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Mortar Research and Design – Preserving the Values of the Danube Limes in Serbia

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Abstract. The research project *Mortar Design for Conservation - Danube Roman Frontier 2000 Years After (MoDeCo2000)* explores Roman mortars of the former Danube Limes in Serbia. It aims to fill in some missing pieces of the puzzle about life in the Roman period in the border territory by examining the creation of fortifications, and public and residential buildings. Finally, the project designs tailor-made conservation mortar mixtures in accordance with these precious data. The project concept is based on the prevailing idea of modern architectural conservation, which requires a holistic approach, combining old building practice and new scientific knowledge about building constructions, technologies, and materials used in the Roman period in the mentioned territory, with the aim of giving science-based recommendations for future practical conservation.

1 Introduction

Architectural analysis of historic built structures can greatly help in solving unclear situations archaeologists face during their research. The knowledge of the forms and geometry of a building, construction and masonry techniques used for its creation, as well as the formation of its basic elements using building materials, can reveal precious data about the process of its erection, but also its further life phases. The same refers to the conclusions connected to the economy and trade, travel routes and infrastructure used for the exploitation and transport of the building materials in a particular period, but also those about the investors, builders, or inhabitants of a building, offering insights into different aspects of life in a territory. At the same time, that knowledge is necessary for the execution of appropriate conservation works in the buildings, giving recommendations for the choice of building materials and technologies for their shaping, production, and application. Probably the most complex of all historic building materials are mortars, representing an integral part of most masonry structures, whilst also contributing, “sometimes intangibly, to the authenticity and the inherent and often subtle aesthetic that makes historic buildings so appealing” [1].

The project *Mortar Design for Conservation – Danube Roman Frontier 2000 Years After (MoDeCo2000)* includes research of the Roman mortars of the Danube Limes in the territory of today's Serbia. Its main scientific objective is to contribute to the knowledge about construction materials and technologies from the Roman period in the territory of Serbia. The specific objectives are focused on the development of a multidisciplinary database linking history, archaeology, architecture, construction, geology, technology, and chemistry; the design and testing of conservation mortars for particular monuments; creating recommendations for the preservation of the future UNESCO site *Frontiers of the Roman Empire - Danube Limes in Serbia* [2]; and contributing to the modern construction industry by promoting the use of traditional technologies and sustainable use of natural resources.

2 Research Context

The Limes was the fortified boundary of the Roman Empire, whose remains stretch through more than twenty modern countries in Europe, Africa, and Asia, with a length of over 7,500 km. The research of the frontier along the Danube in the territory of today’s Serbia has been conducted for over 130 years and, so far, a great number of sites have been explored. Some of them, such as *Viminacium*, have been excavated since the second half of the 19th century [3, 4], while most of the fortifications in the Danube gorge were excavated during the construction of the Đerdap I and II hydroelectric power plants, in the period between the 1960s and 1980s [5].

The Romans conquered the territory of present-day Serbia by the year 15 AD, when the province of *Moesia Superior* was formed. Previously, until the year 9 BC, the territory of today's Srem was conquered and became part of the province of *Pannonia* [6]. The establishment of the fortified Roman border on the right side of the Danube, with a series of fortifications connected by roads, was completed during the 1st century. Chronologically, the Limes and its fortifications had several phases, from its establishment to its demolition during the Hun invasion in 441/443 [7]. The appearance, purpose and strategic distribution of the fortifications have changed over time [8, 9]. In the 6th century, during the reign of Justinian I, the Limes and life on it were renewed, lasting until the end of the same century, and the Avar and Slavic conquests [10].

The *MoDeCo2000* project comprises the research of the sites along the Danube that belonged to the provinces of *Moesia Superior* and *Pannonia Inferior* during the Roman Empire, and *Moesia Prima*, *Pannonia Secunda*, and *Dacia Ripensis* during Late Antiquity and Early Byzantium. There were two legionary fortresses, in *Viminacium* (Stari Kostolac), and *Singidunum* (Belgrade), many medium-sized fortifications, smaller fortifications, watchtowers, collective redistribution centres, and partition walls [7], Roman settlements were developed near fortifications, at the crossroads of important roads, and in the mining centres in the hinterland. The majority of the largest city centres in *Moesia Superior*, such as *Singidunum*, *Margum*, and *Viminacium*, were all situated along the Danube.

The sampled buildings belong to the time span of the period from the 1st to the 6th century, having military or civilian function. Thus, the mortars originate from the walls of legionary fortresses, auxiliary forts, smaller fortifications, and a bridge, but also from baths, villas, city ramparts, and tombs. The archaeological sites and monuments of culture examined along the Danube include all available places, comprising of forty different buildings (Fig. 1). Trajan's bridge, a monumental building and an extreme engineering project of its time, designed and built at the beginning of the 2nd century by Emperor Trajan’s architect and engineer, the famous Apollodorus of Damascus, represents a unique case for the project research in many aspects.

Fig. 1 Remains of Trajan’s Bridge (photo-documentation of the MoDeCo2000 project)

3 Research Methodology

Modern conservation science is one of the research fields that attracts many scientists and professionals in the world. In the field of archaeological heritage, it is almost indivisible from archaeometry, whose research it uses for the creation of recommendations, and solutions for further heritage protection [11]. *MoDeCo2000* project approach uses two already interconnected fields, following the globally accepted concept of a multidisciplinary approach in science, linking humanities, engineering, and natural sciences, in an effort to contribute to the recognition of the need for comprehensive scientific research preceding conservation activities in Serbia. However, conservation works are very financially demanding, and the previous scientific research does not lag behind it in this regard. Thus, the *MoDeCo2000* project aims to contribute to the scientific research in this area, collecting its results in a database that will greatly aid future conservation activities in Serbia.

Fig. 2 The sampling of mortars (photo-documentation of the MoDeCo2000 project)

The concept of the *MoDeCo2000* project starts from the comprehensive cross-disciplinary research into raw materials and building technologies from the times of Roman dominance in the region of today's Serbia, conducted with the aim of providing valuable scientific information that could be used for the practical conservation of structures. Thus, it includes an approach combining: *collection of inputs* with observation, description, analyses, and synthesis of the scientific information from different fields, with sampling of historic materials, and laboratory characterisation of the historic mortar and raw material samples (Fig.

2); *design of outputs* with interpretation and compilation of input data, design and testing of the newly developed conservation mortars; *compilation of outputs* with the establishment of protocols, recommendations and knowledge bases for conservation; *implementation of outputs* with the trial application of the results in conservation practice, and their interpretation for civil engineering; and *communication of outputs* with publication and dissemination of the project research results.

Fig. 3 Mortar samples from different sites (photo-documentation of the MoDeCo2000 project)

When designing the mortars for conservation, there are a few factors that have to be considered. Depending on their position in the structure, they often need to match the properties of historical mortars, satisfying many requirements. After the analyses of the characteristics and condition of the existing masonry and specific mortar, the function, position, and exposure of the proposed work need to be determined, always taking care of the aesthetics [1]. Thus, the mortars sampled during the *MoDeCo2000* project (Fig. 3; Fig. 4) were examined using contemporary laboratory techniques, including stereo optical and digital microscopy, spectrophotometry with colourimetry; analyses of physical and mechanical characteristics; thermal characterisation; and characterisation of samples, binders, and aggregates using XRF, XRD, FTIR and RAMAN spectroscopy techniques.

The laboratory models for conservation were designed and prepared afterwards, using a number of locally available raw materials, and respecting the principles of compatibility and international standards. For the first time recorded, some of the raw materials found in the region of the Danube in Serbia have been used as components in the conservation mortars. The most promising recipes were chosen from the models, tested and exposed to artificial weathering in a climate chamber in which the conditions of the external environment are imitated, but also in indoor laboratory conditions. Additionally, tests of the conservation mortars were performed in real environmental conditions on the experimental, but also authentic, historic structures at the sites and monuments, being monitored and in situ measured afterward.

Fig. 4 Mortar cross sections from different sites (photo-documentation of the MoDeCo2000 project)

Conservation in Serbia is widely recognised as a practice and set of professional skills, however, it is a fast evolving multidisciplinary science and should be acknowledged as such in the region as well. Consequently, the scientific impact of the project *MoDeCo2000* is visible through scientific and popular publications, and laboratory and technical manuals, with presentations of the project results at conferences and workshops. The project collects written resources and reports from the field and laboratory research and organises them as an electronic knowledge base that combines archaeological, geological, architectural and technological data, maps, routes, and technological protocols, which will greatly contribute to heritage protection in Serbia, as an exceptionally important input for conservation practice carried out in accordance with international documents in the field of cultural protection.

The project promotes locally available raw materials for cultural heritage conservation. It also offers new insights into traditional technologies of lime production, which are still kept in some village communities in Serbia but are in danger of being forgotten. The collected information about building technologies and needs of the communities enhance scientific understanding of their everyday lives in one territory through history. At the same time, the research of traditional lime mortars offers important inputs for the development of contemporary construction materials in line with the sustainable use of natural resources.

Finally, the project results are to be incorporated into a national policy document with the proposed methodology for the conservation of the *Frontiers of the Roman Empire – Danube Limes in Serbia,* a site that aspires to be a part of the UNESCO World Heritage List [12], ensuring that future practical conservation works are based on scientific research and careful planning.

4 Conclusions

The *MoDeCo2000* project investigations cover a long time span of the Roman and Early Byzantine period, thus providing the possibility of analysing the development of mortar technology during the entire Roman domination in the territory of today's Serbia. The conducted laboratory analyses have shown the great diversity of samples, and with the help of archaeological, historical, architectural, and geological research, as well as research on historical technologies of mortar production and up-to-date international research in the areas of archaeometry and conservation science, led to the conclusions about construction activities along the Danube, but also about other aspects of life on the Limes in the Roman period.

The concept of architectural preservation requires detailed and serious scientific analyses connected with the origin of raw materials, methods of their exploitation, the technology of their processing, but also their archaeological and architectural context. Thus, the project research approach follows the recognised values of the multidisciplinary approach in European and world cultural heritage conservation. The achievements of collaboration between scientists and professionals are providing valuable results that are then used in practical conservation, for the cause of protecting historical buildings with suitable materials, techniques, and technologies.

Conservation science has a hugely positive impact on the natural environment by promoting the use of naturally based materials. The mortar design proposed in the *MoDeCo2000* project can contribute to the cessation of the use of cement mortar during conservation in Serbia and its replacement with lime mortar, which should be represented in sustainable modern construction as well. The project research can provide valuable information for developing industrial solutions by relying on the history and preserving nature. At the same time, using the results of the research on raw and building materials conducted, the mutual interconnection of local people to their intermediate setting can be improved and turned towards its protection. The protection of historic buildings promoted through the *MoDeCo2000* project entails the preservation of traditional building skills, thus becoming one of the ways of preserving the intangible cultural heritage as well.

The research shown in this paper has potential for future expansion to include the study of not only Roman sites in Serbia other that those situated on the Danube Limes, but also those situated along the Danube and dated to later historical periods. International cooperation with other countries and regions that share the same Roman history could also be sought. These could bring precious knowledge on the trade and transport of building materials and building activities of the people throughout history, having an important influence on the international conservation practice.

5 Acknowledgments

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Landscape and its Traces in Roman Mortars of the Danube Limes in Serbia

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Abstract. The research within the project *Mortar Design for Conservation - Roman Danube Frontier 2000 Years After (MoDeCo2000)*, dealing with Roman buildings in Serbia situated along the former Danube Limes was carried out using data from archaeological, architectural, and geological contexts, combined with mineralogical, chemical and material science research. The aim of the research is to reveal unknown data on ancient provincial construction, but also to contribute to future conservation processes, offering a database of historic mortars and raw materials used at the mentioned territory during the centuries. The research has confirmed the well-known unwritten rule of using local materials in historical constructions. The unique landscape around the Viminacium Archaeological Park with the remains of structures dating to ancient, Early Byzantine, and medieval periods, is an area where four archaeological sites, with nine buildings and forty-two different mortars, were examined, making it an ideal case study for this paper.

1 Introduction

The mighty Danube river flows through the Republic of Serbia for a distance of 588 km. Almost 2,000 years ago, the border of the Roman Empire - the Danube Limes - was established along it. From the 1st to the 6th century AD, dozens of military fortifications, small towns, and large urban centres were built here [1]. Through the project *Mortar Design for Conservation - Danube Roman Frontier 2000 Years After (MoDeCo2000)*, research of this area is conducted on one of the most complex building materials used in the history of construction - mortar. The research includes all available archaeological sites and cultural monuments from the Roman period on the territory of the Danube Limes in Serbia, comprising forty buildings with 117 different lime mortar samples and many bricks, stones, local clays, and sands. One of the leading ideas of the research was connected to the attempt to find traces of local raw materials used in mortars and their role in giving them different properties.

The landscape around the Viminacium Archaeological Park [2] is a plain area named Stig, spreading along the Danube, situated between two ridges. On both of them, structures of fortifications from the ancient period and the Middle Ages are preserved – *Lederata* [3], Braničevo [4], and Ram Fortress [5], while in the middle plain the remains of the Roman city with the legionary fortress of *Viminacium* [2], and an Early Byzantine fortifying structure [6], are situated, making it a perfect case study for the research of raw materials used for the construction activities in a landscape through the ages.

2 Natural Resources and the Landscape

Construction and masonry techniques used for the buildings in the territory of the Danube Limes in Serbia followed basic principles of Roman architecture but used varieties present in the Balkan provinces and created under the influence of eastern parts of the Empire [7, 8]. This architecture, in accordance with the general characteristics of Roman constructions, was rational, with the predominant use of local materials, but also with the use of hard to deliver materials for the most important military and public buildings, or for wealthy private investors [7]. The materials used for lime mortar manufacture and explored through the *MoDeCo2000* project are based on the exploitation of local resources.

It is principally difficult to find traces of ancient works on areas exploited for building stone or raw materials for making lime or mortar itself. If the exploitation has continued throughout history, the traces have been erased, and if it has been stopped, they are mostly hidden under natural layers or construction [8]. The quarries of schist in the villages of Ram and Zatonje situated near the *Viminacium* archaeological site, on the right ridge of the Stig plain, have been exploited for centuries (Fig. 1). This rock is the oldest geological formation in the wider area, with a low degree of metamorphism, formed by the intensive transformation of volcanogenic-sedimentary rocks [9]. Geological research has determined that the rock consists mostly of schists built of albite, epidote, chlorite, and actinolite, and those built of sericite, muscovite, and chlorite [9].

The schist was used as an almost exclusive stone material for buildings in the whole Viminacium area throughout history. We find this stone in the buildings of Roman *Viminacium* and *Lederata*, dated to the period from the 1st to the 6th centuries AD, but also in the walls of the medieval fortresses – Middle Byzantine Braničevo and Ottoman Ram Fortress, later monasteries, and surrounding village houses [7, 8, 10]. The fort of *Lederata*, situated in the village of Ram was built on the schist rock itself. Considering that this rock has been exploited for two millennia, that the level of the Danube rose during the construction of Đerdap hydroelectric power system, and that in the 15th century Ram Fortress was built on the rock, real traces of Roman exploitation cannot be recognized today [8].

Brick manufacture was very well developed on the Danube Limes, especially in the area of *Viminacium* [11, 12], where the soil is rich in clay, and production continued throughout the following centuries [7, 8, 10]. A specific natural material locally named "Crvenka" (*reddish*) is also found in the territory of *Viminacium* as a layer of burnt soil and rock created after coal combustion. Its deposits are situated on the left ridge of the Stig plain (Fig. 1). It can be observed as a kind of "natural brick" and was used by Romans of *Viminacium* for building blocks as well as for wall core infill [7, 8, 10, 13].

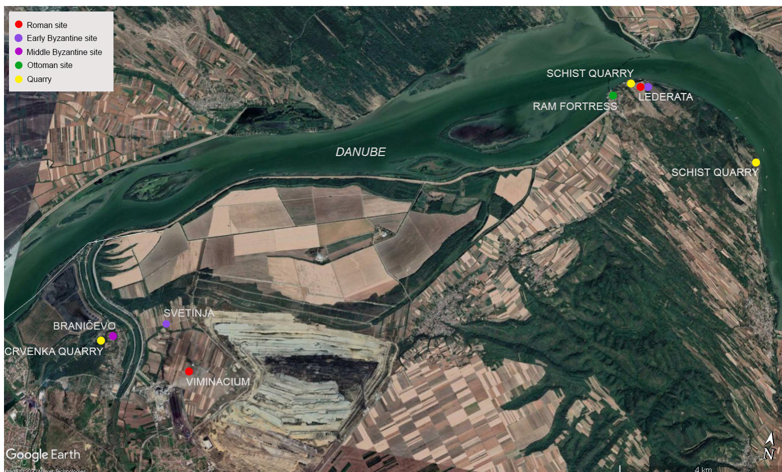

Fig. 1 Viminacium Landscape with locations of mortar sampling and local quarries (Google Earth Pro photo from April 24th, 2021, accessed on March 19th, 2022)

3 Mortar Research

Carbonate rocks are found in different geological periods and, given the very large number of possibilities for their use, are considered the most useful sedimentary rocks. They are generally readily available throughout the whole of Serbia. To produce lime for the buildings of the Danube Limes in Serbia, primarily calcitic limestone has been used. The origin of limestone used for the mortars produced for the historical buildings in the Viminacium landscape has not been determined precisely yet [7, 14, 15]. Petrology analysis of the limestone used for making millstones and querns in *Viminacium* determined it as stone from the upper Badenian – lower Sarmatian age, originating from the surroundings of Belgrade [16]. Considering Roman *Viminacium,* it is worth mentioning that during the recent archaeological excavations of this site, lime slaking pits were found in the vicinity of the buildings, which leads to the assumption that the lime slaking process was carried out in situ during their construction [17].

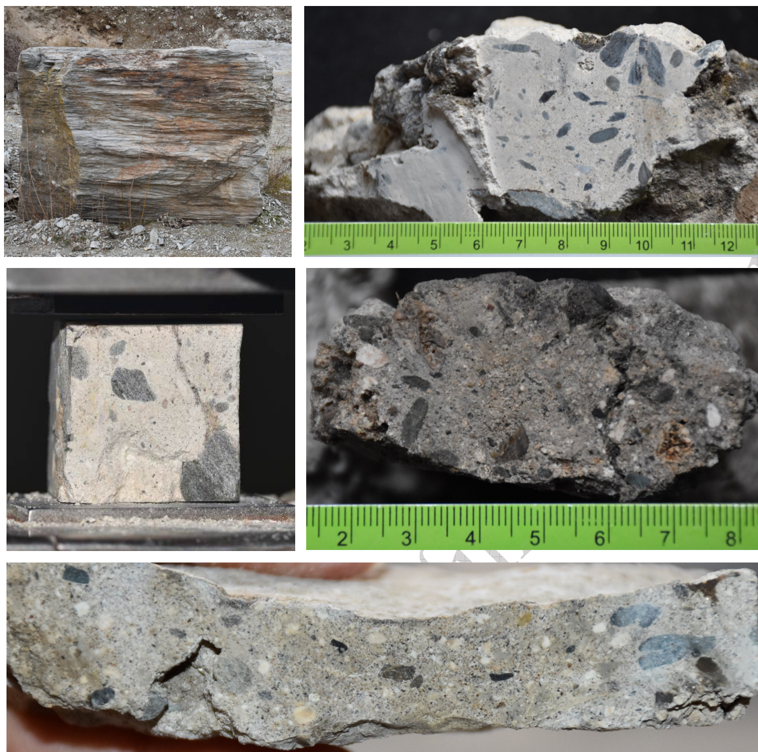

Fig. 2 Schist block in the Zatonje quarry; cross-sections of Lederata mortar samples (Led 1- top right, Led 2 - bottom, Led 3 - middle right) and a compression test specimen (Led 1) - the test was done using an Amsler hydraulic press (Photo-documentation of the *MoDeCo2000* project)

The most commonly used aggregates in the lime mortars examined in the area of the Danube Limes are river sediments of local watercourses. They are most often sand and gravel from the Danube, which has a heterogeneous mineral-petrographic composition, conditioned by the hydrogeological regime, geological structure, i.e. the nature of the rocks exposed to decay within the catchment zones, and geomorphological conditions (various rounded rocks - granitoid, andesite-basalt, sandstone, quartzite, and schist, and grains of minerals - quartz, feldspar, and mica). The aggregate grain size varies, but the most commonly used is up to 10 mm. In addition to sand and gravel, and crushed limestone of various sizes, often up to 20 mm, in the area of the Danube Limes, other local stone fragments were occasionally used as an aggregate, which is most clearly present in the wide area of the Viminacium landscape, that is the village of Ram, where schist grains were predominantly used as the aggregate in the mortars of the *Lederata* fort and a circular building with attached and surrounding walls of a still uncertain date situated inside the Ram Fortress. The size of the schist grains in these samples ranges up to as much as 30 mm (Fig. 2, Fig. 3).

Broken or ground-baked brick, as an artificial material with pozzolanic features [13, 15], was found in the structures of the Danube Limes as an addition in rendering, plastering, or floor mortars, subjected to water, mostly in baths, but there are also examples of brick mortars used for masonry. In the samples originating from structures dating to the 6th century, brick was used as a coarse aggregate for masonry mortars (in fragments up to about 30 mm). However, laboratory mortar models made with the above-mentioned crvenka and lime confirmed its pozzolanic features [10], and, thus, the research of its use in Roman *Viminacium* mortars as a natural material with pozzolanic features, is needed.

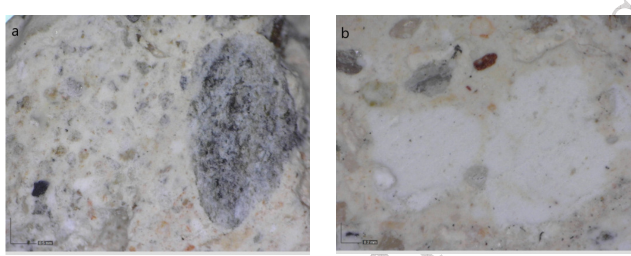

Fig. 3. Microscopic views of a specimen of the sample Led 1 made by Dino-Lite Edge Digital Microscope AF4915ZTL (Photo-documentation of the *MoDeCo2000* project)

A *Lederata* masonry mortar sample originating from the Roman auxiliary fort and dated to the 2nd century - sample Led 1, has extraordinary physical and mechanical characteristics with the highest compression strength of all samples researched during the project *MoDeCo2000*, 15.7 MPa (Fig. 2). Stereomicroscopic examinations determined that the largest part of the aggregate comprises grains of crushed schist (Fig. 3a), while a smaller part originates from the local Danube sand (quartzite, quartz, and mica, in fractions less than 1 mm, schist, and a small percentage of limestone, quartzite, and granitoid, in fractions up to 8 mm). The binder traces - lime lumps, are numerous, and their size is mostly under 1 mm (Fig. 3b). XRD analysis of the sample showed its mineralogical composition made of quartz, calcite, muscovite, clinoptilolite, albite, kaolinite, actinolite, and chlorite (Fig. 4). Some of the minerals belong to the local schist, while the origins of kaolinite and clinoptilolite as natural materials with pozzolanic features are currently being investigated. The presence of clinoptilolite and kaolinite were also confirmed by XRD analysis in a sample that belongs to the succeeding phase of the *Lederata* fortification, and one from the building within Ram Fortress, while the clinoptilolite was found in the central building of the legionary fortress of *Viminacium* (principium) (VPri 1). Zeolites, to which the mineral clinoptilolite belongs, are present in several deposits in Serbia [8, 15, 18], while different types of clays are often found during the excavations of *Viminacium* [19]. The XRD analysis of the mortar originating from the wall of the *Viminacium* legionary fortress' northern gate, dated to the period of the 2nd century (VSk 2) showed it has the same mineralogical composition as the one from the 6th-century (Early Byzantine) *Viminacium* fortifying structure (VSve 1.2), as well as the one sampled from the structure belonging to the fortress of Braničevo, dated to the 12th century (Tod 1), that is, a composition made of quartz, calcite, albite, anorthite, chlorite, and muscovite, confirming the use of same raw materials in the area through the centuries.

Fig.4 X-ray diffractogram of the sample Led 1 - the first phase of the *Lederata* fort, carried out on a Philips PW 1050 X-ray diffractometer (Documentation of the *MoDeCo2000* project)

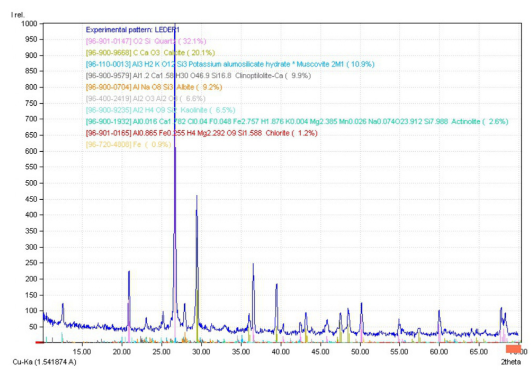

Table 1. Major element chemical composition of masonry mortar samples (in wt%) carried out on a Spectro Xepos XRF Spectrometer (Documentation of the *MoDeCo2000* project)

Masonry mortar samples	SiO_2, %	Al_2O_3, %	Fe_2O_3, %	CaO, %	MgO, %	Na_2O, %	K_2O, %	Loss on ignition (450°C)	Loss on ignition (1000°C)	CaO+MgO	$SiO_2+Fe_2O_3+Al_2O_3$
LEDERATA Corner Tower (Led 2) - 4th - 6th CE	25.82	2.64	1.56	40.30	1.27	0.68	0.41	2.31	27.15	41.57	30.02
LEDERATA Corner Tower 1 (Led 3) - 4th - 6th CE	24.67	3.94	2.66	39.58	1.53	0.51	0.56	2.46	25.33	41.11	31.27
RAM FORTRESS CIRC.BUILD. Surrounding Wall 1 (Ram 7) - Roman or late Middle Ages (?)	24.34	5.62	2.99	37.27	1.50	0.74	0.95	3.37	25.81	38.77	32.95
LEDERATA Corner Tower (Led 1) - 2nd CE	41.97	5.87	2.70	30.09	2.11	0.66	0.50	5.82	15.18	32.20	50.54
RAM FORTRESS CIRC.BUILD. Circular Wall (Ram 2) - Roman or late Middle Ages (?)	37.64	5.53	3.46	29.90	1.86	1.01	0.89	1.69	18.56	31.76	46.63
RAM FORTRESS CIRC.BUILD. Attached Wall (Ram 3) - Roman or late Middle Ages (?)	44.09	5.93	2.66	25.78	1.98	0.71	0.80	1.64	17.02	27.76	52.68
RAM FORTRESS CIRC.BUILD. Surrounding Wall 2 (Ram 8) - Roman or late Middle Ages (?)	43.23	6.19	4.24	23.49	3.46	0.81	0.85	2.97	16.70	26.95	53.66
VIMINACIUM Principia (VPri 1) - 1st CE	53.32	5.92	1.55	23.08	0.89	1.09	1.24	1.42	12.11	23.97	60.79
VIMINACIUM Northern Fortress Gate (VSk 2) - 2nd CE	55.24	5.98	1.39	21.80	0.80	1.08	1.19	1.23	11.77	22.60	62.61
VIMINACIUM City Rampart (VAmf 42) - 2nd CE*	53.38	5.15	2.25	20.92	1.08	0.36	0.48	2.02	15.82	22.00	60.78
VIMINACIUM Fort Rampart (VSve 1.2) - 6th CE	55.47	8.17	2.52	17.67	2.25	0.77	1.58	2.31	10.58	19.92	66.16
BRANIČEVO Fortress Tower (Tod 1) - 12th CE	56.83	5.88	1.41	18.86	0.92	1.17	1.30	3.49	12.75	19.78	64.12
VIMINACIUM Thermae (Vter 9) - 4th CE	58.95	7.08	1.53	16.30	1.45	1.08	1.73	2.56	11.09	17.75	67.56
VIMINACIUM Amphitheatre (VAmf 41) - 2nd CE*	66.84	5.12	1.42	13.21	1.19	0.13	0.46	3.23	10.73	14.40	73.38

* examined in 2011 [14]

ED XRF analyses gave valuable results in the determination of the overall picture of the mortars sampled along the Danube Limes. Since the aggregate was determined as being mostly of a siliceous nature, while the binder was of carbonatic nature, we can perceive the value of CaO+MgO as originating from the binder, while the value of $SiO2+FeO3+Al2O3$ can be accepted as coming from the aggregate [20, 21]. The decrease in the first value almost ideally corresponds to the increase in the second value in the case of the Viminacium landscape masonry mortars. (Table 1). The mortars belonging to these structures showed the contents of oxides that clearly suggests the mutual similarities between the samples of the narrow *Viminacium* site area no matter to which historical period they belong - Roman and Early Byzantine *Viminacium*, and Middle Byzantine Braničevo, as well as between the samples of the narrow Ram village area - structures inside the Ottoman Ram Fortress, and Roman *Lederata*.

4 Conclusions

The research on Roman mortars within the project *Mortar Design for Conservation - Roman Danube Frontier 2000 Years After (MoDeCo2000)*, has confirmed the predominant use of local materials in Roman constructions. Although this can be applied to the whole territory of the Danube Limes in today's Serbia, the landscape around the Viminacium Archaeological Park was taken as a case study for this short study, with its many samples examined and dated to a wide chronological span, giving us an insight into the centuries-long dependence of construction activities on the local raw materials and resources. Many similar studies have already recognized the importance of the topic connected to the technological evolution of historic mortars and its dependence on the availability of raw materials [22].

The mineralogical and chemical research of the mortars originating from the historical buildings in the Viminacium landscape showed mutual similarities between the samples belonging to the structures situated in two narrow areas of the wider landscape – *Viminacium* archaeological site and Ram village and dated to different historical periods, but it also revealed connections between all of them.

Hopefully, further research in the scope of the *MoDeCo2000* project will provide information on the sources of minerals found in particular mortar samples, whose provenance has not yet been confirmed, and which could probably have contributed to their extraordinary mechanical characteristics.

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Following the Ancients – Conservation Mortars for the Danube Limes in Serbia

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Abstract. Sustainable preservation of historic buildings is a long-term process that begins with the analysis of all data related to their creation and further duration and ends with the proposal of measures to preserve their current condition and prevent future damage. In accordance with this, the most important goal of the project *Mortar Design for Conservation - Danube Roman Frontier 2000 Years after - MoDeCo2000*, was set. Data obtained from the archaeological, architectural, and geological context research with the thorough laboratory testing of sampled Roman mortars along the river Danube in Serbia was used to create valuable proposals for the design of compatible mortar mixtures that could be used for the conservation of the structures in the investigated area.

1 Introduction

The topic of this paper is a review of the procedures carried out within the *MoDeCo2000* project, in order to form proposals for the design of mortars that could be recommended for the conservation of monuments along part of the former Danube Limes in present-day Serbia [1]. The investigated buildings are dated to the period from the 1st to the 6th century AD and are currently on the preliminary list for the UNESCO World Heritage List, under the name *Frontiers of the Roman Empire – The Danube Limes (Serbia)* [2].

To create the proposals, laboratory research of a large number of mortar samples originating from 40 built structures from many archaeological sites was performed. In the laboratories, while respecting the principle of compatibility, which means that the new mortar in no way endangers the old material or the structure built from it [3], mortar recipes based on local raw materials were prepared. The technology of making new mortars was based on traditional techniques, whose traces of use throughout history can often be identified through the analysis of old mortars.

2 Process Methodology

Work on the design of conservation mortars during the *MoDeCo2000* project includes the following actions:

- Multidisciplinary research on the spatial context and the choice of structures
- A sampling of the historical mortars from the chosen structures
- Laboratory research of sampled mortars
- Interpretation of the research results
- Search for raw materials
- Design, creation, ageing, and examination of conservation mortars
- Application of conservation mortars in the laboratories and on-site
- Monitoring and examination of applied conservation mortars
- Conclusions with recommendations for the future use of the mortars
- Publication of the project results

After conducting the first four steps, it was concluded that the project *MoDeCo2000* should offer an overall picture of the technology involved in the preparation of Roman mortars and of the use of raw materials, along the large area of 588 km of the Danube flow through the Republic of Serbia. It should also provide recommendations for the preparation of conservation mortars, with numerous possible recipes of compatible mortars. These should then be modified in future, based on further trials and in situ applications at a particular structure within a site. The interpretation of the results of mineralogical, chemical, and analyses of physical and mechanical properties of historic mortars provided necessary data for the creation of the composition and component ratios of new mortars, with the overall aim of fulfilling different criteria as part of mechanical, chemical, and aesthetical compatibility [3].

Fig. 1 Raw materials used during the design of conservation mortars (Photo-documentation of the MoDeCo2000 project)

Following this, the search for raw materials recognised in the historic mortars was conducted. The archaeological site of *Viminacium* [4] is one of the best researched along the Danube Limes in Serbia and it offered us many samples of historic mortars, having various roles in structures (bedding, rubble core, rendering, plastering, and floor mortars), that were used in the buildings of different functions. Since several sites of ancient and modern exploitation of raw materials are situated in its surroundings - the deposits of the schist from the nearby village of Ram, the clay used for the today's local manufacture of bricks, and the layers of rock and soil naturally burnt by the combustion of the lower coal layers and solidified into the natural brick [5], they were all visited and various different raw materials were sampled for further research.

The preparation of the laboratory models of mortars included the use of quicklime, slaked lime (lime putty) and river aggregate of different grain sizes, but also crushed and ground brick, and crushed stone and clays of different origins, which were added to mortar mixtures to improve the properties of their basic mass and give them performance close to that of historical mortars (Fig.1).

After research into the characteristics of the Danube sand and gravel exploited at different sites along the river, it was concluded that they vary minimally and, thus, their exact local origin was not considered important for the choice of aggregate that would be used in the new mortar mixtures. Considering the binder, it was very important to have a good quality lime for the laboratory models. Since the origin of limestone used for the mortars along the Danube Limes was not precisely determined, we have endeavoured to find the one that satisfies the essential need – the reactivity, and that could be produced using traditional firing technologies in lime kilns. Our choice was the lime from the central part of Serbia. However, being limited by the project duration, we used lime whose age ranged from 3 to 6 months. Since the concept of the project relies on the use of local raw materials, and in the territory of Serbia, the production of hydraulic lime was not developed, all models were created with non-hydraulic lime. The DSC/TG/MS analyses of sampled historic mortars gave a direction for the research on the use of hydraulic lime for their preparation. However, based on current knowledge, it cannot be presumed that Romans used hydraulic lime along the Danube Limes in Serbia on purpose, and the presence of impure limestone in the Roman lime kiln could often have been a coincidence [6]. The future research of the found lime lumps will hopefully give us more information.

3 Design of Conservation Mortars

During the design of conservation mortars, the characterisation of their component materials was carried out. The slaked lime-putty contained 26% of free water, so it was not necessary to add additional water to the mortars prepared with it. The content of inextinguishable particles in it is 0.56%, which classifies it as lime of good quality. Quicklime was highly reactive, and by measuring the slaking speed we obtained a value of about 16°C/min. Inextinguishable particles were present in the amount of 0.12%, and the yield was 3.8 dm^3/kg, which also confirmed its good quality [7].

The sand and gravel originating from the Danube were used in fractions of 0-2mm, 0-4mm, and 2-4 mm, in different percentages. The presence of brick was determined in a large number of historic mortar samples, so several series of mortars with a different participation of crushed and ground bricks scattered in fractions of 0-1 mm, 1-2 mm, 2-4mm, and 4-8 mm were prepared. The bricks were Roman, originating from *Viminacium*, but also modern bricks made by crafstmen in Serbia using local raw materials (firing temperature is around 900°C), since it cannot be expected that in future conservation processes ancient bricks will always be available for use in mortars. The amount and fraction of added bricks were also varied in order to obtain a colour that is close to that of the original mortars. In addition to the aforementioned clay from the Viminacium area that was ground in the laboratory, kaolin clay, whose mineral kaolinite was confirmed by XRD as present in some sampled historic mortars of very high compression strength, was also used. However, since the origin (or the occurrence) of the found kaolinite is still unknown, and the thermally activated kaolin clay (metakaolin) is not produced in Serbia [8], kaolin clay from Central Serbia was used and activated by grinding (to get micron particles) [9], to better react with lime. The use of kaolin clay was conducted only in the mixture with slaked lime, since large evaporation during the slaking of quicklime (the temperatures are over 100°C) would leave the clay with insufficient water for the reaction with lime, and the further addition of water would decrease the mechanical properties of the mortar mixture. The process of creating a mortar mixture with satisfactory characteristics would be feasible in laboratory conditions, but this would not be the case on site. The zeolite mineral clinoptilolite was also confirmed in particular historic mortars. It was found independently, but also in combination with kaolinite. This combination was found in the mortar having the highest compression strength of all examined samples – 15.7 MPa. Only a few studies have been done in Serbia related to the potential use of zeolite in conservation mortars [10,11]. Thus, various conservation models with the addition of these natural materials with pozzolanic properties were created and are currently being cured in laboratory conditions. The models with "natural brick" (whose pozzolanic features were investigated [5]) will also be made in the future.

The ratios between the raw materials were determined with the aim of achieving their optimal mutual relationship and the highest possible level of compatibility of the new model with the historical sample. For each ratio of binders and aggregates of historical mortars, two or three mixtures were made, and their ratio varied by a small percentage. For example, for the binder-aggregate ratio 40:60 (volume ratio), models were prepared with the final result of the binder-aggregate ratio in the range from 35:65 to 45:55. In this way, a wider range of ratios is covered, since mortars sampled from the same building sometimes had almost the same compositions and a slightly different ratio of binder to aggregate.

Slaked lime mortar mixtures were prepared using hand tools and mixing a measured amount of aggregates and additives without adding water, while in the quicklime process water was slowly added with constant stirring until a mortar of a consistency suitable for pouring into moulds was obtained. During the preparation of the mortar with quicklime, it was slaked, the exoteric reaction led to the intense release of heat, and the temperature of the mortar rose. The mixtures were installed in moulds measuring 50 x 50 x 50 mm, and cured for 7 days in standard laboratory conditions, after which the samples were removed from the moulds and air-cured for another 28 days, without exposure to increased humidity or water, in standard laboratory conditions, on grid supports, and open on all sides. To test the compatibility, other samples were prepared, in which a piece of old mortar was pressed into the newly prepared fresh mortar. The contact formed between the new and old mortar was monitored, and some samples are still being tested (compression strength tests at 28/90 days after mould removal). In all models, the appearance of cracks and flakes, visual appearance and colour were monitored. After 35 days, the physical and mechanical properties, i.e. compression strength (Toni Technik, model 2020), bulk density, visual appearance, and colour were tested. Their smooth surface was always lighter in colour due to the smoothing of the mortar during the moulding, which draws a larger amount of binder to the surface, which usually has lighter shades than the aggregates and additions. Thus, the visual appearance was observed, and the colour was measured on the obtained fractures with a portable spectrophotometer (ColorLite sph870) (Fig. 2).

Fig. 2 Conservation mortar models - measuring components, manual mixing of mortar, moulding (top); mortar components, testing compression strength, and colour measuring (bottom) (Photo-documentation of the MoDeCo2000 project)

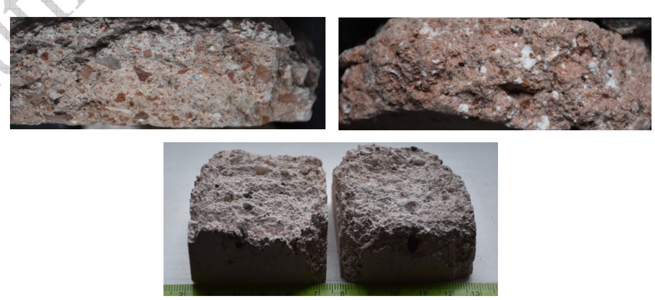

Fig. 3 Work on the conservation mortar model for a floor mortar (Photo-documentation of the MoDeCo2000 project)

After the design and testing of the dozens of conservation models, the most suitable were selected and they were applied, in open-air conditions in the *Viminacium* Archaeological Park, to experimental masonry structures (using different types of stone and brick), and to authentic walls of a tomb near Belgrade (in the village of Brestovik), dated to the period from the 3rd - 4th century CE [12]. The mortars were prepared on site by craftsmen using hand tools, as were the ingredients (crushing of brick and stone, and the comminution of local clay). The condition of the applied mortars is currently being monitored.

As an example, a sample of a floor mortar is shown here (Fig. 3) - original sample (top left), conservation mortar sampled from the trial application in open-air conditions, where it was created by the manual mixing and use of quicklime (top right), and its laboratory model after the compression strength test was completed (bottom). Lime lumps are clearly visible in the conservation mortar, being larger than in the original sample. The compression strength of the conservation mortar prepared and applied by craftsmen, and cured in open-air conditions, was lower than the strength of the more compact model formulated in the laboratory by equipment and cured in a closed and controlled atmosphere for the same period. Work on the optimisation of the model will continue.

4 Discussion of the Laboratory Results

Following the activities on the preparation of conservation mortar mixtures in the laboratories (Table 1), certain conclusions were gained.

All samples made with quicklime had higher values of compression strength, except one, the one with the highest mass (g) of the brick addition (the percentage of the brick addition was 1.6 times higher than the sand aggregate). The lowest values of compressive strength were obtained in models with slaked lime, in which part of the aggregate was replaced with crushed schist grains - up to 0.74 MPa. The values gained in models with quicklime were up to 2.13 MPa, so the samples with the addition of schist showed the greatest difference between the values of compression strength gained with the use of slaked and quicklime. These models will be researched further.

Mortars based on aggregates and lime without additions reached a strength of up to 1.12 MPa in mixtures made with slaked lime, while mixtures with quicklime obtained compressive strengths up to 1.92 MPa. This difference can be attributed to the accelerated hardening reaction in quicklime due to the initial high temperature obtained by releasing energy during hydration, which raises the temperature of the mortar, causing the excess water to evaporate. Considering that the period of 35 days is short for reaching the final strength of lime mortar [13], it is expected that the previously mentioned values will be closer to each other over time.

Table 1. Selected laboratory models for conservation mortars sorted by the increase of the compression strength – with slaked lime (table left); with quicklime (table right) (Documentation of the *MoDeCo2000* project)

sample	aproximate ratio (vol.) binder/aggregate	compression strength (MPa)	sample	aproximate ratio (vol.) binder/aggregate	compression strength (MPa)
11G	60/40	0.49	13Ž	40/60	1.15
10G	60/40	0.72	1Ž	40/60	1.50
9G	60/40	0.74	11Ž	60/40	1.74
4G	50/50	0.82	2Ž	40/60	1.84
6G	50/50	0.88	10Ž	60/40	1.87
8G	30/70	0.94	7Ž	30/70	1.88
5G	50/50	0.98	3Ž	40/60	1.92
7G	30/70	1.01	6Ž	50/50	1.99
1G	40/60	1.06	14Ž	50/50	2.05
2G	40/60	1.08	5Ž	50/50	2.08
3G	40/60	1.12	9Ž	60/40	2.13
14G	50/50	1.64	4Ž	50/50	2.31
13G	40/60	1.97	12Ž	50/50	2.56
16G	50/50	3.54	13ŽP	40/60	2.63
15G	40/60	5.23	16Ž	50/50	2.73

no additions
modern brick
ancient brick

schist
clay
kaolin clay

The already known facts that smaller fractions of bricks (brick dust) contribute to a higher strength of mortar and that bricks baked at lower temperatures, i.e. fragments of bricks taken from archaeological sites, show much better results in terms of pozzolanic features than modern bricks fired at higher temperatures [14,15], were confirmed by making conservation models with different brick fractions of both ancient and modern products. At lower brick firing temperatures (up to 900°C) there is no complete formation of the ceramic structure, so in such bricks minerals are retained that have only lost their crystal structure, and whose pozzolanic properties have, thus, been expressed. The mixtures with ancient bricks that had the largest percentage of the smallest fractions showed the highest compression strength of all mortar models made with quicklime (2.73 MPa), while those with the slaked lime were second best (3.54 MPa).

The strengths of clay mortar mixtures range from a maximum of 2.63 MPa in mixtures with quicklime and ground local clay, to a maximum of 5.23 MPa in mixtures with slaked lime and activated kaolin clay. The last value also represents the highest strength of all models made so far. It is expected that mortars with the addition of more, different, natural materials with pozzolanic features detected in particular samples will gain even higher compression strengths. Interestingly, the models with quicklime and local clay showed the lowest and almost highest values, depending on the amount of water, where the higher amount produced much weaker mortars, which is in accordance with the previously discussed reason for not using quicklime with thermally treated kaolin clay.

5 Conclusions

As has already been mentioned, the conservation mortar models of the *MoDeCo2000* project were made in accordance with the overall data interpretation gained after the research of all sampled historic mortars. It was concluded that for the production of lime mortars in the Roman period, used for the building of the Danube Limes, the same raw materials were used – Danube river aggregate, lime, and brick, while local stones were sometimes used as part of the aggregate. However, a few samples were very characteristic, having natural additions with pozzolanic features in their composition and, thus, possessing great mechanical characteristics. They were researched independently and the conservation mortars based on these samples are currently being created as separate case studies. The results are expected to give directions for the improvement of the mortar models already created.

Although many mortar mixtures were created and examined through the project, its intention was not to provide final mortar recipes for all sampled buildings. Detection of historic raw materials and technologies used in the ancient period, as well as the laboratory and open-air (on-site) trials of many mixtures made with different natural materials available in Serbia, have created a solid base for future conservation works on any Roman site along the former Danube Limes in today's Serbia. When the time for the restoration or repair of a particular building comes, the responsible team of conservators can securely lean on the project conclusions, but would also need to build upon them with further data and research. The choice of conservation mortar depends on the characteristics and conditions of the original mortar, but also the position and exposure of the structure, the function of the conservation works, and aesthetics [13]. Particular conservation mortars should be designed based on the level of presentation, the need for structure repair or maintenance, and the decision as to whether the building will be covered by the protective construction and protected from the violent exterior conditions, or completely exposed to them. In the end, each historic structure is unique in its own particular way, and all conservation works should be carefully planned and preceded by scientific and professional research.

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