Article

Recycling and Reuse of Building Materials in a Historical Landscape. *Viminacium* Natural Brick (Serbia)

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Abstract: During the *MoDeCo2000* scientific and research project on mortars used in the territory of the Roman Danube Limes in Serbia, the biggest challenge was the quest for the provenance of used raw materials. The area where the largest city in the province of *Moesia Superior* developed, with millennial continuity of land use and settlement, was selected as a case study for deeper research. The material and immaterial values of Roman *Viminacium* have survived in the later life of the landscape, through the preserved building remains and artifacts, secondary use of building materials, but also toponyms, customs, and stories. Recycling of materials is commonly recognised in the modern age as the industrial processing of existing products in order to obtain raw materials and later prepare new products, representing one of the basic elements of sustainability. However, people throughout history have always used what they had at hand and the building remains were reused, but also recycled for new constructions. In this study we follow the presence of the specific material we call *natural brick* in the historical Viminacium landscape, focusing on Roman construction and specifically its potential use in lime mortars, connecting humanistic and natural sciences.

Keywords: *Viminacium*; *natural brick*; Roman mortar; historical landscape; the Danube; Roman construction; building material; recycling; reuse; sustainability

1. Introduction

Construction of various buildings was exceptionally developed during the Roman period in all territories that the Roman army reached. It was guided by the architecture developed in central Italy [1–4], but was blended with the traditions, knowledge, and experience of local people that the Roman army conquered, being influenced by the skills and background of soldiers, tradesman and people of different origin traveling all around the Empire. Roman frontier, stretching for over 7,500 km through Europe, Asia, and Africa [5], was the place where the contact, exchange, and communication between different people shaped all life aspects. It was the area where the Romans and barbarians met [6], where Roman culture was transmitted, but where it also absorbed the influences from the outside [7]. One of the frontier's parts was the Danube Limes, 2,000 km long, connecting today's Eining in Germany and the Danube mouth into the Black Sea [8].

The largest number of known or researched archaeological sites on the territory of today's Serbia, which originate from the Roman period, is located along the Danube River, once belonging to the Danube Limes. The only two legionary fortresses in the territory of the province of *Moesia Superior*, later *Moesia Prima*, whose borders broadly correspond to most of modern central Serbia, as well as parts of North Macedonia and Bulgaria, were *Viminacium* (Kostolac) and *Singidunum* (Belgrade), both located on the Danube Limes [9]. Beside the legionary fortresses, many auxiliary forts and observation posts were erected along the Danube [10], while major provincial cities developed as political, economic, and cultural centres [9]. Initial functions of civilian settlements by the fortresses primarily followed the needs of the army, but over time they developed their own life during which various activities took place, among which is the construction.

The territory of the Danube Limes in Serbia has been chosen for the research of the project *Mortar Design for Conservation - Danube Roman Frontier 2000 Years After (MoDeCo2000)* [11], whose focus is on building materials, specifically the mortar, as a binding material whose use and preparation was perfected in the Roman period, but simultaneously on the design of conservation mixtures compatible to historical mortars, using local raw materials. During the project research, the area related to the legionary fortress and city capital of *Moesia Superior*, *Viminacium*, was singled out as an exceptional landscape example in which all aspects of life on the Danube Limes during Roman domination, i.e. in the period from the 1st to the 6th century AD [12–13], can be followed, among which are the building activities and exploitation of the natural resources. Since the 19th century, this has been one of the most important industrial areas of Serbia. After decades of underground coal mining, strip mining has been developing since the 1940s, accompanied by the production of electricity in thermal power plants [14–17].

The course of economic activities related to any product usually includes extraction, production, consumption, and disposal, but we must also add accompanying processes such as reuse, maintenance (including repair), and recycling to the list. The processes of reuse and recycling are both related to the repeated use of some material, in its initial or new shape, but their historical visibility as archaeological traces is not always completely clear [18]. During recycling, materials in new forms can also acquire new functions [19], when objects are decomposed into constituent elements or melted, with each activity requiring energy. In the process of reuse, no initial energy is usually needed to change the object, but on the other hand, cognitive processes related to its new meaning are included. A special type of reuse is repurpose [18]. As an intermediate step between reuse and recycling, the researchers mention reworking, in which already used elements are processed, but their state is not changed [19].

All these processes were an integral part of the construction industry of antiquity. After their use ceased, some Roman buildings were systematically rebuilt in order to obtain material that was reused in the same locality or transported further. Research into the reuse and recycling of materials in Roman construction has been mostly conducted about marble and stone *spolia*, but still very little about the other materials [19]. However, in the field of construction and decoration, Romans recycled a variety of elements made from stone, clay, wood, metal, or textile, among which are stone blocks or slabs, bricks, and mortars [20]. During the excavations of *Viminacium*, the reuse and repurpose of architectural elements, tombstones, as well as building materials, such as stone blocks or bricks, was detected in many ancient buildings and graves [21–25,12,26–30]. Additionally, it is known that the remains of *Viminacium* buildings were decomposed for the removal of the building material in later periods and used for the construction or decoration of medieval fortifications, monasteries, and recent local houses in the landscape itself, but also in surrounding areas [27,31–39].

Building materials used in Roman construction were almost exclusively made from local and available sources. They were transported over long distances, only because of rarity or being suitable and needed for some specific function, that is, mostly connected to large imperial and public buildings [40]. Therefore, although the choice of mortar ingredients was closely related to the mortar function, it was also mostly guided by the economy. Thus, the local geological setting, the availability of fuel as well as their spatial relation to the building site were the most important factors in the production of mortars [41]. Many examples of mortars found in the structures around the former Roman Empire were produced with the local materials that were not always of the best quality, but were "the best choice from an economic point of view" [42], (p. 145). At the same time, we have examples of the intentional mixed use of imported and local raw materials, but even in those case, it was always economically justified as much as it was possible. It has been already established that Romans transported the volcanic pozzolanic materials (*pozzolana*) for mortars from the Bay of Naples along the Italian coast, and it was also assumed that it was the case with the wide Mediterranean area [43]. Recently, during the research on mortars used in the harbor of Sebastos in *Cesarea Maritima*, Israel, volcanic pozzolanic materials imported from the Bay of Naples were detected, but their use was "accurate", limited to the concrete-like structures and masonry walls in the intertidal zone, which confirmed the Roman optimization in the supply of raw materials [44], (p. 19).

The research in this study is precisely related to one aspect of the construction activities in *Viminacium* landscape, that is, the exploitation and use of local raw material for building purposes, with the assumptions made about its possible use in mortars. Through the overview of the red material created out of the clayish sediments baked during the combustion of the coal layers beneath, which we call natural brick and local people call *crvenka (reddish)*, whose bed is situated in the territory of surrounding town and village of the same name – Kostolac, along with the former underground mine, being exploited for the construction purposes from the antiquity to the modern age, we will try to show an example of historical sustainable use of building resources in the landscape, focusing on the Roman period that left the largest number of material remains.

Very noticeable reddish fragments and often red dust that finally gave colour to the mortar mixture itself, have been generally recognised in the Roman mortars as originating from terracotta - fired brick, tiles, amphoras, or other pottery, thus telling us it was recycled from the already used material [45]. Vitruvius himself wrote about the use of crushed and ground brick in the flooring mortars and plasters applied in moist places [46], (VII. 1). Its presence has been historically attested in the mortars that needed resistance to water and moisture. *Viminacium* baths represent a place where this important feature of the terracotta mortars, called *cocciopesto*, was very much needed.

The production of bricks and pottery was developed along the entire Roman Danube Limes, with *Viminacium* as a provincial centre, which has been attested by many brick and pottery kilns and production sites excavated in *Viminacium*. Its products were found during the research of many sites along the Danube, with pottery found in other provinces as well [47–49]. The production is certainly the consequence of the geological characteristics of the area in which *Viminacium* is located, which is characterised by the existence of loess, sands, silts, pebbles, clays, and coal [50], and which provided the inhabitants of this area with an abundance of brick raw materials not only in antiquity but in the later periods. The oldest found kiln in *Viminacium* was for brick and pottery, and dated to the end of the 1st century. A large brick and pottery production site was dated to the 2nd and 3rd centuries, the periods of the most intensified brick and pottery production in *Viminacium*, while other excavated brick kilns in wide *Viminacium* area are dated to the period from the 3rd to the 4th century [47,48,51]. Until the second half of the 20th century, there were numerous village family brick manufacturers, and with the development of industry in the 19th century, numerous brick factories were also established in the wider area [27,52].

During the *MoDeCo2000* project, *Viminacium* mortars with visible red fragments or simply being of a red colour, and almost exclusively used for plastering, rendering, and flooring, were sampled. Those having mentioned functions originated from different structures dated to the period from the 2nd to the 4th century. Large fragments were visible in a strong mortar for the sarcophagus brick-built base, as well as in a bedding mortar of a villa, both dated to the 3rd century. Additionally, a sample of bedding mortar containing large fragments and originating from the 6th century early Byzantine rampart was researched (Figure 1). Were the red fragments that we encounter in these *Viminacium* mortars always created by crushing and grinding the bricks, tiles or pottery, as usual, or the origin of some of them be connected to the natural brick formation? The research on this topic started a few years ago [53], but in the recent period more research aspects were mutually connected, mixing the archaeological view on the topic with laboratory investigation in natural sciences, offering initial chemical, and physical and mechanical characteristics of natural brick, resulting in the creation and application of experimental mixtures of mortar using this material as addition or admixture [54]. This research process provided us with important data that can be used for further research in sciences, but also for future social and economic interpretations of activities of reuse and recycling in the Viminacium historical landscape related to building materials and construction in general.

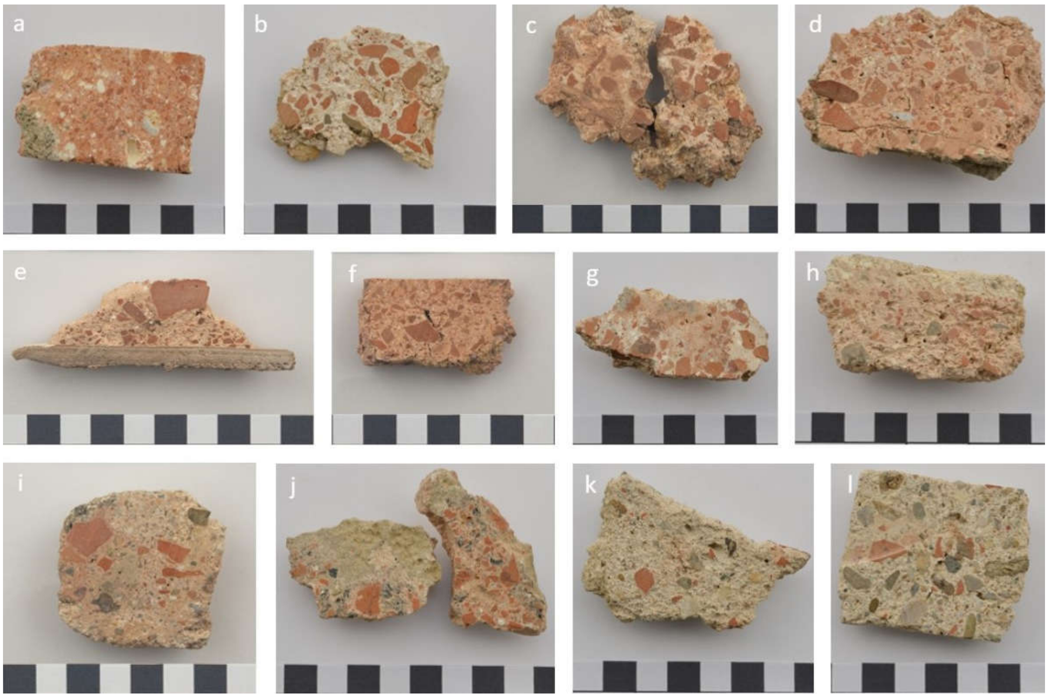

Figure 1. "Brick" mortars from *Viminacium* (dating from the 2nd to the 6th century): a. *principium* floor; b. city baths floor; c. city baths plaster; d. city baths floor; e. city baths plaster; f. city baths plaster; g. city baths plaster; h. tomb plaster; i. sarcophagus base; j. villa floor; k. villa bedding mortar; l. early Byzantine rampart bedding mortar. Photo-documentation of the *MoDeCo2000* project.

In this study, we will try to offer a review of the use of natural brick in ancient *Viminacium* constructions while referring to the archaeological traces. It will also give observations on the possible use of natural brick in *Viminacium* lime mortars in addition to or as a replacement of the man-made fired terracotta products, using initial laboratory research to mutually compare different samples of natural brick, red tesserae in a sample of mosaic and red fragments in mortars of *Viminacium*, as well as to analyse if a natural brick has pozzolanic features so that it could have been used for obtaining hydraulic lime mortars. In the discussion about the possible use of natural brick in mortars, its reuse and recycling are recognised as important topics.

2. Archaeology and Landscape

2.1. Historical Use of Natural Brick

The investigation of natural brick during the *MoDeCo2000* project has been initiated by the assumptions made after long-term archaeological research of Roman *Viminacium*. Given that the past researchers of *Viminacium* encountered this material during excavations as fragmented materials in wall infills and road foundations, its role was not considered as important for drawing conclusions about construction in this city and legionary fortress. However, through analyses of *Viminacium* masonry techniques and their comparison with research notes from the beginning of the 20th century in which the periods of Viminacium life were connected with the use of different building materials and masonry techniques [55–56], and after the initial systematic archaeological research of the legionary fortress in 2002–2003 was conducted, as well as the research of the amphitheatre in the later period, the use of natural brick was connected with *Viminacium* early building phase [37]. After the beginning of large-scale systematic archaeological excavations of the legionary fortress of *Viminacium*, the result of the first Roman extensive building activities in the area, the assumption that natural brick was predominantly used during this phase as the basic building material was proven.

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During the Roman period, the province of *Moesia Superior* was a mining area with rich mineral resources – gold, silver, lead, iron, and copper [57]. However, Viminacium's narrow territory, as a part of the Kostolac lignite basin, one of the most important industrial areas in Serbia today, was rich in coal instead [27,58]. Its exploitation was not mentioned in sources until the 19^{th} century, and underground mining officially started in 1873 [16–17,27,53]. Thus, it is not known if the Romans of *Viminacium* exploited coal as a fuel, but it is possible that they knew about its presence, since its layers were close to the surface [15,53]. One of the historical mining records originating from 1890 and the time of the underground mining in Kostolac in the area of *crvenka* bed, informs us about the coal fires in the mine and a specific combustion material: "At the entrance to the underground ... red clay with fossils is observed. This metamorphosis was caused by fire, which is a very common case with coal found in the soil. In other geological ages, coal may be fired and burnt. This kind of inflammation affects the surrounding rocks and changes them in various ways" [15], (p. 79). In this description, we recognise the natural brick.

Figure 2. Position of *Viminacium* and today Belgrade (*Singidunum*) along the Danube in Serbia, and the close-up of the position of exploited parts of the bed of natural brick. Tags: authors, on the Google Earth Pro photo printed on December 18, 2022 - historical image from August 2022.

Since its bed is located in its nearby area (Figure 2), natural brick was very available for *Viminacium* construction. Its high availability was surely considered the most important and favourable feature during the process of selecting materials for various construction needs by the first builders of *Viminacium*. The walls formed from hewn natural brick blocks were first recorded and explored during the systematic excavations in 2016 when it was detected that the ramparts of the first fortress of *Legio VII Claudia* were built in the last decades of the 1^{st} century from this material, as well as the walls of the *principium* building whose excavations started later (Figure 3). Additionally, channels in the fortress were built of blocks as well, the wall foundations and wall infills were made of fragmented natural brick, substructures and final layers of floors were created of crushed or almost ground natural brick, while small fragments were also used in the formation of the embankment along the rampart [28,30,59,60–62] (Figure 3). Use of natural brick was developed before the locally produced fired bricks and schist quarried in the nearby village of Ram became the main building materials of *Viminacium*, with somewhat less use of limestone. In the near vicinity of Viminacium, there are no known sources of limestone. The source of the limestone blocks found in its buildings has been the topic of different studies over years, but the final conclusions have not been published yet [37].

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Natural brick was also found in the foundations of walls and floors as well as in overground wall structures of modest auxiliary facilities and buildings of peripheral rural estates during later periods, such as structures dated to the wide time span from the 1st to the 4th century [63], those connected to the period of the first half of the 3rd century [23,64], as well as in the buildings of unknown purpose dated to the periods of 3rd and 4th century [65]. In the area of the amphitheatre, as well as in the fortress area we see it under the later phases made of stone, where the ruined structures made of natural brick from the 1st century were either leveled and used as foundations or substructures of the later wall and road structures or were just incorporated in younger structures [28,29,30,59–62,66–68].

Figure 3. Natural brick in *Viminacium* legionary fortress, used in the wall of *principium* in the form of blocks (up left), and the rampart with natural brick in the form fragments used in the foundations and wall infill, as well as fragmented blocks used over ground, near which later stone phase was erected (down left); different fragments of used natural brick collected from the *principium* site (right). Photo-documentation of the *MoDeCo2000* project.

Most of the known archaeological traces of the use of these combustion materials by humans in the world are connected to prehistoric sites [69–71]. It is known that ceramic-like rocks were used by the early Native Americans for tools and blades, throughout the Powder River Basin in Wyoming and Montana [72]. Natural clinkers from sub-arctic Canada were used by hunter-gatherer communities in North America for the same purpose from 10,000 years ago until the arrival of Europeans [68]. It has been also found during archaeological excavations and detected as being used by humans for the polishing of tools during the prehistoric period in the Serbian Kolubara lignite basin [73]. The known traces of the use of these natural combustion products in later periods are generally very scarce. In England, mosaic tesserae and slabs of *opus sectile* technique made of the mudrocks burnt after the combustion of oil shales were found during the excavations in Silchester, Fishbourne, Kent, and Caerleon, and were dated to the late 1st and early 2nd centuries, indicating the existence of workshops of elements for interior decoration here. The elements made from this material were accessible to all social strata, whether for the use in military, public or private buildings [27,53,74–75].

Natural brick from Kostolac was used during the construction of Roman *Viminacium*, but also in the buildings of another nearby Roman city, situated on the confluence of the river Morava to the Danube in today Serbia – *Margum* (Dubravica). In its earliest structure dated to the 1st century "pieces of loess of irregular shape baked on fire in the coal seam below it" from Kostolac were found [76], (p. 119). We do not have records of its use in the *Viminacium* area before the Roman conquest nor in the Middle Ages [34,77–78]. It was exploited until recently for different building purposes, such as covering industrial

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and village roads [27,51–52], from three areas of the bed whose total reserves in 2002 were estimated to be 1,205,000 m³ [79].

The common function of this material throughout centuries in Kostolac and in the world is connected to the building of final or substructure layers of floors, roads, and streets. It is massively used for roads in USA areas where its quantities are abundant and better-quality material is not readily available and thus expensive for transportation. There it is classified as one of the types of crushed stone [80–81], covering one-third of all crushed stone aggregates for the roads in Wyoming [81]. However, the tests in New Mexico showed its variable and marginal quality for use in final layers, considering abrasion. Resurfacing in Arizona needs to be done every 3–6 years depending on its type and uniformity. It has, however excellent drainage properties and is used in mines to control erosion and stabilise the slopes, as well as as a base material below concrete slabs [80].

2.2. Geology of Natural Brick

The material consisting of different sediments created by their burning or melting due to the ignition of other materials in their immediate environment is found in many places in the world and bears different names, depending on its type, among which are clinker, *natural clinker*, porcellanite, buchite and paralava, but also *pseudoscoria* and *scoria* (local name in some USA states, however, incorrect, since scoria is of volcanic origin) [71–72,82–90], along with the more general terms of vitrified or fused and burnt rock [91]. The process is called pyrometamorphism or combustion metamorphism [70]. In this research we call the studied material *natural brick* since it is a brick-like natural product, and had the function of building material in the Roman constructions of *Viminacium* [37].

One of the combustible mineral raw materials in nature is coal, which can be ignited naturally, that is, by spontaneous combustion in contact with oxygen, after lightning, a wildfire burning trees, but also due to man-made fires [82–83,90]. Coal beds can burn when they are relatively shallow, which means that they are unearthed to depths less than a few tens of meters from the surface, and when they are adequately ventilated and above the water table [93].The earliest evidence of this natural process is found in USA (Wyoming and Montana), and began at least two million years ago, producing coal clinker. Hundreds of natural, accidental, or deliberately initiated coal-seam fires are burning today around the world [94]. However, the largest number of coal fires were spontaneous (75% - [95]) and occurred in deposits during the recent geological past [84]. Some fires consume all available energy supply very fast, but others burn for decades or centuries [96].

To most coal geologists clinker "refers to a rock sequence altered by an adjacent coal bed burning in place instead of the manufactured consequence of an industrial operation or electrical generation process" [80], (p. 188). It includes different thermally metamorphosed or melted rocks, depending on the source rock, dynamics of burning, ventilation, and proximity to the fire. They range from thermally altered but not melted rocks (dubbed burnt or baked rocks), partially fused rocks (clinkers) to totally melted rocks (paralava), with porcelanitte being a specific type of clinker heated near the point of melting [70,92]. The rocks are characteristically multicolored [96]. In 1929, a similar division was made for the material present in the coal seam in Most Basin of the Czech Republic [98]: bricklike rocks (clinker), baked but not sintered clays produced by low to moderate thermal alteration (pale red or yellow coloration); porcellanites, dense, partly or completely sintered clays of jasper- or porcelain-like appearance with a conchoidal fracture (pale gray, yellow, apple green, or reddish colour); ferruginous slags and paralavas formed by fusion of various carbonates, more or less holocrystalline, with common drusy vugs containing crystals (from greenish to black colour [97]. Thus, its characteristics range from an entirely or partially fused rock, when it is very close to a source of fire, to slightly baked rocks when it is created at lower temperatures [99]. A similar can be said for the bed of natural brick in the village of Kostolac (Figures 4 and 5).

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Figure 4. Natural brick bed in Kostolac village with visible variety in colours. Photo-documentation of the *MoDeCo2000* project.

In Serbia, material created after the coal combustion is encountered in basins of lignite, which is a low-rank coal with great tendency to self-heat because of its high moisture and oxygen content [80]. All Serbian formations originate from the Pontian age. In the area of Kolubara coal basin these baked clays are called *brand* [100]. An interesting example is found in the Czech Republic, where the Medlovický deposit of this material proclaimed as natural monument, was created above a coal mine after clay burning, and the material name is very similar to Kostolac name - *červenice* and *červenka* [53,101–102].

Figure 5. Natural brick bed in Kostolac village with visible variety in colours, present by dark formations, porcelanitte and clinker, and baked clay. Photo-documentation of the *MoDeCo2000* project.

3. Laboratory research and Experimental Application

Many samples of natural brick for the laboratory research in the project were taken from the bed (Figure 6), as well as obtained from ruins during archaeological excavations of the *Viminacium* legionary fortress (Figure 3). Initial analyses, using macroscopic observations, were done on the samples on natural brick originating from one of the three bed areas which is the closest to the remains of *Viminacium*, on tesserae, nucleus and rudus of the mosaic fragment, as well as on the flooring mortars from the city baths and *principium*.

A mosaic floor fragment was accidentally found by a local villager and is undated. It was visually examined since an assumption was made that its tesserae were made of natural brick as well as red fragments in its nucleus and rudus. Since the building of *principium* was built of blocks of natural brick, an assumption was made that red fragments in its floor were created by crushing and grinding the same material. Considering the mortars from the baths they were used for comparison, since the red admixtures in their matrix were assumed to be fired brick, which was the material used for its erection, along with schist. The samples of various fired bricks from *Viminacium* were also used for their visual comparison with natural bricks (Figures 7, 8, and 9).

Figure 6. Various natural brick samples from the bed. Photo-documentation of the *MoDeCo2000* project.

Chemical analyses and tests on physical and mechanical characteristics were done for the bed samples (samples 1 and 2). The standard test for the determination of a material pozzolanic activity was undertaken for these samples as well, making an experimental lime mortar with this material as an admixture. The experiment was conducted during the workshop masonry work on building a small structure in Viminacium Archaeological Park.

During this research, the obtained results were compared with the already published results on *Viminacium* fired bricks [103], baked clays that were once used for plastering a brick kiln [104], as well with those of natural brick sampled from the same bed, but in the other area, previously published during the research of its potential use in modern building industry [79] (sample 3). Scientific research mention or confirm the pozzolanic features of this natural creation present in varied forms in the world [105–106], which depend on the creation conditions, the firing temperature, and the primary rock. The previous research on the potential use of Kostolac *crvenka* in industry showed its suitability for protective mortars with excellent thermal and hydro potentials in agricultural and industrial buildings as well for the production of decorative renders and plasters [79]. It was proposed that it should be used (as well as Kostolac loess, clay, gravel, and sand) in the industry of tiles, facade bricks, decorative ceramics, and construction elements based on concrete [107].

3.1. Macroscopic Observations, Methods and Results

Visual inspection of five natural brick samples from the bed was performed in order to define colour according to the Munsell Rock Colour Chart, but also using Dino-Lite USB Microscope (model AF4915ZTL) for obtaining results on samples' texture and presence of inclusions, in accordance with EN 12407: 2019 [108]. The samples from the bed were chosen according to their visible differences - from highly baked to those less thermally changed, thus they show obvious mutual differences in color shade and texture, as well as in the presence and type of inclusions. These burnt sedimentary rocks are mostly highly fractured and cracked in the bed, and may occasionally contain faunal remains (Figure 6).

Mutual comparison of the fragments of natural brick sampled from the bed and the two mosaic tesserae showed their great similarity in colour and composition, so the colours of two samples from the bed were determined as identical to these tesserae, according to the Munsell Rock Colour Chart (Figure 7). This can speak in favour of our assumption that the tesserae were made of natural brick, which type was however probably chosen to be resistant to wearing since they composed the final layer of a floor. Red fragments in mosaic layers resemble one of the tesserae.

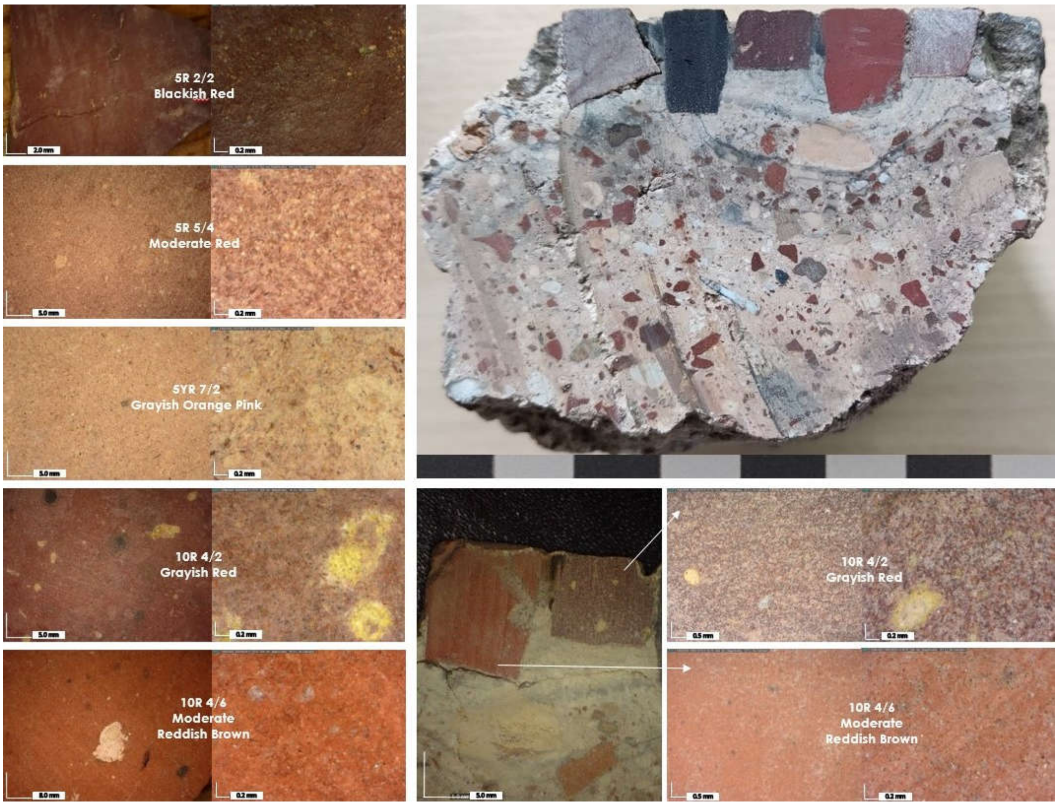

Figure 7. Colours of the natural brick samples from the bed (left) compared to those of mosaic tesserae (right). Photo-documentation of the *MoDeCo2000* project.

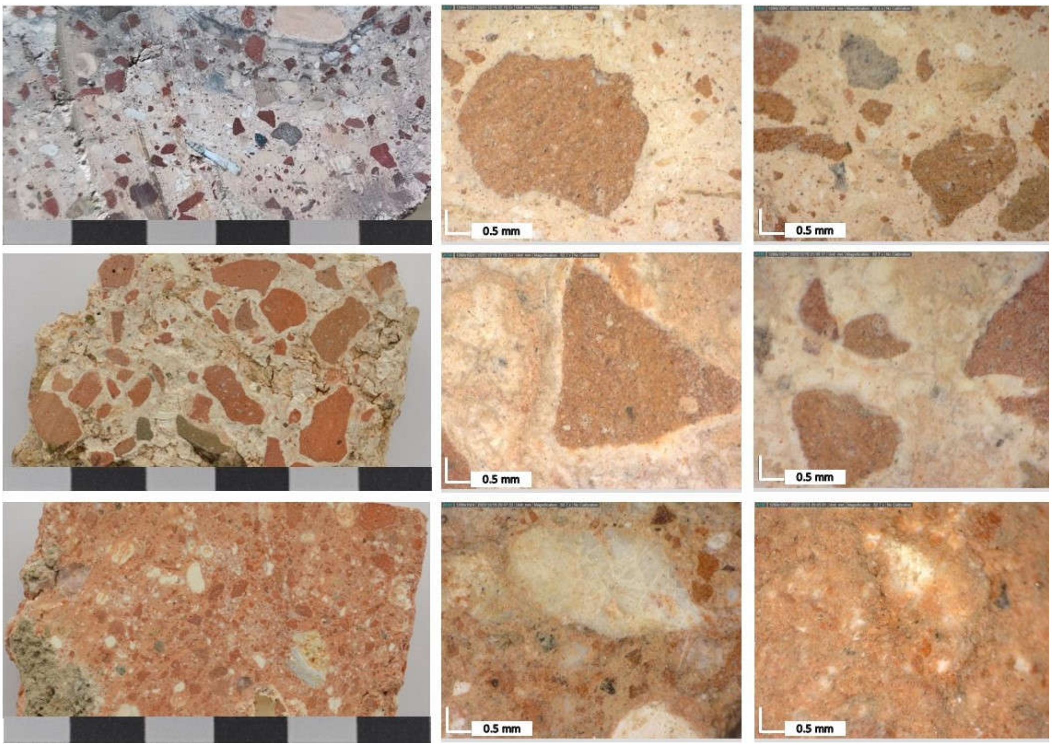

Figure 8. Red admixtures in the mosaic fragment of the unknown date (up) and flooring mortars from *Viminacium* city baths dated to the 4th CE (middle) and *principium*, dated to the 2nd century (down). Photo-documentation of the *MoDeCo2000* project

Floor layers made of crushed natural brick were detected in the first *Viminacium* buildings [29–30,66–67], which can mean that its builders also assumed or were already acquainted with the knowledge of waterproofing and drainage features of natural brick. Although many mortars initially characterised as brick mortars were sampled from *Viminacium* buildings, a mortar sample taken from the floor of the central building of the legionary fortress - *principium* and dated to the 2nd century, was assumed to have natural brick in its composition. It has the largest amount of ground "brick" used for the formation of its binder matrix comparing to all mortars sampled during the *MoDeCo2000* project from *Viminacium*. Visual comparison between cross-sections of a mortar sample used for flooring in the Viminacium baths, dated to the period of the 4th century, mortar forming the nucleus and rudus in a mosaic fragment that was assumed to have red admixtures of natural brick since its tesserae greatly resemble the natural brick itself under the microscope, and floor mortar from *principium*, was done using the microscope. It resulted in the high visual similarity between the first two, but did not offer any reliable data on this topic in the case of the third (Figure 8).

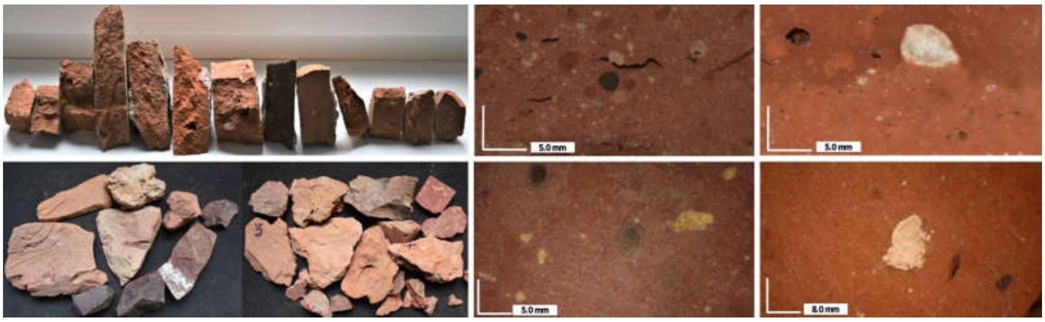

Figure 9. Fragments and colours of the fired brick samples (up) compared to those of natural brick samples from the bed (down) Photo-documentation of the *MoDeCo2000* project.

At the same time, these samples of natural brick from the bed were initially visually compared to two fired brick samples of similar colour originating from different buildings, collected during the excavation and thus dated to different periods (Figure 9). Most of these bricks formed the construction of graves that were disassembled after the excavations as being endangered by the surrounding industry. These funerary structures are mostly dated to the 4th century, but since the bricks were often secondarily used in the graves, this date is not reliable for their dating. Visual similarity of natural and fired bricks actually presents one of the difficulties in the initial determination of red fragments in mortars as originating from natural or fired brick, showing the need for laboratory analyses with reliable methods of determination.

3.2. Physical and Mechanical Characteristics, Methods and Results

Compressive strength testing was performed using standard EN 1926: 2010 [109], in the hydraulic press, on the cubes of natural brick obtained from two bed samples, chosen as being highly mutually different according to the visual observations. One of them in dark red colour can be associated with the rock being baked at higher temperatures, as clinker or porcelanitte, while the lighter one can be connected to the less baked rock. The first one was with cavities and the other had visible inclusions (Figure 10). The testing procedure was however modified since dimensions and the number of cubes were limited to the dimensions of the bed samples. Thus, two cubes with dimensions of ~ 40 mm x 40 mm x 40 mm, per sample, were tested. Their apparent density, water absorption, and absolute porosity were determined as well, according to the standards EN 1936: 2006 [110], and EN 13755: 2009 [111]. While testing the cubes with cavities, attention was given to the direction of the compression force compared to the prevailing direction of the cavities in the cubes, since it was expected that the results would depend on it.

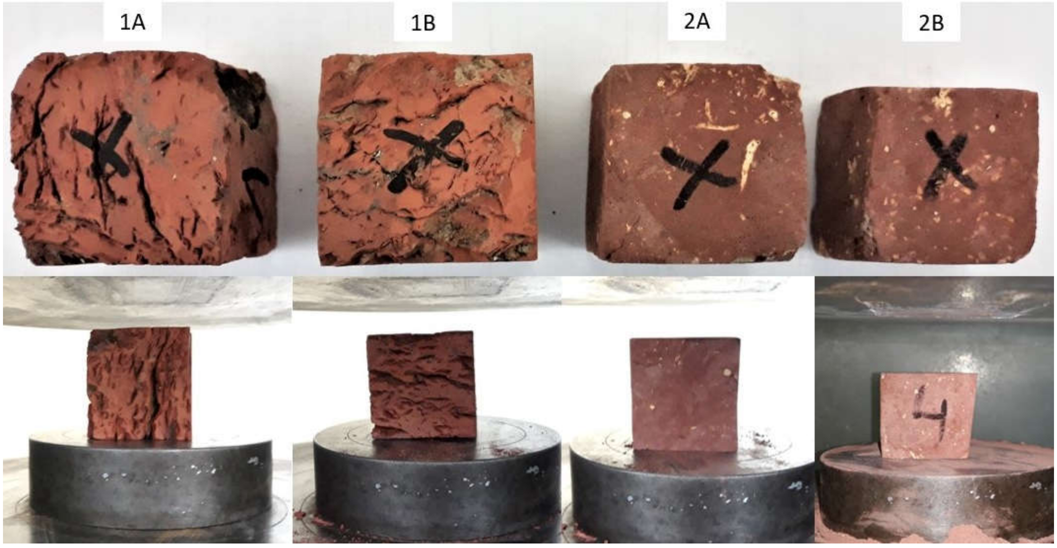

Figure 10. Testing cubes of natural brick from the bed. Photo-documentation of the *MoDeCo2000* project.

Table 1. Physical and mechanical characteristics of the samples of natural brick from the bed

Sample / cube	Compression strength (MPa)	Apparent density (g/cm³)	Absolute porosity (%)	Water absorption (%)
1A	20.67	1.547	41.73	23.67
1B	4.33	1.485	44.07	30.05
2A	3.36	1.682	36.65	22.06
2B	1.42	1.966	25.95	12.76
3	1.98	1.827	28.07	15.48

Testing of physical and mechanical characteristics of the samples of natural brick from the bed named 1 and 2 (Table 1) showed that values for their cubes with yellow inclusions in the form of spots - 2A and 2B, although with no cavities, had lower values of compression strength, namely 3.36 MPa and 1.42 MPa, than the cubes with no inclusions, but with spread cavities probably left after organic inclusions burned out - 1A and AB, which were 20.67 MPa and 4.33 MPa, respectively. It is visible that during the testing on compression strength of the cubes 1A and 1B extremely mutually different results were gained. The cube marked as 1A was tested so that it was positioned with cavities predominantly spread in the same direction as the compression force, while the cavities of cube 1B were more spread perpendicularly to the force direction.

The compression strength tests on *Viminacium* seven fired bricks dated from the period of the 3rd (one sample), 4th (five samples), and 6th century (one sample) were previously conducted and published [103]. The values varied from 9.73 MPa (4th CE) to 21.79 MPa (6th CE), with an average value of 17.67 MPa. The compression strength of the natural brick cube 1A broadly corresponds to the values measured for two out of seven fired bricks (4th and 6th century). Considering apparent density, its average value for fired bricks was 1.78 g/cm³, which is closest to the sample taken from the other area of the same bed during the other research - sample 3, which had compression strength in the range of our sample 2, and whose absolute porosity and water absorption are closest to the cube 2B. Thus, since the previously published research did not cover photos of sample, we can only initially assume it was more similar to our sample 2. One of the tested fired bricks whose research was published was later chemically analysed. Its values of compression strength and density were 17.26 MPa and 1,70 g/cm³ [103].

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3.3. Chemical Analyses, Methods and Results

The chemical composition of two presented samples from the bed was done using the X-ray fluorescence examination. First, they were dried at 105 °C until they reached a constant mass. Using approximately 5 g of powdered clay sample and 1 g of tableting wax (Cereox wax, Fluxana), per sample, the samples were made as pressed pellets (diameter 40 mm) with a laboratory hydraulic press (Specac) using 20 t. The Energy Dispersive X-Ray Fluorescence (EDXRF) equipment, Spectro Xepos, was used in conjunction with a binary cobalt/palladium alloy thick target anode X-ray tube (50 W/60 kV) and combined polarised and direct excitation to perform analyses. The detector for Spectro Xepos was a silicon drift detector (SDD) design with a Peltier cooler device. The Spectro XRF Analyzer Pro Xepos C software manages EDXRF analysis. For this investigation, the method of fundamental parameters for oxide testing was used.

Table 2. Chemical composition of natural brick samples from the bed compared to baked clays used for plastering of a *Viminacium* brick kiln and a fired *Viminacium* brick.

Sample	Loss on ignition (1000°C)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	P_2O_5	MnO	TiO_2	total
Natural brick (1)	1.23	61.97	19.36	8.19	1.70	3.01	0.46	2.18	0.06	0.17	0.28	0.97	99.57
Natural brick (2)	2.29	61.44	17.88	7.16	3.71	3.09	0.87	2.06	0.05	0.17	0.24	0.89	99.86
Baked clays from the brick kiln	1.56-9.27	51.26-68.21	15.01-21.88	2.66-8.53	1.03-8.36	0.73-4.70	0.71-1.38	1.54-2.94		0.05-0.86	0.02-0.16		99.96-100.34
Fired brick	4.09	69.40	10.50	5.20	4.42	2.95	1.59	1.76					99.91

The results of the chemical analysis for two bed samples (Table 2) show that the values of the sum of SiO_2 + Fe_2O_3 + Al_2O_3 for the samples 1 and 2 are 89.52% and 86.48% respectively, fulfilling the chemical requirement for natural pozzolanic materials according to ASTM C 618-22 standard [112], having this value higher than 70%. Also, the SO_3 content is less than 4.0% for both samples, while the loss on ignition at 1000°C is less than 10%, which also comply with the same standard. As for the samples of baked clay from the *Viminacium brick kiln,* the sum of the mentioned oxides ranges from 73.73% to 92.75% [104], while this sum in the analyzed *Viminacium* brick dated to the 4^{th} century is 85.1% [105]. The SO_3 content and loss on firing at 1000°C in bricks and baked clays also meet the mentioned standard. The mentioned sum of the oxides in the fired brick is slightly lower than in one of the samples of natural brick, while the highest value was obtained for a baked clay. The highest values of Fe_2O_3, Al_2O_3, and CaO are recorded with clays as well, while the greatest value of SiO_2 is detected for a fired brick. The contents of SiO_2 and CaO are higher in the fired brick than in natural bricks, while the reverse situation is visible with Al_2O_3 and Fe_2O_3.

Since scientific research on natural pozzolanic materials often shows contradictions between their real performance and given standards, it is advisable to conduct additional research according to additional standards, as well as additional chemical, mineralogical and thermal analyses [113]. In this study, the test on pozzolanic activity for both samples of natural brick was conducted.

3.4. Pozzolanic Activity, Methods and Results

The preparation of mortar mixtures for testing pozzolanic activity of natural brick was done according to SRPS B.C1.018:2015 [114], while the very test was done according to EN 196-1:2017 [115]. Hydrated lime was mixed with ground natural brick, sand (according to CEN standard), and water in the ratio of 1:2:9:2, that is 150 g ± 1 g standard hydrated lime; 300 g ± 1 g natural brick; 1350 g ± 5 g sand (CEN standard sand); and 300 cm3 ± 1 cm3 water. Ground natural brick was obtained from samples 1 and 2. Two different mixtures were made for three test tubes per each, which were tested after 7 days. The flexural strength test was done on three prisms, while the test on compression strength was done on all six halves of prisms obtained after the first test, per each mortar mixture. Sample I was made using ground natural brick marked as 1, while sample II was made using the one marked as 2. After testing, both mixtures showed moderate compression strengths, 3.43 MPa, and 5.12 MPa respectively, while the values of flexural strengths were also moderate, and more close to each other, that is, 1.37 MPa and 1.77 MPa, respectively (Table 3). According to this standard, the compression strength of mortar with natural pozzolanic material cannot be less than 5.0 MPa. Four out of six tested halves of the prisms made with natural brick marked as 2 had values of over 5.0 MPa, with the highest value of 5.3 MPa, one was slightly lower, 4.9 MPa, and one had a value of 5.0 MPa. Considering the flexural strength of these samples, they were in the range of 1.60 MPa to 2.00 MPa. It is visible that the mortar mixed with the use of sample 1 had lower strengths than the one made with the sample 2, although the sum SiO_2 + Fe_2O_3 + Al_2O_3 in this sample was slighlty higher.

Table 3. Mechanical features of the mortar samples made with natural brick.

Sample	Compression strength (MPa)	Flexural strength (MPa)
I1	3.50	1.20
I2	3.20	1.40
I3	3.60	1.50
I4	3.50	
I5	3.40	
I6	3.40	
I (avg.)	**3.43**	**1.37**
II1	5.30	1.60
II2	5.20	2.0
II3	5.20	1.7
II4	5.10	
II5	5.00	
II6	4.90	
II (avg.)	**5.12**	**1.77**

According to the standard ASTM C 618 – 22 both samples of natural brick had pozzolanic features. However, according to the gained compression strength of mortars mixed with these material, natural brick had moderate reactivity after 7 days. In the future, tests can be repeated by monitoring the mixtures for a longer period, since some materials can exhibit their pozzolanic activity later, but also using additional types of analyses [113]. During the world research of pozzolanic activity of naturally fired sediments for the purpose of its use in natural-pozzolana cement for concrete, the conclusions were made that they mainly can comply with ASTM standards for natural pozzolans and Portland-pozzolan cement, but that limited number exhibit good pozzolanic properties in reality and contribute to the high early strength. However, those that do not contribute still can be used in cases where early strength is not demanding [105].

The concrete and asphalt with this kind of combustion material as aggregate were experimentally made in Arizona. The material took too much water and decreased the strength of the concrete, sometimes even weathered out, leaving holes in concrete, while in asphalt, it absorbed much oil [80]. However, in North Macedonia, the material from the bed in Delčevo village in the Bregalnica region has been already used in the building industry for the production of concretes [116–117]. During the research on the potential use of natural brick from one of the Kostolac beds (sample 3 in Table 1) [117], the experimental mixtures of concrete were made with the natural brick as aggregate, cement CEM I 32.5 as a binder, and water, in the ratio of 1:4.5:1. After 7 days, the average compression strength of the cubes was 6.50 MPa, after 14 days it was 8.625 MPa, and after 28 days it was 12.375 MPa. The values of the static module of elasticity showed that these concretes were much more deformable than classic concrete of the same strength. Its thermal conductivity was very good. Considering its resistance to frost, the research showed that these concretes should not be subjected to low temperatures and saturated with water at the same time. The natural brick used in this research had many admixtures, sometimes even insufficiently baked clay, or the clay not baked at all, and thus soluble in the water (which confirms our assumption that it resembles sample 2). The research suggested use of the grains above 8 mm for concrete blocks since they are compact and better-baked clay, the remaining grains are proposed for the production of ecological brick, mixing natural brick as aggregate with pozzolanic features, hydrated lime, low amount of cement, and accelerators, suggesting these bricks would be successful in the regulation of the humidity, while the additives could improved its thermal insulation characteristics [117]. Although conducted on different mixtures, this research can be used in the future studies of the possible function and role of natural brick in different Roman structures.

Our research was done using ground natural brick for the creation of mortar, and thus, enabled it to fully react with lime, and the other research on concrete used this material as aggregate, with cement as a binder. However, they both initially confirm that natural brick can be used as pozzolanic material. Considering lime mortars, the properties of mixtures of lime and pozzolanic material are determined by many factors and their mutual relationships. The pozzolan surface area, its particle size, chemical, and mineral composition and amorphousness, and water demand for workability, all affect its reactivity, and thus mortar strength [118], and have to be taken into account in future laboratory research. One of the important proofs of the possibility of using natural brick as a pozzolanic material in lime mortars can be practical application of these mortars which can greatly help in the future conservation of the historical monuments whose mortars, and building materials in general, are scientifically researched.

3.5. Experimental Application

Trials of mortar mixtures made with the addition of crushed and ground natural brick were executed in Viminacium Archaeological Park with the traditional method of hot mixing [119]. The process happened during the *MoDeCo2000* project international workshop with a conference held in June and July of 2022, named *Science for the Conservation of the Danube Limes* [11] (Figure 11), led by the building conservator and mason Nigel Copsey [119]. The wall structure was built using mixtures made with quicklime, Danube sand, zeolite, schist and natural brick, and their compositions depended on their function in the structure (bedding, pointing, or coping mortar). As building elements, fired bricks, fragments of schist, blocks of natural bricks, and limestone, all once being a part of Roman structures and found in ruins during the excavations of *Viminacium* were used, since it was aimed to test their contact with newly prepared mortar. The structure has been monitored since and its mortars will be tested in the laboratory in spring 2023. The results will lead us to further conclusions on the possibilities of the use of natural brick in *Viminacium* mortars by its builders as well as to the possibilities of its use in future conservation mortars.

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Figure 11. Hot mixing during the *MoDeCo2000* workshop and building a wall structure with lime mortars having natural brick addition. Photo-documentation of the *MoDeCo2000* project.

An individual demonstration mixture with natural brick was also made during the workshop, using quicklime, natural brick, and sand, in a ratio broadly corresponding to the one that Vitruvius recommended for lime mortars, that is lime: crushed/ground brick: river sand ratio of 1:1:2 [46, (II. 5), 119]. Although mixing mortars in laboratory conditions is different than the one that can be expected on the site during the mixing done by masons in the process of conservation, even when the mortar components and their ratio are the same, the attempt was made to initially compare the results on compression strengths of mixtures made in the laboratory during the tests on pozzolanic activity and the one made during the demonstration on site. After the mixture made on-site was molded and aged for 35 days in the laboratory, its compression strength was tested, giving the result of 1.85 MPa. The natural brick used for the mixture can be comprehended as having similar characteristics as the sample of the natural brick from the bed marked as 2, which was used for the pozzolanic activity test, giving the values of mortar compression strength that vary from 4.90 MPa to 5.30 MPa after 7 days.

The mutual differences between the compositions of laboratory and on-site mixture were in the type of lime (hydrated vs. quicklime), and consequently method of mortar preparation; type, purity, mineralogy, and granulation of sand (standard pure quartz vs. fine and sharp building river sand); as well as the granulation of natural brick (ground vs. a mix of coarse and ground). The ratios were also mutually different (1:2:9 vs. 1:1:2), however, the laboratory mixture was prepared using mass ratio, while during the on-site preparation volume ratio was used in a way that the masons would use, with no absolute precision in measuring, so the exact comparison of their mechanical features cannot be made. Furthermore, in the on-site mixture, about one half of the brick was ground and acted as pozzolanic material, and the other coarse part acted as aggregate, giving the roughly calculated final ratio binder: reactive pozzolanic material: aggregate for the on-site mixture as 1:0.5:2.5, while in the laboratory mix, all amount of brick (ground brick) reacted with lime as pozzolanic material, which helped gaining strength.

4. Discussion

Natural brick - *crvenka* is probably the first raw material suitable for building that Roman soldiers encountered when they arrived at the Stig plain near the Danube, in the 1st century, apart from wood, which was abundant in the area until the 19th century and the development of the mining industry [27]. It seems that the availability of natural brick made its use very economically advantageous for the ancient *Viminacium* construction activities. However, according to the results of the archaeological excavations, the conclusion can be made that natural brick was abundantly exploited from the bed and used in the 1st century for the building of the legionary fortress, but also as fragmented material in the second half of the 3rd century and during the 4th century for peripheral civilian buildings. Since the recorded use of natural brick in *Viminacium* buildings dated to the period after the 2nd century is connected to its fragments, it can be maybe assumed that those fragments were reused building blocks of the first Viminacium fortress, which can further support the new assumption that its extensive exploitation could have been even stopped after the building of the fortress. The reasons can be primarily sought in its qualities as the main structural building material, which were probably recognised by the Romans as insufficient. However, did they know this from the very start, or just realised over time, and then started to use other materials more suitable for structural purposes? It is certain that after the 2nd century, we do not encounter blocks made of natural brick in *Viminacium* buildings, according to archaeological research conducted so far.

This study can further suggest that spatial availability of this material was not that important in the 2nd century and the first half of the 3rd century which were the most prosperous periods of *Viminacium* city [12], when the schist originated from the quarry in the Ram village, 15 km away using the water courses, and locally produced fired brick were used. The erection of structures of the excavated building complex of assumed agricultural character on a site very close to the bed of the natural brick was dated to the period between the 2nd and the 3rd century, the renewal was done at the end of the 3rd or the beginning of the 4th century, while on the transition from the 4th to the 5th-century buildings were built above a part of the complex. The structures were built of stone, while a building from the youngest phase was built of fragments of stone, bricks, and tile [34], as probably cheap and secondary used material. Since natural brick is not mentioned in records, the previous assumption that it was not used for building elements in the prosperous phase of Viminacium because it was not needed might be confirmed, but also the one that it was not even exploited in the later period, being used in a very limited number of structures built on the suburban zones, as fragmented secondary used material.

The natural brick presence has been rarely recorded in the graves or tomb structures of *Viminacium* [121]. It can possibly be connected to the fact that in the period of its extensive exploitation for the fortress erection, cremation was the prevailing method of burial, and only much later masonry burial constructions came into the funerary practice of *Viminacium*. Although the first recorded inhumation burial is dated to the end of the 1st century, only during the 2nd century the inhumation started to develop in *Viminacium* [120]. Its rise is connected to the second half of the 2nd century and the final domination happened in the middle of the 3rd century. In this process, the building of masonry structures for the inhumated happened in the very end [122]. Additionaly, these periods are connected with the most intensive brick production, and thus it was extensively used material for the construction of the graves and tombs.

The research conducted so far has not recorded the use of natural brick in *Viminacium* city buildings [55–56,123–126]. During his excavations in 1902, the archaeologist Miloje Vasić detected the first phase of the city construction as made of wattle and daub (from 70 AD – 100 AD to the second phase), the second one with the use of schist and brick (end of the 2nd and the 3rd century), and the third phase with constructions built of fragments of different materials (from the end of the second period to the Huns invasion in the middle of 5th century) [55–56]. He did not mention any material similar to *crvenka*, but it cannot be excluded it was among the different materials in the youngest phase.

Additionally, he excavated only a small part of the residential city quarter with workshops. Considering other excavated city public buildings, the use of schist in the urban area started before the end of the 2nd century. The change of the wooden structure of amphitheatre to the wooden-stone structure happened in the first half of the 2nd century after which it was incorporated into the city being initially erected as a military building [127] (the surfaces with *crvenka* were found during the research of the early phase of the life of the amphitheatre - [66–67]). The city baths, where the building phases were dated to the period from the 1st to the 4th century, were built of schist and brick entirely, but its first phase assumed to be dated to the 1st century, has not been investigated [125–126], so as to offer us the data on the used building materials in that period. Since the research has been scarcely conducted in the inner city zone of *Viminacium*, only future archaeological excavations will give us more information about the building materials used for its construction.

Roman lime mortar is one of the most interesting historic building materials, and for a long time a hot topic in the archaeological, geological, and material sciences. Although hydraulic mortars and natural as well as artificial pozzolanic materials (terracotta - bricks, tiles, and pottery) were used before the Romans in the Mediterranean world [128–129], only the development of mortars with the abundant use of natural pozzolanic materials of the volcanic origin enabled full use of their potential for structural purposes, that resulted in the formation of *Roman concrete* [43], and the erection of the most known monumental Roman constructions. Natural materials with pozzolanic features recorded in historic mortars are those of volcanic origin from the area of Naples, Santorini, or Eifel region in Germany [128,130], and include tuffs and ashes. The Greeks used the potential of natural and artificial materials for gaining the waterproofness of plasters and flooring mortars, but its use was not recorded in structural mortars before the Romans [128]. Although both materials can contribute to the formation of strong hydraulic mortars, lime mortars with the addition of natural pozzolanic materials gained ultimate strength quicker, and thus were used for structural purposes [131], as well as in marshy and salt-water environments [128], while lime mortars with brick as artificial pozzolanic material were used in structures in humid and warm environments, as well as in external coatings, due to their higher resistance to water penetration [130–131], thus having flooring, rendering or plastering functions. On the other hand, the use of both materials in one Roman mortar can be encountered as well [131].

However, in most of the Empire, volcanic materials were not available, but the massive constructions were still made, some of them still standing. The building methods were thus adapted to the locally available materials, and most of the provincial Roman builders created walls with non-hydraulic mortars, although occasional use of natural hydraulic limes originating from the impure limestone, as well as often negligent, but also intentional use of different inclusions, sometimes led to the creation of hydraulic mortars [57]. The type of lime used in *Viminacium* is currently under research since the lime remains originating from the lime pit excavated near a Viminacium villa [132], are being investigated. Although is it still not proven that Romans intentionally used hydraulic limes, examples were found in ancient Greece, and it was not unusual practice in the Middle Ages [133].This practice was later used in the Byzantine as well as Ottoman constructions [134–135].

In the harbour of *Cesarea Maritima*, builders used *pozzolana* from the Bay of Naples for the exposed structures, but also local artificial pozzolanic material, i.e. combustion residues (ash and charcoal) traditionally used in the area before the Roman conquest, for all other structures, and finally both materials in the most exposed and underwater structures. This confirms intentional use of raw materials for the need of reactive processes in mortars, according to the environment [44]. Mix of local and Roman practices using both ash and charcoal and crushed ceramics, was observed during the research of mortars from the Punic-Roman site of Nora, Sardinia [129].

Terracotta can be occasionally seen as the pozzolanic material in structural mortars in Roman buildings (Hadrian's Wall - [136]; hydraulic structures in Le Vieil-Evreux,

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France – [42]; *Singidunum* fortress, Serbia – researched during the *MoDeCo2000* project, etc.), but especially in those used in the early Byzantine period (all samples from the 6th century researched in the *MoDeCo2000* project have terracotta in their structure). In this case, terracotta dust was used as highly reactive pozzolanic material, while coarse fragments more acted as porous aggregate [136], [137]. The mortar of Hagia Sophia, with this lightweight aggregate in the wide mortar joints, became a form of concrete according to the researchers [137–139]. However, the research showed that the quality of these mortars is high also due to the nature of the hydraulic binder that was made of marly limestone or limestone-clay mixtures [139].

Clay minerals and carbonate content of the raw product have the greatest influence on brick properties after it is fired, but they depend on the firing temperature [140].The temperatures in which bricks obtain pozzolanic features can be put in the range between 600°C and 900°C or between 450°C and 800°C [130,140,141], and with higher temperatures in the mentioned ranges the features are better [73], It is known that the pozzolanic features of bricks fired at temperatures over 800°C–900°C are lower until they become completely non-reactive [134,142]. However, modern research showed that some contemporary bricks made in Britain, Denmark, Lithuania, and Poland, fired at higher temperatures still have pozzolanic features up to 1100°C [143]. According to the experimental research of making bricks using raw materials from modern production in Turkey, compression strength gradually increased with increasing temperature from 700°C to 950°C, but afterward, it significantly decreased, depending on the mineralogical composition. After the temperature of 1000°C–1100°C the bricks started to melt [144–145]. Most Roman pottery, bricks, and tiles were made with clay which becomes reactive with lime when fired at temperatures of 600–1000°C. The degree of its reactivity increases from 600°C until about 930°C and then starts to decrease. At around 1050°C it vitrifies and loses reactivity. Thus, both bricks and pottery can be good pozzolans, except fine ware fired at temperatures at or above 1050°C [142].

The firing temperature of the researched Roman bricks was estimated to be mostly up to 900°C (Pergamon - [146]), and less, that is 800°C-850°C (*Romula*, Romania - [147]). It is, however, known that some bricks could have been fired in Roman kilns even at higher temperatures (Padua, 900°C -950°C - [148]), depending on their proximity to the fire [149]. Research showed that a brick used as a building element in a *Viminacium* grave was fired at a temperature higher than 900°C [74]. In *Viminacium*, a brick kiln with vitrified, melted, glass-like material remained, was found [47], indicating that the temperature in some spots of the kiln reached a much higher temperature [150], An example of researched pottery kilns in *Aventicum* (today Switzerland) showed that the temperature could have been from less than 500°C to 1200°C, depending on the part of the kiln [149]. The temperature developed in the *Viminacium* pottery kilns was determined by analyses as at least 850°C–900°C and up to 1050°C [151].

While researching Ottoman mortars from the 14th and 15th-century baths buildings in Turkey, the researchers made an assumption that their builders particularly chose brick with pozzolanic features for producing hydraulic mortars and plasters. They researched bricks for the construction of the dome, as well as some plasters, and conclude that those used for the construction had poor pozzolanic features, compared to those used for plasters. According to them, it was a consequence of the intentional use of different materials in the production of bricks made to be used as elements, and those intended for use in plasters [134]. However, we know that the fragments of bricks left after the demolition of a building were reused for the infill of later walls, with debris from stone cutting, broken tiles, and different stones, which were all bonded with lime mortar [120]. There are also records that Romans occasionally used old crushed bricks for the creation of new bricks [152]. Thus, it seems more probable that Romans recycled many types of used bricks and used them also in mortars, but that they could experientially and according to visual observation choose those fragments they knew could have better characteristics (that we call pozzolanic), rather than they intentionally produce special bricks for mortars. Vitruvius writes about the quality of brick, telling us that if it is not made of good clay or it is poorly baked, it is shown immediately when it is exposed to the ice or frost [46], (II. 8). Similar doubt in the interpretation of the previous research is shared by Lynne Lancaster, since the material used in mortars can also originate from tiles or pottery, anything that was cheaper or easier to process, and not only brick [153]. Ancient people indeed had experience with the quality and characteristics of terracotta considering the firing temperature and raw materials, and one of the examples of this comes from the pre-Roman period (Iberian), where the researchers made a conclusion that the specifically composed pottery was intentionally fired at a specific temperature since the higher temperatures could cause its shrinkage [154].

Considering the mechanical strengths of the bricks depending on the firing temperature, possible "overfired" terracotta was probably later rejected by Romans, as having lower values of mechanical properties [145] for use as building elements. We do not know if these elements, fired on a temperature higher than the average limit for having pozzolanic features, but less than the average limited melting temperature (depending on the particular composition) were sometimes used by Romans in Viminacium as mortar additions instead since they could still have pozzolanic features, or they were rejected and used as a rubble material for the wall infills. Analogously, the choice of natural brick for making building blocks in *Viminacium*, the Romans probably made visually, according to its colour, texture, and, thus strength. We encounter dark fragments connected to the natural brick fired at higher temperatures used only for the wall infills, while the blocks were lighter, and probably obtained from the material created at lower temperatures.

Some natural brick material could have been created at low temperatures, due to its distance from the coal fire. Thus, some red fragments in mortars can be both natural and fired brick, no matter of the firing the temperature , except those that are fired at extremely high temperatures in which case they can be most probably determined as fragments of natural brick. Considering the maximum temperature in a coal bed, the intensity and speed of the fire can be low, when the coal smolders, but also more than 1200°C [95]. Combustion-metamorphism generally occurs at high (>600°C) to ultra-high (>1000◦C) temperatures, but also extreme temperatures can occur in the range from 1500°C to 2100°C close to the coal fire and with fresh oxygen supply [98]. In the Dacian basin of Romania, the temperature range is most often from 250°C to 400°C but can go up to 1200° [86], [155], while in the Czech Most Basin the temperature of ~ 980°C to 1330°C was determined [96].

Roman builders, who had already used the terracotta mortars for waterproof lining were familiar with its higher resistance to cracking during the hardening process, and probably realised that they could also use it in the walls. They had empirical knowledge that ground terracotta and natural *pozzolana* had similar properties, which Marcello Mogetta validates with the citing of Vitruvius [46] (II.6) who connected the quality of *pozzolana* with the fire effects [156]. The Romans probably accepted terracotta which was obtained by firing as well, as an artificial variety of *pozzolana*, but they never used it for structural purposes massively [156]. For Mogetta, the main reason for this is that mass production of ground terracotta would have had much higher costs than the quarrying of volcanic pozzolanic materials [156]. However, it can be the reason only if this material was obtained as tuff and not ash since tuff would also have to be further processed, in order to obtain fine grains and increase reactivity for the purpose of use in lime mortars [152]. Also, in the territories with the absence of natural pozzolanic material, builders did not use terracotta massively in structural mortars, thus modifying building methods where needed. Considering mortars that needed to be waterproof, although there are examples that Romans even added *pozzolana* to the brick mixtures, "it never really replaced ground terracotta" according to Mogetta, who further adds an interesting assumption that they wanted to preserve the "red hue of the mortar that made it popular in the first place" [156], (p. 32).

This can speak in favour that Romans in Viminacium could have comprehended *natural brick* as a terracotta-like variety of pozzolanic material of natural origin, actually the rock whose qualities were changed during the fire effects. Thus, ground and crushed terracotta-like materials for *Viminacium* mortars could have been obtained using real terracotta, but also much easier, using natural brick instead, by recycling the already used building blocks of this material, or directly exploiting it from the bed where it is often already crushed and available in many quantities and thus costs less than processes connected with fired bricks. Its possible use in all types of mortars in all *Viminacium* periods, even when it was probably not exploited for obtaining blocks, thus can be more justified. However, except for the flooring, rendering, and plastering mortars, we have encountered only a few structural mortar samples with red admixtures in *Viminacium* during the project research, moving us away from the assumptions considering the reasons for the justification of use of natural brick as pozzolanic material in mortars connected to the costs.

A part of the Viminacium city with residential zone was revealed in 1902, and later excavations in the city were done in the nearby area, at the sites of the city baths and the amphitheatre. During the excavations of the baths, many scattered mosaic tesserae, small fragments of mosaic floors with tesserae, as well as in situ remaining part of the floor in one apse, were found [125]. This is the only *in situ* mosaic found thus far in *Viminacium*. It encompassed white, grey, and black stone tesserae. Whether its tesserae present fired or natural brick, the mosaic fragment observed in this study, as a unique find in *Viminacium*, is thus, very important. Only after future archaeological excavations reveal other *in situ* mosaic floors or their traces, we can make some conclusions on this type of decoration in *Viminacium*. The connection of the use of shaped natural brick within certain time periods, in case further research reveals that tesserae were made of this material, can be very important in this process.

There can be many possible ways of the use of natural bricks in Roman constructions of *Viminacium*. Like for other building materials during human history, life of a material included basic process of extraction, processing (production), use (consumption) and disuse (disposal). Although it is not the case in the modern world, this flow was almost always historically widened with reuse, repurpose and recycling. One of the examples of these processes is use of fired bricks or tiles, as building elements, rubble and mortar admixture. If *crvenka* as a brick-like natural creation was used instead brick during the production of *Viminacium* mortars in which we recognize red admixtures, we would be able to comprehend it as a kind of a material that encompassed functions and features of both natural and artificial materials with pozzolanic features.

Laboratory research of natural brick samples, as well as the study in their practical use in mortar showed promising results on its pozzolanic features. However, only after careful inspection of many *Viminacium* mortars and their widened laboratory research, along with the deeper study of natural brick from the bed as well as from *Viminacium* Roman buildings, sufficiently justified conclusions on the characterisation of the red mortar fragments as terracotta or natural brick can be made.

5. Conclusions

Builders of *Viminacium* were always focused on the local building materials, commonly using processes of reuse and recycle. The re-use and repurpose processes are very visible in its remains, so we can encounter fragments of whole building elements originating from old buildings as well as reused building materials in the later structures. The same tradition continued even after *Viminacium* ceased to exist, up to the 19th century. These processes we can observe as a sort of historical sustainability since before the industrial age it was usual to use old materials to make something new, "it was the norm in all civilisations", "an evolutionary, additive process", "taken for granted", with "the material resource value to individuals and communities" as "the primary motivation", in the time when "top-down academic interpretations of cultural significance had not been formulated and played no part" [157], (p. 189). The practical reasons for recycling building materials could be numerous. Was there a shortage of any material? Were cheaper and more profitable alternatives sought? Did the value of recycled material change or increase? [18]. Was it simply process considered important for the preservation of nature?

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"For now, as for the ancient world, recycling and reuse are fundamentally important processes in the economy, and cannot be seen as simply a passive reaction to economic change" [18], (p. 457).

Natural brick as a local material was present in different life phases of *Viminacium*, in the buildings of public and private purposes, having several different functions as a main building material in the early phase, and limited use as fragmented material in later phases. Since its features greatly depend on many conditions connected with its creation, we know that building elements made of it could not be uniform. Did the Romans in *Viminacium* recognised the features of natural brick and could predict its behavior in the building, experientially knowing that its wide range of red nuances speaks about the level of its baking, similarly as they did with fired bricks? Its use as shaped building blocks is not recorded after the first period of Roman *Viminacium*, but its assumed waterproofing and drainage properties were recognised as important for the construction of floors and roads from the very beginning of *Viminacium* and even much later, since this practice is used even in modern times in the area.

In this research, a small attempt was made to get closer to the answer to the question of whether Romans in Viminacium used natural brick as a material with pozzolanic features in lime mortars. The possible conclusion that it was used instead of terracotta or along with it, whether as a result of recycling or exploitation, can offer new information for the research of Roman provincial construction, but also for deepening our overall understanding of Roman knowledge about the characteristics and behaviour of different pozzolanic materials in mortars. Conducted laboratory research is only a small part of scientific procedures that natural sciences can offer to humanities while answering their questions, and can be significantly widened in the future with an aim of gaining more results on the characteristics of the examined material that could be important for the advance of knowledge in natural sciences connected to materials. In this study, we have tried to present many topics considering construction activities in *Viminacium* through the archaeological context, but using the laboratory research as a *companion* and a *trigger* for the development of further research connecting natural and humanistic sciences.

The use of terracotta for making hydraulic mortars throughout construction history is an example of the recycling process. If the Romans of *Viminacium* used natural brick for the same cause, it would be one more confirmation of the known fact that Roman builders, as well as all historical builders, created buildings as sustainably as it was possible. The best question we can ask is whether they ever conducted any construction process as completely unsustainable, with the exception of the examples of luxurious imperial projects and wishes of wealthy investors. In this case, the proximity of the raw materials and the methods of their obtaining, and thus the cost and practicality in construction with recycling and reuse of materials were almost irrelevant. Considering the construction of public buildings where the costs could have been high as well, even if there was no recycling and reuse was actually substainable, since use of high-cost or less available materials was conducted only when it was technologically needed.

The conclusions and open questions in this study have shown that this kind of multidisciplinary research can reveal many aspects of the life of Roman *Viminacium*. We hope that after future archaeological excavations, accompanied by historical, and architectural research, the performance of additional laboratory analyses connected to raw and processed building materials, interpretation based on the cooperation of the humanities and natural sciences, as well as practical work on the use of these materials in building conservation, answers will be obtained to numerous questions related to reuse and recycle processes in the construction of *Viminacium*, and consequently, about its economy.

The focus on the way "how the past was managed in the past" approaches archaeology to the anthropological theories of value. Through the research on how materials, artifacts, and buildings were reused, renovated, and preserved, but also built over, added to, and in the end eventually destroyed we learn about people's attitudes towards the past [158], (p. 84). Therefore, the research of building materials used throughout history in different ways across the *Viminacium* area, where the natural brick plays an important role

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as a specific local material that can be comprehended as one of the carriers of the landscape immaterial values, can lead us to the knowledge on the values people attributed to them, from its first inhabitants until today.

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