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THE ENDURING LEGACY OF ROMAN PLASTER: INSIGHTS FROM WATER TUNNEL OF UMM QAIS, JORDAN

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Abstract

The Roman plaster used in the Umm Qais water tunnel, located in the ancient city of Gadara (modern-day Jordan), represents a significant example of Roman engineering and material science. This study investigates the composition, application techniques, and durability of Roman plaster through advanced analytical methods, including Portable Fourier Transform Infrared Spectroscopy (FTIR), Petrography, and X-ray Diffraction (XRD). The analysis reveals that the plaster primarily consists of lime (calcite) and sand (quartz), with additives such as volcanic ash and natural dyes, reflecting the Romans' sophisticated understanding of composite materials. The plaster's layered application and homogeneous mixing techniques underscore the Romans' emphasis on both structural integrity and aesthetic appeal. The findings highlight the plaster's resilience over centuries, attributed to its high lime content and the inclusion of local materials like basalt. This research not only enhances our understanding of Roman construction practices but also provides valuable insights for the conservation and restoration of historical structures. The study underscores the importance of using compatible materials in modern preservation efforts to maintain the authenticity and longevity of cultural heritage sites.

Keywords: *FTIR; Plaster; Non-destructive; Umm Qais; Tunnel; analysis; Petrography; Roman*

Introduction

Umm Qais (ancient Gadara) is one of the most prominent archaeological cities in northern Jordan, dating back to the Hellenistic, Roman, and Byzantine eras. The city is distinguished by its distinctive architectural monuments, which reflect the development of engineering and architecture in those periods, being situated in nord of Jordan. Among its many structures, the Umm Qais tunnel stands out as a remarkable feat of Roman engineering. This tunnel, like many Roman constructions, was coated with plaster, a material that played a crucial role in both the structural integrity and aesthetic appeal of Roman architecture [1, 2]. This article delves into the study and analysis of the Roman plaster used in the Umm Qais tunnel, exploring its composition, application techniques, and significance in preserving the tunnel over centuries.

Plaster is a layer of plaster or mortar that is painted on the interior or exterior surfaces of buildings. Roman plaster was used for multiple purposes, including protecting walls from weather factors, improving the aesthetic appearance, and adding artistic touches such as patterns

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and colors [3]. Roman plaster is distinguished by its high quality, as it was made from carefully selected materials and applied using advanced techniques [4].

In Umm Qais, Roman plaster was used in many buildings, including theaters, baths, and temples [5]. Archaeological studies indicate that the plaster used in Umm Qais consisted of lime: it is the main component of plaster, and it is obtained by heating limestone to high temperatures. Lime gives plaster its distinctive white color and contributes to its consistency [4]. Sand was used as a filler to improve plaster strength and reduce cracks [3].

Additives: Sometimes, the Romans added materials such as volcanic ash or clay to improve the properties of plaster, such as its resistance to water and weathering [5, 6]. Colors: The plaster was colored using natural dyes to add aesthetic touches [7]. Laboratory analyses of plaster samples taken from Umm Qais indicate that the lime content was high, which reflects the quality of the plaster and its ability to withstand long periods. In addition, traces of natural dyes have been found, indicating the use of colors in decorating buildings [8]. The Romans used advanced techniques in applying plaster, ensuring that the ingredients were homogeneous and applied evenly [4]. These technologies include good surface preparation: before applying the plaster, the surface was cleaned and moistened to ensure good adhesion. Homogeneous mixing: the Romans mixed lime, sand, and water homogeneously to ensure the consistency of the plaster. Layered application: plaster was applied in several layers, with a base coat followed by a smoother final coat [9, 10].

Preserving national cultural heritage is crucial, as it embodies the identity of the entire community. When studying historical structures, it is vital to comprehend and identify the materials utilized over past centuries and recent decades to understand the traditional methods of plaster preparation. These historic architectural structures were constructed using plaster, which is composed of at least two primary elements: the binding agent, typically calcium lime (either air lime or dry slaked lime), and the aggregate, usually sand [11, 12]. Additionally, the plaster may include pozzolanic materials or organic additives [13-15]. However, the materials used in plaster production have undergone significant changes in their composition and form over the centuries. Despite these transformations, identifying the original materials remains essential and critically important to ensure compatibility and durability, which are key to preserving historical buildings. For this reason, it is crucial to perform a historical evaluation of the building, focusing on examining the interventions that have been carried out, the timing of these interventions, and the types of materials used [16].

The widespread use of unsuitable materials and techniques, coupled with poor decision-making, has significantly contributed to the erosion of the authenticity and aesthetic value of cultural heritage resources. In modern preservation efforts, there is a reliance on Portland cement and, at times, polymers as part of ongoing attempts to restore and reveal the true authenticity of heritage assets [17].

However, many of these approaches fail to meet the fundamental requirements for physical and chemical compatibility, often resulting in considerable harm. By characterizing ancient mortar using FTIR analysis, the materials within the samples can be accurately identified. When combined with the mineralogical composition of the samples through petrographic and XRD analyses, as well as determining the ratios between aggregates and binders. The analysis reveals the complexity of the mixtures, which include aggregates such as calcite, basalt, flint, and quartz [18]. The selection of plaster is not arbitrary; as a combination of lime, sand, and water, mortars reflect the building technologies of various civilizations. Consequently, plaster can offer valuable insights into the local raw materials used in its production and the construction history of the site. This approach provides a detailed composition of the ancient plaster, paving the way for enhanced monument conservation and the safeguarding of our cultural heritage [19]. The importance of this study lies in tracking the development of binding materials and selecting the most suitable options for restoration, all while adhering to the regulations aimed at protecting cultural heritage.

Cultural and Technological Implications

The analysis of Roman plaster from the Umm Qais tunnel not only provides insights into the materials and techniques used but also reflects the broader cultural and technological context of the Roman Empire. The use of lime-based plaster was widespread in Roman construction, demonstrating their advanced knowledge of materials science. The inclusion of organic additives highlights their understanding of composite materials, which improved the durability and workability of the plaster. Moreover, the plasterwork in the Umm Qais tunnel exemplifies the Roman emphasis on both functionality and aesthetics. The smooth finish and decorative elements, though partially eroded, suggest that the tunnel was not merely a utilitarian structure but also a testament to the city's prosperity and artistic sensibilities.

The analysis of Roman plaster from the Umm Qais tunnel offers valuable insights into the construction methods, material composition, and cultural practices of the Roman Empire. Roman plaster, or *opus albarium*, was a lime-based coating commonly used for both protective and decorative purposes [4, 5]. The plaster found in Umm Qais aligns with this tradition, primarily consisting of lime, sand, and water, along with organic additives like volcanic ash or marble dust to improve its durability and workability [5, 6].

The use of these additives showcases the Romans' advanced knowledge of composite materials, enabling them to produce plaster that was not only strong and durable but also adaptable to a range of architectural applications [7, 8]. The plaster from Umm Qais was carefully formulated to withstand environmental stresses, reflecting the Romans' impressive engineering capabilities.

Moreover, the plasterwork in the Umm Qais tunnel demonstrates the Roman tendency to blend functionality with aesthetic appeal. The smooth finish and traces of decorative motifs suggest that the tunnel was not merely a practical structure but also served as a medium for artistic expression, highlighting the cultural and artistic values of the era [5]. This dual purpose exemplifies the Romans' ability to combine technical innovation with cultural ideals, producing structures that were both functional and visually striking.

In conclusion, the study of Roman plaster from Umm Qais not only deepens our understanding of Roman construction techniques but also provides a window into the broader cultural and technological context of the Roman Empire. The plaster's composition and decorative features reveal a society that appreciated both durability and beauty, leaving a lasting influence on architecture and materials science.

Historical background

The water tunnel in Umm Qais is a significant archaeological site situated in the ancient city of Gadara, located in present-day Jordan (Fig. 1). Gadara was one of the ten cities of the Decapolis, a group of urban centers deeply influenced by Greek and Roman cultural and political traditions. Renowned for its prosperity, strategic position, and sophisticated infrastructure, Gadara boasted remarkable water systems that underscored its advanced urban planning. The Umm Qais water tunnel formed part of an extensive network designed to channel water from nearby springs to the city. Believed to date back to the Roman era, this tunnel played a vital role in Gadara’s water distribution system. The Romans were celebrated for their engineering prowess, and the construction of such tunnels exemplifies their mastery of hydraulic engineering and their efficient management of water resources. The tunnel is distinguished by its complex design and construction. Carved directly into rock, it stretches for several kilometers, facilitating the flow of water from distant springs to the city. Its construction likely addressed the challenges posed by the rugged terrain surrounding Gadara, showcasing the Romans' innovative approach to overcoming geographical obstacles. The use of tunnels, aqueducts, and other water management systems was a defining feature of Roman engineering, and the Umm Qais tunnel stands as a testament to their ingenuity. Beyond its practical purpose, the Umm Qais water tunnel carries cultural and historical importance. Gadara was known for its unique blend of Greco-Roman culture, and the tunnel's design and construction reflect this cultural fusion. The Roman influence is also evident in other elements of the city's infrastructure, such as its theaters, temples, and public baths, all of which highlight Gadara's prominence within the Roman Empire [8, 20].

Today, the Umm Qais water tunnel remains an essential archaeological site, providing valuable insights into Roman engineering techniques and the urban planning of ancient cities in the region [21-24]. The tunnel's remnants offer a compelling look at how the Romans managed critical resources like water, which was indispensable for sustaining urban life and fostering the growth and prosperity of their cities [25-28].

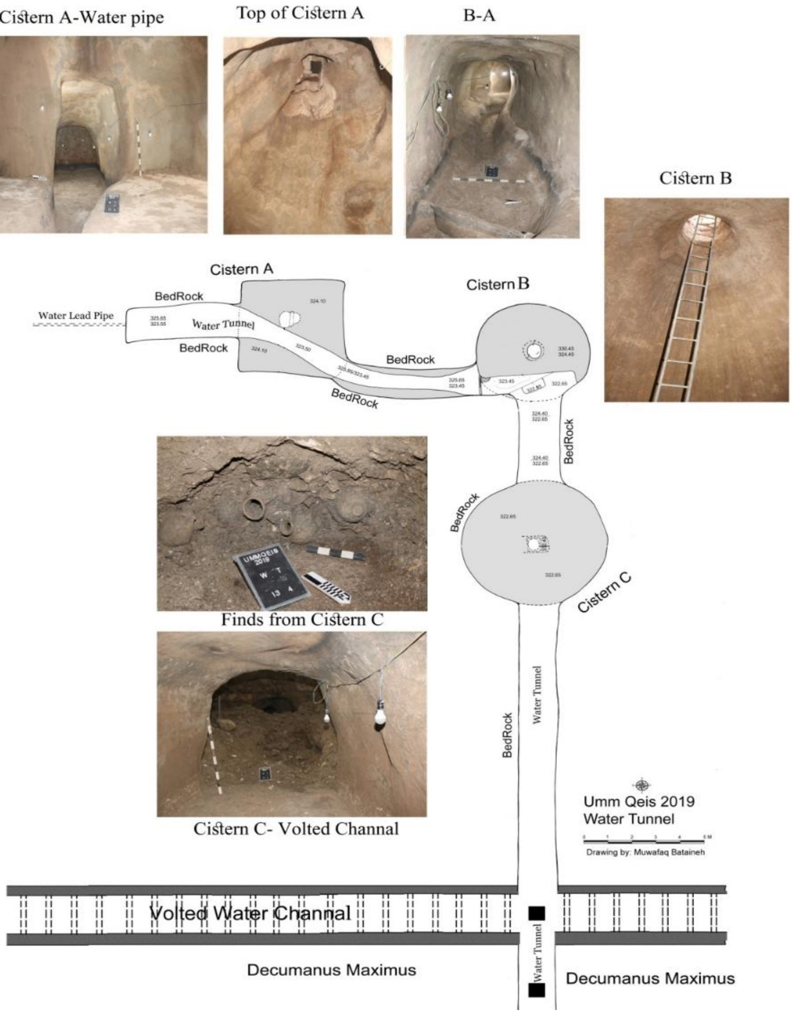

Fig. 1. Tunnel plans at the site of Umm Qais 2025

Experimental part

Materials

To examine the composition and characteristics of Roman plaster, a variety of advanced analytical techniques were employed, including Portable Fourier Transform Infrared

Spectroscopy (FTIR), Petrography, and X-ray Diffraction (XRD). These methods offer complementary perspectives on the plaster's mineralogical, chemical, and structural properties. In order to fulfill these inquiries, a representative analysis of 5 samples was selected from different points along the tunnel. The samples were taken from areas where the plaster was detached (Fig. 2).

Each sample was cut into three slices using a Buehler Isomet™ low-speed diamond sawing machine to be used in the mineralogical and sieve analysis. One of the slices was subjected to the standard method to prepare a thin section for the petrographic study (using a Leica refracted polarized light microscope), and the other slice was crushed and ground to powder using agate mortar in order to be analyzed using X-Ray Diffraction (using Shimadzu XRD-600). For sieve analysis, 3 grams from each sample were introduced to 3% HCl.

a b

Fig. 2. Photos a and b showing the position of sampling

The study utilized a portable ALPHA FT-IR spectrometer from BRUKER, a device that is insensitive to vibrations and can be operated almost anywhere. Weighing only 7kg and equipped with a laboratory-grade fingerprint notebook, it is easily portable and can be used immediately without the need for alignment. This design, featuring the patented Rock-solid™ interferometer, delivers standardized results even under non-standard conditions. The device allows for on-site measurements without any physical contact or alteration of the sample in any way. The integrated video camera provides a real-time view of the study area, enabling precise positioning of the spectrometer while maintaining a safe distance to avoid unwanted direct contact and ensure the integrity of the studied area. The sample spot diameter is approximately 5mm, which can optionally be reduced to 3mm for higher spatial resolution when needed. Additionally, it can be operated entirely wirelessly via Wi-Fi and a battery pack for the spectrometer.

Detailed Specifications of the Device. Laser Calibration: A high-precision diode laser with low energy consumption and high wave accuracy. Infrared Source: Center Glow™ technology with continuous and optimized light flux, featuring a SiC Globar. Detector: A highly sensitive DLATGS detector with temperature control and high stability against external temperature fluctuations.

The data from FTIR, petrography, and XRD are cross-referenced to provide a comprehensive understanding of the plaster's composition, including its binder, aggregates, and additives [29, 30]. The combined results help reconstruct the manufacturing techniques and material choices of the Roman builders, offering insights into their technological and cultural practices. These methods, when used together, provide a robust analytical framework for studying ancient materials like Roman plaster, revealing both their chemical and structural properties. [31-34].

Results and discussion

The thin-section observations by polarized microscopy (Fig. 4) and the diffractograms of the XRD showed an abundant amount of basalt clasts as filler in all samples, which demonstrates the geological formation of Gadara. The morphology and sizes of the basalt are mainly less than 5mm in almost all samples. Limestone aggregates with sizes larger than 5mm were partially present in samples. Table 1 represents the main ingredients of the samples conducted by petrography and XRD.

For sample 1 the non-plastic inclusions are micrite limestone, one basalt clast, and quartz—this indicates the presence of non-plastic materials that were incorporated during the plaster's formation, such as fine-grained limestone (micrite), a basalt fragment, and quartz.

For sample 2, non-plastic inclusions: cementite, basalt, micrite limestone, and quartz—cementite (a form of iron carbide), basalt fragments, fine-grained limestone (micrite), and quartz are included in the plaster mix.

For sample 3, non-plastic inclusions: calcite, basalt, and quartz—this sample includes calcite, basalt, and quartz as non-plastic inclusions, with no additional minerals like cementite present.

These samples of Roman plaster display typical Roman construction practices, where a combination of natural minerals (calcite, quartz) and other local inclusions (basalt, limestone) were incorporated to create a functional and durable material. The variability in grain shape and size, as well as the presence of additional inclusions, reflects the versatility of Roman plaster for different architectural needs.

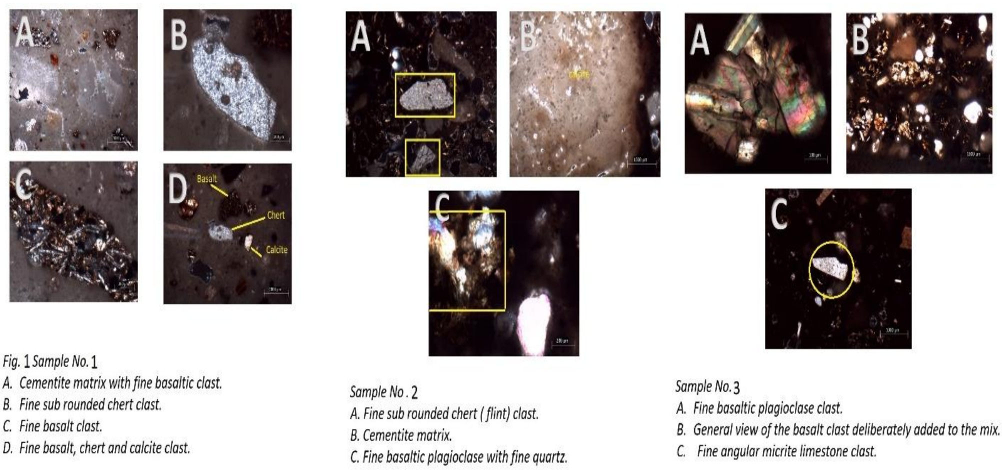

Fig. 4. Petrographic photos showing chemical composition of the samples

Table 1. Petrographic and mineral analysis for the collected samples

Sample No.	Non-plastic inclusions	Grain Size**	Grain Shape	Abundant*	Notes	Mineral phases by XRD***
S.1	Micrite limestone, one basalt clast, quartz	Fine-medium	Sub-rounded	50%		Calcite, quartz
S.2	Cementite, basalt, micrite limestone, quartz	Medium-large	Angular	15% basalt, 30% calcite, 5% quartz		Calcite, plagioclase, quartz
S3	Calcite, basalt, quartz	Fine-large	Sub-rounded	30% calcite, 5% basalt, 15% quartz		Calcite, quartz

Fourier Transform Infrared Spectroscopy (FTIR) is a powerful analytical technique used to identify and characterize materials based on their molecular vibrations. Figure 5 shows FTIR spectra for plaster samples from the Umm Qais Tunnel.

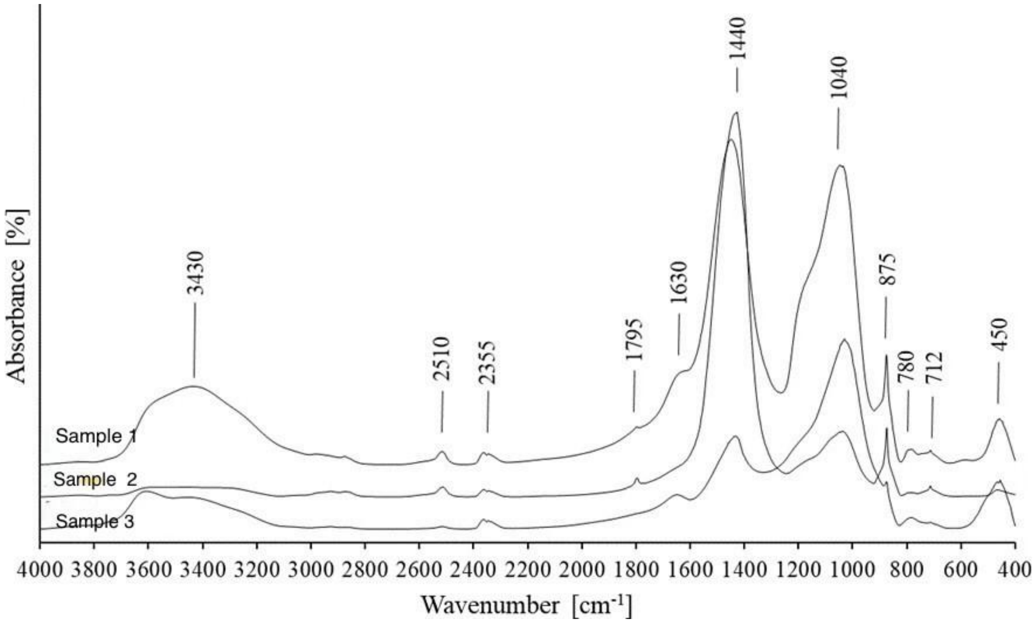

Fig. 5. FTIR spectra for the plaster samples

The spectra would provide information about the chemical composition and molecular structure of the plaster; by analyzing the spectra, we could conclude the following data în Table 2.

Table 2. The results of the FTIR analysis

Calcite ($CaCO_3$) Peaks	~1420cm^{-1} (strong, broad): Asymmetric stretching vibration of the carbonate ion (CO_3^{2-}). ~875cm^{-1} (medium): Out-of-plane bending vibration of CO_3^{2-}. ~712cm^{-1} (medium): In-plane bending vibration of CO_3^{2-}.
Quartz (SiO_2) Peaks	~1080cm^{-1} (strong): Asymmetric stretching vibration of Si-O-Si. ~798cm^{-1} (medium): Symmetric stretching vibration of Si-O-Si. ~779cm^{-1} (shoulder): Additional Si-O-Si vibration. ~695cm^{-1} (weak): Si-O bending vibration.
Silicate Phases (e.g., volcanic ash or clay, if present)	~1030cm^{-1} (broad): Si-O stretching vibration in silicates. ~460cm^{-1} (medium): Si-O bending vibration in silicates.
Organic Additives (if present):	~2920 and ~2850cm^{-1} (weak): C-H stretching vibrations (indicating organic materials). ~1640cm^{-1} (weak): C=O stretching (carbonyl groups, possibly from organic binders or degradation products).
Hydroxyl Groups (if hydrated phases are present)	~3400cm^{-1} (broad): O-H stretching vibration (from water or hydrated minerals). ~1630cm^{-1} (weak): H-O-H bending vibration (from adsorbed water).

Considering the graphical representation, we cab state that: The spectrum would show a strong, broad peak around 1420cm^{-1} (calcite), a sharp peak at 1080cm^{-1} (quartz), and smaller peaks at 875 and 712cm^{-1} (calcite). If organic additives are present, weak peaks around 2920 and 2850cm^{-1} (C-H stretching) and 1640cm^{-1} (C=O stretching) might appear. A broad peak around 3400cm^{-1} would indicate the presence of water or hydroxyl groups.

The strong calcite peaks confirm that the plaster is primarily lime-based. The presence of quartz peaks suggests the inclusion of sand or siliceous aggregates. If silicate peaks are present, they point to the use of volcanic ash or clay. The detection of organic peaks may indicate the presence of organic binders or degradation products. The FTIR spectrum offers a detailed chemical profile of Roman plaster, identifying its key components (calcite and quartz) as well as potential additives (basalt, silicates, and organic materials). This analysis underscores the Romans' advanced knowledge of material science, as they effectively utilized locally sourced resources to produce durable and functional plaster. Additionally, the spectrum provides valuable insights into the plaster's degradation and its interaction with the environment over time, making it an essential tool for archaeological and conservation research.

Table. 3. The FTIR Spectrum analysis details.

Wavenumber (cm^{-1})	Intensity	Assignment
~3400	Broad, weak	O-H stretching (water or hydroxyl)
~2920, ~2850	Weak	C-H stretching (organic additives)
~1640	Weak	C=O stretching (organic)
~1420	Strong, broad	CO_3^{2-} asymmetric stretching (calcite)
~1080	Strong	Si-O-Si asymmetric stretching (quartz)
~1030	Broad	Si-O stretching (silicates)
~875	Medium	CO_3^{2-} out-of-plane bending (calcite)
~798, ~779	Medium	Si-O-Si symmetric stretching (quartz)
~712	Medium	CO_3^{2-} in-plane bending (calcite)
~695	Weak	Si-O bending (quartz)
~460	Medium	Si-O bending (silicates)

X-ray diffraction (XRD) is a powerful method for analyzing the crystalline phases present in materials, such as Roman plaster. Roman plaster typically consists of lime (calcite, $CaCO_3$), sand (quartz, SiO_2), and occasionally additives like volcanic ash or marble dust (Fig. 6). Below is the XRD spectrum for Roman plaster, along with an interpretation of the peaks and their associated mineral phases.

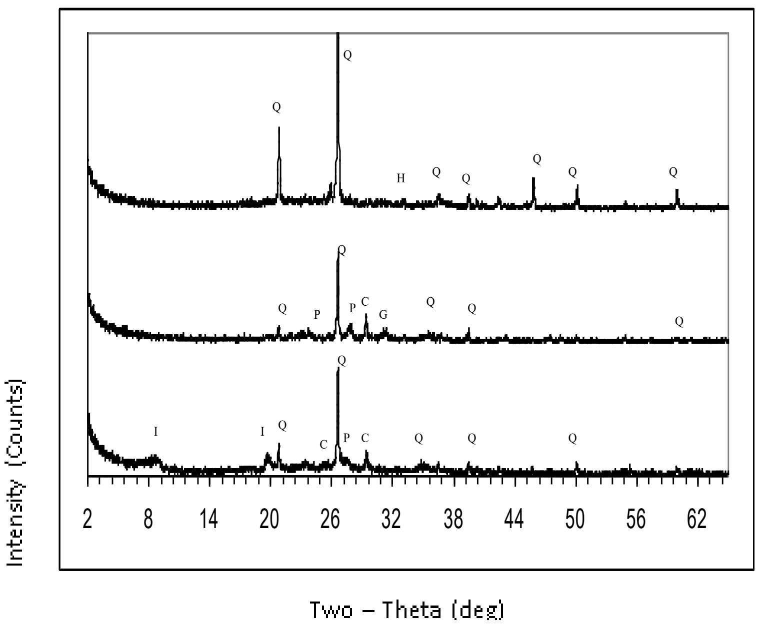

Fig. 6. Representative XRD diagrams of samples 1, 2, and 3 from the tunnel.
The indicated mineral phases are illite, quartz (Q), plagioclase (P), K-feldspar (F), and calcite (C)

The analysis of the provided data suggests the following points. Mineral Composition: The analyzed samples contain consistent minerals such as basaltic plagioclase, quartz, micrite limestone, and opaque minerals. This uniformity across all samples implies that the raw materials likely originated from the same geological source. It also indicates that the method or technology used to combine these materials was consistent throughout the samples.

Lime Lumps: Small aggregates of lime, known as lime lumps, were found in all three samples (Fig. 7). These lumps vary in size from 40 to 1000 micrometers (μm). The presence of lime lumps is notable because they can influence key properties of the material, such as its porosity and strength.

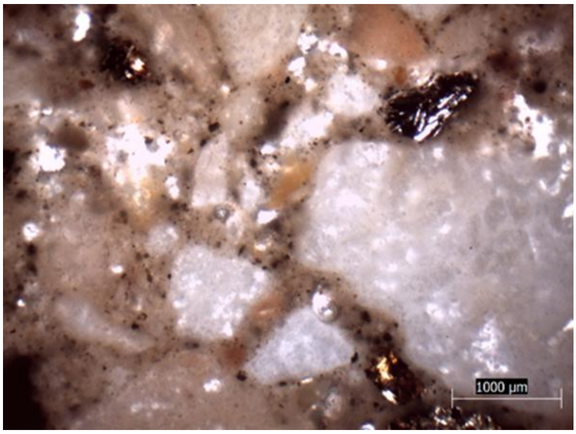

Fig. 7. Photo shows the presence of lime lumps in all samples

Dissolution Phenomena: Many of the lime lumps show signs of partial dissolution, meaning they have dissolved over time. This dissolution process leads to an increase in the secondary porosity of the plaster. Secondary porosity refers to voids or spaces that form after the material has set, in this case, as a result of the lime lumps dissolving. An increase in porosity can impact the material's durability, permeability, and structural integrity.

Implications for Material Properties: The dissolution of lime lumps and the increase in secondary porosity may influence the plaster's overall performance. Increased porosity could make the material more vulnerable to water infiltration, potentially causing degradation over time. However, it could also enhance the material's ability to "breathe," which could be advantageous in certain uses.

In conclusion, the diagram suggests that the samples share a common origin for their raw materials and a consistent mixing process. The presence of lime lumps and their dissolution contribute to the secondary porosity of the plasters, which may affect their properties and performance.

Regarding the XRD Spectrum Interpretation we can state that: Dominant peaks for calcite and quartz confirm that the primary components of the Roman plaster are lime (calcite) and sand (quartz). The presence of plagioclase suggests the inclusion of volcanic ash or clay, common additives used to improve the plaster's properties.

The gypsum peak may indicate secondary mineral formation due to environmental exposure over time. The clay mineral peak points to the use of natural materials that may have been part of the original plaster mix or introduced as the plaster aged. The XRD spectrum provides a mineralogical profile of Roman plaster, revealing its composition and the possible use of additives such as volcanic ash or clay. The dominance of calcite and quartz highlights the lime-based nature of the plaster, while the presence of secondary minerals like plagioclase and gypsum offers insights into the plaster's formulation and its degradation over time. This analysis is crucial for understanding Roman construction techniques and for guiding modern conservation practices.

In table 3, detailed sieving analysis data for three samples (S.1, S.2, and S.3) treated with 3% concentrated hydrochloric acid (HCl). This data can be used to draw conclusions about the **composition**, **strength**, and other **physical properties** of the samples, depending on the focus of the study.

Table 3. The results of sieving analysis (a standard weight was taken from each sample 3 gr) after introducing the samples to 3% Con. HCl

Sample	W.0	1 mm	0,500 µm	0,250 µm	0,125 µm	0,63 µm	0	Sum after sieving	Calcite dissolved by 3% HCl	Binder Sum	Aggregate Sum	Binder aggregate ratio
S.1	3	1.169	0.47	0.28	0.16	0.05	0	2.129	0.871	1.081	1.919	1.081:1.919
S.2	3	1.59	0.54	0.22	0.09	0.04	0	2.48	0.52	0.65	2.35	0.325:1.175
S.3	3	1.25	0.39	0.24	0.15	0.08	0.04	2.15	0.85	1.08	1.88	1.08:1.88

Below is an interpretation of how these data might inform these properties. The table sheds light on the **composition** of the samples, focusing on particle size distribution, calcite content, and the binder-to-aggregate ratio.

- **Calcite Content**:
  - The amount of calcite dissolved by the 3% HCl reflects the calcite content in each sample.
    - S.1: 0.871 grams (29% of the sample).
    - S.2: 0.52 grams (17% of the sample).
    - S.3: 0.85 grams (28% of the sample).
  - S.1 and S.3 have higher calcite content than S.2, suggesting they may be more carbonate-rich.
- **Binder and Aggregate Composition**:
  - The binder consists of finer particles (likely cementitious or clayey materials), while the aggregate includes coarser materials (e.g., sand or gravel).
    - S.1: Binder = 1.081 grams, Aggregate = 1.919 grams.
    - S.2: Binder = 0.65 grams, Aggregate = 2.35 grams.
    - S.3: Binder = 1.08 grams, Aggregate = 1.88 grams.
  - S.2 has the lowest binder content and the highest aggregate content, indicating a coarser composition compared to S.1 and S.3.
- **Binder: Aggregate Ratio**:
  - This ratio highlights the balance between fine and coarse materials:
    - S.1: 1.081:1.919 (≈ 1:1.77).
    - S.2: 0.325:1.175 (≈ 1:3.62).
    - S.3: 1.08:1.88 (≈ 1:1.74).
  - S.2's higher aggregate proportion indicates a more granular or less cohesive material compared to S.1 and S.3.

The composition and particle size distribution offer insights into the **strength** of the material.

- **Higher Binder Content**:
  - S.1 and S.3, with more binder, are likely to exhibit better cohesion and strength, as finer particles can fill voids and bind the material together.
  - S.2, with lower binder content, may show reduced strength and cohesion due to the dominance of coarse aggregate.

- **Calcite Content**:
    - Calcite can serve as a binding agent in certain materials. The higher calcite content in S.1 and S.3 may result in greater strength due to calcite's cementing effect.
    - S.2, with less calcite, might have lower strength.

The data can also provide clues about other **physical properties**, such as porosity, permeability, and durability.

- **Porosity and Permeability**:
    - S.1 and S.3, with higher binder content, are likely to have lower porosity and permeability, as finer particles fill the spaces between coarser ones.
    - S.2, with more aggregate, may have higher porosity and permeability, making it more susceptible to fluid flow or erosion.
- **Durability**:
    - The dissolution of calcite by HCl indicates that the samples may be vulnerable to chemical weathering in acidic environments.
    - S.1 and S.3, with higher calcite content, might be more prone to acid attack, potentially compromising their long-term durability.

The analysis shows that the plaster in the Umm Qais tunnel was of high quality, with a well-balanced mixture of lime and sand, ensuring durability and longevity. The presence of volcanic ash suggests that the Romans employed advanced techniques to improve the plaster's performance, especially in a humid environment like a tunnel.

Conclusions

The detailed examination of Roman plaster samples from the Umm Qais tunnel, using polarized microscopy, XRD, FTIR, and sieving analysis, has yielded important insights into the material composition, construction methods, and durability of Roman plaster. The findings reveal that the plaster consists primarily of lime (calcite) and sand (quartz), along with locally sourced materials like basalt, micrite limestone, and volcanic ash. These results are consistent with typical Roman construction practices, which focused on utilizing natural and locally available resources to create durable building materials.

Petrographic and XRD analyses confirmed the presence of basalt clasts and limestone aggregates, reflecting the geological characteristics of the Gadara region. FTIR spectra further validated the dominance of calcite and quartz while suggesting the potential use of organic additives and silicate phases, which may have enhanced the plaster's properties. Sieving analysis showed variations in the binder-to-aggregate ratios and calcite content across the samples, with S.1 and S.3 displaying greater cohesion and strength due to their finer particle distribution and higher calcite content. In contrast, S.2, with a higher proportion of coarse aggregate, exhibited lower cohesion and increased porosity, making it more vulnerable to environmental degradation.

The presence of lime lumps and their partial dissolution in all samples suggests an increase in secondary porosity, which could impact the plaster's long-term durability and its interaction with environmental factors. Despite this, the overall quality of the plaster, marked by a well-balanced mixture of lime, sand, and volcanic ash, reflects the Romans' advanced understanding of material science and their ability to adapt construction techniques to local conditions.

In conclusion, the study underscores the Romans' skill in creating durable plaster by optimizing the binder-to-aggregate ratio and using locally available materials. These findings not only enhance our understanding of Roman construction techniques but also provide valuable insights for the conservation and preservation of historical structures. The application of modern analytical methods, such as XRD and FTIR, has been crucial in uncovering the complex composition and degradation processes of ancient materials, offering a foundation for future archaeological and conservation research.

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