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RESEARCH ARTICLE / ARAŞTIRMA MAKALESİ

Material Characterization and Damage Assessment of Byzantine Rock-Cut Monastery: A Case Study of Kiyikoy Hagia Nicholas*

Bizans Dönemi Kaya Oyma Manastırının Malzeme Karakterizasyonu ve Hasar Değerlendirmesi: Kıyıköy Aya Nikola Manastırı Örneği*

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Abstract

Rock-cut historical structures have been constructed worldwide for various functions throughout history, including during the Byzantine Empire. The Kiyikoy Hagia Nicholas Monastery is an exceptional one of the surviving rock-hewn buildings in the Thrace Region. It has a basilical plan and was constructed in the Early Byzantine Period. The study goals are to provide original material characterization, suggestions for damage prevention and conservation measures for rock-cut structures of Byzantine architecture through this monastery case. Therefore, firstly the distinct architectural style of the building was revealed through a comprehensive analysis and by comparing it with similar structures. Then, a damage reconnaissance was performed and material samples were subjected to mechanical, physical, and chemical analyses and acid treatment experiments. Investigations focused on identifying the original materials and understanding the reasons for various decay and damage types observed in the monastery. Proposals for materials compatible with the original material, considering physical, mechanical, and chemical properties, were developed. The effectiveness of the characterization methods was explained. To prevent the effect of cracks, which is the main structural damage, constructing strengthening structural elements by using suitable materials was recommended. For non-structural damages, the removal of moisture in the main rock was recommended, and possible actions for surface cleaning, conservation and consolidation were described. It is concluded that the documentation, diagnostic and restoration steps developed for this monastery can be applied to similar Byzantine rock-cut structures.

Keywords: Byzantine rock-cut heritage, Damage, Material characterization, Chemical analyses, Holistic conservation

Öz

Tarihî kaya oyma yapılar, Bizans İmparatorluğu Dönemi de dâhil olmak üzere tarih boyunca çeşitli işlevler için inşa edilmiş eserlerdir. Kıyıköy Aya Nikola Manastırı, Trakya Bölgesi›nde inşa edilen ve günümüze ulaşan nadir kaya oyma yapılardan biridir. Erken Bizans Dönemi'nde inşa edilmiştir ve bazilikal planlıdır. Bu çalışmada manastır örneği üzerinden Bizans mimarisi kaya oyma yapıları için özgün malzeme karakterizasyonu, hasar önleme önerileri ve koruma önlemleri oluşturmak amaçlanmıştır. Bu sebeple, öncelikle yapının kendine özgü mimarisi kapsamlı bir analiz ve benzer yapılarla karşılaştırma yoluyla ortaya çıkarılmıştır. Sonrasında hasar tespiti yapılmış ve malzeme örneklerinde mekanik, fiziksel,

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kimyasal analizler ve asit kaybı deneyleri gerçekleştirilmiştir. Araştırmalarda özgün malzemenin tanımlanması ve manastırda gözlemlenen çeşitli bozulma ve hasar türlerinin sebeplerinin anlaşılmasına odaklanılmıştır. Fiziksel, mekanik ve kimyasal özellikler dikkate alınarak orijinal malzeme ile uyumlu malzeme önerileri geliştirilmiştir. Karakterizasyon yöntemlerinin etkinliği açıklanmıştır. Temel yapısal hasar olan çatlakların etkilerini önlemek için uygun malzemeler kullanılarak sağlamlaştırma elemanlarının inşa edilmesi önerilmektedir. Yapısal olmayan hasarlar için ana kayadaki nem sorunlarının giderilmesi tavsiye edilmiş ve yüzey temizleme, koruma ve sağlamlaştırma için yapılabilecek çalışmalar aktarılmıştır. Bu manastır için geliştirilen belgeleme, teşhis ve restorasyon adımlarının benzer Bizans kaya oyma yapılarında uygulanabileceği sonucuna varılmıştır.

Anahtar Kelimeler: Hasar, Malzeme karakterizasyonu, Kimyasal analizler, Bütüncül koruma

Genişletilmiş Özet

Dünyanın hemen her bölgesinde oluşturulmuş olan kaya oyma yapılar, toplumların mekânsal, tarihî, sosyal ve kültürel yaşamına dair değerli bilgiler taşımakta, oluşturuldukları dönemin mimari tarzına ve inşaat tekniğine dair bilgiler vermektedir. Bizans İmparatorluğu Dönemi'nde inşa edilmiş kaya oyma yapılar da dâhil olmak Türkiye'nin her bölgesinde farklı dönemlerde çeşitli fonksiyonlara hizmet için oluşturulmuş yüzlerce kaya oyma yapı bulunmaktadır. Bunlardan Kırklareli Kıyıköy'de bulunan Aya Nikola Manastırı, Erken Bizans Dönemi'nde inşa edilmiş önemli bir kaya oyma yapı örneğidir. 6. yüzyılda yapılan ve ilk adı Ayia Triada olan bu manastır 1922 yılına kadar aktif olarak kullanılmıştır. Yapı 3 nefli, bazilikal planlıdır. Bu yapı türünün plan tipi ve üretim yöntemi olarak benzerleri Erken ve Orta Bizans Dönemi'nde Frigya, Likonya, Kapadokya ve Kilikya'da da oluşturulmuştur. Kaya oyma tarihî yapılar oldukça fazla olsa da bu yapıların incelenmesi ve restorasyonuna dair çalışmalar diğer yapı türleri hakkında yapılan çalışmalara göre oldukça kısıtlı ve yüzeyseldir. Bu çalışmada literatürdeki bu eksikliğin giderilmesine katkı sağlamak hedeflenmiş ve Aya Nikola Manastırı'nda yapılan çalışma sonuçları kullanılarak Bizans Dönemi'nde benzer tipte oluşturulmuş kaya oyma yapılar için kapsamlı koruma adımlarının sunulması amaçlanmıştır. Çalışmanın yöntem aşamaları manastırın mevcut durumunun analizini, manastıra ait yapı malzemelerinin fiziksel, mekanik ve kimyasal özelliklerinin belirlenmesini ve koruma önlemleri ile önerilerinin sunularak çalışmada uygulanan yöntemlerin benzer yapılarda da kullanılabilmesi için temel bir adım setinin oluşturulmasını içermektedir.

Kıyıköy Aya Nikola Manastırı'nda (KANM) ilk aşamada yapılan mimari incelemeye göre bu yapı Soğucak Kireçtaşı Formasyonu'nda bulunan masif bir kayanın oyulmasıyla oluşturulmuş ve bazı tavanlara yığma yapıdaki gibi beşik tonoz şekli verilmiştir. Manastır, bazilikal planlı, üç nef ve üç apsisli bir kilise, ayazma ve mezar odası olmak üzere üç ana bölümden oluşmaktadır. Kutsal su içerdiği kaynaklarda bildirilen ayazmada hâlen su mevcuttur. Yapının tek cephesi olan kuzey cephesinde yığma revaklardan oluştuğu tahmin edilen ek bir mekânın izlerine rastlansa da kaya oyma kısım ve bu alan arasındaki duvarlar yıkılmıştır ve kalıntılar tam değildir.

Çalışma yönteminin ikinci aşamasında Aya Nikola Manastırı'ndan taş, tuğla ve harç örnekleri alınarak, elde edilen bu orijinal malzemelerin mekanik, fiziksel ve kimyasal özellikleri tespit edilmiştir. Ayrıca Bizans Dönemi tuğlaları ve kaya oyma yapılar hakkında daha önce gerçekleştirilmiş benzer çalışma verileri ve elde edilen bulgular kullanılarak sistematik bir karşılaştırma yapılmıştır. KANM'nin kaya ve tuğla malzemesinin fiziksel, mekanik ve kimyasal özelliklerini değerlendirmek için yapılan deneylerde, kaya örneğinin düşük dayanımlı (~6 MPa), yüksek poroziteli ve kapiler su emme katsayısı yüksek (~10 >3 $kg/m^2\sqrt{h}$) bir kireçtaşı olduğu tespit edilmiştir. Ayrıca, tuğlanın basınç dayanımının (~13 MPa) kayanınkinden yüksek olduğu ve bu değerin literatürde Bizans tuğlası için bildirilen ilgili değerlere yakın olduğu görülmüştür. Tuğlanın da su emme katsayısı ve porozitesi kayanınki gibi yüksektir.

Kayanın kimyasal özellikleri X-Işını Kırınımı (XRD), X-Işını Floresansı (XRF) ve Fourier Dönüşümlü Kızılötesi Spektroskopisi (FTIR) teknikleri kullanılarak analiz edilmiştir. Bu deney sonuçlarına göre kaya yüksek miktarda CaO ve az miktarda MgO ve Fe_2O_3 içeren yüksek karbonatlı bir kireçtaşıdır. Yapıdan alınan harç örneğinde gerçekleştirilen asit kaybı deneyine göre harçta bağlayıcı/agrega oranının 1:2 olduğu belirlenmiştir. Bu deneyde harçtaki karbonatlı agregaların asitte çözünerek bağlayıcı/agrega oranını etkilememesi için deney öncesinde bu çalışmada malzeme eksikliği sebebiyle gerçekleştirilmeyen petrografik analizin de yapılması ve bu analizin kayaç içeriğinin belirlenmesinde de alternatif olarak değerlendirilmesi önerilmektedir. Bu sonuçlara göre tuğla ve kaya onarımında kullanılacak malzemenin basınç dayanımının sırasıyla 13 ve 6 MPa basınç dayanım değerinde olması gerekmektedir. Onarım malzemelerinin toplam porozitesi %34'ten az, gerçek yoğunluğu yaklaşık 2.6 g/cm^3 ve su emme katsayısı en çok 10 $kg/m^2\sqrt{h}$ olmalıdır.

Manastırda yapılan hasar analizine göre strüktürel olan ve olmayan pek çok hasar tespit edilmiştir. Strüktürel hasarlar; parça kopması ve yapısal çatlaklar, strüktürel olmayan hasarlar ise parça kopması, kavlanma, kabuklaşma, çiçeklenme, biyolojik kolonizasyon, lekelenme, erozyon ve aşınmadır. KANM'deki çatlakların depremlerden veya kaya oluşumundan kaynaklandığı gözlemlenmiş olup çatlak ve yarıklar bulunan bu yapıyı sağlamlaştırmak için özgün malzeme ile uyumlu malzemelerden yapılmış ek taşıyıcı yapı elemanlarının tasarlanması önerilmiştir.

Yapısal olmayan hasarlardan en çok görülen çiçeklenme ve biyolojik kolonizasyonun ana sebebi, yapının oluşturulduğu kayanın üzerindeki toprak tabakasından yapıya geçen nemdir. Bu nem kaynağını kesmek için toprak ve kaya arasına ayırıcı tabakaların tasarlanması veya yapı çevresine kuyular açılması öngörülmüştür. Biyolojik kolonizasyonda öncelikle kaya yüzeyindeki likenlerin faydalı mı yoksa zararlı mı olduğu tespit edilmelidir. Bunlara müdahale gerekliyse su buharlı temizlik gibi geleneksel bir yöntem veya temizleyici bakteri ve jeller kullanılabilir. Çiçeklenmenin önlenmesi için bu hasara sebep olan üç ana faktörden birinin bertaraf edilmesi gerekmektedir. Kumlama veya lazerle temizleme gibi yöntemler bu hasarın sadece belirtilerini ortadan kaldırmaktadır. Yapıdaki su sorununun çözülmesi ile bu zararın ortadan kaldırılabileceği, tuz çıkarma yönteminin malzemeden tuzu uzaklaştırarak bu hasarı önleyeceği tespit edilmiştir Yapısal olmayan diğer hasarlara çözüm olarak, yapıdaki nem kaynağının ortadan kaldırılması, yüzeyi korumak için çeşitli su iticiler, emülsiyonlar, grafiti önleyici yüzey kaplamaları kullanılması önerilmiştir. Bu tür yüzey koruma ürünlerinin kaya yüzeyine zarar verdiği birçok restorasyon uygulaması mevcuttur. Kullanılacak ürünler seçilirken kayada oluşacak yan etkiler de göz önünde bulundurulmalıdır.

İnsan kaynaklı hasarları önlemek için eğitim ve bilinçlendirme; mekân içinde iklimsel etkileri azaltmak için nem ve sıcaklık kontrolü ve yapı genelinde önleyici koruma önlemlerinin oluşturulması önerilmektedir.

Kaya oyma Kıyıköy Aya Nikola Manastırı'nın ender görülen mimari üslubuna ve özgün malzemesine rağmen, bu çalışmanın yöntem ve sonuçları ile benzer özellikler taşıyan diğer Bizans Dönemi kaya oyma yapılarında da uygulanabilecek kapsamlı bir belgeleme, teşhis ve restorasyon yöntemi ortaya koymuştur. Benzer kaya oyma yapıların korunması için temel uygulama adımları oluşturulmuş ve hasarları gidermek için bazı önlemler önerilmiştir. Sonuç olarak, laboratuvarda ve sahada yürütülen çalışmalarla, kaya oyma yapıların korunması, sağlamlaştırılması ve gelecek nesillere aktarılmasına katkı sağlanması amaçlanmaktadır.

Introduction

Millions of rock-cut structures in the world comprise many things about the spatial, historical, social, and cultural life of civilizations. These structures have been used for different purposes in countries such as India, Ethiopia, China, Egypt, Cyprus, Iran, Jordan, Spain, and Italy for thousands of years[1] . Turkey also has prosperous rock-hewn structures such as rock-cut temples, tombs and dwellings. During the Byzantine Period, numerous rock-cut religious complexes and buildings were constructed around Cappadocia, Phrygia[2], Lycaonia[3], Cilicia [4]and in the Black Sea, Central Anatolia and Marmara Regions. The Hagia Nicholas Rock-Cut Monastery in Kiyikoy, Kirklareli, which was examined in detail within the scope of this study, is one of them.

Approximately 50 of the hundreds of Byzantine castles and religious buildings in Turkey are located in the Thrace Region. The locations of 59 buildings built during the Roman and Byzantine periods are shown in F. 1. Among all these structures, the Kiyikoy Hagia Nicholas Monastery is one of the significant exemplars of rock-cut architecture. Although 36 of these structures have completely disappeared, Hagia Nicholas Monastery is the rare one whose function has not been changed and functional authenticity has been preserved. However, it cannot be used due to the ruined and damaged parts.

The history of settled life in Kiyikoy **(F. 1)**, formerly known as Midye, dates back to the Thracians between 3000-2500 BC. The reign of the Roman Empire started in the 190s BC[5]. During the Roman period, many religious and military structures were built in and around Kiyikoy. Hagia Nicolas Rock-Cut Monastery **(F. 1)** and Midye Castle are the only surviving structures from that era[6].

1 José María Fuentes Pardo and Ignacio Cañas Guerrero, "Subterranean Wine Cellars of Central Spain (Ribera de Duero): An Underground Built Heritage to Preserve", *Tunneling and Underground Space Technology* 21 (2006): 477.

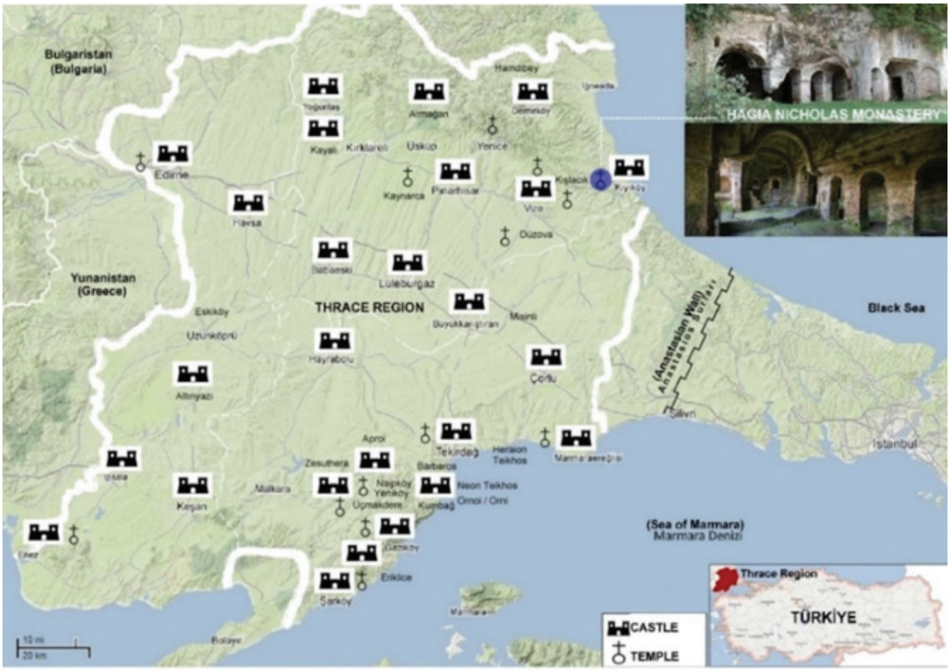
2 Seçkin Evcim, "Frigya Bölgesi'nde Bizans Dönemi Kaya Mimarisi", *ODU Journal of Social Science Research* 6/3 (2016): 862.

3 İlker Mete Mimiroğlu, "Konya'nın Bizans Dönemi Dini Mimarisi" (PhD dissertation, Selcuk University, 2015), 398-420.

4 Özlem Doğan, "Kilikia Bölgesi'nde Bulunan Bizans Dönemi Kaya Kiliseleri" (MA Thesis, Mersin University, 2021), 23.

5 Feridun Dirimtekin, "Midye Surları ve Aya Nikola Kilisesi", *Ayasofya Müzesi Yıllığı - Annual of Ayasofya Museum (No. 5)* (Istanbul: İstanbul Matbaası, 1963), 47-55.

6 Dirimtekin, "Midye Surları ve Aya Nikola Kilisesi", 1963, 47-55.



F. 1: Location of Thrace Region, Kıyıköy and Hagia Nicholas Monastery (The map showing the castles and temples was taken from Sarıoğlu)[7]

Kiyikoy is geologically located in the Sogucak Formation (Kirikkale limestone)[8]. The Kiyikoy Hagia Nicholas Monastery was carved into the rock within this formation. It is one of the most important monasteries belonging to the Early Byzantine period in the Thrace Region. According to Dirimtekin[9], it has been built during the reign of the Byzantine Emperor Justinianus (527 - AD 565) in the 6th century while Eyice and Thierry[10] claimed that the church was built between the 7th and 9th centuries. Also, some indications, details of which are shared below, point out that the structure was built in the 6th century.

The Thrace Region, where the monastery is located, is dominated by a continental climate specific to this region. Winter is cold, precipitation is usually in the form of rain, and the lowest temperature in Kırklareli since 1959 is -15.8°C and the highest

7 Özge Özgür Sarıoğlu, "Trakya'da Roma ve Bizans Dönemi Yerleşmeleri, Anıtları, Erken Cumhuriyet Döneminde Koruma ve Restorasyon Modaliteleri Üzerine Bir Araştırma" (PhD dissertation, Trakya University, 2012), 218.

8 Bala Ekinci Şans, "Kuzeybatı Trakya'da (Lalapaşa-Pınarhisar) İslambeyli Formasyonu'nun ve Bentonit Oluşumlarının Jeolojisi, Mineralojisi, Jeokimyası ve Teknolojik Özellikleri" (PhD diss, Istanbul Technical University, 2018), .

9 Dirimtekin, "Midye Surları ve Aya Nikola Kilisesi", 1963, 47-55.

10 Semavi Eyice and Nicole Thierry, "Le Monastere et Le Source Sainte Die Midye En Thrace Turque", *Cahiers Archéologiques* 20 (1970), 52.

is 42.5°C [11]. The negative effect of climate on the structure is inevitable in this area where precipitation is observed approximately 100 days of the year[12] and some days are under the effect of freezing and thawing.

This monastery demonstrates the exceptional architectural style and construction technology of its period. It has high cultural, historical, environmental, social, and functional value along with authenticity. However, it is in urgent need of protection as it is subject to many anthropogenic and natural influences.

This study aimed to constitute an integrated and comprehensive conservation method proposal for Byzantine rock-hewn structures with the case study carried out on Kiyikoy Hagia Nicholas Monastery via using the results obtained by determining the chemical, mechanical and physical properties of the original historical building materials and the architectural survey that includes the building damages in detail. Used chemical analyses are X-Ray diffraction (XRD), X-Ray fluorescence (XRF), and Fourier Transformed Infrared spectroscopy (FTIR). In this context, the study was carried out in three stages:

- Analysis of the current state of the rock-hewn monastery by survey, diagnosis of the deteriorations through archive review and observation,

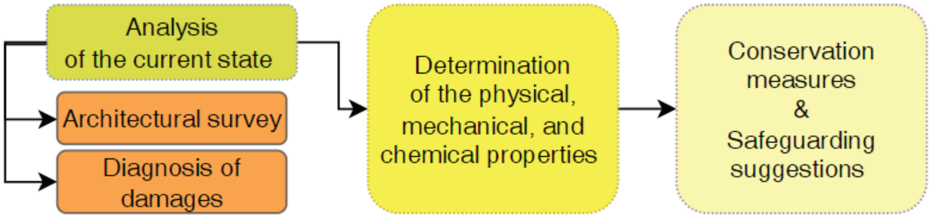
- Determination of the physical, mechanical, and chemical properties of the main rock and building materials that form the structural system,

- Presenting conservation measures and conceivable safeguarding suggestions by synthesizing architectural review, damage assessment and the realized mechanical, physical and chemical test results.

With the method steps described in **F. 2**, the historical development process of the building in the architectural context was investigated, the current situation of the monastery was documented, and a detailed characterization of the building materials was provided.

11 "Official Statistics / Kırklareli", General Directorate of Meteorology, accessed June 10, 2023, https://www.mgm.gov.tr/veridegerlendirme/il-ve-ilceler-istatistik.aspx?m=KIRKLARELI.

12 "Official Statistics / Kırklareli".



F. 2: Method steps (Prepared by authors)

After analyzing the complete set of data, appropriate measures were identified and broad recommendations were suggested to ensure the complete safeguarding of structures, such as the Hagia Nicholas Monastery, which possesses significant historical, cultural, and traditional architectural characteristics. The general overarching objective is to effectively transmit these attributes to future generations and to strive for the persistence of their socio-cultural significance and authentic material qualities.

1. Architectural Review

One of the thousands of structures constructed in different plan types during the Byzantine Period, Kiyikoy Hagia Nicholas Monastery which used to be called Ayia Triada[13] has a basilical plan with three naves **(F. 3, F. 5)**. From the 4th to the 10th centuries, Byzantine masonry religious buildings with three naves and basilical plans were built in various locations[14]. However, rock-cut structures in this plan type are fewer than masonry examples. There are 11 rock-hewn structures of this plan type in Lycaonia[15] and Cappadocia[16] and 5 in Phrygia[17]. In Cilicia, there are 3 in the form of rock-cut and masonry[18]. Kiyikoy Hagia Nicholas Monastery is a rare example in Thrace. Examples of buildings of similar plan types in different regions are presented in **F. 3**.

13 Sarıoğlu, "Trakya'da Roma ve Bizans Dönemi Yerleşmeleri, Anıtları, Erken Cumhuriyet Döneminde Koruma ve Restorasyon Modaliteleri Üzerine Bir Araştırma", 103.

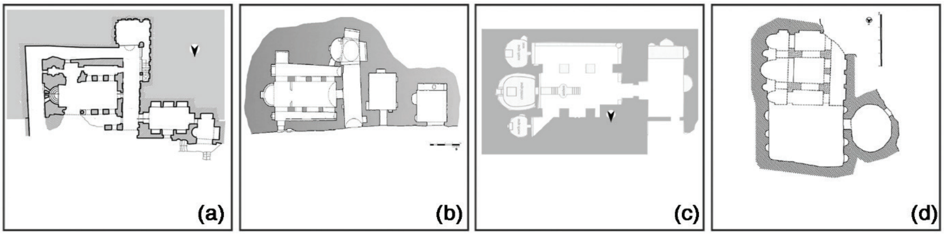
14 Seckin Evcim, "Dağlık Frigya Bölgesi Bizans Dönemi Kaya Mimarisi" (PhD dissertation, Anadolu University, 2015), 106.

15 Mimiroğlu, "Konya'nın Bizans Dönemi Dini Mimarisi", 329

16 Sue Anne Wallace, "Byzantine Cappadocia: The Planning and Function of Its Ecclesiastical Structures V.II" (PhD dissertation, Australian National University, 1991), 167-230.

17 Evcim, "Dağlık Frigya Bölgesi Bizans Dönemi Kaya Mimarisi", 106-107

18 Doğan, "Kilikia Bölgesi'nde Bulunan Bizans Dönemi Kaya Kiliseleri", 27.



F. 3: Examples of three-naved basilical plans of Byzantine rock-cut religious structures in (a) Kiyikoy Hagia Nicholas in Thrace (b) Kayadibi Church 1 in Lycaonia (Mimiroğlu, "Konya'nın Bizans Dönemi Dini Mimarisi", 326) (c) Durmus Kadir Church in Cappadocia (Wallace, "Byzantine Cappadocia: The Planning and Function of Its Ecclesiastical Structures V.II", 411) (d) Ayazin Church D in Phrygia (Evcim, "Dağlık Frigya Bölgesi Bizans Dönemi Kaya Mimarisi", 144) (Prepared by Şerife Özata)

The architectural and structural features of these buildings are presented in Table 1. In the buildings dated to the Early Byzantine Period, elements such as the ambon and synthronon are important elements indicating this period[19]. The fact that Ayazin Church D, which does not have such elements, was built in the 10th century supports this information. The year of construction of Kiyikoy Hagia Nicholas Monastery which had previously been dated to the 6th century [20] has been confirmed based on similar examples in different regions. In the 3-naved basilica plan-type buildings in rock-cut Byzantine architecture, regardless of the year of construction, the barrel vault form was generally preferred and the apse ceiling was built in the form of a semi-dome (Table 1).

As can be seen from **Table 1** and **F. 3**, the architectural features specific to Kiyikoy Hagia Nicholas, which are in resemblance with Byzantine religious buildings of the same plan type in different regions, are explained below.

19 Evcim, "Dağlık Frigya Bölgesi Bizans Dönemi Kaya Mimarisi", 107.

20 Dirimtekin, "Midye Surları ve Aya Nikola Kilisesi", 1963, 47-55.

Table 1. The architectural and structural features of Byzantine rock-cut temples with basilical plans in different areas (Prepared by Şerife Özata).					
Building	**Name**	*Kiyikoy Hagia Nicholas*	Kayadibi Church 121	Durmus Kadir Church22	Ayazin Church D 23
	Region	***Thrace***	**Lycaonia**	**Cappadocia**	**Phrygia**
	Construction Century	*6th*	5-8th	6th	11th
Architectural Spaces	**Apse(number)**	*✓(3)*	✓(3)	✓(3)	✓(3)
	Nave(number)	*✓(3)*	✓(3)	✓(3)	✓(3)
	Narthex	✓	✓	✓	x
	Additional space(s)	*Corridor, holy spring, monk's cell, burial chamber*	Chapel	Burial chamber	Burial chamber
Other Architectural Parts / Elements	**Synthronon**	✓	✓	✓	x
	Altar	*x*	x	✓	✓
	Ambon (pulpit)	*x*	x	✓	✓
	Mural painting	*x*	✓	✓	x
Form of Ceiling	**Flat**	*x*	x	✓	x
	Barrel vault	✓	✓	✓	✓
	Groin vault	✓	x	x	x
	Dome	*Semi dome*	Dome, semi-dome	Semi dome	Semi dome

The monastery was actively used until 1922[24] and it is covered with earth, vegetation, and different types of trees. It has one facade on the north and its current situation was shown in **F. 4a**. The structure in **F. 4b**, depicted as an old photo of the Kiyikoy Hagia Nicolas Monastery in places around the monastery inadvertently and in a conference paper[25], belongs to the monastery of the same name in Mustafapasa, Cappadocia.

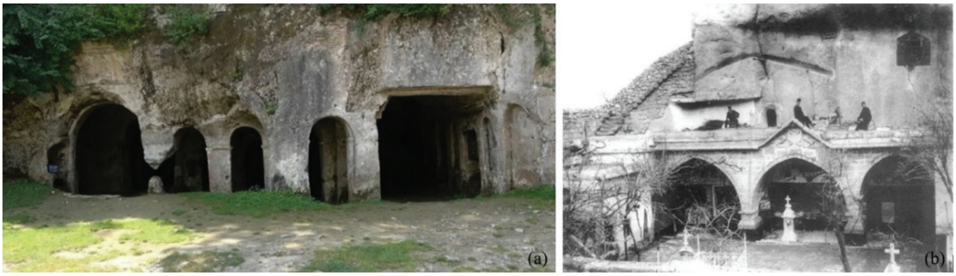
21 Mimiroğlu, "Konya'nın Bizans Dönemi Dini Mimarisi", 61-67.

22 Wallace, "Byzantine Cappadocia: The Planning and Function of Its Ecclesiastical Structures V.II", 409-418.

23 Evcim, "Dağlık Frigya Bölgesi Bizans Dönemi Kaya Mimarisi", 106-113.

24 Pantelis K. Lekkos, *OI Μονες Της Βορειας Και Της Ανατολικης Θρακης (The Monasteries of Northern and Eastern Thrace)* (Thessaloniki: Ekdosis Deduni, 1999), 5.

25 Gülsen Erginal, "Kültür Mirası Turizmi Açısından Kaya Oygu Aya Nikola Manastırı (Kıyıköy, Kırklareli) ve Antropojenik Etkiler", Proceedings of *International Geography Symposium on the 30th Anniversary of TUCAUM*, (Ankara: Ankara University Research Center of Turkish Geopraphy, 2018), 493.



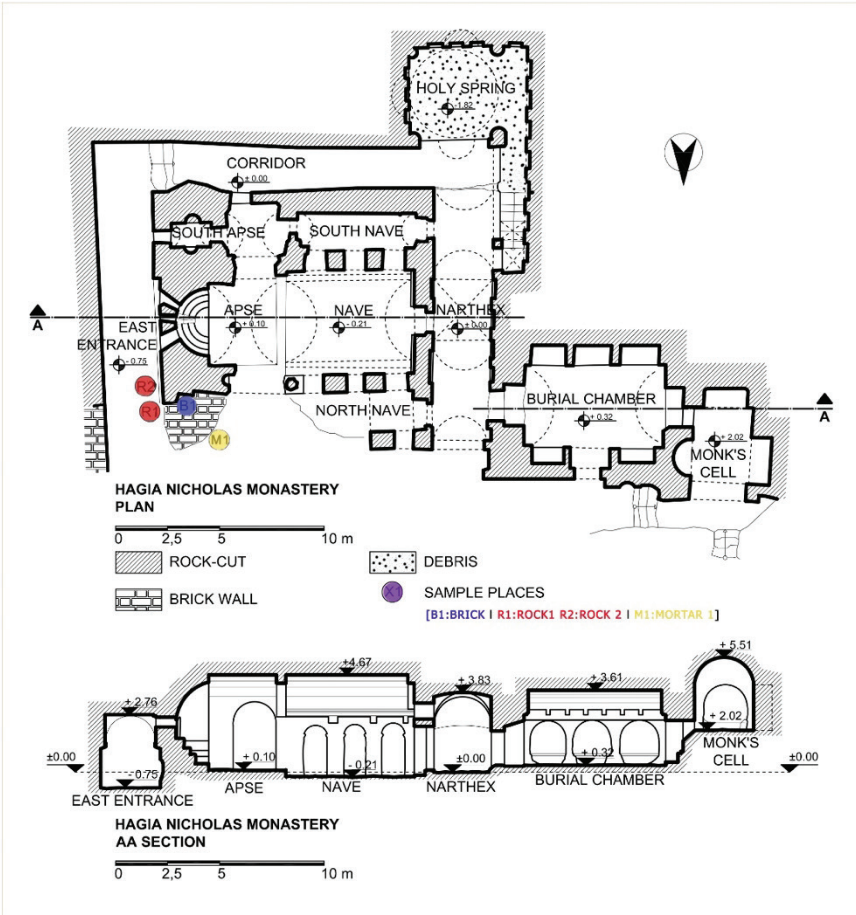
F. 4. (a) Kiyikoy Hagia Nicholas Monastery façade (Şerife Özata Archive, 2020) (b) Nevsehir Hagia Nicholas Monastery (1924) (https://mustafapasakapadokya.org/en/yapilar/st-nicholas-monastery-and-church)

The present basilical plan and cross-section are illustrated in **F. 5**. The temple was formed by carving massive rock, and some ceilings were carved as barrel vaults. Unlike the main rock-hewn structure, the porticoes were constructed of stone and brick as masonry. The flat brick patterns, which were generally used in the Byzantine Period and are still found in the remaining masonry on the north. The dimensions of the bricks could not be determined exactly, but they were in the form of flat bricks in the vault and the form of rectangular prisms on the walls. Almost all of these masonry exterior sections were demolished.

One of the three parts of the monastery is the church with apses, naves and a narthex **(F. 5)**. The other section consists of the holy spring and the corridor in the south of the monastery. The third section is the burial chamber and the monk's cell.

The main church is on the east side of the narthex. The church has a basilical plan with three naves and three apses. Of the three apses, the one to the north is destroyed. The large nave measures 6 × 5 m and the others are approximately 5.75 m × 1.80 m in rectangular plan **(F. 3)**. The naves end with the apse in the east, and a synthronon (rows designed for religious officials to sit) can be seen in the apse. There are three windows in the Byzantine style above these rows. The middle window is round, the side windows are rectangular and larger than the middle one. All these windows open to the east entrance. Dirimtekin[26] stated that there is an inscription between the windows, but it is not seen currently due to the biological damage. The north wall of the north aisle has collapsed and its remains are missing. It is thought that this wall may have been destroyed by an earthquake or since it was built with bricks that are not as strong and durable as the rock, it was destroyed over time.

26 Dirimtekin, "Midye Surları ve Aya Nikola Kilisesi", 1963, 47-55.



F. 5: The up-to-date plan and section of the monastery (Drawn by Engin Aktürk and Şerife Özata, 2023)

There is a narthex to the west of the naves. The burial chamber is accessed through a door on the eastern wall of the narthex. Dirimtekin[1] defined this door as a window. The burial chamber measures approximately 4 m × 6.8 m. There is an apse on the west wall of the room and a total of five niches on the north and south walls. There is a door opening to the outside between the two niches on the north wall. It is possible to enter the monk’s cell through the window in the niche on the west wall **(F. 5).**

The holy spring (ayazma), which is accepted as a source of holy water is on the southwest side of the church. The holy spring is descended by using the stairs and the current elevation of it is higher than the original due to the debris inside. The natural water source is still active and the holy spring is filled with water **(F. 6a).** There are semi-domed niches on the side walls of the floor of this space, and arched niches are lined up on these niches **(F. 6b).** This place is covered with a dome and it is known that there is an angel figure depicted on the dome[27]. However, this figure does not exist in situ, nor does it appear in the engraving by Hell in 1846 **(F. 6c).**

F. 6: (a) Eastern wall of holy spring and debris on the floor and in the eastern niche (Şerife Özata Archive, 2020) (b) Current situation of the southern niches and wall (Şerife Özata Archive, 2020) (c) Hell's engraving of the holy spring as viewed from the southwest of the holy spring (Semavi Eyice, *Trakya'da Bizans Devrine Ait Eserler*, 60.)

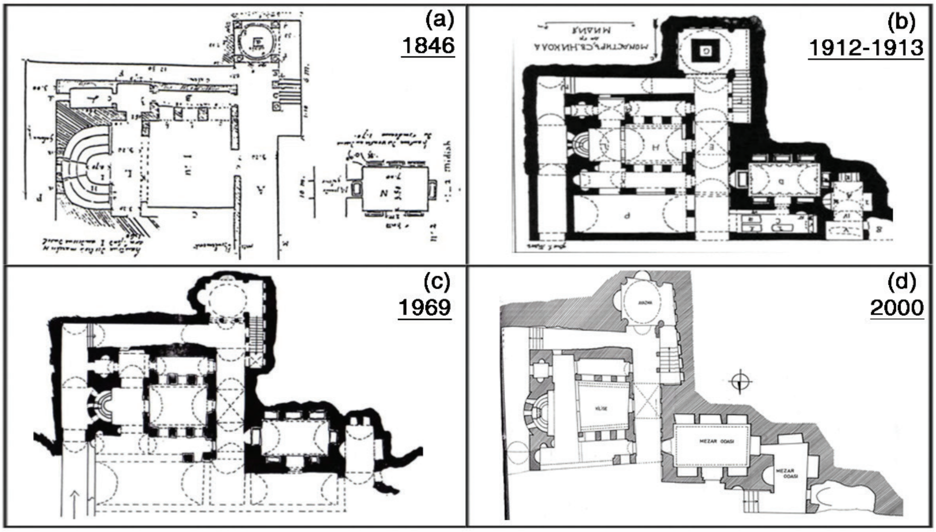
There are some remnants on top of the above-mentioned spaces. There were rooms in the upper northern part of the church according to old figures[28], but they do not exist now.

Over time, the plan and layout of the monastery underwent alterations due to both natural causes and human-induced effects. In the archival research carried out to understand the causes and stages of the partially damaged condition of the monastery, a detailed written source could not be found. From 1846 to 2000, various researchers/travellers drew up the plan of the monastery. The previously drawn plan sketches and brief explanations about them are presented in **F.7.** When these sketches are examined, it is understood that the northern facade was not destroyed until 1912-1913. Although some figures are seen in the holy spring in the sketches of Hell and Skorpil seen in **F.7a** and **F.7b** respectively, they are not seen in later drawings. Semavi Eyice sketched by specifying the destroyed parts in 1969. The structural system and damaged parts in **F.7c** and **F.7d** are almost identical to those in the current plan in **F. 5**. It is thought that the reason for the damaged parts may have been the earthquake in Edirne in 1953[29]. Also, climatic effects, disasters and human-induced damages are other probable reasons for this destruction.

27 Yücel Yaman, 'Kırklareli', *Yurt Ansiklopedisi,* vol. 7 (Istanbul: Anadolu Press, 1983). 58.

28 Eyice, *Trakya'da Bizans Devrine Ait Eserler,* 49.

29 The Union of Chambers of Turkish Engineers and Architects, *Türkiye'de Deprem Gerçeği ve TMMOB Makina Mühendisleri Odasının Önerileri Oda Raporu* (Istanbul: Ankamat Printing, 2022), accessed October 12, 2022, http://www1.mmo.org.tr/resimler/dosya_ekler/8273773702779a0_ek.pdf.



F. 7: Plan sketches of the Hagia Nicholas Monastery drawn by (a) (Hell Eyice, *Trakya'da Bizans Devrine Ait Eserler*, 50), (b) Skorpil (Duman, "Kırklareli İli Vize Ilçesi Kıyıköy Beldesi Toplumsal Yaşamı Üzerine Bir İnceleme", 104), (c) Eyice (Eyice, *Trakya'da Bizans Devrine Ait Eserler*, 51), and (d) Saraç (Kocaaslan, "Trakya, Kıyıköy Monografyası", 124) in different years

2. Material Characterization

Material characterization is as essential as the architectural survey phase in restoration since it provides detailed information about the building's original materials. The properties of materials such as stone, brick, mortar and plaster that constitute historical buildings should be determined and the main source of the problems should be examined by analyzing all data for holistic restoration suggestions.

The data obtained as a result of the determination of the original material properties enable the selection of the correct and suitable repair material and technique for all kinds of conservation work to be applied in the building. In case of incompatibility, the original and new materials may damage each other[30]. The necessary data for the similarity and compatibility in physical, chemical and mechanical properties between the original materials of the structure and the repair materials are provided by the relevant experiments described below.

The main structural elements of Kiyikoy Hagia Nicholas Monastery are mostly composed of rocks and partially bricks. Based on visual observations, the main rock is a beige-light brown type of limestone with low abrasion resistance and high porosity. The brick was used only at the northern entrance and a small remnant of them are still

30 Maria Stefanidou, Ioanna Papayianni, and Vasiliki Pachta, "Analysis and Characterization of Roman and Byzantine Fired Bricks from Greece", *Materials and Structures/Materiaux et Constructions* 48/7 (2015), 2251–2260, doi:10.1617/s11527-014-0306-7.

standing. The fallen rock, mortar and brick samples were collected from areas indicated in **F. 5** without damaging the structure, and the properties of these materials were examined. While the samples were taken, care was taken to ensure that they represent the overall structure. The rock samples were named R1 and R2 **(F. 8a)**, mortar sample entitled as M1 and the brick sample taken from the entrance was termed as B1 **(F. 8b)**. The mechanical, physical and chemical properties of them were determined by the following experiments.

F. 8. (a) Location of a rock samples (b) Location of brick and mortar samples (Şerife Özata Archive, 2023)

2.1. Laboratory Tests and Results

The experiments and results carried out to determine the mechanical, physical and chemical properties of the stone and brick materials of the monastery are shared below.

2.1.1. Mechanical and Physical Properties

Apparent and real density, open and total porosity values of stone and brick samples of Kiyikoy Hagia Nicholas Monastery (KHNM) were determined according to EN 1936[31]. Samples were cut in dimensions of 50 × 50 × 50 mm, and compression strength tests were performed as stated by TS EN 12390-3[32]. Capillary water absorption capacities of the samples were found according to methods of TS EN 15801[33].

The test results of the physical and mechanical properties of brick and rock along with the related values reported in the literature are shared in **Table 2** and **Table 3**

31 "TS EN 1936: Doğal Taşlar - Deney Yöntemleri - Gerçek Yoğunluk, Görünür Yoğunluk, Toplam ve Açık Gözeneklilik Tayini (Natural Stone Test Methods. Determination of Real Density and Apparent Density, and of Total and Open Porosity)", *Turkish Standardization Institute* (2010), 1-8.

32 "TS EN 12390-3 : 2010 AC : Temmuz 2012 Beton - Sertleşmiş Beton Deneyleri - Bölüm 3 : Deney Numunelerinin Basınç Dayanımının Tayini Testing Hardened Concrete - Part 3 : Compressive Strength of Test Specimens", *Turkish Standardization Institute* (2012), 1-6.

33 "TS EN 15801: Kültürel Varlıkların Korunması - Deney Metotları - Suyun Kılcal Emiliminin Tayini (Conservation of Cultural Property - Test Methods - Determination of Water Absorption by Capillarity)", *Turkish Standardization Institute* (2010), 1-13 .

respectively. A systematic comparison with the results of previous studies was carried out to better understand the material properties.

Table 2. The physical and mechanical properties of Byzantine and KHNM brick (Prepared by Şerife Özata)								
Reference (Year)	**Period (Century)**	**Comp-ressive strength (MPa)**	**Physical Properties**					
			Real density (g/cm³)	Apparent density (g/cm³)	Total porosity (%)	Open porosity (%)	Saturation (%)
Kahya (1992)[34]	4th -14th	16.9-50.2	2.62-2.84	1.55-1.89	23.7-39.0	-	-
Cardiano et al. (2004)[35]	8th -11th	-	-	1.52-1.72	31.4-42.6	-	-
Kurugöl and Tekin (2010)[36]	8th-14th	7.9-33.0	2.29-2.68	1.33-2.05	-	20.1-47.4	-
Stefanidou et al. (2015)[37]	7th -14th	4.50-20.7		1.46-1.84	-	-	-
Ulukaya et al. (2017)[38]	11th-12th	9.2-11.0	2.60	1,7	35.3	-	-
Çam (2022)[39]	4th-14th	4.16-46.1	-	1.17-1.81	24.3-56.2	-	70.0-92.0
KHNM	***6th***	***12.8***	***2.61***	***1.72***	***34.2***	***26.4***	***77.2***

34 Yegan Kahya, "İstanbul Bizans Mimarisinde Kullanılan Tuğlanın Fiziksel ve Mekanik Özellikleri" (PhD dissertation, Istanbul Technical University, 1992), 61.

35 Paola Cardiano, Salvatore Ioppolo, Concetta De Stefano, Antonello Pettignano, Sergio Sergi, and Pasquale Piraino "Study and Characterization of the Ancient Bricks of Monastery of 'San Filippo Di Fragalà' in Frazzanò (Sicily)", *Analytica Chimica Acta* 519 (2004), 103–111, doi:10.1016/j.aca.2004.05.042.

36 Sedat Kurugöl and Çiğdem Tekin, "Anadoluda Bizans Dönemi Kale Yapılarında Kullanılan Tuğlaların Fiziksel, Kimyasal ve Mekanik Özelliklerinin Değerlendirilmesi", *Gazi Üniversitesi Mühendislik Mimarlık Fakültesi Dergisi* 25/ 4 (2010), 767-777.

37 Stefanidou, Papayianni and Pachta, "Analysis and Characterization of Roman and Byzantine Fired Bricks from Greece", 2252-2258.

38 Serhan Ulukaya, Afife Binnaz Hazar Yoruç, Nabi Yüzer, Didem Oktay, "Material Characterization of Byzantine Period Brick Masonry Walls Revealed in Istanbul (Turkey)", *Periodica Polytechnica Civil Engineering* 61/2 (2017), 209-213, doi:10.3311/PPci.8868.

39 Elif Çam, "Characteristics of Byzantine Period Building Bricks Used in St. Jean Basilica (Ayasuluk Hill) and Anaia Church (Kadıkalesi)" (MA Thesis, Izmir Institute of Technology, 2022), 16-96.

Table 3. Physical and mechanical characteristics of carved rocks and the rock of KHNM (Prepared by Şerife Özata)

Reference (Year)	**Compressive strength, (MPa)**	**Physical Properties**				
		Real density (g/cm^3)	Apparent density, (g/cm^3)	Total porosity (%)	Open porosity (%)	Saturation (%)
Erguvanlı and Yüzer (1977)[40]	5.5	-	1.15	28	-	-
Aydan and Ulusay (2003)[41]	1.0-10.4	-	1.12-1.43	14.1-37.6	-	-
Kaşmer and Ulusay (2013)[42]	3.85-6.32	-	1.19-1.46	19.5-41.1	-	-
Özata and Arun (2018)[43]	9.55-31.8	2,3	1.50-1.60	29.2-35.3	17.8-24.7	57.7-73.8
Sülükçü (2019)[44]	1.24-7.93		1.17-1.52	29.0-58.0	22.6-36.7	-
KHNM	***5.8***	***2.64***	***1.73***	***34.6***	***29***	***83.8***

The apparent density of the rock and brick was found to be about 1.7 g/cm^3 and the real density of them was approximately 2.65. Open porosity and total porosity values of the rock were found to be 29% and 35% respectively. The density and porosity values of both materials were within the range of the respective values of the materials in which they were compared. The open porosity of brick is slightly lower than that of rock. The total porosity values are very close to each other. The freeze-thaw durability of KHNM rock is low since its saturation, 83.8%, is higher than the limit value (80%), and this value is also higher than the corresponding value of other rocks carved for construction. Thus, the probability of freeze-thaw-based damage to the rock is high. The degree of saturation of the brick was 77.2% (< 80%). Accordingly, it was concluded that the bricks used in the building were more durable than the rock under the freeze-thaw effect.

The average compressive strength of the stones was found to be 6 MPa, and of the brick was approximately 13 MPa. Both compressive strength values coincide with the values obtained from the literature. According to the International Society of Rock

40 Kemal Erguvanlı and Erdoğan Yüzer, “Past and Present Use of Underground Openings Excavated in Volcanic Tuffs at Cappadocia Area”, *Proceedings of the 1st International Symposium on Storage of Excavated Rock Caverns* (New York: Pergamon Press, 1977), 31–36.

41 Ömer Aydan and Reşat Ulusay, “Geotechnical and Geoenvironmental Characteristics of Man-Made Underground Structures in Cappadocia, Turkey”, *Engineering Geology* 69/3–4 (2003), 245–272, doi:10.1016/S0013-7952(02)00285-5.

42 Özgü Kasmer and Resat Ulusay, “Effects of Geo-Engineering Characteristics of the Soft Tuffs and Environmental Conditions on the Rock-Hewn Historical Structures at Zelve Open Air Museum, Cappadocia, Turkey”, *Environmental and Engineering Geoscience* 19/2 (2013), 149–171, doi:10.2113/gseegeosci.19.2.149.

43 Şerife Özata and Emine Görün Arun, “Damage Assessment of Rock-Cut Ortahisar Castle in Cappadocia Region”, *Gazi University Journal of Science* 31/1 (2018), 7.

44 Selma Sülükçü, “Kapadokya Bölgesi’ndeki Kayadan Oyma Yeraltı Depolarının Duraylılığının Değerlendirilmesi” (PhD dissertation, Hacettepe University, 2019), 37-153.

Mechanics (ISRM)[45], the rock of KHNM is in the weak rock group as the rock of Nevsehir Hagia Nicholas Monastery[46].

Capillary water absorption coefficient (WAC) values of the rocks and bricks are shared in **Table 4**. According to the WAC values of KHNM rock that vary between 10.2 - 13.2 kg/m^2√h, it is classified as a "highly absorbent rock"[47]. The WAC value of the KHNM rock is both close to and lower than the WAC value of previously carved structures' rock. The coefficient of the brick was determined as 11.2 kg/m^2√h, and it is also highly absorbent. The Byzantine bricks were very absorbent, but the KHNM brick has a lower WAC value compared to them.

Table 4. Capillary water absorption coefficients of the carved rocks and Byzantine bricks (Prepared by Şerife Özata and Büşra Aktürk)

Reference	Kahya[48]	Kurugöl and Tekin[49]	Stefanidou et al.[50]	***KHNM***
WAC of bricks (kg/m^2√h)	13.13-22.78	10.5-34.80	15.78-29.80	***11.2***
Reference	Topal and Doyuran[51]	Kaşmer and Ulusay[52]	Özata and Arun[53]	***KHNM***
WAC of rocks (kg/m$_2$√h)	21.60-29.30	13.70-33.21	8.60-13.60	***10.02-13.20***

45 Reşat Ulusay, *The ISRM Suggested Methods for Rock Characterization, Testing and Monitoring:2007-2014*, ed. Reşat Ulusay (Cham: Springer, 2015), https://link.springer.com/content/pdf/10.1007/978-3-319-07713-0.pdf.

46 Şerife Özata and Emine Görün Arun, "Damage Assessment of Rock-Cut Ortahisar Castle in Cappadocia Region", *Gazi University Journal of Science* 31 (2018), 8.

47 Siegfried Siegesmund and Rolf Snethlage, *Stone in Architecture: Properties, Durability*, (London: Springer Berlin Heidelberg, 2014), 125.

48 Kahya, "İstanbul Bizans Mimarisinde Kullanılan Tuğlanın Fiziksel ve Mekanik Özellikleri", 59:

49 Kurugöl and Tekin, "Anadoluda Bizans Dönemi Kale Yapılarında Kullanılan Tuğlaların Fiziksel, Kimyasal ve Mekanik Özelliklerinin Değerlendirilmesi", 772.

50 Stefanidou, Papayianni, and Pachta, "Analysis and Characterization of Roman and Byzantine Fired Bricks from Greece", 2255-2256.

51 Tamer Topal and Vedat Doyuran, "Engineering Geological Properties and Durability Assessment of the Cappadocian Tuff", *Engineering Geology* 47/ 1–2 (1997), 178-179, doi:10.1016/s0013-7952(97)00017-3.

52 Kasmer and Ulusay, "Effects of Geo-Engineering Characteristics of the Soft Tuffs and Environmental Conditions on the Rock-Hewn Historical Structures at Zelve Open Air Museum, Cappadocia, Turkey", 159.

53 Özata and Arun, "Damage Assessment of Rock-Cut Ortahisar Castle in Cappadocia Region", 7.

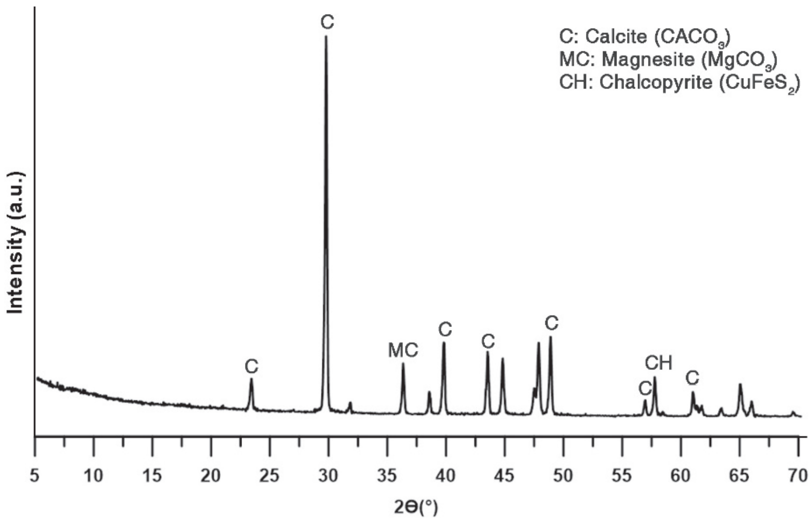
2.1.2. Chemical Properties of The Rock

X-Ray fluorescence spectrometry analysis was performed to determine the chemical composition of the rock and the results are shared in **Table 5**. Accordingly, it has been determined that the stone contains a very high amount of CaO along with a little amount of MgO and Fe_2O_3 mainly. Hence, the KHNM rock can be classified as a high-carbonate limestone based on its carbonate while it can be said that it is a high-calcium limestone according to the classification of limestone structure[54].

Table 5: The chemical composition of the rock. (Prepared by Büşra Aktürk)

Minerals	CaO	MgO	Fe_2O_3	SrO	RuO_2	CuO
%	95.69	2.00	0.57	0.22	0.70	0.11

In **F. 9**, the peaks obtained as a result of X-Ray diffractometry are shared. International Center for Diffraction Data (ICDD) and some other sources [55] were used for peak analysis. The rock has abundant calcite ($CaCO_3$) peaks as its main component. The observed small peaks of magnesite ($MgCO_3$) and chalcopyrite ($CuFeS_2$) confirm the XRF results. XRD results also approve that the material is limestone.

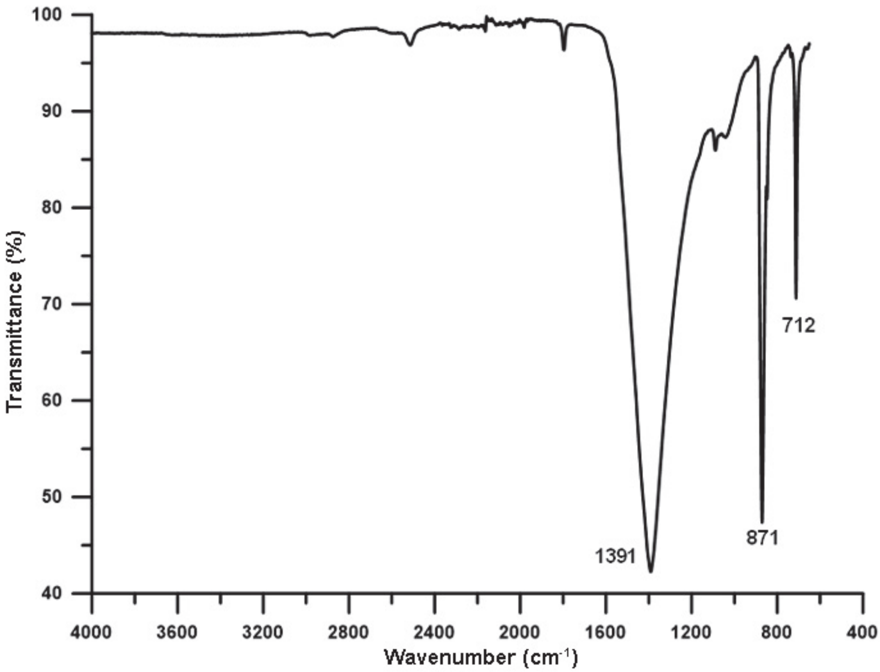


F. 9: X-Ray diffraction of the rock (Prepared by Şerife Özata and Büşra Aktürk)

54 State Planning Organization (Devlet Planlama Teşkilatı), *Sekizinci Beş Yıllık Kalkınma Planı, Alçı-Kireç-Kum-Çakıl-Mıcır-Boya Toprakları-Tuğla Kiremit Çalışma Grubu Raporu* (Ankara: State Planning Organization, 2001), 19.

55 Nsengimana Serge, Ashutosh Panigrahi, and Senthil Kumar, "A Comprehensive Study of Crystalline Limestone : A Case Study from Khondalite A Comprehensive Study of Crystalline Limestone : A Case Study from Khondalite Supergroup Rocks Belonging to Usilampatti Block, Tamil Nadu, S . India", *International Journal of Basic and Applied Research* 8/12 (2018), 575–586; Chaouki Sadik, Omar Moudden, Abdselam El Bouari, Iz-Eddine El Amrani "Review on the Elaboration and Characterization of Ceramics Refractories Based on Magnesite and Dolomite", *Journal of Asian Ceramic Societies* 4/3 (2016), 219–233, doi:10.1016/j.jascer.2016.06.006.

In this Fourier-transform infrared spectroscopy (FTIR) graph, in **F. 10**, prominent peaks were seen in wave numbers of 712 cm^{-1}, 871 cm^{-1}, and 1391 cm^{-1}, respectively. It is a typical calcite absorption band seen at 712 cm^{-1}[56]. The peak around 871 cm^{-1} is attributed to the out-of-plane bending vibration of CO_3^{2-}[57]. The peaks seen at approximately 871 cm^{-1} and 1391 cm^{-1} wave numbers generally represent O-C-O tension bonds belonging to the υ_3-CO_3^{2-} and υ_2-CO_3^{2-} carbonate groups, respectively, and indicate the presence of high-carbonate calcite[58]. The presence of the main oxide, CaO, confirms the presence of $CaCO_3$ compounds with carbonate phases in the sample.



F. 10: FTIR spectrum of the rock (Prepared by Büşra Aktürk and Şerife Özata)

2.1.3. Determination of Binder/aggregate Ratio by Acid Treatment

This experiment aims to determine the aggregate-to-binder ratio of the mortar sample used between the brick samples. The acid treatment experiment was carried

56 Nikos V. Vagenas, Alexopoulos, Gatsouli, and Christos G. Kontoyannis, "Quantitative Analysis of Synthetic Calcium Carbonate Polymorphs Using FT-IR Spectroscopy", *Talanta* 59/4 (2003), 831–836.

57 Rajeb Salem Hwidi, Tengku Nuraiti Tengku Izhar, and Farah Naemah Mohd Saad, "Characterization of Limestone as Raw Material to Hydrated Lime", *International Conference on Civil & Environmental Engineering* (Kuala Lumpur; EDP Science, 2018), 5.

58 Bo Yuan, Qingliang Yu, and H. Jos Brouwers"Time-Dependent Characterization of Na2CO3 Activated Slag", *Cement and Concrete Composites* 84 (2017), 188–197, doi:10.1016/j.cemconcomp.2017.09.005.

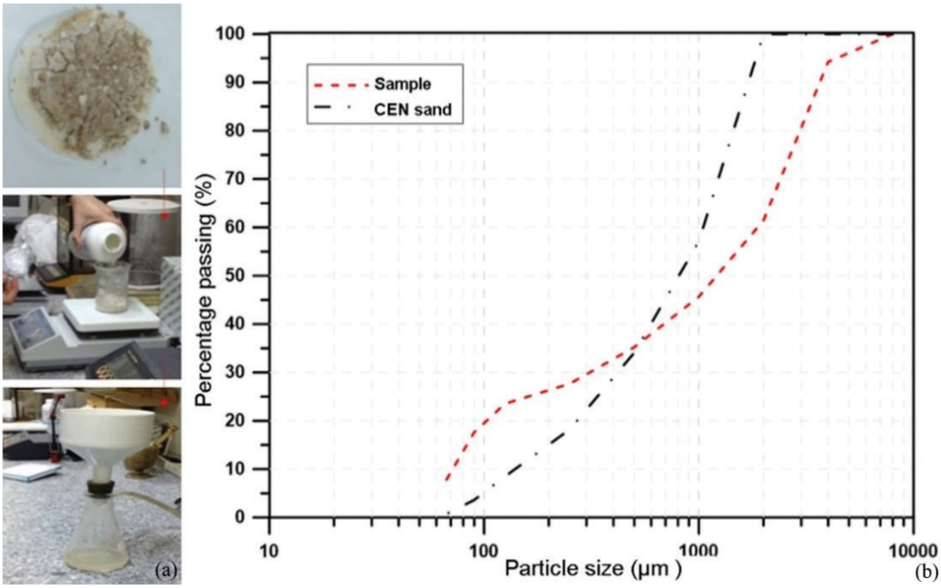
out according to a recommended method[59]. The mortar sample was separated into aggregate and binder using dilute hydrochloric acid (HCl). The most important assumption for determining the binder/aggregate ratio obtained from acid dissolution is that the binder exposed to acid dissolves and the silica-based aggregate remains intact as it will not be affected by acid. If there is carbonated aggregate in the material content, it will react with acid and the aggregate amount will be low. In similar studies, it would be useful to perform petrographic analysis, which cannot be done in this study due to material limitations, and to obtain information about the origin and mineral content[60], then perform this experiment.

50 g of the mortar sample obtained from the monastery was carefully crushed by hand. HCl (1N) was added and mixed in a magnetic stirrer at 1000 rpm for 60 minutes. At the end of this period, the remaining aggregate was filtered under constant pressure with a glass microfiber filter **(F. 11a)** and then dried at 105 °C for 24 hours. The dry aggregate was weighed and sieved. Sieve analysis results are shown in **F. 11b**. As a result of the experiment, the binder/aggregate ratio was found to be 1:2. In the literature, it is known that the binder/aggregate ratios are in various ratios such as 1:2, 2:3 and 1:1 as a result of the analyses carried out on the original mortar samples taken from the historical buildings built in the Roman, Eastern Roman, Seljuk and Ottoman periods[61].

59 Caspar Groot, Geoff Ashall, and John Hughes, *Rilem Report 28: Characterisation of Old Mortars with Respect to Their Repair*, (Paris: RİLEM Publishing 2004), 1-10.

60 Murat Eroğlu, Muhammet Bilgen, Ezgin Yetiş, Yusuf Kağan Kadıoğlu, and Kıymet Deniz, “Archaeometric Analyses of the Building Materials for the Karabük Ovacik Çukur Mosque”, *Art-Sanat Dergisi* 16 (2021), 151–179, doi:10.26650/artsanat.2021.16.0006; Namık Aysal, Sinan Öngen, Ertekin M. Doksanaltı, Okay Şahin, Ergün Çağıran, Derya Şahin, Mustafa Eruş, Mustafa Baykır, and Fatih Kocaışık “Mineralogical-Petrographical Investigations of the Building Blocks and Mortar-Plaster Samples of the Knidos Ancient City”, *Restorasyon ve Konservasyon Çalışmaları Dergisi* 19 (2019), 46–62.

61 Fatma Meral Halifeoğlu, Halide Sert, and Süheyla Yilmaz, “Tarihi Kurt Köprüsü (Mihraplı Köprü, Vezirköprü) Restorasyonu Proje ve Uygulama Çalışmaları”, *METU Journal of the Faculty of Architecture* 30/ 2 (2016), 81–104.



F. 11: (a) Acid treatment steps (Taken by Büşra Aktürk) (b) Granulometry results of aggregate (Prepared by Büşra Aktürk and Şerife Özata)

3. Damages and Deteriorations

Numerous environmental and human-induced factors affect historical buildings. Climate crisis, disasters and anthropogenic reasons such as vandalism, uncontrolled visits, inadequate maintenance, and inappropriate repair and restoration processes are among the main causes of historical structure deterioration.

The terms determined by the International Scientific Committee for Stone[62] were used while describing the damages. The deterioration and damage in the spaces of the monastery and the northern facade are shared in **F. 12** and **F. 13** respectively. Damages are listed as low, medium and high according to their intensity level in **Table 6**.

The monastery exhibits structural damages in the form of cracks and fragmentation, while non-structural damages include spalling, efflorescence, biological colonization, graffiti and scratches, staining, crust, weathering, and crumbling.

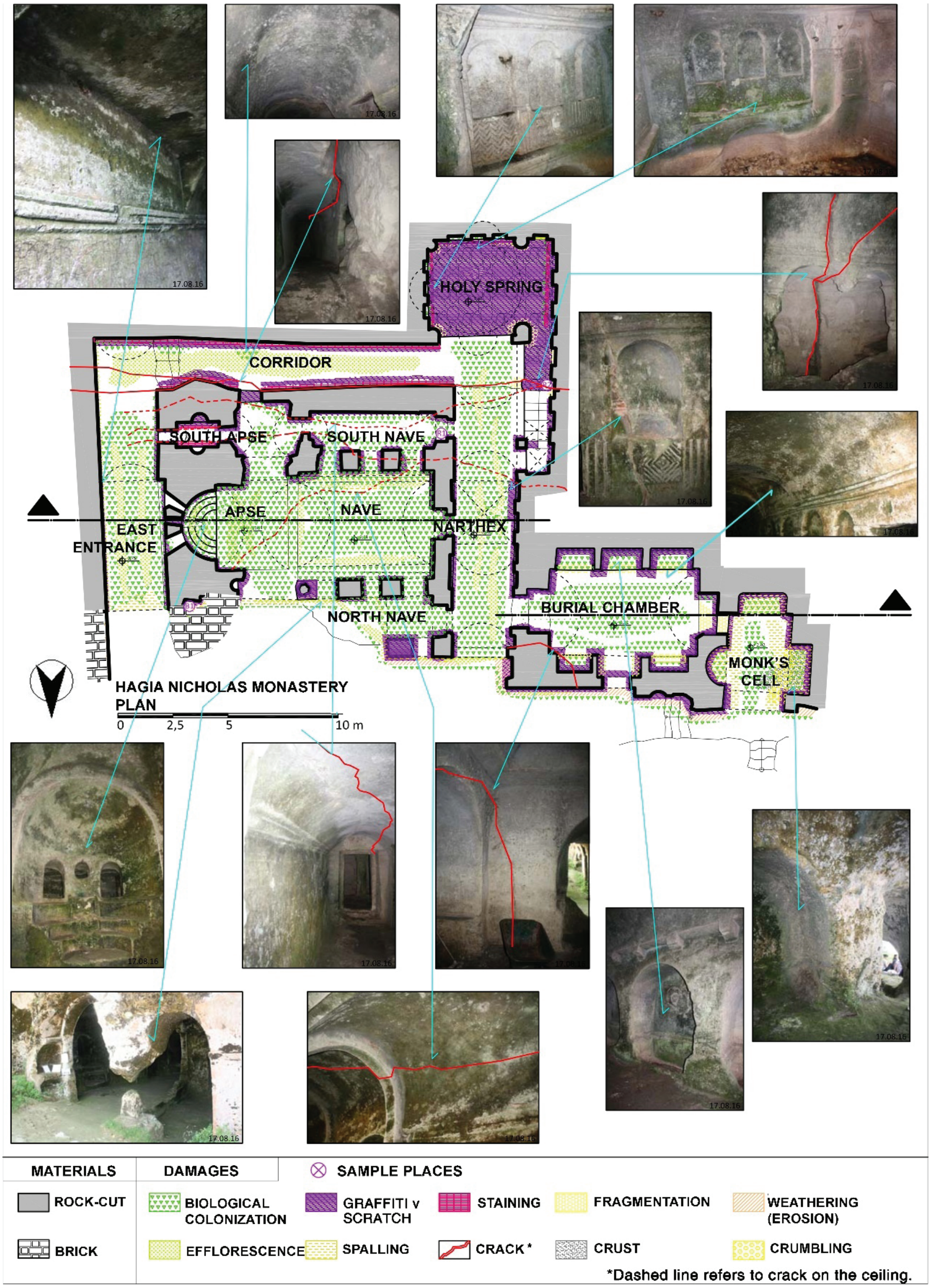
Spalling, efflorescence and biological colonization like algae, lichens and mosses exist on the ceiling of the eastern entrance. Also, there is graffiti and scratching on the east and west walls of the **(F. 12, F. 13)**. Staining is partly seen on the northern and southern walls of the corridor. There is biological colonization on some parts of

62 The International Council on Monuments and Sites / International Scientific Committee for Stone, *Illustrated Glossary on Stone Deterioration Patterns* (France: The International Council on Monuments and Sites, 2008), 1-85.

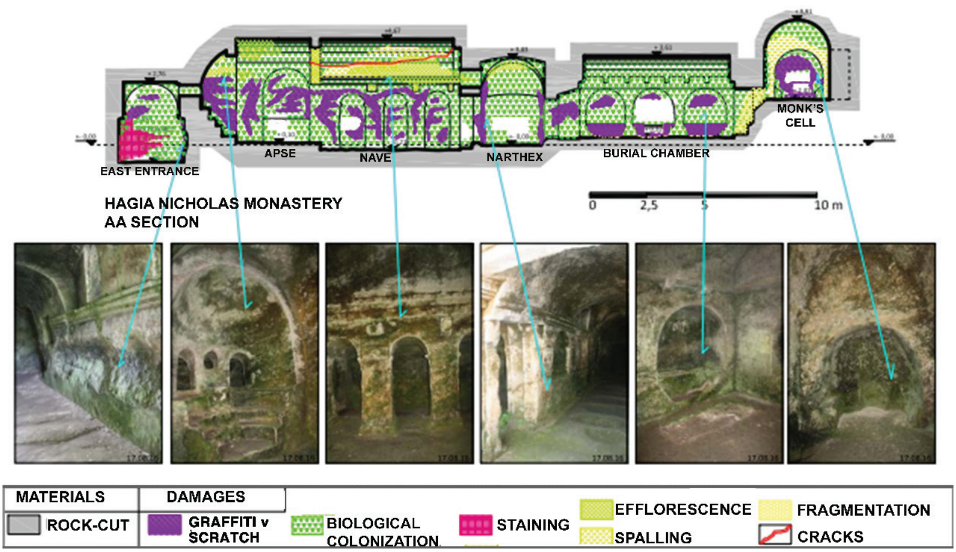
the southern wall that take sunlight. Cracks on the ceiling and floor are shown with a line in **F. 12** and crack on the ceiling are shown with the dashed line. Cracks in the corridor divide the building into two pieces. The crack widths start at 1 cm, and in some places, the width extends up to 25 cm and becomes a fracture.

The floor of the holy spring cannot be seen due to water and debris and destroyed pieces of corner columns. There are structural cracks and fractures on the floor and ceiling. They caused fragmentation on the eastern wall **(F. 12)** and at the bottom of the columns. Biological damages along with staining, efflorescence and spalling are seen on each wall of the holy spring.

Destruction, spalling and biological colonization are seen on the columns and walls of all naves. Devastated parts are generally in the north nave. The bottom of the one column in the north of the nave and some part of the floor is destroyed and fragmented. There are efflorescence and cracks on the ceilings of the naves. Wild vegetation exists on the floor **(F. 12)**. Walls and ceilings of the apses have efflorescence, biological colonization and scratches **(F. 13)**.



F. 12: Damages in the reflected ceiling plan of Hagia Nicholas Monastery (Prepared by Şerife Özata and Engin Aktürk)



F. 13: Damages in the section of Hagia Nicholas Monastery (Prepared by Şerife Özata and Engin Aktürk)

Table 6: Main deteriorations and damage of the monastery spaces and north facade (+: low, ++: medium, +++: high) (Prepared by Şerife Özata)

Spaces / Facade	Efflores-cence	Biological Coloniza-tion	Staining	Fragmen-tation	Vanda-lism	Spalling	Cracks	Crust	Erosion	Crumb-ling
East Ent-rance	++	+++	+	-	++	+	++	+	+	-
Corridor	-	+	++	-	+	-	+++	-	-	-
Holy spring	++	+++	+	+	+	+	++	+	+	+
Holy spring stairs	++	-	-	+	+++	-	+	+	+	-
Narthex	++	+++	-	+	++	-	++	+	+	-
Burial chamber	+	+++	-	+	+	-	+	+	+	-
Monk's cell	++	++	-	+++	++	+	-	+	++	+++
Nave	++	+++	-	-	++	+	++	++	++	+
Apse	++	+++	-	-	+	-	-	+	+	-
South Nave	-	++	-	+	+	-	+++	+	-	-
South Apse	-	++	+	-	++	-	+++	+	-	-
North Nave	-	+++	-	+++	-	+	-	+	-	-
North Facade	++	+++	-	+++	++	+	-	++	+++	-

There are rectangular graves on the floor of the narthex. Eastern and western walls, ceilings and floors have cracks, biological colonization and efflorescence and scratches are seen on these walls **(F. 12, F. 13)**.

The thin grave walls in the burial chamber are destroyed and fragmented. Graffiti, scratches, and efflorescence are seen on the walls together with biological deteriorations on the ceiling and floor. Monk's cell does not have a north wall. All its walls, floor and ceiling have scratches, spalling and biological colonization. There is the crust and crumbling on its west wall **(F. 12)**.

The only facade in the north has biological colonization, scratches, graffiti, efflorescence, fragmentation, spalling and weathering (erosion).

4. Material Characterization and Damage Based Conservation Assessment

According to the results of the material characterization experiments, the values of physical properties and compressive strength of the stones and Byzantine bricks were consistent with the values in other studies. Thus, it is recommended that the mechanical and physical of the stones and bricks to be used in the restoration of the monastery should be close to the original values or compressive strength of them may be partially higher.

Byzantine bricks and rocks were highly absorbent. Therefore, the capillary water absorption coefficients (WAC) of the stone and brick to be used in the restoration should be lower than the current values, both for freeze-thaw resistance and to prevent water damage. If there are different materials compatible with the original material to be used, it is suggested to use the material with the lower WAC value.

The main material of the monastery, which was carved into a rock in the Soğucak limestone formation, is high-calcium limestone. The chemical content of the stones and rocks to be used in restoration must be compatible with this material.

Since petrographic analysis could not be performed with the acid treatment test, the binder/aggregate ratio was found to be 1:2 by excluding carbonated aggregates, if any, in the material. Also, It was determined that the grain size distribution of the CEN (Commission for European Normalization) standard sand was close to the original mortar. Accordingly, it would be appropriate to use the binder/aggregate ratio of 1:2 in the mortar to be used in the brick wall restoration of the Hagia Nicholas Monastery and to use CEN sand as aggregate.

According to the observations made in the rock-cut Hagia Nicholas Monastery, the most common structural damage is crack and non-structural damages are efflorescence, biological colonization and graffiti.

The precautions to be taken to reduce the deterioration are summarized as follows:

Structural cracks may occur due to inherent characteristics of the rock, ground subsidence, excessive load, or earthquake. Two structural cracks in the monastery divide the structure in two. The reason for these cracks in the monastery may be due to rock formation, as in many rock-cut structures or an earthquake. Cracks can also trigger the mass falling of rock and fragmentation. Various damages around the crack also increase and expand the crack width. Endoscopic examination, georadar scans or motion meters can be performed periodically to monitor the structural crack mechanism. If the cracks are moving, additional structural elements made of materials compatible with the rock can be used. The use of steel materials in rock-cut structures is not recommended because the thermal expansion coefficients of steel and rock are quite different[63]. If an addition is to be made, it should not threaten the historical building's authenticity, although it is physically connected to it[64]. Fragmentation usually occurs around cracks. Therefore, it is necessary to intervene promptly to prevent the breakage of parts. In addition, rocks that are likely to break should be dropped in a controlled manner.

It is noteworthy that since the investigated structure was formed by carving a rock, any issues associated with the main rock directly impact the structure itself. This particular issue is unique to rock-cut structures and does not arise in any other structural systems. Therefore, when developing the proposal, the damage reasons identified in the first environment, the main rock, and the second environment around the rock should be taken into account. Since there is a layer of soil on the bedrock, the moisture in the soil is transmitted directly to the structure. Most of the recommended treatments for cleaning, consolidation and surface protection without cutting off this humidity supply will be the act of removing the symptom of the damage. To prevent the structure from water-induced damage, wells can be drilled around the structure and/or a waterproof layer created with natural or artificial materials may be designed to block the permeability of water between the bedrock and the topsoil.

Organisms such as lichens, algae, cyanobacteria, bacteria and fungi proliferate on the surface of the material at appropriate humidity and temperature and cause biological deterioration[65]. Although they generally cause biodegradation on the rock, some types of lichens can only reach 1 cm thickness in 300 years[66] and they prevent rock erosion by protecting surfaces from the effects of crumbling, spalling and changing weather conditions[67]. It is not recommended to intervene in lichens that occurred out-

63 Özata and Arun, "Damage Assessment of Rock-Cut Ortahisar Castle in Cappadocia Region", 10.

64 Jonathan Letzter, "Additions to Historic Buildings: Between Parasite and Prosthetic Architecture", *Journal of Architectural Conservation* (2022), 1–21, doi:10.1080/13556207.2022.2095803.

65 Georgia Toreno, Daniela Isola, Paola Meloni, Gianfranco Carcangiu, Laura Selbmann, Silvano Onofri, Giulia Caneva, and Laura Zucconi "Biological Colonization on Stone Monuments: A New Low Impact Cleaning Method", *Journal of Cultural Heritage* 30 (2018), 100–109, doi:10.1016/j.culher.2017.09.004.

66 İlyas Yılmazer, Saim Kale, and Behiç Çongar, "The Time Factor Accelerating Deterioration in the Göreme Historical Site", *The Safeguard of the Rock-Hewn Churches of the Göreme Valley International Seminar Proceeding*, (Rome: A & J Servizi Grafici Editoriali, 1995), 82.

67 Serife Ozata and Emine Gorun Arun, "Damage Assessment for Rock-Cut Dwellings and Warehouses: A Case Study in Bahceli Village, Cappadocia", *Masonry International* 30/3 (2018), 81–90.

side the structure if they protect the naturally occurring oxidation shells. If lichens are found to be harmful, these biological formations can be removed by dry ice application, laser cleaning or the traditional method of steam cleaning[68]. Innovative solutions, such as using nano-biocide-based intervention materials[69], bio-cleaning bacteria[70] and environment-friendly gels[71]are also other ways of removing harmful organisms. If there are wild herbs and grasses on these surfaces, the surface must be completely cleaned. Herbicides have also been used in the literature[72] to remove such plants from historical buildings.

Although the mechanism of efflorescence is not simple, the occurrence of this damage relies on three fundamental components; soluble-salt, sufficient moisture in the material and a path for the soluble salts to migrate through to the surface. The moisture and water retained by the highly permeable building material accelerate this process. Also, it should be checked whether there are water-soluble nitrate and sulphate salts in the original and repair materials, and exposure of the materials to water from any source should be prevented. Although sandblasting, laser cleaning, and chemical-biological cleaning processes can relieve the symptoms[73] of this damage, salt extraction[74] can provide a permanent solution as it eliminates one of the components that make up the efflorescence.

Climatic conditions and fire may cause spalling, staining, crust, weathering and crumbling. Wetting-drying and freeze-thaw effects are present in the region and the water absorption capacity and saturation degree of the brick and rock is high. Also, their strength is low. Therefore, it is expected to observe such damages in the structure. In order to reduce such non-structural damages, sources of moisture in the structure should be eliminated. Inorganic consolidants, alkoxy silanes or various polymers can also be used to consolidate the rock[75]. In addition, various water repellents, emulsions, and anti-graffiti surface coatings may be used to protect surfaces[76]. However, in some

68 Ahmet Ersen, “Taş Korumada Son 20 Yıldaki Gelişmeler ve Yenilikler”, *Restorasyon ve Konservasyon Çalışmaları Dergisi* 10 (2013), 2-12.

69 Javier Becerra, Maripaz Mateo, Pilar Ortiz, Ginés Nicolás, and Ana Paula Zaderenko, “Evaluation of the Applicability of Nano-Biocide Treatments on Limestones Used in Cultural Heritage”, *Journal of Cultural Heritage* 38 (2019), 126–135.

70 Khaled Z. ElBaghdady, Sahar T. Tolba, and Soha S. Houssien, “Biogenic Deterioration of Egyptian Limestone Monuments: Treatment and Conservation”, *Journal of Cultural Heritage* 38 (2019), 118–125.

71 Toreno, Isola, Meloni, Carcangiu, Selbmann, Onofri, Caneva, and Zucconi, “Biological Colonization on Stone Monuments: A New Low Impact Cleaning Method”, 102.

72 Gülçin Kahraman and Seden Acun Özgünler, “Aizanoi Antik Kentinde Bulunan Odeion Yapısının Malzeme Özellikleri ve Hasar Durumunun Incelenmesi”, *Art-Sanat* 16 (2021), 355–379, doi:10.26650/artsanat.2021.16.0012.

73 “Efflorescence: Cause and Control” Masonry Institute of America, accessed June 08, 2023, https://www.masonryinstitute.org/pdf/612.pdf

74 Ersen, “Taş Korumada Son 20 Yıldaki Gelişmeler ve Yenilikler”, 5.

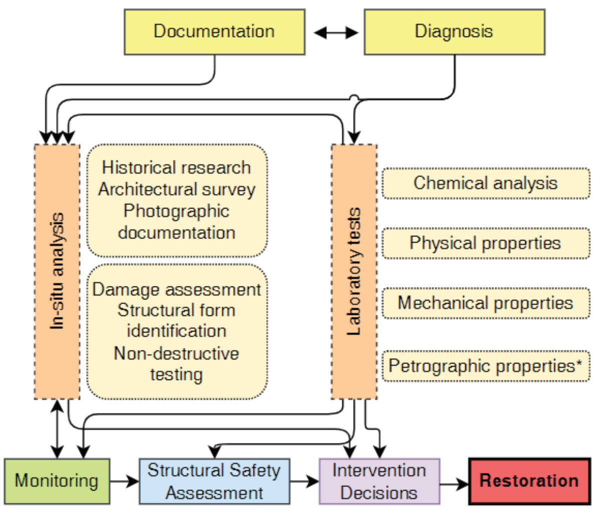
75 Ersen. “Taş Korumada Son 20 Yıldaki Gelişmeler ve Yenilikler”, 6-12.

76 Ersen. “Taş Korumada Son 20 Yıldaki Gelişmeler ve Yenilikler”, 8-9.

cases, the application of a water-repellent substance to the rock surface is generally not beneficial for the rock and may cause new damage such as spalling and cracking[77]. The adverse effects of such practices can be seen in the restoration practices applied in Goreme Open Air Museum Sarica Church in Cappadocia.

Human-induced damages such as graffiti and scratches are usually made by unconscious individuals and are sometimes done deliberately. Anti-graffiti surface coatings can be used to protect surfaces[78]. Informing the public through awareness training is essential not only for the preservation of this historical monastery but also for all other heritage monuments. Also, preventive protection measures such as limiting visitors, controlling humidity and temperature in the structure may help reduce the damage.

In **F. 14**, the flow and feedback mechanism of a Byzantine rock-cut structure restoration involves thorough analysis and various experiments. In addition to the experiments performed, petrographic analysis, which enables rock identification and classification, is a useful alternative to chemical experiments. Additional tests to determine the type of salt in the material are also proposed to better understand the mechanism of efflorescence.



F. 14: Restoration steps chart of a Byzantine rock-cut structure[79] (Prepared by authors)

Restoration works cannot be a linear study. Almost every step feeds some others and provides data for precise and ideal results this fact was confirmed in the result of Hagia Nicholas Monastery. In all types of repair and restoration works, interventions

77 Eddy De Witte, "Conservation of the Göreme Rock", *The Safeguard of the Rock-Hewn Churches of the Göreme Valley International Seminar Proceeding* (Rome: A & J Servizi Grafici Editoriali, 1995), 122-123.

78 Ersen, "Taş Korumada Son 20 Yıldaki Gelişmeler ve Yenilikler", 9.

79 Petrographic properties could not be determined in this study due to limitations in available materials.

should be reversible and the materials to be used in restorations must be compatible with the original material. Mechanical and physical experiments are a must but should be supported by chemical or petrographic analyses to define materials in detail.

Conclusions

Many Byzantine rock-cut structures with significant universal value are in a state of disrepair around the world. The aim of this study is to define the diagnosis, repair and restoration steps that can be applied in buildings of similar periods and types with the examination, analysis and experiments carried out on the example of Kiyikoy Hagia Nicholas Monastery (KHNM), which has a basilical plan with 3 naves and was built in the Early Byzantine Period. The general results obtained from the experimental, observational and comparative analyses conducted for this purpose are as follows:

- The experiments conducted to assess the physical, mechanical, and chemical properties of the rock and brick material of KHNM revealed that rock has low strength and is highly absorbent limestone. Furthermore, it was observed that the compressive strength of the brick was higher than that of the rock and similar to the values reported for Byzantine brick in the literature.

- By determining the density, porosity, compressive strength and capillary water absorption coefficient (WAC) values of the original materials through physical and mechanical tests, compatible repair materials that have at least 13 and 6 MPa compressive strength for brick and rock respectively were proposed. The total porosity of repair materials must be less than 34%, the real density of them should be approximately 2.6 g/cm^3 and the WAC of them should be less than 10 kg/m$^2\sqrt{h}$.

- With the XRD, XRF and FTIR experiments, it was determined that the rock is high carbonate limestone and its main component is calcite. FTIR method contributed less in determining the oxides and rock type than XRD and XRF. It was suggested that petrographic analysis could also be performed instead.

- With acid treatment in mortar it was suggested that the binder/aggregate ratio of the repair mortar to be used in this monastery should be 1:2 and CEN sand can be used.

- The building which is the Byzantine-era rock-hewn monastery in the Thrace region has suffered severe damage. It has been observed that cracks in the KHNM are caused by earthquakes or rock formation, and additional structural elements made of compatible materials can be used to strengthen the building that has cracks and fractures. Non-structural damages, especially efflorescence and biological colonization are caused by moisture of the soil layer above the main rock. In order to cut off this water source, it was suggested that the separating layers between soil and rock could be designed and wells drilled around the structure, which was applied in traditional methods.

- In biological colonization, firstly it should be determined whether lichens are beneficial or harmful, and if intervention is necessary, a traditional method such as steam cleaning or bio-cleaning bacteria and gels can be used. In order to prevent efflorescence, it was determined that the final solution could be reached by cutting one of the three main factors causing it, and it was determined that this damage could be eliminated by solving the water problem in the structure. It was seen that the salt extraction method would prevent this damage by removing the salt from the material. Methods such as sandblasting or laser cleaning were determined to remove its symptoms.

- As solutions to non-structural damages other than the above-mentioned ones, it was suggested to eliminate the source of moisture in the structure and to use various water repellents, emulsions, and anti-graffiti surface coatings to protect the surface. These repair products must be selected by considering their adverse effects since there are lots of restoration works where such surface protection products damage the surface of rocks.

- Education and awareness raising to prevent human-induced damages; humidity and temperature control to reduce direct climatic effects and preventive protection measures throughout the building are recommended.

Despite the distinct architectural style and unique materials of the rock-hewn Kiyikoy Hagia Nicholas Monastery, the results of this study have generated inclusive findings that can be applied to other rock-cut structures sharing similar features. Comprehensive documentation and diagnosis methods were carried out on samples from an Early Byzantine Period rock-hewn structure, based on their suitability for implementation. Subsequently, a basic but fundamental set of steps for the preservation of similar rock-cut structures was developed and some damage-remedial measures were suggested. Consequently, through the work conducted in the laboratory and on-site, the conservation enhancement of rock-cut structures, and ensuring their transmission to future generations were provided.

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