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

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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.

Archaeological excavations of the Limes in Serbia have been going on for more than one hundred and thirty years, and their results have shown the exceptional importance of this part of the former empire for its development over the centuries.

Evidence of numerous historically significant events for the entire then known world, and consequently our modern one, are located along the Danube in Serbia. The remains of *Viminacium* - the capital of the province of Upper Moesia, Trajan's Tablet, and Trajan's Bridge - a wonder of the ancient world, are still available to researchers, but a large number of sites were flooded during the construction of the hydropower system between Serbia and Romania.

Through the project *Mortar Design for Conservation - Danube Roman Frontier 2000 Years After (MoDeCo2000),* research is conducted on one of the most complex building materials used in history - mortar.

The project, which is being conducted in the period from 2020 to 2022, is financed by the Science Fund of the Republic of Serbia and implemented by the Institute of Archaeology, the Faculty of Technology in Novi Sad, and the Institute for the Testing of Materials.

The research includes all available archaeological sites and cultural monuments from the Roman period on the territory of the Danube Limes in Serbia, comprising 40 buildings and 117 different mortar samples and many bricks and, stones, as well as local clays and sands.

The significance of the project is that the initiative for its launch came from the archaeological context, in which mortar had mostly been neglected as a carrier of important information about the past. This, consequently, led to the formation of a highly multidisciplinary team of researchers from the fields of archaeology, architecture, materials' engineering, geology and chemistry.

Through a combination of archaeometry and conservation science, the project aims to bring new insights into the mortars used in the Roman period on the Danube Limes in Serbia, whilst at the same time offer recipes for conservation mixtures for use in the future preservation of monuments belonging to this unique series of buildings, which are currently on the preliminary list of UNESCO World Heritage named *Frontiers of the Roman Empire - The Danube Limes in Serbia.*














The aim of the project is to offer new information and to highlight current knowledge regarding the preservation of the physical fabric of the buildings, but also of all their intangible values, including architectural, cultural, historical or sociological, from which can often be gained economic value, in accordance with international recommendations and national laws and regulations.

The MoDeCo2000 project is the first of its kind in Serbia. The formation of a database of Roman mortars, raw materials used for their formation, as well as tested conservation mixtures, will offer precious information for future researchers and conservators, as well as make a valuable contribution to the nomination dossier for the *Frontiers of the Roman Empire - The Danube Limes in Serbia.*

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

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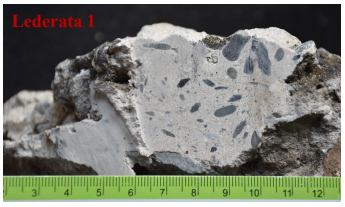
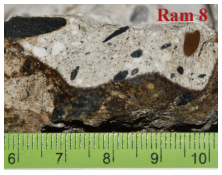
Research on Roman mortars within the project *Mortar Design for Conservation - Roman Danube Frontier 2000 Years After (MoDeCo2000)* has confirmed the well-known unwritten rule of using local materials in Roman constructions. This applies to all mortar ingredients - aggregate, binder, and additions that improved its particular properties. However, the laboratory analyses have also shown the limited use of some materials whose provenance has not yet been determined, such as those of volcanic origin.

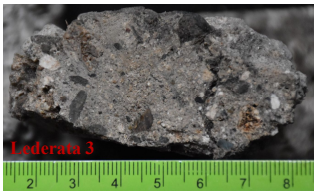
The most frequently used aggregates in mortars are Danube river sediments - sand, and occasionally gravel, of heterogeneous mineral-petrographic composition (various rounded rocks - granitoid, andesite-basalt, sandstone, quartzite, schist, and grains of minerals - quartz, feldspar, and mica). The aggregate grain size varies, but the most commonly used is up to 10 mm. The presence of crushed limestone of various sizes, often up to 20 mm, has also been determined.

Fragments of local stone were occasionally used as aggregate, which is most clearly visible at the *Lederata* auxiliary fort, dated to the period from the beginning of the 2nd CE to the 6th CE and located in the village of Ram, where schist grains from the local quarry have been found to be used extensively in mortars. Their size ranges up to 30 mm. This rock is the oldest geological formation in the wider area, with a low degree of metamorphism, and was used as an almost exclusive stone material for buildings in the whole area (*Viminacium* and *Lederata*) in the Roman and medieval periods.

Schist with mortar



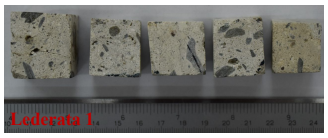




Certain similarities of the Ram mortars to those of the *Lederata* fort gave a small hint of the chronology of the building, which had a number of building phases.

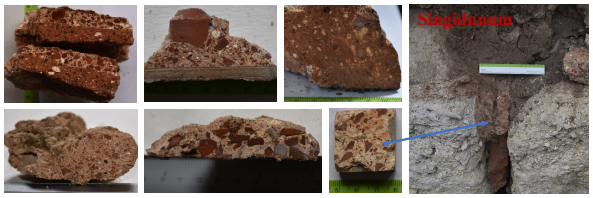
Masonry mortars, of an unknown date, from the circular building and surrounding walls, situated inside the Turkish fortress from the 15th CE in the village of Ram, demand further research with multiple methods.

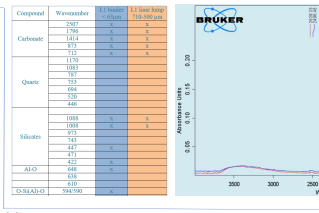
A *Lederata* masonry mortar dated to the 2nd CE had the highest compression strength of all the samples - 15.7 MPa. A sample from a *Cuppae* (Golubac) rampart dated to the period of the 1st to the 4th CE, with an addition of schist, also had a high compression strength - 9.2 MPa. XRF analyses of the schist rock sampled with the *Lederata* 1 mortar showed the potential for having pozzolanic features which will be researched further.

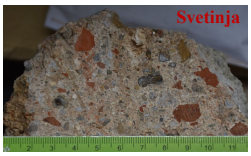


	L.I. 250°C, %	L.I. 450°C, %	L.I.1000°C, %	SiO2, %	Al2O3, %	Fe2O3, %	CaO, %	MgO, %	Na2O, %	K2O, %	SO3, %	P2O5, %	MnO, %	TiO2, %	Cl, %	sum	Hydraulicity Index
Ram 2	1.11	1.69	18.56	37.64	5.53	3.46	29.90	1.86	1.01	0.89	0.15	0.41	0.10	0.42	0.024	99.95	9.98
Ram 3	1.15	1.64	17.02	44.09	5.93	2.66	25.78	1.98	0.71	0.80	0.06	0.19	0.21	0.26	0.014	99.70	9.38
Ram 7	1.97	3.37	25.81	24.34	5.62	2.99	37.27	1.50	0.74	0.95	0.05	0.30	0.09	0.36	0.004	100.02	6.66
Ram 8	2.21	2.97	16.70	43.23	6.19	4.24	23.49	3.46	0.81	0.85	0.24	0.23	0.15	0.45	0.013	100.05	4.62
Lederata 1	3.35	5.82	15.18	41.97	5.87	2.70	30.09	2.11	0.66	0.50	0.12	0.12	0.06	0.24	0.01	99.63	1.61
Lederata 2	1.24	2.31	27.15	25.82	2.64	1.56	40.30	1.27	0.68	0.41	0.06	0.11	0.05	0.18	0.01	100.24	10.75
Lederata 3	0.99	2.46	25.33	24.67	3.94	2.66	39.58	1.53	0.51	0.56	0.07	0.23	0.15	0.27	0.01	99.51	9.30
Schist	0.74	1.17	5.21	43.62	11.29	14.38	9.50	11.37	2.38	0.07	0.03	0.17	0.32	1.66	0.00	100.00	

Brick manufacture was very well developed on the Danube Limes, especially in *Viminacium*, where the soil is rich in clay, and production has continued up to the present day. Broken or ground-baked brick was found in rendering, plastering, or floor mortars, subjected to water, mostly in the baths. The highest compression strength determined to date for these mortars was 6.23 MPa. There are a few masonry mortars with brick, such as that from the *Singidunum* rampart, 2nd CE, which had the highest compression strength of all brick mortars tested to date - 6.36 MPa.

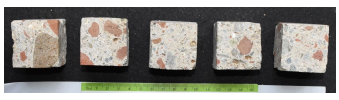


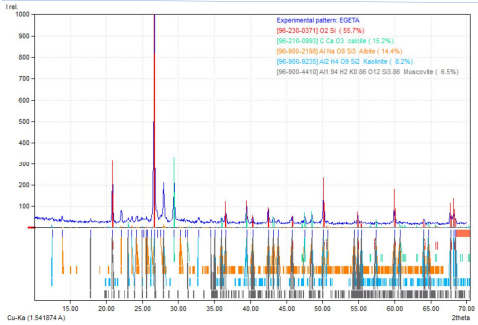




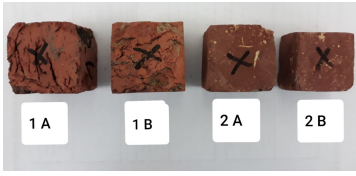
Brick was mostly used in the 6th CE masonry mortars, in fragments up to about 30mm, as a coarse aggregate, contributing to a higher compression strength, but there are also some examples from the 2nd and 3rd CE as mentioned above.

One of the masonry mortar samples with brick originates from a structure dated to the period from the 4th to the 6th CE, being a part of the fort of *Egeta* III, near Brza Palanka. XRF analyses showed it has almost the same characteristics as the sample from the 6th century *Viminacium* structure of Svetinja. Its compressive strength is the second highest of all samples to date - 11.49 MPa.





A specific material is found in the territory of Roman *Viminacium* as a layer of burnt soil and rock created after coal combustion. It can be called "natural brick" and was used by Romans for building blocks as well as for wall core infills. Tests have confirmed its pozzolanic features and, thus, its possible use in mortars as a natural addition of this kind, used instead of brick, has been the subject of ongoing research.



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

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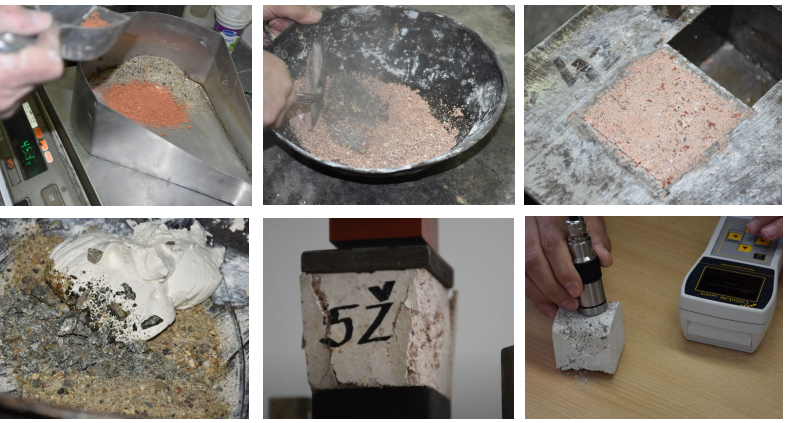
Data obtained from the archaeological, architectural, and geological research with the thorough laboratory testing of Roman mortars sampled during the project *Mortar Design for Conservation - Danube Roman Frontier 2000 Years after (MoDeCo2000)* which deals with the part of the former Danube Limes in today's Serbia, was used in the formulation of compatible conservation mixtures.

The mixtures were based on available local raw materials whose presence was determined during the characterization of historical mortars, and traditional production technologies whose traces can often be identified through the analysis.

Laboratory models included the use of quicklime and slaked lime, stone aggregate of different grain sizes, crushed stone of different origins, crushed and ground brick, and clay.

The ratios between the raw materials were determined with the aim of getting their optimal mutual relationship and the highest possible level of compatibility of the new model with the historical sample.



Dozens of models of mineral mixtures were designed and tested. A number of samples were exposed to aging in closed and open laboratory conditions and artificial aging in a chamber that imitates the conditions of the external environment.

The evaluation of the models included their physical and mechanical properties, with an emphasis on the compression strength, monitoring of the contact that was formed between the new and original mortar, and the overall appearance and colour of the model.

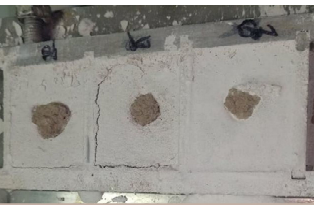
samples with slaked lime	aproximate ratio (vol.) binder/aggregate	compression strength (MPa)
11G	60/40	0.49
10G	60/40	0.72
9G	60/40	0.74
4G	50/50	0.82
6G	50/50	0.88
8G	30/70	0.94
5G	50/50	0.98
7G	30/70	1.01
1G	40/60	1.06
2G	40/60	1.08
3G	40/60	1.12
14G	50/50	1.64
13G	40/60	1.97
16G	50/50	3.54
15G	40/60	5.23

slaked lime mixtures

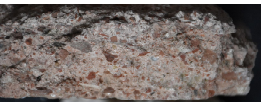
samples with quicklime	aproximate ratio (vol.) binder/aggregate	compression strength (MPa)
13Ž	40/60	1.15
1Ž	40/60	1.50
11Ž	60/40	1.74
2Ž	40/60	1.84
10Ž	60/40	1.87
7Ž	30/70	1.88
3Ž	40/60	1.92
6Ž	50/50	1.99
14Ž	50/50	2.05
5Ž	50/50	2.08
9Ž	60/40	2.13
4Ž	50/50	2.31
12Ž	50/50	2.56
13ŽP	40/60	2.63
16Ž	50/50	2.73

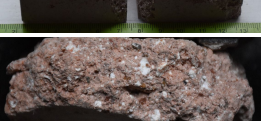
quicklime mixtures

no additions | stone | clays and bricks



After the design of the conservation models, the most suitable were selected, and their application was performed in real conditions at the *Viminacium* site - on experimental masonry structures (using different types of stone and brick), but also on authentic historical walls from the 3rd - 4th CE in a tomb near Belgrade (the village of Brestovik). Their behaviour is currently being monitored and tested using on-site measurement, and they are also periodically sampled and tested in laboratories. The results so far appear to be satisfactory.





As an example, a sample from the floor of the tomb is shown here - original sample (top), conservation model after the compression strength was completed (middle), and conservation mortar sampled from the site application in open-air conditions (bottom). Large lime lumps are visible in the conservation mortar - larger than in the original mortar. The compression strength of the conservation mortar, applied by masons, using their specific tools, and skills, and using raw materials prepared by hand tools and cured in open-air conditions (2.05MPa) was lower than the strength of the more compact model formulated in the laboratory using raw materials prepared by laboratory equipment and cured in a closed and controlled atmosphere (2.56MPa). Work on the optimisation of the model for this sample will continue.

Work on the design of conservation mortars during the MoDeCo2000 project:

- Multidisciplinary research on the spatial context and the choice of structures
- Sampling of the historical mortars
- Laboratory research of original 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

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