remnants.

The results of other isotopes – isotope ratios of different Pb isotopes – and Sr isotope ratios are interesting regarding the inter-comparison of different sites, for the identification of material sources and for the study of weathering impacts.

Moreover, carbon-14 dating was carried out in order to substantiate the hypothesis, that the hardening process of Roman mortars is not a fast and well defined process but rather a long and slow one controlled by pore-size and pore connectivity and correlated CO_2 diffusion. For this purpose 24 samples have been analyzed for ^{14}C. Mortar cores of 30 cm diameter were disaggregated and micro-samples were taken along depth profiles of these cores.

Care was taken to take binder fragments and to avoid taking fragments of filling material, if possible. The mortar shows a high variability in carbon-14 and in other isotope data. The samples 1A through 29A with a pair sample taken at about 5 cm depth derive from the 3rd sampling campaign in Xanten (Figure 23). In this case, disintegrated calcitie filling material from marls mixed with the calcite formed during the hardening of the mortar, resulting in low pmC values. The apparent age is higher than the actual formation age of the calcite due to a mixing with 'geologic' material sources.

The sample X1A modern represents a sample taken in Xanten from young mortars used for repair of wall structures and surfaces. This sample gives a reference value for a recent mortar in terms of age dating: younger mortars should have higher pmC values (or be closer to the modern value of about 100 to 105 pmC); older samples should have lower pmC values. As the half time of the carbon-14 is 5730 years, values of less than about 50 pmC indicate a substantial mixing with geologic material, the carbon-14 value of which can be less than the detection limit due to complete decay of the radioactive components since their formation. However, in Xanten such values – indicating mixing – are not observed. Therefore, the carbon-14 method can be used as an indicator for how recent the formation of calcite or the calcification of lime took place. At least three samples have pmC values of more than 100 % indicating young calcite formation. Another three values indicate ages that are far more recent than the construction time of the buildings in Xanten. It can be concluded that calcification even in thick wall fragments is a dynamic process that stretches far beyond the construction date of the building and the initial hardening.

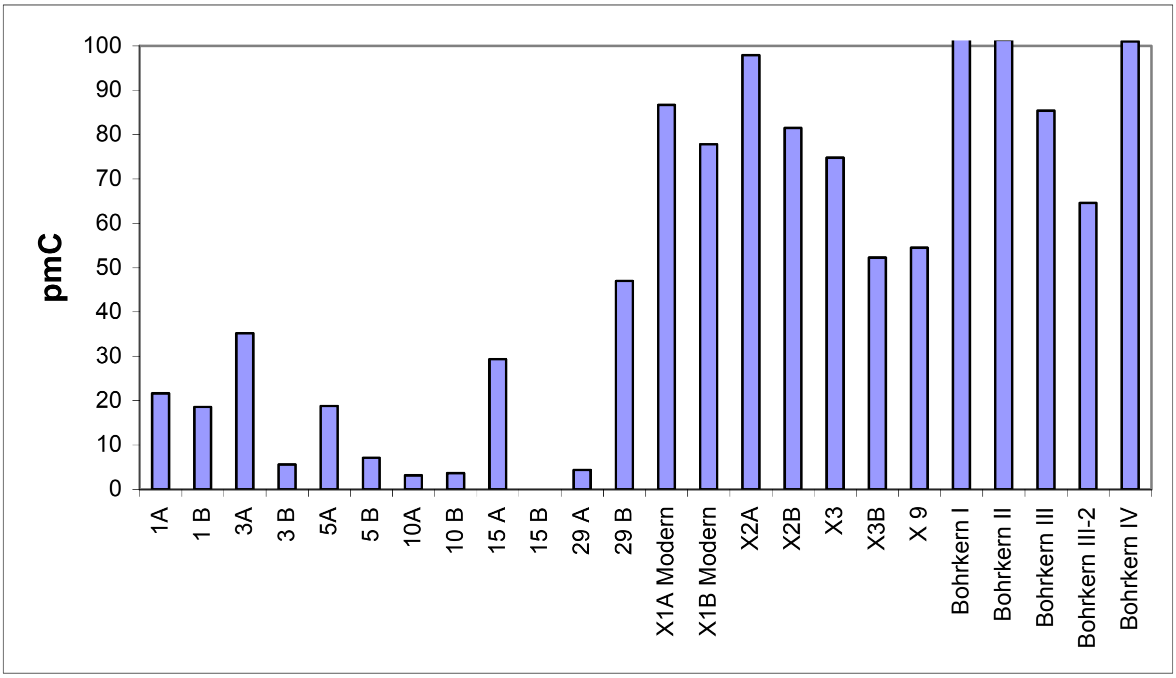

Figure 23 *Carbon-14 data of samples taken in Xanten showing the age distribution within cores of mortar*

6 Prototypes

Based on the analytical data, Krusemark has developed prototypes at laboratory level. The prototype design and testing has been described in non public analytical reports.

The results of the study and the conceptual model have been integrated in the preparation of the prototypes.

Several important findings were confirmed by the ITER project and have become the base for the re-design of mortars:

- Production techniques are important (selection of sand and lime) and the instructions in the texts of Vitruvius can be implemented regarding this aspect of mortar production (refer to Chapter 2);
- Roman Mortars have a much higher ratio of binder to aggregate than modern mortars;
- It is not possible to simply increase the ratio: an increase of the ratio would cause cracks;
- Alternative production techniques are needed that allow high binder to aggregate ratios and that 'hide' part of the binder material forming deposits for reactions at a later stage.

A key element has been the formation of nodules during the preparation process, which means producing aggregates that encapsulate lime during the hardening. In such way a reaction potential is created. The formation of aggregates of slacked lime allows working with high binder\aggregate ratios, as observed in the ancient mortars, without affecting the physical properties.

The physical analysis of the prototypes showed that the strategy has been successful. Water absorption with nodules/aggregates has a lower water absorption potential and lower tendency of shrinking although a higher binder: aggregate ratio is used. Extension and density are similar for samples with and without nodules. However, the samples prepared with nodules / aggregates have a higher volume of pores. As a result the shrinking (cracks) is much lower by about 0.88 mm/m to 2.44 mm/m (conventional).

The pressure resistance is the only factor that is affected in a negative way.
Further tests are needed to find ways of compensating this property.

Figure 24 *Sample of Roman mortar as compared with the modern ITER mortar prototype, presented by FUTUREtec (Eng. Druta, Dr. Rehm-Berbenni) and Landesverband Rheinland (Dr. Kienzle) at the European Parliament during the exhibition "Our Heritage for Tomorrow" (31st January to 4th February 2005)*

7 Conclusions

During the ITER project the morphological study of ancient Roman Mortars and the ^{14}C analysis have provided data substantiating the hypothesis that Roman lime mortars have a reaction potential.

Crystallization of Roman mortars might not be limited to a defined time span close to the time of construction of the building; crystallization might place during hundreds, in some cases thousands of years. This is only possible if part of the lime used is inactive at the moment the building is constructed, and during the initial hardening process.

The morphological analysis has shown that this storage of reactive lime mortar might be provided by an encapsulation of lime nodules. While the outer surface is calcified sealing the inner part, the core of the nodule still contains Calcium-Hydroxide that can react upon physical stress, cracking and associated contact with CO_2.

The encapsulation of part of the binder in nodules therefore is an important part of the preparation technique. In fact, due to encapsulation the amount of active or reactive binder at the moment of construction should be close to the binder-aggregate ratios that are being used in modern mortars. The rest of the binder can be encapsulated representing storage. This property can explain the durability of Roman mortars. Upon access of CO_2 due to cracks, the capsules react. The formation of a calcite vein along the crack represents the self healing-capacity of the material.

There is little chemical evidence for the slow hardening process of the Roman mortar, except for the obvious difference in binder-aggregate ratios. Therefore, only the Isotope investigations identified the slow hardening process.

The major results of the ITER project are:

- Extended Sampling Methodology for Isotope Analysis of Roman Mortars;
- Isotope Techniques Applied to Roman Mortars;
- Specific Ancient Mortar Design and Production Using Isotope Data;
- Database of Ancient Mortars and Results of Isotopic Analysis.

In the frame of the sampling methodology a extensive sampling protocol was elaborated including instructions for core drilling and documentation of the samples location.

An extended sampling technique with dry coring was tested and proved to be feasible. Small samples of about 100 g were found to be sufficient for carrying out the analyses. CNR worked on cores or pieces of cores using mineralogical techniques. One inch coring was taken with sample splitting (4 parts, 2 for mineralogy, 2 for isotopes, 1 of each as stored sample part). The sampling technique coring with a hand-held driller of up to 1 inch diameter was tested successfully during the ITER Project. The option of using nitrogen as cooling medium and at the same time as gas atmosphere in order to avoid secondary reactions during the sampling, e.g. with CO2, was discarded as a result of the first sampling campaign. Although the application of nitrogen during the drilling in principle was possible with the available core driller, it was very difficult to apply it in the field. As a result of the sampling in Rome, a routine procedure was established for the other sites.

Isotope techniques e.g. ^{13}C and ^{18}O as well as the ^{34}S and ^{15}N values has given insight into the type of materials used and the source of additives. The stable carbon isotope data also indicate that the hardening process of Roman mortars is not a fast process but rather a long and slow one controlled by pore-size and connectivity and correlated CO_2 diffusion. These processes form distinct isotope profiles as a result of diffusion and fractionation. In some samples indications of the use of organic additives have been found.

This information can now be used to re-design mortars. The mechanism of aggregation and its positive effect on the physical properties have been demonstrated by the first prototypes. The production of such nodules represents a technical challenge. The SME partner responsible for the production of mortars, Krusemark, has developed technologies to produce nodules and to imitate the behaviour of ancient mortars. The nodule technology can also be used for other modern applications by adding substances that can absorb atmospheric pollutants or acids.

Through the investigations of ancient mortar decay processes it has been possible to gather new information about environmental changes during the life of ancient monuments, from their construction until today and their capability to survive environmental changes.

The ITER SMEs are now the joint owners of a new methodology on isotopic analysis, as well as a profitable database for examining and checking the chemical and physical characteristics of various mortars.

Several are the target sectors for the dissemination and exploitation of these results. They are:

- Analysis of building materials, as well as monitoring and condition assessment;
- Conservation of historical buildings;
- Production of raw materials for construction;
- Environmental monitoring, maintenance and new building technologies.

…Conserving the past, building for the future!

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