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Research Article

One pier with two stones: A case study on different stones used in the foundation of a Roman bridge on the Batman Stream, Turkey

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ABSTRACT

Perpira is a registered ancient bridge, probably constructed during the Late Roman/Early Byzantine, to span the banks of the Batman Stream. The foundations and the piers are the surviving remains of this bridge. It is known that the bridge has not been repaired since it was discovered. Therefore, the remaining parts of the structure, especially the cut stone blocks, are original and contain precious information about the construction techniques and material selection of the period in which it was constructed. During the site investigations, it has been found that the stones used in the downstream and upstream sections seem to be different. In order to examine this unique application, samples were collected from the piers' downstream and upstream sections. The samples were then used to evaluate their petrographic, geochemical and engineering properties. At the macro scale, the questioned samples' petrophysical characteristics seem similar. The variations in the physicomechanical, petrographic, and mineralogical characteristics of stones used in these sections, however, indicate that they have noticeably different properties. The laboratory results demonstrate that the stone used in the downstream section is dolomite and has a strength of 25.21 MPa and a porosity of 25.38 percent, while the one used in the upstream section is limestone and has a strength of 59.93 MPa and a porosity of 5.80 percent. According to the experiment results, it can be stated that Romans constructed this structure using highly competent engineering knowledge and material optimization. The findings also highlight how even a single piece of artefacts may provide new insights for understanding ancient material application practices.

The location is not already there before the bridge is.
Martin Heidegger

Introduction

The history of bridge construction reached its peak during the Roman period. Since the Romans achieved a very high degree of engineering skill, we still appreciate and utilize the bridges they built [1]. The Early Roman bridges were built entirely of wood. The oldest bridge of ancient Rome is supposed to be the Pons Sublicius, built spanning the Tiber River in Italy by Ancus Marcius, and constructed of wood in the sixth century BC [2,3]. By the second century, the stone was used to construct bridges [2-5]. O'Connor [5] has catalogued some 330 Roman stone arch bridges and mentioned that many of them are still in operation today. Since they are water-crossing structures and subject to different types of weathering compared to those on terrestrial land, it is crucial to examine the impact of material selection on the performance of the stone bridges that have survived to this day. It is well known that choosing the appropriate material and using it effectively requires a great deal of knowledge and experience. On the other hand, constructing long-lasting structures requires not only choosing materials compatible with the local environment and the function of the building but also the supply of that material. Since the building material selection of the Romans was chiefly influenced by access to the material, the majority of the bridge was made of locally available stone material. As a result, utilization of locally unavailable material was somewhat limited. However, it is also known that when a variety of local sources are available, contractors have the option to select different stones based on their qualities or appearance [6,7]. The ancient bridges are significant assets of historical-artistic heritage and unique elements of the fluvial landscape. It is known that even the ruins of these structures are visible evidence of ancient construction techniques and material practices. Perpira, as the case of the present study, is an ancient bridge (Figure 1), probably constructed during the Late Roman/Early Byzantine period to span the banks of the Batman Stream [8]. The bridge collapsed due to uncertain reasons, and it is now in ruins. The current condition of the bridge suggests that it has not been repaired since it was discovered. Hence, it can be inferred that the remaining parts of the structure, especially the cut stone blocks, are original. In this respect, the bridge symbolizes tangible evidence and contains precious information on past construction techniques and material selection. Therefore, the bridge is unique and worth examining. It is also known that understanding the material properties and structural behavior is vital for any project related to the conservation of architectural heritage.

Figure 1. Location and an aerial view of the ruins of the Perpira Bridge

Therefore, this paper aims to evaluate and characterise the materials used in the construction of the Perpira Bridge, which could be crucial for conservation and restoration activities.

A preliminary form of this study has been previously published at the MERSEM-2021 Conference [9].

Historical Background and the State of Conservation

Geographically, Perpira Bridge is located in the province of Batman city in southeastern Turkey (Figure 2). There are some ancient settlements on the right and left banks of the river/stream, close to the borders of the bridge, including Mound Grê Migro and Pîleka (Figure 2).

Although some archaeological surveys were conducted on these ancient settlements and their vicinities [8,10-13], no study is available in the literature related to the bridge's history. In some of these studies, the bridge has been barely mentioned as a "*ruined Roman/Byzantine bridge*" [8] and as "*Harap bridge*" [11]. On the other hand, these studies did not specify the period when the bridge was constructed, the function of its construction, or its relationship with the nearby settlements. The bridge is a registered structure, yet since its discovery, it has not been the subject of any conservation projects.

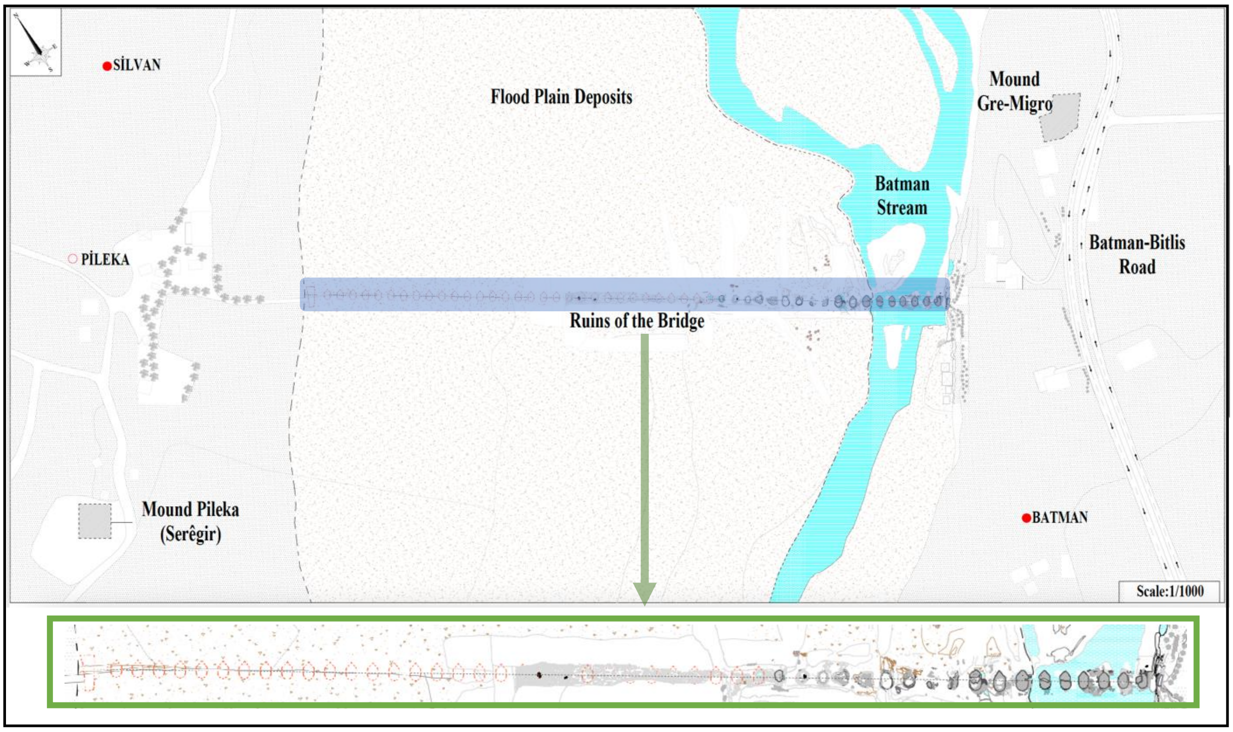

Figure 2. The location (up) and the plan view of the ruins (down) of the Perpira Bridge (the dashed red lines indicate the possible piers covered with debris)

Conservation campaigns have been undertaken to restore and understand the bridge's original structural conditions following years of neglect. The bridge was discovered in a collapsed state. It is currently in ruins for uncertain reasons. Additionally, the way and period of the destruction are not mentioned in any historical or archaeological records.

The only remaining parts of this bridge are the foundation piers, together with some flooring connecting the piers. Ten piers/foundations and an approach wall were initially visible. However, by the end of this year of 2022, eight additional piers (covered by the river sediments) were unearthed (Figure 3). Additional piers will likely be unearthed shortly, considering the flood plain and the bridge's connection to the right bank of the river (Figure 2,3).

The superstructure of the bridge is no longer visible due to its collapse. On the south side of the bridge, some displaced ashlar stone blocks were found in different places along the riverbed. These blocks differ in size and shape from those used for piers, foundations and flooring. These findings suggest that the bridge's superstructure was probably made of stone.

Material and Methods

Several site investigations were carried out to assess the state of conservation and understand the materials used for the construction. The bridge was constructed by employing stone material. It is clear from the bridge's ruins that the constructed piers were faced with *opus quadratum*. In order to fill the cores, *opus caementicium* (a roman concrete composed of large aggregates) was used (Figure 4). The stones utilized in the downstream and the upstream (cutwater) sections of the piers have different colours and textures, which were observed during the site investigations (Figure 4). Thus, much attention was given to the stones used in these sections. To investigate, samples were collected from the two sections of the P9 foundation/pier (Figures 3, 5). Samples were collected from both the downstream and the upstream sections of the bridge's ruins to assess the mineralogical, petrographic, geochemical, and index properties of the material (The downstream section sample and upstream section sample will henceforth both be abbreviated as DS and US, respectively). Two thin sections were prepared from the DS and US for examination under an optical microscope in order to evaluate their mineralogical and petrographic characteristics.

To examine the chemical compositions of the collected samples, the X-Ray fluorescence (XRF) method was used. Finally, 28 samples with 5-centimetre edge lengths (14 from each section) were prepared to examine physicomechanical properties (Figure 5). During the laboratory studies, the engineering properties of the samples, including the effective porosity, unit weight, water absorption, sonic velocity and uniaxial compressive strength (UCS), were measured. The samples' engineering properties were determined per the suggestions and recommendations of ISRM [14] and RILEM [15]

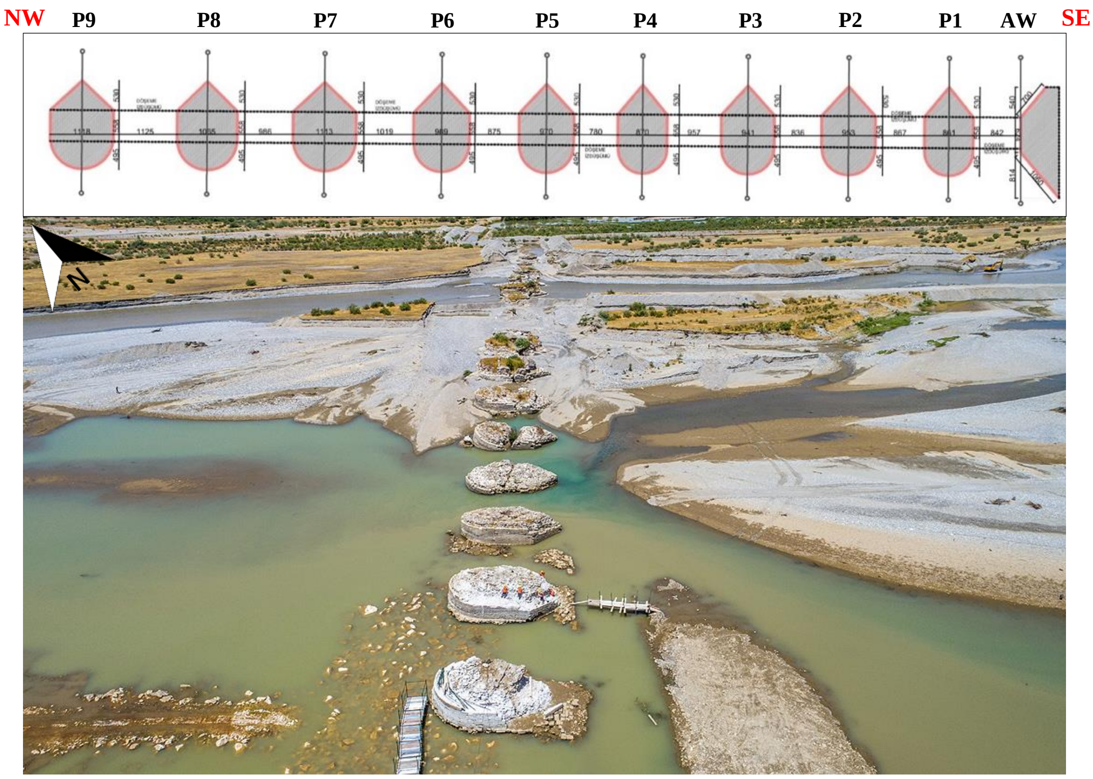

Figure 3. A drawing indicating the dimensions of the approach wall (AW) and some of the piers (P) (up); an aerial view of the ruins of the Bridge and Batman Stream (down)

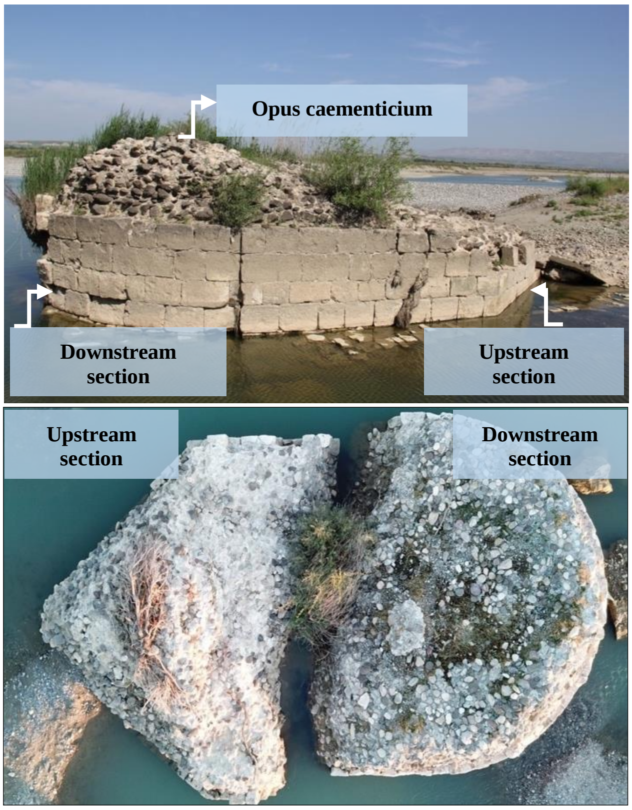

Figure 4. Different views from the piers/foundations

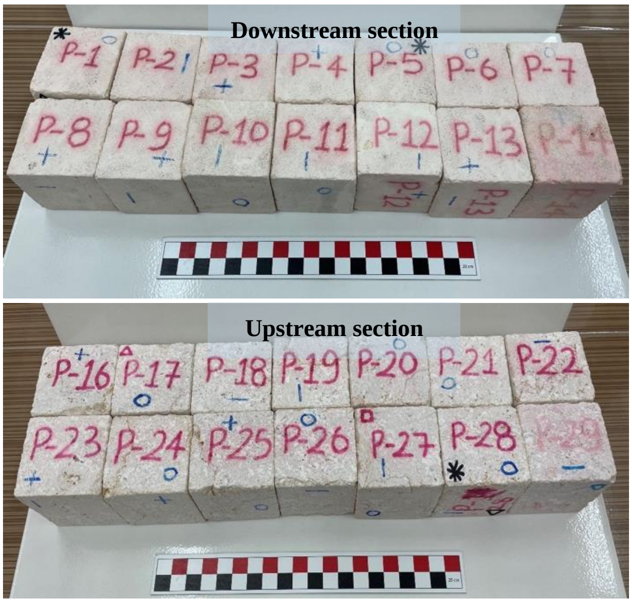

Figure 5. Samples used in the experimental studies

Results and Discussions

Petrographic and Geochemical Characteristics

Different petrographic parameters, including mineral content, grain size, and texture, have an impact on the mechanical behaviour and durability of the rock material. Therefore, a petrographic description of rocks for engineering purposes is essential for determining the parameters that cannot be identified through a macroscopic examination [14]. During the investigation, much attention was devoted to the matrix, organic material content and packing of the samples collected from different sections of the same foundation/pier.

Petrographic investigations on the DS indicate that the matrix is dominated by carbonate minerals (predominantly dolomite and less calcite). Mosaic texture, in which dolomite crystals are tightly packed and in contact with each other by regular grain boundaries, is the typical characteristic of the examined sample (Figure 6-a). The US, on the other hand, is dominated by calcite minerals and exhibits clastic texture. The calcite minerals are composed of micro/cryptocrystalline calcite, whose texture is called micrite. Micrite is occasionally observed at the boundaries of the fossils. The sample is an example of reefal limestone with dense red algae. The unit also contains fragments of red algae and benthic foraminifers. Black and white calcite minerals, as well as micrite, serve as the binder. It is probably the Early Miocene in age (Figure 6-b).

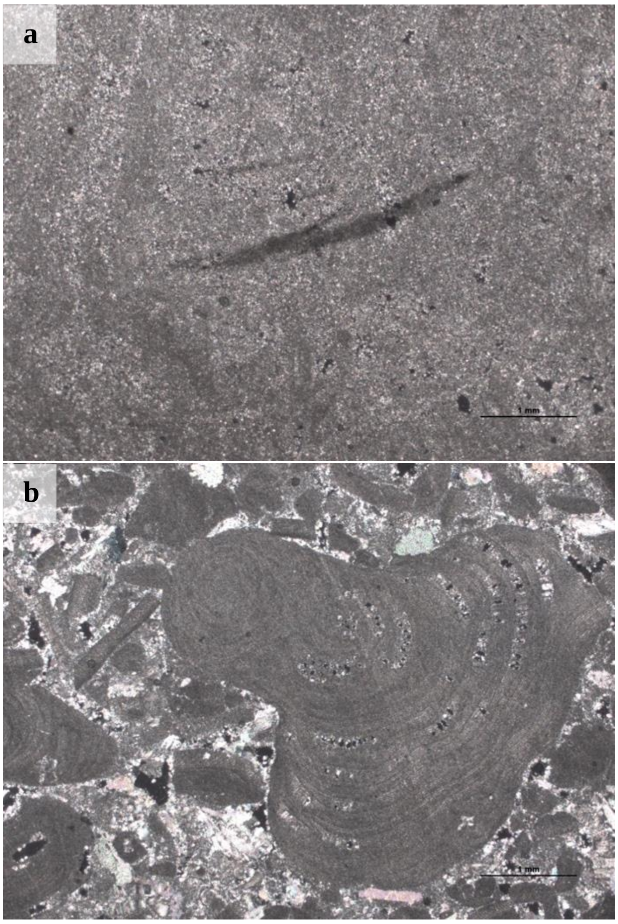

Figure 6. Photomicrographs of the samples collected from downstream (a) and upstream (b) sections of the bridge

The major oxides of the selected samples are tabulated in Table 1. The XRF results reveal that CaO is the most abundant component. The DS contains CaO and MgO as the major constituents. The remaining oxides are represented in low concentrations (less than one percent). It is understood from the overall evaluation of the major oxides that the questioned sample has a $CaCO_3$ and MgO composition of 78.73% and of 19.7%, respectively. The US, on the other hand, contains CaO as the major constituent. The remaining oxides are present in minor concentrations (less than one percent). It is understood that $CaCO_3$ forms more than 98 % of the US.

Based on the chemical composition and petrographic descriptions, modal analysis, a method suggested by ISRM [14], was used to estimate the mineral composition of the questioned samples. The results of the modal analyses indicate that DS has a mineralogical composition of 9.2 % calcite and 90.8 dolomite, while US has 98.2 calcite and 1.84 % dolomite. The abundance of the MgO in the DS supports the petrographic investigations that the stone employed in this section of the bridge is dolomite. On the other hand, the abundance of the CaO proves that the stone used in the upstream section of the bridge is limestone. Since the investigated US consists of macrofossils, it is described as fossiliferous limestone.

Physical and Mechanical Properties

Once it was determined that different stone materials were used in the downstream and upstream sections of the bridge's foundation, a new question arose within the scope of this study. What are the engineering performances of these materials? The physicomechanical properties mainly affect the engineering performance of the stone material. In an attempt to evaluate the durability of the stone material, it is crucial to test its index properties. In reference to the experimental studies conducted within the scope of the present study, a summary of the results for the questioned samples is tabulated in Table 2. Effective porosity and unit weight are two essential index properties of rock that can affect its durability. The structure of a rock material becomes weaker and more deformable when pores are present [14]. Unit weight, which correlates strongly with porosity, strength, and mineral composition, can also be used to assess the physical properties of rock material [16]. The same test can be used to determine those index properties. The effective porosity and dry and saturated unit weights of the questioned samples were determined using the saturation and buoyancy methods suggested by ISRM [14].

Based on measurements of 28 samples from the different sections of the bridge foundation, the DS have effective porosities varying from 24.04% to 27.63%, with an average of 25.3%. The DS's dry and saturated unit weights are measured as 19.27-20.46 kN/m3 (with an average of 20.03 kN/m3) and 21.98-22.82 kN/m3 (with an average of 22.52 kN/m3), respectively. On the other hand, the US has effective porosities ranging between 2.65% to 10.97%, with an average of 5.80%. Here it is worth mentioning that the majority of the effective porosity values for this section are less than 7%. The US's measured dry and saturated unit weights are between 17.66-25.55 kN/m^3 (with an average of 24.04 kN/m^3) and 18.25-25.81 kN/m^3 (with an average of 24.61 kN/m^3), respectively. According to Anon [16], the DS have high porosity (25.3%) and a low unit weight (20.03 kN/m^3), whereas the US have a medium porosity (5.80%) and moderate unit weight (24.04 kN/m^3).

Water absorption is an important parameter that affects the durability of rock material. It is the difference between the weight of a sample when it is dry and when it is completely submerged in water. This test was performed to measure the amount of water that rock can absorb under a certain pressure in a vacuum vessel, and the results are expressed as percentages. The test was conducted using the procedures suggested by RILEM [15]. During the test, water absorptions by weight and volume were determined for the samples collected from the downstream and upstream sections of the bridge. The water absorptions by weight and by volume of the DS lie between 11.53%-14.07% and 17.34%-20.72%, respectively. The average water absorption by weight and volume values for this sample group are 12.44% and 19.12%, respectively. The water absorption by weight and volume of the US are in the range of 1.02% to 4.65% and 1.96% to 8.73%, respectively. The average water absorption by weight and volume results for this sample group are measured as 2.42% and 4.98%, respectively.

As a non-destructive test method, Sonic velocity is a parameter used to evaluate rock materials in terms of their elasticity, anisotropy, degree of fissuring, porosity and state of deterioration. Moreover, this test can monitor rock material's degradation mechanisms under such different cyclic loads as wetting and drying, freezing and thawing, and salt crystallization. The sonic velocity measurements of the samples collected from the different sections of the bridge were carried out according to the recommendations of ISRM [14].

Table 1. Chemical composition (wt%) of the samples (downstream and upstream sections) determined by XRF

Oxides										
AlO_3	**CaO**	**Fe_2O_3**	**K_2O**	**MgO**	**MnO**	**Na_2O**	**P_2O_5**	**SiO_2**	**TiO_2**	**LoI**
Downstream Section Sample										
0.2	31.8	0.1	< 0.1	19.7	< 0.1	0.2	<0.1	0.6	< 0.1	46.95
Upstream Section Sample										
0.2	54.7	0.1	< 0.1	0.4	< 0.1	0.1	0.1	0.4	< 0.1	43.70

Based on the measurements, the dry sonic velocity of the DS ranges from 2625.39 to 3182.42 m/sec., with an average of 2914.82 m/s. In contrast, the saturated sonic velocity of this sample group is between 2356.40 and 2946.55 m/s, with an average of 2691 m/s. Sonic velocity measurements of the US for the dry condition range from 4302.5 to 5060.4 m/s, with an average of 4743.61 m/s, ranging from 4454.87 and 5202 m/s, with an average of 4877.55 m/s for saturated condition. Based on the rock classification for the sonic velocity of the rock materials proposed by Anon [16], the DS is classified as having "low" sonic velocity for both dry and saturated states. On the other hand, the same classification groups the US in the "high" sonic velocity category. Compressive strength is another important parameter to characterize the material. The average UCS values of the samples collected from the downstream and the upstream sections were measured as 25.21 and 59.93 MPa, respectively. It is inferred from the experimental results that the UCS of the DS was approximately 60 percent lower than the US. According to the rock classification for the strength of rocks proposed by Anon [16] and BSI [17], the downstream and the upstream section samples are classified as "moderately strong" and "strong", respectively.

Experimental studies show that the physicomechanical behaviour of these two stones is quite different. According to the results, the porosity of DS is roughly five times higher than that of the US, and this situation corresponds to a similar path in hygric values. It is found that the average water absorption values indicate that the stone employed in the upstream section has an approximately 80 percent lower water absorption than that employed in the downstream section. DS's higher water absorption capacity means it can absorb more water than the US. Since the porosity and fluid content of porous rocks significantly impact their acoustic velocities, rocks with lower porosities exhibit a distinct linear relationship between the porosity and the ultrasonic wave velocities [18]. These two stones exhibit significant variances in dry and saturated sonic wave velocities. The findings suggest that the material's decay can describe the DS's "low" wave velocity.

DS are classified as having a "low" sonic velocity compared to the US. In addition to water content and porosity, it is thought that a weathering-related decrease in the cohesion and elastic coupling between the dolomite calcite crystals also impacts this situation [18]. The compressive strength also verifies the variations of the investigated samples. It can be followed through Table 2 that the compressive strength of the US is more than two times higher than that of the DS.

According to the test results outlined above, the material used in the upstream section is considerably more durable, especially in terms of water absorption, porosity, and mechanical strength, than the material used in the downstream section. Although the stones in both sections seem relatively durable, it was observed that the crack development and the surface abrasions were more evident in the downstream section. The petrographic and physicomechanical variations between the materials used in different sections of the bridge pier indicate that this choice of material was not decided by chance. Bridges are susceptible hydraulic structures to flow-induced impacts. It is known that the flow regime significantly impacts the upstream section of the bridges and may damage the bridge's elements [19]. Construction of cutwater structures at the upstream section of the bridge piers is a common practice today as a countermeasure for such impacts. Cutwaters can be described as wedge-shaped bridge foundations. The primary objectives of the cutwaters are to *(i)* prevent the local erosion that might result in scour holes, *(ii)* reduce the impact of the flow pressure, *(iii)* control potential damages induced by floods and deflect tree roots and flood debris [20-23].

To construct such a structure, choosing a material with low water absorption and high strength is essential. The results obtained within this study's scope revealed that the stone material selection in the cutwater/upstream section of the Perpira bridge resulted from an engineering experience. In addition, it reflects the optimization; with the limited sources, they effectively employed the locally available material. Without knowledge of the material performance, it cannot be applied to such a unique and critical engineering project of that time.

Table 2. Physicomechanical properties of the samples (downstream and upstream sections) based on the experimental studies

Properties	**Number of Tested Samples**	**Test Results (Mean±SD†)**	
		Downstream Section (DS)	Upstream Section (US)
Dry unit weight (kN/m^3)	15/15	20.03±0.30	24.04±1.89
Saturated unit weight (kN/m^3)	15/15	22.52±0.22	24.61±1.81
Effective porosity (%)	15/15	25.38±0.89	5.80±2.50
Water absorption by weight (%)	15/15	12.44±0.63	2.42±1.11
Water absorption by volume (%)	15/15	19.12±1.01	4.98±1.96
Dry sonic velocity (m/s)	15/15	2914.82±119.91	4743.61±197.04
Saturated sonic velocity (m/s)	15/15	2691.0±130.68	4877.55±205.47
Uniaxial compressive strength (MPa)	10/10	25.21±9.13	59.93±22.81

†: Standard Deviation

Conclusions

Perpira is a stone bridge recently was recently discovered in a collapsed state. It is currently in ruins for uncertain reasons. Except for the limited number of archaeological and surface surveys carried out within the study area, written sources about the Perpira bridge are scarce; therefore, the story of its construction remains a mystery. The foundation piers and some flooring connecting the piers are the only remaining parts of this bridge. This study aims to evaluate the lithological and physical characteristics of the stones used in different sections of the remaining parts. The site observations and laboratory studies indicate that the stones used in the bridge's downstream and upstream (cutwater) sections exhibit different petrographic, geochemical and physicomechanical properties. Dolomite is the stone employed in the downstream section, and limestone is the stone used to construct the upstream section. The preliminary findings suggest that while the material used in the upstream section is suitable for such structures constantly in contact with water, the material used in the downstream section is not suitable. It is assumed that the lack of local availability of the upstream section stone in the region limited its use in both sections of the bridge pier. Engineers and architects were therefore forced to make decisions regarding the most effective use of resources. Additionally, the results emphasize some critical remarks that even ruined artefacts provide valuable knowledge regarding ancient times' material application practices. Therefore, preserving these structures is necessary for maintaining their stability and understanding historical material use patterns.

Here it is important to note that these findings, obtained within the scope of this study, were based on the examination of samples collected from a single bridge pier. Due to ongoing conservation works, it was unable to collect sufficient samples to confirm whether this unique material application is replicated at other piers. In the near future, the continuation of this situation will be questioned through a systematic sampling from the other piers of the bridge.

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