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Architectural Investigation and Material Characterization of Byzantine Brick Masonry Church: A Case Study of the Üç Ayak Church

Bizans Dönemine Ait Tuğla Yığma Kilisenin Mimari İncelemesi ve Malzeme Karakterizasyonu: Üç Ayak Kilisesi Örneği

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Abstract

The Üç Ayak Church in Kırşehir, Türkiye, is a notable example of middle-Byzantine architecture with a double-nave plan and exceptional masonry, including hidden bricks and double-layer lime mortar. This study investigates the historical significance of the Üç Ayak Church and promote its preservation through comprehensive material characterization and architectural analysis. To achieve these objectives, first he architectural features of the building that was built in the 11th century were discussed. The architectural study concludes that the distinctive features of this endangered Byzantine monumental structure, which represents a crucial aspect of cultural heritage, must be preserved and thoroughly examined. This survey investigates not only the notable features, structural alterations, materials, and construction techniques of the building but also integrates data from previous studies, on-site observations, and comparisons with structures of similar typology. Furthermore, mechanical and chemical analyses were employed to thoroughly examine the mortar and brick properties of the church. Mortars display a 3.6 MPa compressive strength, limiting the hydraulic potential. The bricks exhibited 9.8 MPa, aligning with Byzantine brick studies. XRD analysis inferred the firing of bricks at 850-900°C. SEM-EDS confirmed the absence of vitreous phases, affirming the heterogeneous structure. Findings guide selecting materials for restoration endeavors.

Öz

Kırşehir'de bulunan çifte planlı tarihî Üç Ayak Kilisesi, Orta-Bizans mimarisinin nadir bir örneğidir. Bu kilisede gizli tuğla tekniği ve çift katmanlı kireç harcı uygulaması içeren yapıya özgü duvar yapım teknikleri bulunmaktadır. Bu çalışmada, Üç Ayak Kilisesi'nin öneminin açığa çıkartılması ve malzemelerinin karakterizasyonu yoluyla yapının gelecek nesiller için korunmasının kolaylaştırılması amaçlanmaktadır. Çalışmada ilk olarak, 11. yüzyılda inşa edilen yapının mimari özellikleri ele alınmıştır. Mimari araştırma yapılarak yok olma tehlikesiyle karşı karşıya olan, korunması gereken ve önemli bir kültürel miras eseri olan Bizans anıtsal yapısının ayırt edici özellikleri kapsamlı bir şekilde incelenmiştir. Araştırmada, yapının dikkat çekici özelliklerinin yanı sıra, yapıdaki değişiklikler, malzeme, yapım tekniği ve benzer plan tipolojisine sahip yapıların karşılaştırılması gibi konular ele alınmış, bu özellikler yapı üzerinde yapılan çalışmaların derlenmesi ve yerinde yapılan gözlemlerden elde edilen veriler ile açıklanmıştır. Sonrasında, mimari araştırmanın yanı sıra kiliseye ait harç ve tuğla özelliklerini keşfetmek için mekanik ve kimyasal analizler kullanılmıştır. Harçlar ortalama 3.6 MPa basınç dayanımı gösterirken hidrolik olma potansiyelini de kısıtlamaktadır. Tuğlaların ortalama 9.8 MPa olan basınç dayanımı değeri literatürdeki Bizans tuğla çalışmalarıyla uyumludur. XRD ile tuğlaların pişirme aralığı 850-900°C olarak belirlenmiştir. SEM-EDS ile heterojen yapıyı teyit eden camsı fazların olmadığı doğrulanmıştır. Bulgular, özellikle restorasyon çalışmalarında malzeme seçimi için rehberlik sağlamaktadır.

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Keywords Üç Ayak Church · Material Characterization · Twin Church · Endangered Heritage · Byzantine Architecture · Brick Masonry

Anahtar Kelimeler Üç Ayak Kilisesi · Malzeme Analizi · İkiz Kilise · Tehlike Altındaki Miras · Bizans Mimarisi · Tuğla Yığma

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Genişletilmiş Özet

Anadolu toprakları, yüzyıllar boyunca birçok medeniyete ev sahipliği yapmış ve bu medeniyetler, yaşamları boyunca inşa ettikleri tarihî yapılarla Türkiye'nin kültürel zenginliğine büyük katkılarda bulunmuştur. Bu yapılar, geçmiş ve gelecek arasında bir köprü kurarak toplumsal ve sosyal hafızanın oluşumuna destek olmuş, kültürel mirasın sürekliliğini sağlamıştır. Bu bağlamda, tarihî yapıların korunması, 21. yüzyılın en önemli mimarlık sorunlarından biri haline gelmiştir. Tarihî yapıların korunması, önceden yapılmış araştırma ve analizlerin kapsamı ve derinliği ile doğrudan ilişkilidir. Detaylı analizler, korunması gereken yapıların anlaşılmasını ve doğru restorasyon müdahalelerinin yapılmasını sağlayarak, bu yapıların gelecek kuşaklara aktarılmasına katkıda bulunur. Bu nedenlerle, Kırşehir-Merkez ilçesine bağlı Taburoğlu köyü yakınlarında bulunan ve Kültür Varlıklarını Koruma Bölge Müdürlüğü tarafından tescillenen Bizans Dönemi'ne ait tarihî Üç Ayak Kilisesi'nin korunması amacıyla kapsamlı mimari ve malzeme analiz çalışmaları gerçekleştirilmiştir. Bu analizler, kilisenin özgün yapısal ve malzeme özelliklerinin detaylı bir şekilde incelenmesini sağlayarak, yapının korunması ve restorasyonu için gerekli bilgileri sunmaktadır. Bizans Dönemi'ne ait olup 11. yüzyılda inşa edildiği belirlenen Üç Ayak Kilisesi, özellikle son yıllarda hem antropojenik hem de doğal etmenler nedeniyle önemli ölçüde hasar görmüştür. Bu hasarların sonucunda, yapının bazı bölümleri tamamen yıkılmış ve yalnızca kalıntıları günümüze ulaşabilmiştir. Bu yapı, Bizans mimarisinin nadir ve özgün örneklerinden biri olarak dikkat çekmektedir. Özellikle simetrik çifte kilise planı, tamamen tuğladan inşa edilmiş olması ve yerleşim alanlarından uzak, açık bir düzlükte yer alması gibi özellikleriyle öne çıkmaktadır. Ayrıca, kilisenin hiçbir yapı kalıntısının bulunmadığı bir alanda inşa edilmesi, yapının mimari bağlamında belirsizlikler ve özgünlükler barındırmaktadır. Bu nedenle, Üç Ayak Kilisesi, Bizans mimarisinin araştırılması ve korunması açısından büyük önem taşımaktadır.

Yaklaşık iki asırdır çeşitli şekillerde araştırmalara konu olan Üç Ayak Kilisesi, ilk kez 1842 yılında İngiliz seyyah W. I. Hamilton'un kitabında yer alarak bilim dünyasına tanıtılmıştır. Bu ilk referans, yapının tarihi ve kültürel önemi hakkında ilk izlenimleri sunmuş ve kilisenin bilimsel araştırmalara açılmasının kapılarını aralamıştır. Takip eden yıllarda, İngiliz araştırmacı W. Ainsworth, bu yapıyı ziyaret eden ilk kişi olarak kaydedilmiştir. Ainsworth, kısa bir tanımlama yaptıktan sonra kilisenin gravürünü çizmiş ve bu da yapının görsel belgelenmesine katkıda bulunmuştur. 1900'lerin başlarından itibaren, Üç Ayak Kilisesi, çeşitli araştırmacıların ilgisini çekmiştir. Bu dönemde, H. H. Graf Von Schweinitz, Hititolog H. H. von der Osten, R. Krautheimer, S. Curcic, Hild ve Reitle gibi isimler, yapının tarihî ve mimarî özelliklerini inceleyerek çeşitli çalışmalar yapmışlardır. Bu araştırmalar, kilisenin Bizans dönemi mimarisi ve dinî mimarisi açısından ne denli önemli olduğunu vurgulamış ve yapı hakkında çeşitli bilgiler sunmuştur. Türk sanat tarihçisi Semavi Eyice, 1968 yılında gerçekleştirdiği detaylı çalışmada, Üç Ayak Kilisesi'nin mimari yapısını ve tarihini kapsamlı bir şekilde ele almıştır. Eyice'nin bu kapsamlı araştırmaları sonucunda, kilisenin planı ayrıntılı bir şekilde ortaya konmuş ve yapı hakkında birçok önemli bilgi elde edilmiştir. Özellikle, Eyice'nin çalışmaları, kilisenin mimari özelliklerini ve tarihî bağlamını anlamada büyük bir katkı sağlamıştır. Son yıllarda da, çeşitli araştırmacılar Üç Ayak Kilisesi üzerinde detaylı incelemeler yaparak yeni ve önemli bulgular elde etmişlerdir. Bu çalışmalar, kilisenin hem Bizans mimarisi hem de dinî mimarisi açısından büyük bir öneme sahip olduğunu göstermektedir. Yapının tarihi ve mimari değeri, bu tür bilimsel araştırmalar sayesinde daha iyi anlaşılmakta ve korunma çabalarına ışık tutmaktadır.

Çalışmanın saha aşamasında, ilk olarak Üç Ayak Kilisesi'ne dair yapılan yerinde gözlemler ile geçmişte gerçekleştirilen araştırmalar bir araya getirilmiştir. Bu kapsamlı analizler sonucunda, kilisenin plan tipi, yapım tekniği ve kullanılan malzemeler detaylı bir şekilde belirlenmiştir. Bizans mimarisinde ikili, üçlü plan tipleri bulunmaktadır ancak bu yapılar sonradan eklenen parçalar ile ikili veya üçlü plan tipine dönüştürülmüştür. Yapımında ikiz olarak tasarlanan yapı ise bilinmemektedir. Bu bağlamda Üç Ayak Kilisesi tuğla yığma tekniğiyle oluşturulmuş türünün nadir örneğidir. Yapının çifte plan tipi ve gizli tuğla tekniği ile oluşturulduğu bilinmektedir. Apsis cephesinin çok yüzlü olduğu, narteksinin tek katlı olduğu, naos üstündeki kubbenin pandantiflerle taşındığı, cephelerdeki nişlerin ve niş içinde iç içe tasarlanmış pencerelerin varlığı tespit edilmiştir. Tuğla aralarından düşen üç farklı harçta yapılan deneyde harcın

ortalama basınç dayanımı 3.6 MPa olarak tespit edilmiştir. Gözlemler, bu harcın dayanımının el ile kolayca ufalanabilecek kadar düşük olduğunu göstermektedir. Ancak, tuğla derzlerinde kullanılan özel derzleme harcı, dış etkilerden doğrudan koruma sağlayarak ve cephede estetik bir görünüm kazandırarak düşük dayanımlı harçların korunmasına katkıda bulunmuştur. Ayrıca, 90 cm kalınlığındaki taşıyıcı duvarlarda tasarlanmış kemerlerin üst kısmında kalacak şekilde zeminden yaklaşık 380 cm yükseklikte çapı genelde 18 cm olan birer adet daire formlu ahşap hatıl bulunmaktadır. Boyutları yaklaşık 140x170 cm olan ayaklarda ise taşlarla oluşturulmuş 50 cm yüksekliğindeki subasman seviyesi üzerinden başlanarak yaklaşık 40 cm, 160 cm ve 300 cm yüksekliklerinde üçer adet 18x18 cm ebatlarında ahşap kare hatıl mevcuttur.

Kullanılan yatay ahşap hatıllar taşıyıcı duvar narinliğini düşürmüş ve yapının depreme dayanıklılık performansını arttırmıştır. Tuğlaların yığında pişirme yöntemi ile oluşturulduğu tahmin edilmektedir. Bizans Dönemi'nde tuğla pişirmek için özel fırınların kullanıldığı bilinse de yapının yakın çevresinde buna dair herhangi bir kalıntı saptanmamıştır. Tuğlalar yığın hâlinde yakılarak da pişirilebilmektedir. Ancak yapıda kullanılan tuğlaların pişirme yöntemine dair kesin bilgi için yapı çevresinde kapsamlı kazı yapılması ve bu bilgiye dair veri sağlayacak olumlu ya da olumsuz kanıt aranması gerekmektedir. Tuğla işçiliğine bakılarak taşıyıcı duvarların *Opus latericium* tekniğiyle inşa edildiği saptanmıştır, ancak temelde ve bazı duvarların üzerinde kesme taşlar da bulunduğu için yapının genelinde hibrit yapıyı karakterize eden *Opus mixtum* tekniği kullanıldığı düşünülmektedir.

Çalışmanın deneysel aşamasında, Üç Ayak Kilisesi'nden alınan harç ve tuğla numuneleri üzerinde detaylı karakterizasyon çalışmaları gerçekleştirilmiştir. Bu süreçte, harç ve tuğla örneklerinde malzeme özelliklerini belirlemek için çeşitli analiz yöntemleri kullanılmıştır. Özellikle, harç örneklerinde X-Işını Kırınımı (XRD) yöntemi kullanılarak malzemenin mineral bileşenleri ve kristal yapısı hakkında kapsamlı veriler elde edilmiştir. Ayrıca, tuğla örneklerinde X-Işını Floresansı (XRF) yöntemi uygulanmış ve tuğlanın kimyasal bileşimi hakkında bilgi toplanmıştır. Bunun yanı sıra, Taramalı Elektron Mikroskobu Enerji Dağılım Spektroskopisi (SEM-EDS) tekniği ile tuğlaların mikro yapısı ve elementel kompozisyonu detaylı bir şekilde incelenmiştir. Bu analizler, malzemelerin fiziksel ve kimyasal özelliklerine dair kapsamlı veriler sağlamış ve yapı malzemelerinin karakterizasyonunu derinleştirmiştir. Sonuç olarak, elde edilen bu veriler, hem yapının mevcut durumunun anlaşılmasına hem de gelecekteki restorasyon ve korunma stratejilerinin belirlenmesine katkıda bulunmuştur. Tuğla ve harçta yapılan malzeme karakterizasyonu ile çoğunlukla alümino silikat mineralleri olmak üzere tuğlada koesit, hematit ve kalsit gibi mineraller de görülmüştür. Tuğlada yapılan ve XRF ile elde edilen oksit oranları da bu sonucu destekler niteliktedir. Harçta yapılan XRD deneyinde belirlenen mika ve bazı alümino silikat türleri harç içindeki kilin belirtisidir. Yoğun görülen kalsiyum pikleri ise kirecin göstergesidir. Buna göre harcın kireç harcı olduğu saptanmıştır. Ayrıca kil içeren XRD deseninde C-S-H piki görülse de bu pik çok zayıf olduğu için harcın hidrolik özelliğinin olmadığı düşünülmektedir. Harcın düşük basınç dayanımı (3.6 MPa) da harcın hidrolik olmadığı yönünde veri sağlamaktadır. Ancak harcın hidrolik olup olmadığını belirlemek için XRD ve basınç dayanımı deneyi tek başına yeterli değildir. Harcın niteliğine dair daha net sonuç elde etmek için Termogravimetrik ve Diferansiyel Termal (DTA-TG) analiz yapılması önerilmektedir. Tuğladaki mineral oluşum ve yok olma sıcaklıkları incelendiğinde, tuğlanın pişirilme sıcaklığının yaklaşık olarak 850-900 °C arasında olduğu tespit edilmiştir. Bu tespit, yapılan deneysel analizler ve elde edilen verilerle sınırlı kalmıştır. Tuğlanın pişirilme sıcaklığı hakkında daha kesin ve ayrıntılı bilgi elde etmek için Diferansiyel Termal Analiz (DTA) ve Termogravimetrik Analiz (TG) yöntemlerinin uygulanması önerilmektedir. Bu analizler, malzemenin termal özelliklerini daha hassas bir şekilde belirlemeye olanak tanır ve tuğlanın üretim süreci hakkında daha detaylı veriler sağlayabilir. DTA-TG analizleri, tuğlanın pişirilme sıcaklığının yanı sıra, pişirme sırasında meydana gelen kimyasal ve fiziksel değişimleri de ortaya koyarak, malzemenin karakterizasyonunu daha derinlemesine anlamamıza yardımcı olabilir. Bu tür kapsamlı analizler, restorasyon ve koruma süreçlerinde gerekli olan bilgilerin elde edilmesini destekleyecektir.

Tuğlada yapılan SEM-EDS (Taramalı Elektron Mikroskobu Enerji Dağılım Spektroskopisi) analizi, malzemenin mikro yapısına dair önemli bulgular sunmuştur. Bu analiz sonucunda, tuğlanın içinde camsı bir yapı görülmemiş olup, heterojen bir mikro yapı ile karşılaşılmıştır. Bu durum, tuğlanın pişirilme derecesi aralığını belirlemek amacıyla yapılan XRD (X-Işını Kırınımı) analizleriyle tespit edilen pişirme sıcaklıklarıyla uyumlu olduğunu doğrulamıştır. SEM-EDS analizi ayrıca, tuğlanın rengini veren demir (Fe) elementlerinin varlığını da teyit etmiştir. Kuvars 1050°C sıcaklıkta eridiği için 850-900°C'de pişirildiği tespit edilen tuğlanın iç yapısı heterojen kalmış, erime neticesinde oluşan camsı kristal bir iç yapı gözlemlenmemiştir. Daha geniş malzeme alanına dair veri elde edilmesi için mikroskobik inceleme de yapılabilir çünkü SEM_EDS analizi malzemenin çok kısıtlı bir alanında gerçekleştirilmektedir. Tuğla numunelerde gerçekleştirilen basınç deneyi neticesinde tuğlanın ortalama basınç dayanımı 9.8 MPa olarak tespit edilmiştir. Bu özellikler ile malzemelerin mekanik ve fiziksel özelliklerinin açığa çıkarılması ve dayanıklılık deneylerinin yapılması

bu verileri daha da kuvvetlendirecektir. Herhangi bir onarım veya restorasyon durumunda malzemelerin tespit edilen bu özellikleri yeni malzeme önerisi geliştirmeyi kolaylaştırıcı bir altyapı sunmaktadır.

Mevcut durumda hasar oranı oldukça ileri seviyeye ulaşmış olan Üç Ayak Kilisesi gibi tarihî yapıların korunması ve muhafaza edilmesi, kültürel mirasın sürekliliği açısından hayati bir önem taşımaktadır. Bu yapılar, sadece kültürel ve tarihî değerlerinden dolayı değil, aynı zamanda yapıldıkları dönemin mimari ve teknolojik bilgilerini yansıttıkları için de korunmalıdır. Bizans dönemine ait bu tür yapıların korunması, sadece geçmişin izlerini korumakla kalmaz, aynı zamanda medeniyetimizin teknoloji ve sanat alanındaki gelişimlerini de belgeleyerek geleceğe aktarır. Dolayısıyla, bu tür tarihî yapıların korunması, medeniyetimizin kıymetli mirasını gelecekteki nesillere güvenilir ve sağlam bir şekilde ulaştırmak için vazgeçilmez bir yoldur. Bu bağlamda, bu çalışma aracılığıyla Üç Ayak Kilisesi ve benzeri tarihî yapıların korunmasına yönelik önemli veriler elde edilmiştir. Bu veriler hem mevcut yapıların korunmasını hem de insanlığın ortak mirasına katkıda bulunacak şekilde gelecekte benzer yapıların ayakta kalmasını sağlamaya yönelik bilimsel ve pratik yaklaşımları destekleyecektir.

Introduction

Anatolian lands have hosted many civilizations for centuries. Numerous civilizations enriched Türkiye in terms of historical artifacts and structures they built during their lifetime, and they left many exceptional buildings. One of these special assets that was constructed during the Byzantine era within the borders of Türkiye is the Üç Ayak Church. To ensure the sustainability of these structures and to guarantee that they are passed on to future generations in a secure manner, the structures should be examined in detail and comprehensive analyses should be carried out for any type of conservation practice to be carried out.

The Üç Ayak Church is located on a plain between Kırşehir and Yozgat cities, at coordinates 39.4134° N and 34.1712° E, in the middle of Türkiye (Figure 1). During its construction, it was located in proximity to the borders of Galatia and Cappadocia, which were both provinces of the Byzantine Empire[1]. It is situated 3 km away from the Kırşehir-Yozgat road, between the villages of Taburoğlu and Homurlubeşler, and to the east of Bozluk Mountain currently (Figure 1).

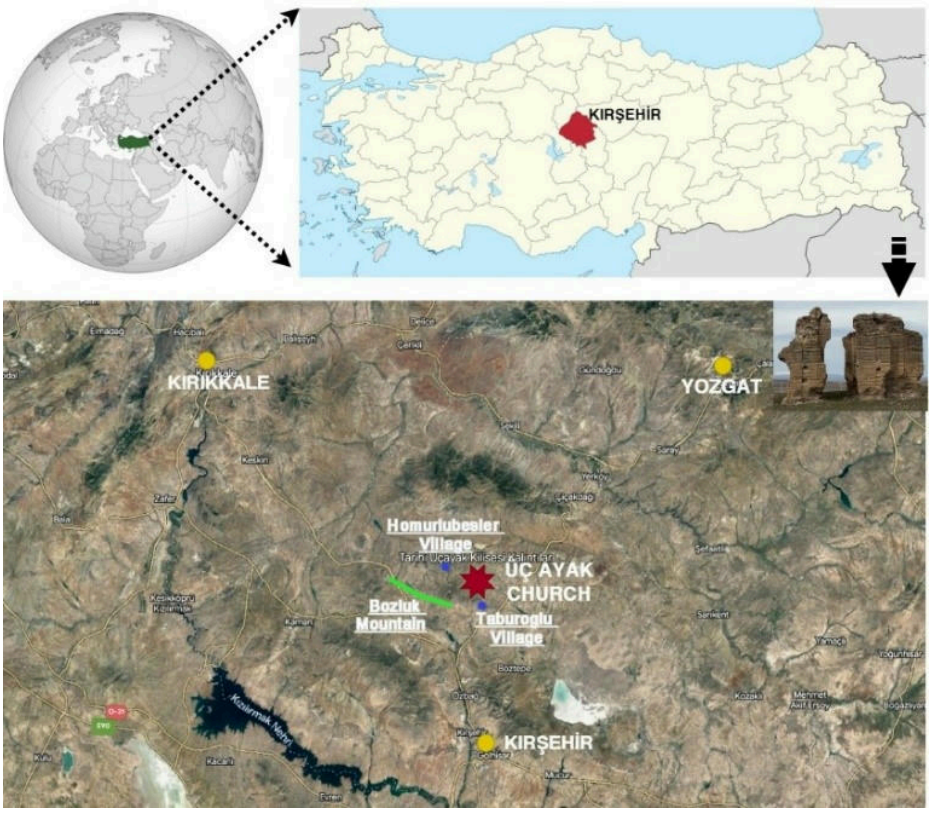

Figure 1: *Location of the church*
Source: Prepared by M. Başgül

It stands as the region's one of the most distinguished historical buildings, distinguished by its predominantly brick construction, with stone plinth walls rising approximately 50 cm in height. In the past, the church attracted attention with the presence of three arches carrying its dome and for this reason, it is called "Üç Ayak" among the locals. The term "Üç Ayak (tripod)" is derived from the structural shape of the building[2].

[1] Semavi Eyice, "Kırşehir'de Üç Ayak Adındaki Yapı Kalıntısında Araştırmalar/ Untersuchungen in Der 'Üç-Ayak' Genannten Ruinenstatte Bei Kırşehir," *Anatolian Research* 17/2 (2004), 126-127.

[2] Semavi Eyice, "La Ruine Byzantine Dite 'Üç Ayak' Pres De Kırşehir En Anatolie Centrale," *Cahiers Archeologiques* XVIII/18 (1968), 137-138.

The church, which belonged to the Christian community of the period and is thought to have been built in the 11th century, is located as a single building in a large area. Since there are no other remains around it, this building is not considered as part of any religious structure. The ceramic pieces from the Byzantine period found in the vicinity of that building previously indicated the existence of only a small Turkish settlement or village. However, if such a settlement existed, no evidence of its inhabitants had been found other than ceramic remains[3]. The observations of Ainsworth's[4] on the Muslim graves in the area are not available any longer. It is thought that these graves belong to an unknown village or town in the surrounding area. Excavations are necessary to obtain deeper information about the region.

The building is organized as a twin church, which is relatively rare in the context of Byzantine architecture[5]. Üç Ayak Church has two adjacent apses, and researchers have proposed two possibilities for this unusual plan typology. The first is that it is one of the so-called "double martyriums" built to commemorate the Saints. The second is that it was a church built by the Emperor and his Consort. The absence of a cell where the relics were kept weakened the possibility of the church being a martyrium, so Strzygowski[6]stated that the second hypothesis may be more likely to be correct. Eyice[7]claimed that the Church of the Üç Ayak may have been built to commemorate a victory won by two emperors in this region and to celebrate the Feast Day of a Saint who was believed to have supported the soldiers of the emperors. As a result, the dedication of the church remains unknown, which has made its construction purpose unidentified.

From an architectural point of view, the architecture of the Üç Ayak Church has not been fully explained. The main features mentioned by almost all researchers are that the building has an indeterminate plan, a striking construction technique, and an extremely sophisticated exterior façade. The excellent craftsmanship displayed in the building contrasts with its remote location from the centers, and the innovative aspect of the brick technique used increases a distinct aspect of concealment to the building.

The first objective of this study is to examine the plan typology, the observable features of the used materials and techniques, the damages that have occurred over the years, and the current damage status of the building. The second goal of the study is to characterize the material by conducting experiments on samples taken from the building, thereby obtaining data on its mineralogy and microstructure, as no material-based tests or analyses were conducted during previous studies of this structure.

1. Materials and Research Methodology

In the Üç Ayak Church, three mortar and four brick samples were collected from distinct areas under the supervision of the authorities. Notably, the structural integrity of the standing portion of the building remained unaffected, as the samples had already fallen. The mortars, identified as M1, M2, and M3, along with the bricks denoted as B1, B2, B3, and B4, are depicted in (Figure 2). The marked areas in red in (Figure 2). indicate the estimated falling locations of the samples.

[3]Eyice, "Kırşehir'de Üç Ayak Adındaki Yapı Kalıntısında Araştırmalar Untersuchungen in Der 'Üç-Ayak' Genannten Ruinenstatte Bei Kırşehir," 127.

[4]William Francis Ainsworth, *Travels and Researches in Asia Minor, Mesopotamia, Chaldea, and Armenia* (London: John W. Parler West Strand, 1843).

[5]Marina Mihaljević, "Üçayak: A Forgotten Byzantine Church," *De Gruyter* 107/2 (2014), 725-754, https://doi.org/10.1515/bz-2014-0018.

[6]Josef Strzygowski, *Kleinasien Ein Neuland Der Kunstgeschichte* (Leipzig: J. C. Hinrichs'sche Buchhandlung, 1903), 32-41.

[7]Eyice, "La Ruine Byzantine Dite 'Üç Ayak' Pres De Kırşehir En Anatolie Centrale," 154.

Figure 2: *Estimated location of the taken brick and mortar samples*
Source: Ş. Özata Archive, 2023

Within the framework of the purposes explained above, the three stages of the research methodology in this study, which was carried out as a case study in the architectural context and revealed the original material properties by performing various analyses on the various samples of the building, are as follows:

- First, the literature review prepared with the study of different references that examine the features of the Üç Ayak Church will be examined to understand how the building came to its current architectural state,
- Second, an architectural survey, including data on plan type, structural system, building technique and materials, will be carried out to reveal any details worth preserving in the architecture of the building.
- In the final phase of the research, the brick and lime production during the Byzantine Period was examined. The compressive strengths of all the mortar and brick samples were determined. Then, the chemical characterization of the four different pieces of one mortar (M1) and one brick sample (B1) collected from the Üç Ayak Church, a Middle-Byzantine Period work, was carried out using X-ray diffraction (XRD). This experiment was performed with a Rigaku Ultima-IV X-ray diffraction device. X-ray fluorescence (XRF) and scanning electron microscopy with energy dispersive spectroscopy (SEM-EDS) techniques were employed to conduct chemical and morphological characterization, respectively, on the collected brick sample. XRF analysis was performed with X-MET 920 XRF-Analyzer and QUANTA INSPECT F50 device was used for SEM-EDS. All experiments were conducted at the General Directorate of Mineral Research and Exploration.

With the method steps basically described above, detailed data will be provided for all kinds of repair and restoration projects to be implemented in the fragment order to convey the building, whose dome and some of the façade walls have been demolished due to various anthropogenic and natural factors for years, to future generations. The research carried out in the context of the architectural investigation and characterization of the microstructural properties of the original material to be able to use compatible materials during the restoration was presented.

2. Literature Review of the Üç Ayak Church

Üç Ayak Church was not easily noticed when passing through the main travel routes since there is Bozluk Dağ to the west. Also, there are no historical buildings in the immediate vicinity of the Üç Ayak Church from the period when it was built. The region was sparsely populated, with only scattered rural settlements. Although visitors have mentioned the presence of a cold-water spring close to the site, all reports empha-

size the complete isolation of the building[8]. Despite the observation of several unidentified archeological remains in the area, there is no evidence of any existence of monastic or residential buildings[9].

Hamilton, an English traveler, wrote one of the earliest sources that mentions the existence of the Üç Ayak Church[10]. Although he mentioned the existence of the church, he did not actually visit the site. The first documented visit to the structure was made by the English researcher, W. Ainsworth, who created the engraving that was shared in (Figure 3). He provided a brief description of Üç Ayak. His publication[11] stated that there were Turkish tombs and a fountain in the vicinity of the building, but he also stated that he did not find any architectural remains in the surrounding area. His description of the church is significant as it provides a more complete view of the building. Ainsworth noted the presence of large arches, which were used to bear the dome and cover the narthex. Although he noted the presence of six large brick arches in the building, they are no longer extant at present. It is estimated that these arches were destroyed in the Kırşehir-Kaman earthquake of 1938.

In the early 1900s, J. W. Crowfoot visited Üç Ayak and created a sketch of the structure while taking valuable photographs. However, instead of using this data himself, Crowfoot passed it on to Strzygowski[12], who authored a book on Byzantine Art in Anatolia in 1903 and dedicated a significant portion of it to the crucial information provided by Crowfoot. Because of this publication, the Üç Ayak structure has been acknowledged in the scientific community in great detail.

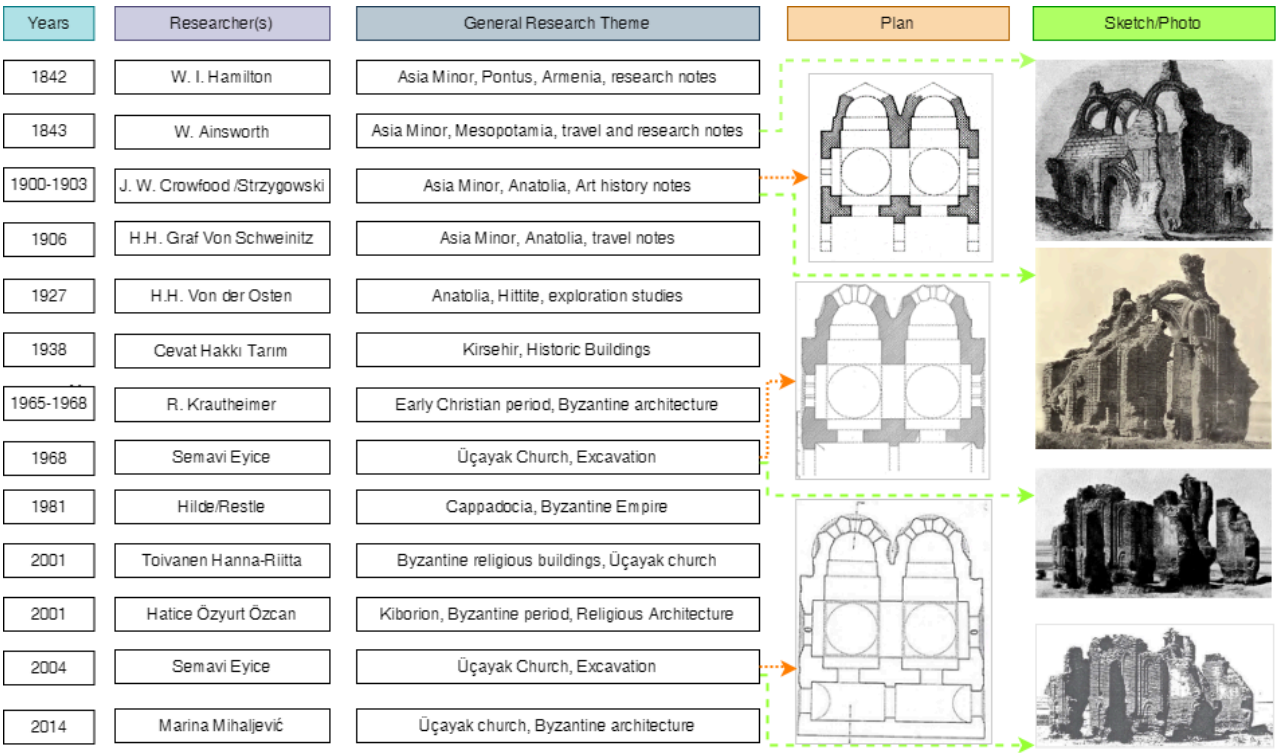

Figure 3: *Chronological order of the studies on the Church of Üç Ayak, plan survey development, and altered facades*
Source: Illustrated by M. Başgül and prepared by authors

[8] Mihaljević, "Üçayak: A Forgotten Byzantine Church," 727-728,

[9] Hanna-Riitta Toivanen, "Byzantine Church at Üçayak (Kirşehir, Cappadocia)," *Encyclopaedia of the Hellenic World, Asia Minor* ((Athens: Foundation of Hellenic World, 2001), 1-5.

[10] William John Hamilton, *Researches in Asia Minor, Pontus and Armenia* (London: John Murray, 1842).

[11] Ainsworth, *Travels and Researches in Asia Minor, Mesopotamia, Chaldea, and Armenia,* 162-163.

[12] Strzygowski, *Kleinasien Ein Neuland Der Kunstgeschichte,* 33.

At the beginning of the 20th century, the Üç Ayak site has piqued the interest of several researchers who have occasionally visited the site. Notable among these researchers are H. H. Graf Von Schweinitz[13], who took photographs during his visit, and Hittitologist H. H. von der Osten, who provided brief information about the structure in his work[14]. Although R. Krauthammer published a comprehensive book on Byzantine architecture in 1965, but it did not include the Üç Ayak structure in its first edition[15]. It was later included in the 5th edition thanks to S. Curcic's additions in 1985. Moreover, Hild and Restle's books on their research in the Cappadocia Region in 1981 also contained information on the structure[16].

The Turkish art historian Semavi Eyice visited Üç Ayak during a research trip with his students in 1965 and prepared a preliminary report with notes, measurements, and photographs he took at the site. Later, he presented this report at the 13th Byzantine Studies Congress held in Oxford in 1966. However, the collective book of speeches at the congress was not published, and Eyice's report remained unpublished. In 1968, he published a detailed and comprehensive article on the Üç Ayak Church in a French archeology journal[17]. His study revealed that the church had an impressive height of 17 m with its dome when it was constructed[18]. Furthermore, this structure was identified as the only and first example of a completely brick-built church within the borders of Türkiye.

In 1970, Eyice conducted a research excavation to provide a more accurate construction date for the Üç Ayak Church. Despite limited funding, the complete plan of the building was successfully revealed and this study provided answers to some long-standing questions[19]. Crowfoot's drawing showed the apses with a pointed end, but the excavation revealed that this plan was incorrect. Eyice's research helped us gain a better understanding of the structure, which is considered one of the most significant Byzantine buildings in Central Anatolia.

Many researchers have conducted studies on the Üç Ayak Church in the following years. In 2001, Hanna Toivanen published a study that described the church's location, history, architectural features, and structure[20]. Özcan[21] also used the Üç Ayak Church as an example of the ciborium type when discussing the historical development of Byzantine religious architecture and its Anatolian examples in the same year. Marina Mihaljević's study highlighted the significance of the structure and discussed its architectural and structural features, as well as its interior and construction techniques[22]. These studies collectively demonstrate the importance of the Üç Ayak Church in Byzantine and religious architecture.

Within these studies, different ideas have been proposed about the construction date of the building. Strzygowski believed that the Church of Üç Ayak was an archaic building constructed in the 5th –6th century[23]. However, Eyice's study of the building's characteristics led him to conclude that this date was too early and that the church was actually built in the 10th –11th century.

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[13] Hans Herman Von Schweinitz, *Kleinasien, Ein Reitausflug Durch Das Innere Kleinasiens Im Jahre 1905* (Berlin: Universitäts- und Landesbibliothek Sachsen-Anhalt, 1905), 190-194.

[14] Hans Henning Von Der Osten, *Explorations in Hittite Asia Minor* (Chicago: The University of Chicago Press, 1927).

[15] Richard Krautheimer, *Early Christian and Byzantine Architecture* (London: Oxford, 1986).

[16] Friedrich Hild and Marcell Restle, *Kappadokien Tabula Imperii Byzantini II* (Wien: Österreichische Akademie der Wissenschaften, 1981), 301.

[17] Eyice, "La Ruine Byzantine Dite 'Üç Ayak' Pres De Kırşehir En Anatolie Centrale," 137-155.

[18] Eyice, "Kırşehir'de Üç Ayak Adındaki Yapı Kalıntısında Araştırmalar Untersuchungen in Der 'Üç-Ayak' Genannten Ruinenstatte Bei Kırşehir," 133.

[19] Eyice, "Kırşehir'de Üç Ayak Adındaki Yapı Kalıntısında Araştırmalar Untersuchungen in Der 'Üç-Ayak' Genannten Ruinenstatte Bei Kırşehir," 129.

[20] Toivanen, "Byzantine Church at Üçayak (Kirşehir, Cappadocia)," 1-5.

[21] Hatice Özyurt Özcan, "Bizans Dini Mimarisinde Kiborion Tipinin İstanbul ve Anadolu'daki Örnekleri Işığında Değerlendirilmesi, Cilt: 1 (Metin)" (PhD diss. Istanbul University, 2002), 124-129.

[22] Mihaljević, "Üçayak: A Forgotten Byzantine Church," 746-754.

[23] Strzygowski, *Kleinasien Ein Neuland Der Kunstgeschichte, 34*.

3. Architectural Survey

The plan, structure, noticeable features of materials, and construction technique of the Üç Ayak Church were analyzed within the scope of the architectural review.

3.1. Plan Type and The Structural System

The double and triple churches in Byzantine architecture are common, but they are usually constructed adjacently in different successive periods[24]. The most known existing examples of adjacent churches are Lips Monastery (Fenari İsa Mosque), Pantokrator (Zeyrek Church Mosque), and Pammakaristos (Fethiye Mosque). An example of a double structural design can be seen in the Çanlı Church, which is an 11th-century church situated in the Cappadocia Region. Although Üç Ayak is a double church, it is completely different from all these examples. In contrast, Üç Ayak is unique in that it was designed and built as a whole twin structure[25].

The double-plan type of ruined Üç Ayak Church features two identical naves positioned side by side (Figure 4a). Two separate apses, bemas, naoses[26] , and narthexes were designed. The twin structure is shaped with a narthex in the west, a naos in the middle with a deep bema, and an apse in the east (Figure 4a-b). The completely ruined narthex covers the western façades (Figure 4c-d) of the structures and has a rectangular plan. Based on the remains, it can be inferred that there was an arch passing through the middle of the narthex[27] that is still in place. From the marks of the arch starting points on the structural walls, it can be inferred that there was a vault above the narthex. Each nave had its independent entrance (Figure 4c-e) from the narthex, and they were separated by a structural wall.

The two naves had a quadrangular shape and extended toward the east with externally polygonal apses. The width of each naos is 5.9 m, while its length is 7.02 m up to the bema and 8.10 m up to the apse. The eastern section of the cross-planned naos measures 185 cm, while the other parts are 85 cm. 4 arches were designed over the structural walls and pendentives were constructed between them. Then, the dome, which does not exist at present, was built over the pendentives. The bema, which is 4.20 m wide, is separated from the apse by a vault.

The structural walls, measuring 90 cm in thickness, were spanned with arches, and measures were implemented to enhance stability through the integration of wooden bond beams of varying numbers and dimensions. Furthermore, brick piers measuring 140x170 cm were erected to provide support for the thrust generated within the arches. Bonding beams of different heights, totaling three on each pier, were meticulously designed to ensure structural stability.

[24] Toivanen, "Byzantine Church at Üçayak (Kirşehir, Cappadocia)," 2.

[25] Eyice, "Kırşehir'de Üç Ayak Adındaki Yapı Kalıntısında Araştırmalar Untersuchungen in Der 'Üç-Ayak' Genannten Ruinenstatte Bei Kırşehir," 129-130.

[26] Naos is an alternative term for the nave of a Byzantine church.

[27] Eyice, "Kırşehir'de Üç Ayak Adındaki Yapı Kalıntısında Araştırmalar Untersuchungen in Der 'Üç-Ayak' Genannten Ruinenstatte Bei Kırşehir," 130.

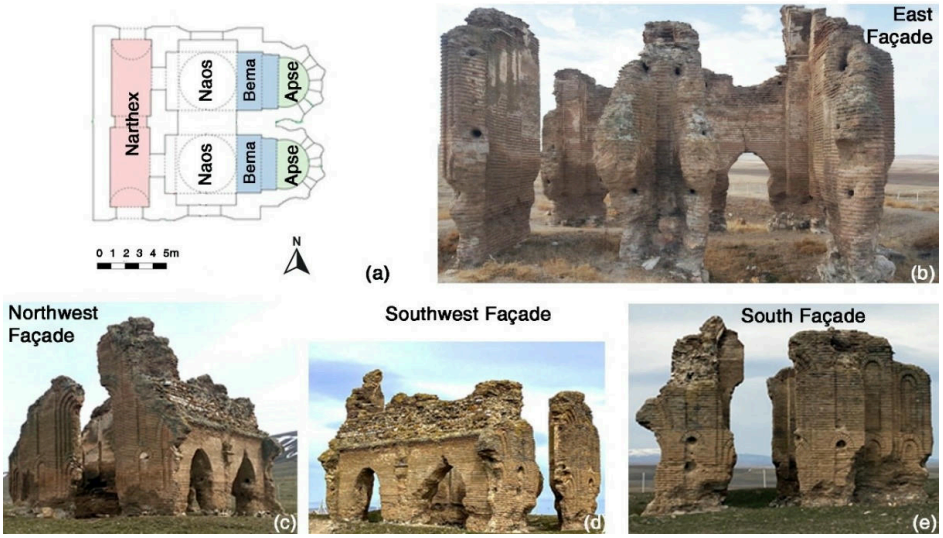


Figure 4: *Figure 4: (a) Plan of Üç Ayak Church, (b) Current situation of the south façade, ruined apses, (c, d, e) Current condition of the façades*

Souce: a. (drawn by M. Başgül Archive); b. (Ş. Özata Archive, 2023); c, d, e. (M. Başgül Archive, 2023)

Based on the comparison of the old photographs in (Figure 3) and the up-to-date photo in (Figure 4), it can be deduced that a section of the apse has been missing since the early discovery of the building. It is estimated that there was a semi-dome over the apse. The apse in the plan shared in (Figure 3) drawn by Crowfoot[28] differs from the actual apse discovered during excavations[29], which has five facades that add dynamism to the building's design.

3.2. Façades and Architectural Elements

The highest point of the remaining walls, which were constructed without plaster, is 10 m (Figure 5). The style of the narthex walls remains unknown as they have not survived to this day, but the narthex has a single story. Despite the center of the north façade of the church being destroyed, it is clear that there are two different levels of niches on this façade made up of four intertwined arches. The architectural survey depicts that the upper sections of the niches were designed with round arches and double-triple windows set into these niches. The evidence of triple windows was found on the apse façade. Although it is stated that there is a drum in the dome, which is claimed to be about 17 m high[30], the accuracy of this information is doubtful since the cupolas are generally built without a drum on the pendentive structural elements. If the dome were built using squinches on a square plan, the drum part might have been formed. Based on this information, two different possible restitution drawings of the north façade are presented in (Figure 5). These drawings on the left and the right have been modified from sources published by Eyice in 1968[31] and 2004, respectively, and[32] the remains are shown in (Figure 5).

[28] Strzygowski, *Kleinasien Ein Neuland Der Kunstgeschichte,* 33.

[29] Eyice, "Kırşehir'de Üç Ayak Adındaki Yapı Kalıntısında Araştırmalar Untersuchungen in Der 'Üç-Ayak' Genannten Ruinenstatte Bei Kırşehir," 163.

[30] Eyice, "Kırşehir'de Üç Ayak Adındaki Yapı Kalıntısında Araştırmalar Untersuchungen in Der 'Üç-Ayak' Genannten Ruinenstatte Bei Kırşehir," 133.

[31] Eyice, "La Ruine Byzantine Dite 'Üç Ayak' Pres De Kırşehir En Anatolie Centrale," 150.

[32] Eyice, "Kırşehir'de Üç Ayak Adındaki Yapı Kalıntısında Araştırmalar Untersuchungen in Der 'Üç-Ayak' Genannten Ruinenstatte Bei Kırşehir," 150.

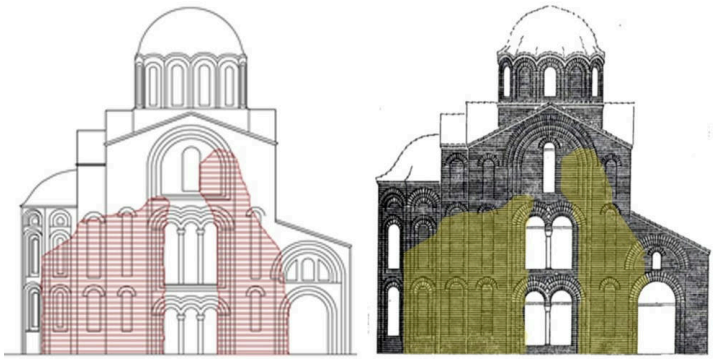


Figure 5: *Different representative restitutions of the north façade*
Source: Prepared by Eyice (a) in 1968[33] (b) in 2004[34]. Remaining parts colored by authors.

3.3. Building Technique and Material

The foundations, plinth, and upper-inner parts of the west façade of the Üç Ayak Church were constructed using rubble stone, whereas the rest of the building was made entirely of brick material. The masonry building was constructed using the hidden brick technique, which was developed in the 11th century[35]. Thus, the use of the hidden brick technique in the construction of this edifice serves as a strong indication that it belongs to the 11th century. The bricks used in the construction were mostly 35 cm x 35 cm in dimension, with occasional use of larger 70 cm x 35 cm bricks. Nevertheless, in exceptional instances, certain bricks were noted to measure 21x35 cm. The thickness of the bricks ranged between 3 and 4 cm, and the mortar used between the bricks was observed to be around 3-7.5 cm thick (Figure 6). Furthermore, the mortar used had a soft consistency and a dirty white, which differed from the present-day lime mortars. It is observed that to protect the soft mortar, a thinner layer of more durable and red mortar was added in front of it. This application applied to mortar joints is called weathered or struck pointing. Since the mortar applied for struck pointing is red, which is different from the main mortar, it is thought that it contains ground brick dust fragments and therefore has pozzolanic properties.

The used technique and type of mortar are unique features that have not been found in the wall craftsmanship that was discovered in the Üç Ayak Church.

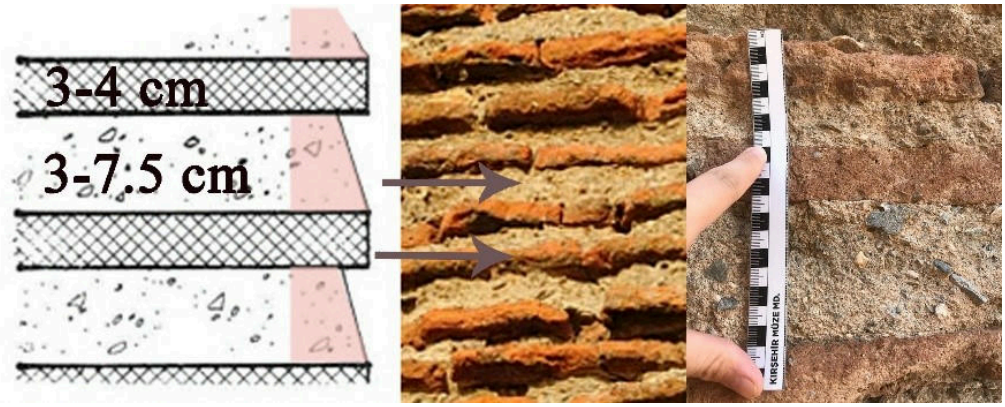


Figure 6: *(a) Structural wall detail of Üç Ayak Church.*
Source: Prepared by authors

[33] Eyice, "La Ruine Byzantine Dite 'Üç Ayak' Pres De Kırşehir En Anatolie Centrale," 150.

[34] Eyice, "Kırşehir'de Üç Ayak Adındaki Yapı Kalıntısında Araştırmalar Untersuchungen in Der 'Üç-Ayak' Genannten Ruinenstatte Bei Kırşehir," 162.

[35] H. Hale Kozlu, "Characterization of Historical Mortars and Features of Restoration Mortars in Kayseri District" (PhD diss. Istanbul Technical University, 2010), 64.

Based on the brick workmanship, it can be said that the walls were built with the *Opus latericium technique*, while the *Opus mixtum* technique, which characterizes hybrid construction, was used throughout the building since there are also stones. The types of brick quality mentioned are marked on the image in (Figure 7).

Upon the 90-cm-thick structural walls, a single circular wooden bond beam measuring 18 cm in diameter is positioned at approximately 380 cm above the ground level, resting atop the designated arches. On the piers measuring approximately 140x170 cm, three square wooden beams, each measuring approximately 18x18 cm, are installed at heights of around 40 cm, 160 cm, and 300 cm, originating from the stone-formed plinth level, which stands at 50 cm high. Some of these bonding beams are shown in (Figure 7). Schweinitz[36]stated that wooden beams placed inside the walls during the construction of the building increase the resistance of the building against earthquakes. This information is partially correct because the bonding timbers used with a certain level of spacing within the brick masonry wall reduce the slenderness and improve the earthquake performance and the stability of the structure.

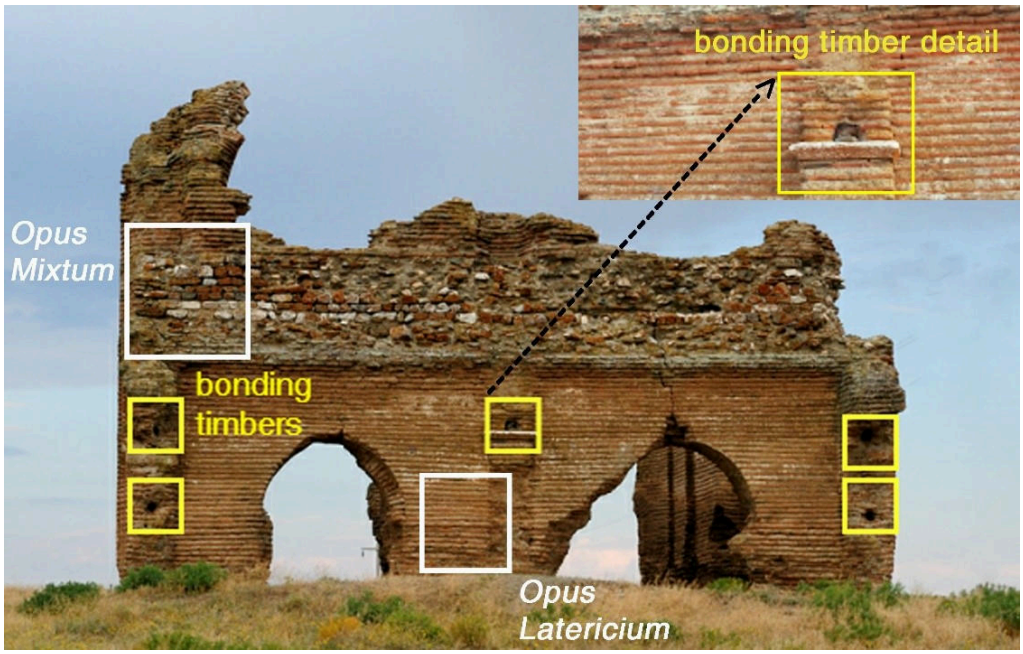


Figure 7: *The bonding timbers in between the masonry brick wall and brick quality samples on the west façade*
Source: Prepared by Ş. Özata

3.4. Comparison of The Double-naved Plan Typology

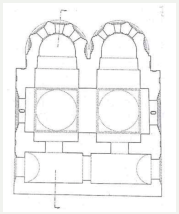
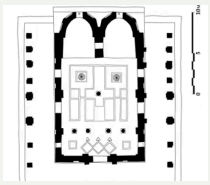
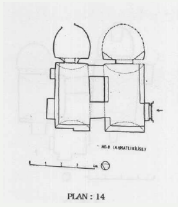
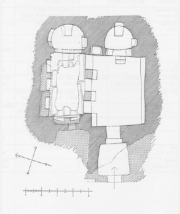
The first examples of the double-naved plan type consisting of two naves were seen in the houses of the Havran Region, Syria. The two-nave plan type started to be used in religious buildings in Tur Abdin, Türkiye since the 5th century[37]. The first surviving example of this typology in Anatolia is the baptistery of the Alahan Monastery in Cilicia, dating back to the 6th century[38]. The examples of this plan typology in Türkiye are generally seen in the rock-carved structures in Cappadocia, and the number of masonry examples does not exceed 10; Üç Ayak Church is one of these examples. Among these buildings, 4 with the same plan typology were selected and the comparison was made. Information about the buildings is presented in Table 1 and their similarities and differences are presented.

[36]Schweinitz, *In Kleinasien, Ein Reitausflug Durch Das Innere Kleinasiens Im Jahre 1905,* 156.

[37]Özlem Doğan, "Byzantine Period rock-cut churches in Cilicia Region" (MA thesis, Mersin University), 88.

[38]Doğan, "Byzantine Period rock-cut churches in Cilicia Region", 88.

Table 1: *Examples of two-naved plans of Byzantine religious structures*
Source: Prepared by Ş. Özata

Building	**Image**				
	Region/City	**Kirsehir**	**Serbia**	**Cappadocia**	**Cappadocia**
	Construction Century	11th	13th	10-11th	10th
	Name	*Üç Ayak Church*	*Saint Nicholas Church*[39]	*Ahmatlı Church*[40]	*Goreme 11, Saint Eustathios Church*[41]
	Material	*Brick and Stone*	*Brick and Stone*	*Rock*	*Rock*
	Techniques	*Opus mixtum + Opus Latericium*	*Opus mixtum*	-	-
Spaces	**Apse(s)**	✓(2)	✓(2)	✓(2)	✓(2)
	Nave(s)	✓(2)	✓(2)	✓(2)	✓(2)
	Nartex	✓	✓	x	x
Other parts/ elements	**Synthronon**	x	✓	✓	x
	Altar	x	✓	x	✓
	Mural painting	x	x	✓	✓
Ceiling	**Flat**	x	✓	x	x
	Barrel vault	✓	✓	✓	✓
	Groin vault	x	✓	x	x
	Dome	Dome &Semi dome	Dome &Semi dome	Semi dome	Semi dome

When the plan types with two naves formed in different areas are analyzed and shared in Table 1, it is seen that brick and stone were used in the masonry structure and the *opus mixtum* technique was used in these buildings. The narthex is not common in the rock-hewn type of twin churches. Synthronon, which is a semi-circular or polygonal seating arrangement found in the apse of a church, is a common architectural element in some of these churches. While rock-hewn examples of twin churches contain mural painting, it is not found in masonry examples. The semi-dome and barrel vault are the most common ceiling types for the twin Byzantine churches.

In the following section, the characteristics of the brick-and-mortar materials used in the building are investigated in detail and their features are shared.

4. Analysis of the Byzantine Mortar and Brick

Within the context of discussing the characterization of the bricks and mortars used in the construction of the Üç Ayak Church, an overview of brick and lime making is presented to give a brief insight into how

[39] Mihaljević, "Üçayak: A Forgotten Byzantine Church", 746.

[40] Sacit Pekak, "Güzelyurt'ta (Gelveri) Bulunan Bizans/Post-Bizans Dönemi Kiliseleri 1-2," *Hacettepe University Journal of Faulty of Letters* 10/2 (1994), 136-137.

[41] Sue Anne Wallace, "Byzantine Cappadocia: The Planning and Function of Its Ecclesiastical Structures V.II" (PhD diss. Australian National University, 1991), 629-639.

these materials were made in the Byzantine period. Subsequently, the analysis delves into the specifics of the building materials used in the Üç Ayak Church, combining various analytical techniques to obtain detailed insights into their composition and properties. By correlating the results with the historical context, a comprehensive understanding of the building techniques employed in the church is achieved.

4.1. Brick and Lime-making Process

Clay, a plastic and malleable material that turns into a solid when it dries and acquires mechanical properties, has been used as a raw material in architecture for centuries. Although materials such as wood, leaves, and animal skins were the main components in the early architecture of countries with warm climates, clay has been and continues to be the main raw material for building materials in areas such as Mesopotamia, where it is warmer and vegetation is scarce.

The sun-dried clay was not a sufficiently efficient material because it was not resistant to water. The waterproof material obtained by firing clay by potters began to be used as a building material centuries later. Clay was fired to form bricks, but since it was mostly used in dry areas, it was first used in parts that were not intended to pass water, such as gutters, pipes, and building façades[42].

In the Western world, both Greek and Roman, the firing of clay appeared much later, and for a long time (until about the first century BC), only fired clay was used for tiles and roofing[43].

Bricks can be formed from various stones and soils such as clay, claystone, mudstone, clay shale, slate, and glacial clays[44]. Firing clay in a kiln destroys vegetable and mineral substances. The logic of brick kilns is the same as in pottery, but larger in scale. The stages of mixing and preparing the clay, molding, and firing are shown in (Figure 8). The illustrated process in (Figure 8) may serve as a model for producing materials to be used in future restoration projects employing traditional methods. However, it is crucial to establish the methodology employed in the production of the bricks.

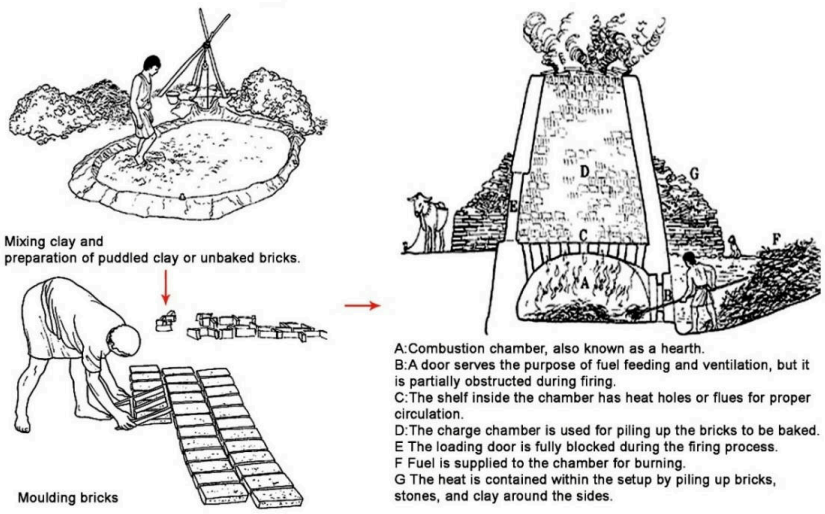


Figure 8: *Brick-making process during the Byzantine Era*
Source: The figure was shaped by combining and rearranging images that are separate in Adam's book[45]

[42] Olivier Aurenche, "Dictionnaire Archéologique Des Techniques, Article Brique: Asie Occidental et Égypte I," *Dictionnaire Illustré Multilingue de l'architecture Du Proche-Orient Ancien*, (Paris: MOM Editions, 1977), 40-42.

[43] Anastasions K. Orlandos, *Les Matériaux de Construction et La Technique Architecturale Des Anciens Grecs* (Paris: E. de Boccard, 1966), 101-105.

[44] Murat Müdüroğlu, "Investigation of the Properties of Clay Raw Materials Used in Brick Making" (MA thesis, Istanbul Technical University, 1999), 10-14.

[45] Jean Pierre Adam, *Roman Building-Materials and Techniques* (London: Routledge Taylor and Francis Group, 1994), 104.

The variability of the firing time can be attributed to various factors such as the furnace size, atmospheric conditions, and fuel type. In the charging chamber, the temperature near the inner shelf is approximately 800°C, while it is around 450°C near the top outlet. It is worth noting that the clay is not solidified at 450°C, which means that the top layer of the bricks is unsuitable for construction[46].

Another firing method that does not require the construction of a kiln is stack firing. In this method, unbaked bricks are piled up and one or more combustion chambers are located under the stack. Large quantities of material can be fired with this technique, while the surrounding materials are wasted because they are not fired sufficiently. It is not certain whether stack firing, still practiced by artisans in Greece and especially in Türkiye, was used in antiquity.

Some craftsmen marked their products, and for this reason, many tiles and bricks bear a stamp that provides valuable information about their origin or date. However, no such mark was found on the bricks of Üç Ayak Church.

The invention of firing rocks to produce binders appears to be as old as the art of pottery; plaster coatings adorned the walls of Çatalhöyük in the sixth millennium BC, but the idea of bonding stones with lime mortar first appeared in Egypt in the third millennium[47]. To fire the limestone, kilns similar to brick kilns were built. In some places, the limestone and bricks were even fired together. Limes are grouped as non-hydraulic or aerial lime and hydraulic.

4.2. Mechanical Feature

The compression strength as a mechanical feature was determined with three mortar and four brick samples. They were prepared with dimensions of 50x50x50 mm, and compression strength tests were conducted according to the specifications outlined in TS EN 12390-3[48]. The average compressive strength of the bricks was determined to be 9.8 MPa, while that of the mortar was approximately 3.6 MPa.

Kurugöl and Tekin (2010)[49], Stefanidou et al. (2015)[50], Ulukaya et al.(2017)[51], as well as Çam (2022)[52]in their studies on the compressive strength of Byzantine bricks achieved values similar to those observed in the bricks of this particular structure.

4.3. Characterization of the Brick and Mortar Samples of Üç Ayak Church

X-Ray diffraction (XRD) was employed to characterize four different pieces of a single sample brick (B1), which were named as B1a, B1b, B1c, and B1d, as well as four parts of a mortar sample (M1) from Üç Ayak Church, designated as M1a, M1b, M1c, and M1d. X-Ray fluorescence (XRF) was also performed on the same brick. Scanning electron microscopy with the energy-dispersive spectroscopy (SEM-EDS) technique was used to conduct morphological analyses on four different parts of one brick sample from Üç Ayak Church.

[46] Adam, *Roman Building-Materials and Techniques*, 107-109.

[47] Adam, *Roman Building-Materials and Techniques*, 116.

[48] "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.

[49] Sedat Kurugöl and Çiğdem Tekin, "Evaluation of Physical, Chemical and Mechanical Characteristics of Bricks Used in Castle Structures of Byzantine Period," *Gazi University Faculty of Engineering and Architecture Journal* 25/ 4 (2010), 767-777.

[50] Stefanidou, Papayianni and Pachta, "Analysis and Characterization of Roman and Byzantine Fired Bricks from Greece," *Materials and Structures* 48/7 (2015), 2252-2258.

[51] Serhan Ulukaya, Afife Binnaz Hazar Yoruç, Nabi Yüzer and 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.

[52] 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.

4.3.1. X-Ray Diffraction and X-Ray Fluorescence Analyses

Within the scope of X-Ray diffraction (XRD) experiments performed on the powdered materials obtained from the bricks and mortars that once belonged to the walls of Üç Ayak Church, underwent analysis to determine their crystallographic properties. X-Ray fluorescence (XRF) was used to detect major oxides in the brick. The compounds and minerals they contained were identified. While determining the XRD peaks, The International Center for Diffraction Data and publications[53] that have conducted detailed studies on the subject were used.

As a result of the XRD analysis of the ethylene glycol-treated four brick samples between 2°-30° (2θ), phlogopite ($KMg_3(AlSi_3O_{10})(OH)_2$), muscovite ($KAl_2(AlSi_3O_{10})(OH)_2$), albite ($Na(AlSi_3O_8)$), anorthite ($CaAl_2Si_2O_8$), quartz ($SiO_2$), coesite ($SiO_2$), calcite ($CaCO_3$), hematite ($Fe_2O_3$) and amphiboles ($X^{54}{}_7Si_8O_{22}(OH)_2$) peaks were observed, which were shared in F.8. Doyleite ($Al(OH)_3$), calcium-silicate-hydrate ($CaSi_8O_{24})_{12}$ H_2O compounds along with amphibole, quartz, albite, anorthite and muscovite were detected in the mortar samples (Figure 9).

As seen in Table 2, SiO_2 is the most common major oxide identified in the brick substance because of XRF. The fact that many minerals detected in the XRD result shared in F.9 are also from the silicate group confirms this result. In the silicate group observed in XRD, albite is a Na-feldspar and anorthite is a Ca-feldspar (Figure 9). These minerals are known to be present in fired bricks over a wide range between 450 °C and 1100 °C[55]. Phlogopite and muscovite are mica from the alumina silicate group. The muscovite peak was generally observed in bricks fired between 700 °C and 900 °C[56]. Coesite and quartz are a form (polymorph) of silicon dioxide. However, coesite occurs at moderately high temperatures (~700 °C)[57].

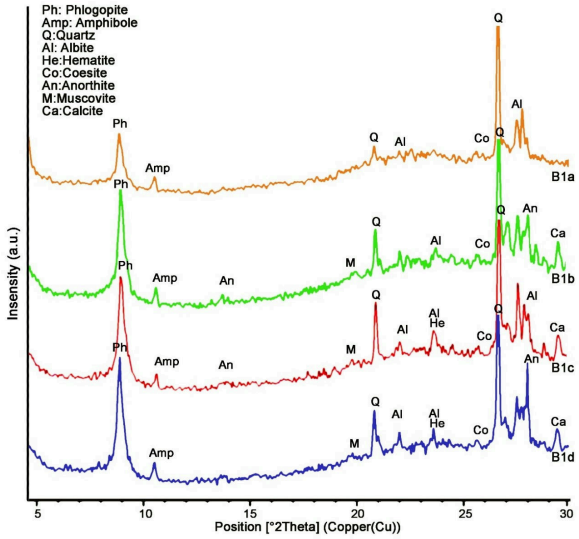


Figure 9: *XRD patterns of four different parts of Üç Ayak Church brick (B1)*
Source: Prepared by authors

[53] Elif Çam, "Characteristics of Byzantine Period Building Bricks Used in St. Jean Basilica (Ayasuluk Hill) and Anaia Church (Kadıkalesi)," 1-112; Serhan Ulukaya, Afife Binnaz Hazar Yoruç, Nabi Yüzer and Didem Oktay, "Material Characterization of Byzantine Period Brick Masonry Walls Revealed in Istanbul (Turkey)," *Periodica Polytechnica Civil Engineering* 61/2 (2017), 209-215, https://doi.org/10.3311/PPci.8868; Özlem Aslan Özkaya and Hasan Böke, "Properties of Roman Bricks and Mortars Used in Serapis Temple in the City of Pergamon," *Materials Characterization* 60 (2009), 995-1000, https://doi.org/10.1016/j.matchar.2009.04.003.

[54] X can be magnesium (Mg), calcium (Ca), sodium (Na), iron (Fe), or combination of them.

[55] Çam, "Characteristics of Byzantine Period Building Bricks Used in St. Jean Basilica (Ayasuluk Hill) and Anaia Church (Kadıkalesi)," 55-81.

[56] Meriam El Ouahabi, Lahcen Daoubi, Frederic Hatert, Nathalie Fagel, "Modified Mineral Phases during Clay Ceramic Firing," *Clays and Clay Minerals* 63/5 (2015), 404-413, https://doi.org/10.1346/CCMN.2015.0630506.

[57] Robert M. Hazen, *The Diamond Makers* (Cambridge: Cambridge University Press, 1999), 91.

Table 2: *Major oxides of Üç Ayak brick (B1) according to XRF*
Source: Prepared by authors

SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	K_2O (%)	MgO (%)	MnO (%)	Na_2O (%)	P_2O_5 (%)	TiO_2 (%)	Loss of Ignition (%)
65.5	14.0	5.8	4.5	2.7	1.7	0.1	1.5	0.1	0.8	2.60

According to the literature[58], brick firing temperatures vary between approximately 450 °C and 900 °C. Since coesite was formed in the material, it can be estimated that the Üç Ayak bricks were fired at 700-900 °C. Quartz was not observed in the bricks fired at 1050 °C. Calcite is a carbonate group mineral that starts to appear in fired bricks at 800°C and decomposes at 870°C[59]. It can be inferred that the use of calcium-deficient clays from locally available non-calcareous raw material sources is likely, given the low levels of Ca detected in the composition Table 2. Hematite is produced in non-calcareous bricks at a firing temperature of 850°C, and its presence indicates the temperature at which the bricks were fired[60]. The amphibole peaks indicate the formation of other minerals such as Mg and Na. The relatively small number of these oxides in Table 2 supports this argument. According to these data and the analyzed XRD peaks, the firing temperature of the Üç Ayak Church bricks is estimated to be between 850 °C and 900 °C.

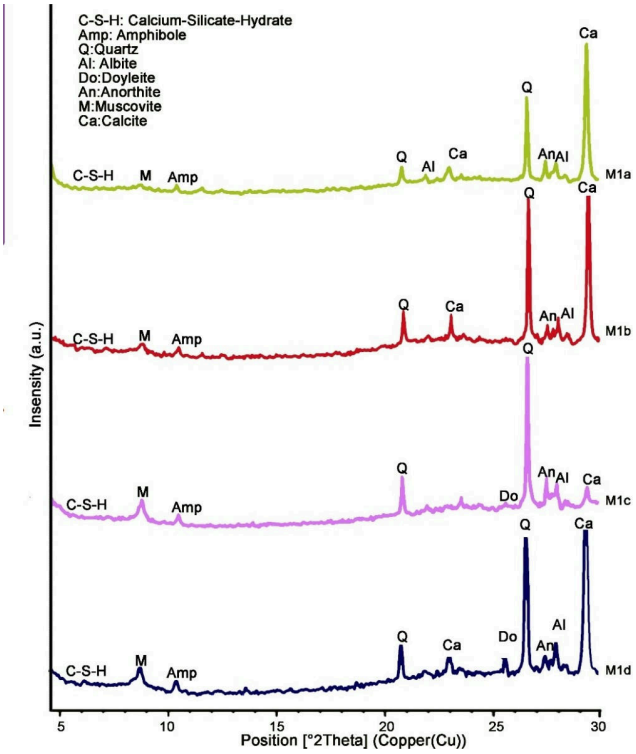


Figure 10: *XRD patterns of four different parts of Üç Ayak Church mortar (M1)*
Prepared by authors

[58] Adam, *Roman Building-Materials and Techniques*, 112-115; Ulukaya et al., "Material Characterization of Byzantine Period Brick Masonry Walls Revealed in Istanbul (Turkey)," 209-215.

[59] Giuseppe Cultrone, Carlos Rodrıguez-Navarro, Eduardo Sebastian, Olga Cazalla, Maria Jose De La Torre, "Carbonate and Silicate Phase Reactions during Ceramic Firing," *European Journal of Mineralogy* 13/3 (2001), 621-634, https://doi.org/10.1127/0935-1221/2001/0013-0621.

[60] Elif Uğurlu Sağın and Hasan Böke, "Characteristics of Bricks Used in the Domes of Some Historic Bath Buildings," *Journal of Cultural Heritage* 14/3, 73-76 (2013), https://doi.org/10.1016/j.culher.2012.11.030.

The hardness of the mortar taken from the building is quite weak, unlike the brick. Therefore, in the first observation, it was thought that the mortar was made without the use of hydraulic lime. However, it would be more accurate to conduct additional experiments that will help to understand whether the mortar has hydraulic properties. The mica and some alumina silicate structures seen in the XRD peaks shared in (Figure 10) indicate the clay in the mortar. The calcium peaks are also quite prominent since lime was used in the mortar. Quartz peaks are also thought to originated from the sand in the mortar.

Doyleite is a rare type of aluminum oxide that is detected weakly in some samples. Although the presence of C-S-H is obviously a significant indication of hydraulicity[61], the peaks are quite weak. These are sometimes caused by pozzolanic activity at the interface between the brick and mortar. Accordingly, the main materials of the mortar are considered sand and lean lime, which is produced by calcining and slaking limestone that contains 2% to 8% clay[62].

4.3.2. Morphological Analysis

Morphological analysis was conducted using scanning electron microscopy with the energy dispersive spectroscopy technique. The Byzantine brick's microstructure and morphology were examined with high spatial resolution using Scanning Electron Microscopy (SEM). Energy-dispersive spectroscopy (EDS) is an analytical technique utilized for the chemical characterization and elemental analysis of the brick. (Figure 11). displays 800-21,000× magnified images and element weights obtained as a result of EDS. By conducting an EDS analysis on specific spots of the brick, the composition of elements such as O, Fe, Na, Mg, Al, Si, K, and Ca was determined.

It is anticipated that no vitreous phase is found in the bricks fired between 800 °C and 870°C[63]. The heterogeneous morphology observed in the SEM images serves as evidence that there is no vitreous phase present. The SEM images depicting a partially compact morphology provide further confirmation that the brick was formed at a temperature of 850-900°C, consistent with the XRD phases.

[61] Ulukaya et al., "Material Characterization of Byzantine Period Brick Masonry Walls Revealed in Istanbul (Turkey)," 209-215.

[62] Adam, *Roman Building-Materials and Techniques*, 128-130.

[63] Çam, "Characteristics of Byzantine Period Building Bricks Used in St. Jean Basilica (Ayasuluk Hill) and Anaia Church (Kadıkalesi)," 89-99.

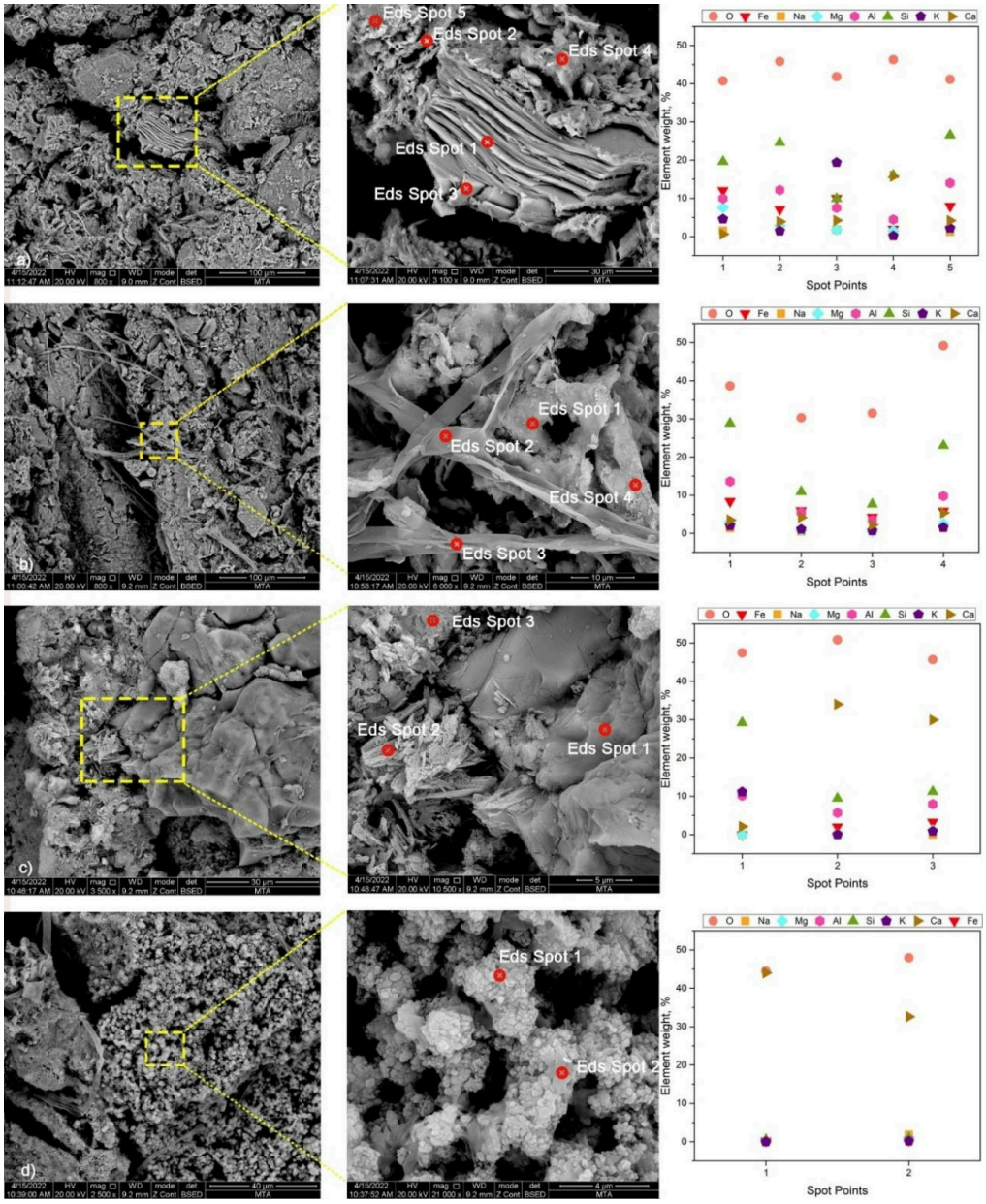


Figure 11: *SEM micrographs magnified 800-21.000× and EDS spot points along with element weight percentages of the same brick sample from Üç Ayak Church*
Source: Prepared by authors

All EDS spots in (Figure 11a) have a high amount of Si, as expected according to the XRD phases of the Byzantine brick. EDS spot #4 has a high amount of Ca as this area may be an intersection between mortar and brick. Since hematite is also seen in the brick, iron is detected at certain levels in all spots in (Figure 11a). For a vivid red to be seen on the bricks, there must be at least 5% iron[64]. The EDS results clearly show that the observed redness of the Byzantine bricks is due to iron.

In (Figure 11b), EDS spots#2-3 show that the elements are distributed relatively balanced in the matrix and the fibrous structure is estimated to belong to the amphibole or feldspar group from the minerals detected by XRD. The high Si ratios of the other spots indicate that they belong to the sand-clay mixture used in brick production.

[64] Müdüroğlu, "Tuğla Yapımında Kullanlan Kil Hammaddelerinin Özelliklerinin İncelenmesi," 10.

Due to the high Si and K in EDS spot #1 in (Figure 11c), it is thought to be a mica-type mineral and the particle in the other spot is a sandy matrix. Although clay has a homogeneous structure alone in this section, it is seen that it cannot form an integrated interface with other minerals in the matrix as the brick firing temperature does not reach 900 °C.

In the very detailed image in (Figure 11d), which is magnified up to 21000×, it is seen that the Ca ratio is quite high since the fired calcite matrix.

Conclusion

The Üç Ayak Church is a valuable monumental structure constructed in the middle-Byzantine period in the 11th century, featuring a fully symmetrical double-plan type and the use of the concealed brick technique. It has been studied by many researchers from the 19th century to this day. Through intermittent research, both superficial and partially detailed, it has been discovered that the apse façade consists of five facets, the narthex is single-story, the dome above the naos is carried by pendentives, and there are niches on the façades with nested windows inside. The top height of the remaining walls is 10 m. Since the 19th century, this exceptional structure has been referenced, depicted, or conceptualized in written sources, noting that a portion of it has gradually vanished during each period of investigation. Through this study, an aim is to furnish comprehensive data regarding its features before further deterioration occurs, thereby paving the way for future restoration endeavors.

As a result, analyzing plan types with double naves in different areas revealed the use of brick and stone in the masonry structure, employing the opus mixtum technique. The absence of a narthex is notable in the rock-hewn variations of this type, while the presence of a synthronos is common. Mural paintings are found in rock-hewn examples but not in masonry ones. Semi-domes and barrel vaults are the prevalent ceiling types.

Although the building mortar's hardness is weak and its strength is low (3.6 MPa), it has been confirmed that the mortar between the bricks and its outer surface is still in good condition due to the struck pointing. It has been observed that the slenderness is reduced and earthquake resistance and stability are increased by using wooden bonding timbers in the thick 90 cm brick structural walls, which have a high degree of slenderness due to their height.

While it is confirmed that the bricks utilized in the construction of the building were subjected to firing, the lack of any remnants of a brick kiln in close proximity suggests that the stack firing technique might be employed. However, to ensure accuracy regarding the firing style, comprehensive excavations in the vicinity of the church are necessary. To attain more precise outcomes, it is recommended that the scope of the search for remnants of firing systems be broadened.

The average compressive strength of the mortar, tested on three different samples between the bricks, was found to be 3.6 MPa. The mortar's low strength diminishes its hydraulic potential. Meanwhile, the compressive test on the brick samples revealed an average strength of 9.8 MPa. The strength of the bricks is consistent with the findings from Byzantine brick studies in the literature.

Based on the XRD results of the brick, it was fired between 850 °C and 900° C, as indicated by the formation temperatures of calcite, muscovite, coesite, quartz, and hematite. However, for a more precise determination of the firing temperature, additional analysis using DTA-TG is recommended, as XRD alone may not provide sufficient detail. In alignment with the XRD phases observed in the mortar, the prominent calcium peaks suggest the presence of lime within its composition. The primary constituents of the mortar are presumed to be sand and low lime content, derived from the calcination and slaking of limestone, typically containing clay ranging from 2% to 8%.

SEM-EDS analysis and morphological examinations conducted at various magnifications on the brick sample revealed the absence of vitreous phases, affirming a firing temperature below 1050°C and resulting in a heterogeneous structure. EDS analysis also identified Fe minerals that are the cause of the brick's red coloration. In addition, the identified mica exhibited limited intersection with silica. These findings offer a firm and conclusive foundation for potential material recommendations in scenarios involving repair or restoration efforts. However, to develop a material proposal for restoration, it is imperative to discover the additional mechanical properties along with the physical and durability properties of the material. Some chemical experiments conducted on bricks should also be replicated for mortar to ensure inclusive understanding and analysis. In addition, a study in which the detailed structural problems and material deterioration of the building are revealed and the alterations are observed regularly every year, if possible with digital systems, would also be useful within the scope of future conservation and renovation.

The preservation and conservation of historical buildings such as the Üç Ayak Church, which are currently in an advanced state of damage, are of vital importance. These buildings are not only of cultural and historical significance but also rare and precious structures that convey the technology of the time in which they were built. Safeguarding historical structures is an essential means of transmitting the significant contributions of past civilizations to future generations. Accordingly, immediate restoration initiatives are imperative for the Üç Ayak Church to ensure its enduring preservation.

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