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Assessment of the Current State of Construction Materials of Some Historical Monuments in Georgia

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Abstract

The study aims to assess the current condition of construction materials used in four significant historical monuments in Georgia - Sioni Cathedral (Tbilisi, VI-XI century), Anchiskhati Basilica (Tbilisi, VI century), Barakoni Church (Racha region, XVIII century), and Nikortsminda Cathedral (Racha region, XI century) - through mineralogical and physical-mechanical analyses. The methodology combines X-ray diffraction (XRD) analysis and standard physical-mechanical tests, and the results are compared with established reference values.

XRD analysis revealed distinct mineralogical compositions for each structure. In Sioni's tuff slabs (19th century), the dominant phases include quartz (40%), kaolinite, and Na-montmorillonite - all of which are highly hygroscopic and sensitive to moisture-induced degradation. Anchiskhati's dressed tuff showed 25% quartz, Ca-Na feldspar, clay phases, and traces of kaersutite, indicating a relatively complex and weather-sensitive matrix. Barakoni's dolomitic stone contains (Ca, Mg)CO_3 dolomite and $CaCO_3$ calcite, both susceptible to chemical weathering, especially from acid rain and salt crystallization. In Nikortsminda's sandstone, dominant phases include calcite, quartz, and clinoptilolite (a zeolite), which contributes to increased capillarity and water retention, enhancing decay risks.

Physical-mechanical analysis indicates significant deterioration across all sites: the porosity of the Sioni building material increased by 12.5%, water absorption increased by up to 5%, and the strength decreased by 24%. In Anchiskhati, the porosity increased by 5%, and the strength decreased by 28%. In Barakoni, the strength decreased by 38%, while the porosity of Nikortsminda sandstone increased by 33%, and the strength decreased by 29%.

The results demonstrate that the presence of clay minerals, zeolites, and carbonates correlates with increased porosity, reduced strength, and higher susceptibility to environmental factors. These findings emphasize the necessity of tailored conservation approaches to ensure the long-term protection of Georgia's architectural heritage.

Keywords

Heritage, Cathedrals, Construction Stones, Physical-Mechanical Properties, Degradation.

1. Introduction

Historical monuments are key witnesses to a nation's cultural heritage, architectural evolution, and identity. In Georgia, a country with a millennia-old Christian tradition and a rich architectural legacy, church buildings occupy a central place in both religious practice and cultural memory (Khoshtaria, 2023). Over the centuries, these sacred structures have been subjected to a multitude of stressors – including natural disasters, warfare, urban development, and, most critically, the progressive impacts of climatic variability (Sesana, 2012). The visible deterioration of many historic churches and monasteries across Georgia attests to the severity of these influences, raising urgent questions about the sustainability and preservation of the country's built heritage.

A major concern in recent decades has been the increasing trend of unplanned or poorly executed restoration practices. In many cases, monuments have been "restored" using modern synthetic materials incompatible with the original fabric, often without proper documentation, material analysis, or structural diagnostics (Smith & Jones, 2018; Kanth & Soni, 2023). Such interventions not only compromise the historical authenticity and aesthetic integrity of the sites but also accelerate further degradation by introducing new physical and chemical instabilities (Alves et al., 2021). These processes underscore the necessity for systematic, interdisciplinary approaches to monument assessment and conservation, particularly in the context of climate change and intensified anthropogenic pressures (Cacciotti et al., 2024).

The present study addresses this urgent need by focusing on the diagnostic evaluation of construction materials used in four architecturally and historically significant religious buildings located in urban and rural regions of Georgia: the Sioni Cathedral (VI century) and Anchiskhati Basilica (VI century) in Tbilisi, and the Barakoni Church (XVIII century) and Nikortsminda Cathedral (XI century) in the mountainous Racha region. These sites were selected to represent a spectrum of architectural typologies, geological contexts, and environmental exposures – ranging in elevation from 380 to over 1,200 meters above sea level, and encompassing both dry urban microclimates and humid mountainous ecosystems (Elizbarashvili, 2007).

The principal aim of this research is to perform a preliminary assessment of the weathering and degradation status of the exterior building materials used in these churches. By integrating mineralogical analysis through X-ray diffraction (XRD) and standardized physical-mechanical testing (porosity, water absorption, compressive strength, etc.), we seek to understand the materials' vulnerability to environmental factors and to establish a basis for more comprehensive, long-term conservation methodologies (Espinosa-Marzal et al., 2011; Cardell et al., 2008). Special attention is paid to the role of mineral composition, microstructural features, and environmental exposure in determining the durability and resilience of historical masonry (Alves et al., 2021; El-Gohary, 2016).

To achieve this, a multi-stage methodology has been developed. The field phase includes visual inspections and geomorphological mapping of the sites. Material samples were collected and analyzed for porosity, hygroscopicity, salt content, and elemental composition. Meteorological data – including humidity, precipitation, temperature, and wind speed – were obtained from national hydrometeorological services and project-specific monitoring (National Environmental Agency of Georgia, 2024). Selected atmospheric precipitations were chemically analyzed to assess pH and major ionic components. Additionally, a long-term climate dataset was constructed from institutional archives to contextualize the observed degradation processes in relation to historical climate trends (Cappai et al., 2024).

Through this approach, the study aims to identify the dominant environmental and anthropogenic drivers behind the decay of these four emblematic churches. By presenting evidence-based findings, it contributes to the development of targeted conservation recommendations and adaptive strategies that are compatible with the original materials and architectural value of these unique monuments (Godts et al., 2023). Ultimately, this research serves as a foundation for the responsible safeguarding of Georgia's ecclesiastical heritage amid growing climatic and environmental challenges.

2. Materials and Methods

This study focuses on four architecturally and historically significant Georgian churches: Anchiskhati Basilica and Sioni Cathedral in Tbilisi, and Barakoni and Nikortsminda churches in the mountainous Racha region. All four monuments were selected due to their differing climatic exposure, anthropogenic influence, and construction materials, enabling a comparative evaluation of their structural degradation over time.

2.1. Research objects and architectural context

Anchiskhati Basilica (**Figure 1**), dating from the VI century, is a three-nave hall-type church located in the center of Tbilisi, near the Mtkvari (Kura) river. Originally built with squared blocks of yellow tuff, the upper parts of the walls and internal columns were reconstructed using brick during the XVII century. Its external and internal walls are faced with yellowish tuff tiles (Beridze, 2014).

Figure 1. Anchiskhati Basilica - main entrance.
Note. Photograph by N. Dzebisashvili, 2025.

Sioni Cathedral (**Figure 2**), a cross-in-square/crossed-dome Georgian Orthodox church, construction of which was initiated by Vakhtang I Gorgasali, King of Iberia (Georgia) at the end of the V century and completed in the VI-VII centuries, was built under the patronage of Dachi of Iberia Ujarmeli, Guaram I Kouropalates and Adarnase I of Iberia. The Sioni Cathedral was damaged several times and rebuilt/repaired, but the basic elements of the existing structure date from the XI-XII centuries. It is also located in Tbilisi on the right bank of the Mtkvari (Kura) river and constructed from dressed stone quarried in Algeti-Bolnisi and faced with yellowish sandstone-tuff slabs (Beridze, 2014; Beridze, 1954).

Figure 2. Sioni Cathedral - north-eastern façade
Note. Photograph by N. Dzebisashvili, 2025.

Barakoni Church (**Figure 3**), a prominent example of XVIII-century domed architecture, is located on the right bank of the Rioni River at the confluence with the Lukhuni River in the Racha region. It is a domed cruciform church and one of the last important monuments in the tradition of medieval Georgian architecture - adorned with rich ornamentation (Beridze, 2014). Built from locally sourced dolomite and calcite-based stone, it stands in close proximity to the large Shaori Reservoir constructed in the 1950s, potentially contributing to microclimatic changes affecting the monument (Beridze, 1974; Chokheli & Khelidze, 2022).

Figure 3. Barakoni Church - eastern facade.
Note. Photograph by N. Dzebisashvili, 2025.

Nikortsminda Cathedral (**Figure 4**) is a masterpiece of national architecture. Constructed in the early 11th century by King Bagrat III of Georgia the Unifier, it is a Georgian cross-dome style church, with six-conches within a short-armed rectangular cross plan, which is located in the eponymous village in Racha. The decor of the exterior of Nikortsminda is an achievement of Georgian monumental plastic art. Nikortsminda has one of the richest and most beautiful decorations/stone carvings of all Georgian churches and cathedrals, with a fusion of several different styles. The monument has not undergone major changes during its existence, and the dome of the temple has remained in its original form. Its construction material primarily consists of sandstone containing calcite, quartz, and clinoptilolite, a zeolite phase known for high water retention and capillarity (Beridze, 2014). As the Nikortsminda Cathedral is located approximately 4 km north of the Shaori Reservoir, the influence of microclimatic changes on the monument is even more likely than in the case of Barakoni (Beridze, 1974; Chokheli & Khelidze, 2022). Since 2007, the cathedral has been on the Tentative List for status as a UNESCO World Heritage Site (UNESCO, 2025); however, its assignment to World Heritage status was postponed, both due to the lack of a comprehensive management and conservation plan for the monument and to the lack of scientific documentation of the material condition and environmental impact.

Figure 4. Nikortsminda Cathedral - southern facade (N. Dzebisashvili, 2025)

2.2. Sampling Procedure and Analytical Methods

To assess material integrity, stone samples were extracted from the exterior walls of each church. Sampling focused on both visually deteriorated and relatively intact areas to provide a comprehensive overview of material condition. Samples underwent mineralogical analysis using X-ray diffraction (XRD) to identify their compositional phases (Figure 5, Figure 7, Figure 9 & Figure 11), and petrographic analysis was used to examine surface microstructures and detect weathering features such as micro-cracks, efflorescence, and particle disintegration (Figure 6, Figure 8, Figure 10 & Figure 12).

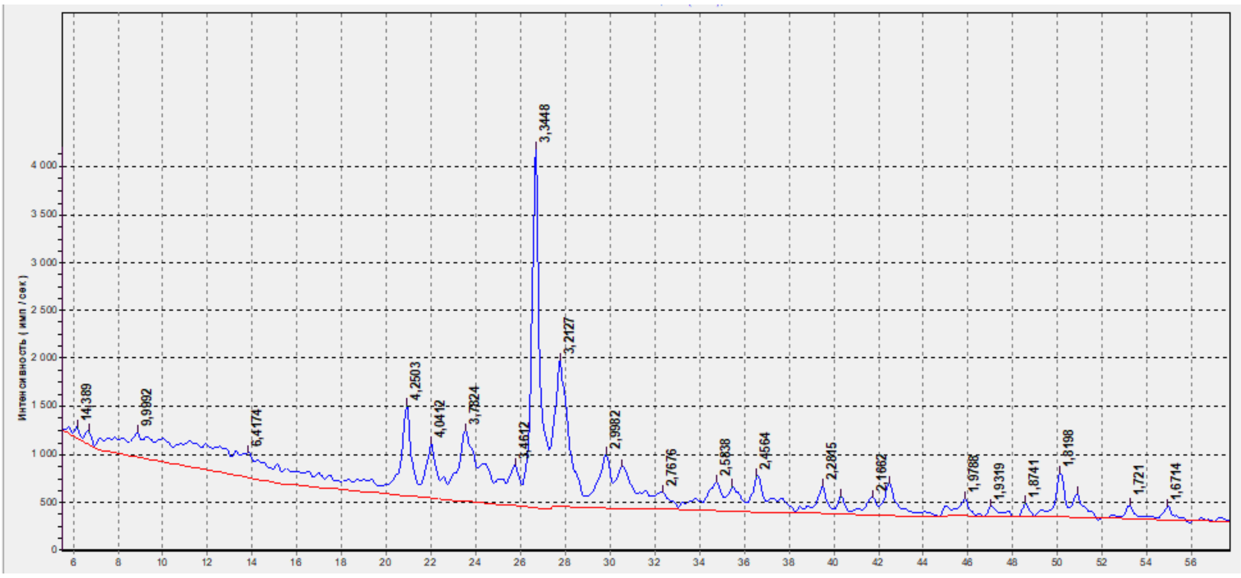

Figure 5. Result of Anchiskhati XRD analysis.
Source. GTU (2024)

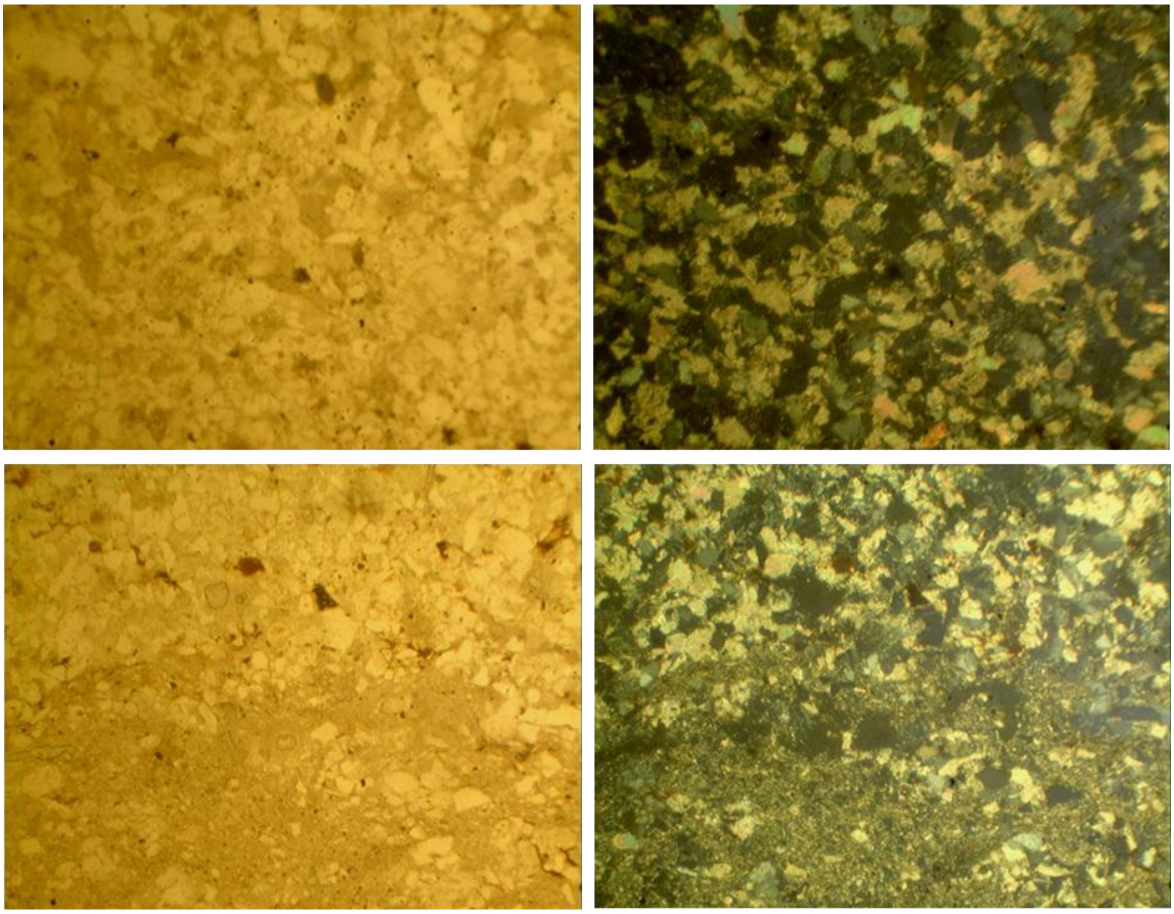

Figure 6. Result of Anchiskhati Petrographic analysis (left: single Nicol (-); right: crossed-Nicols (+))
Source. GTU (2024)

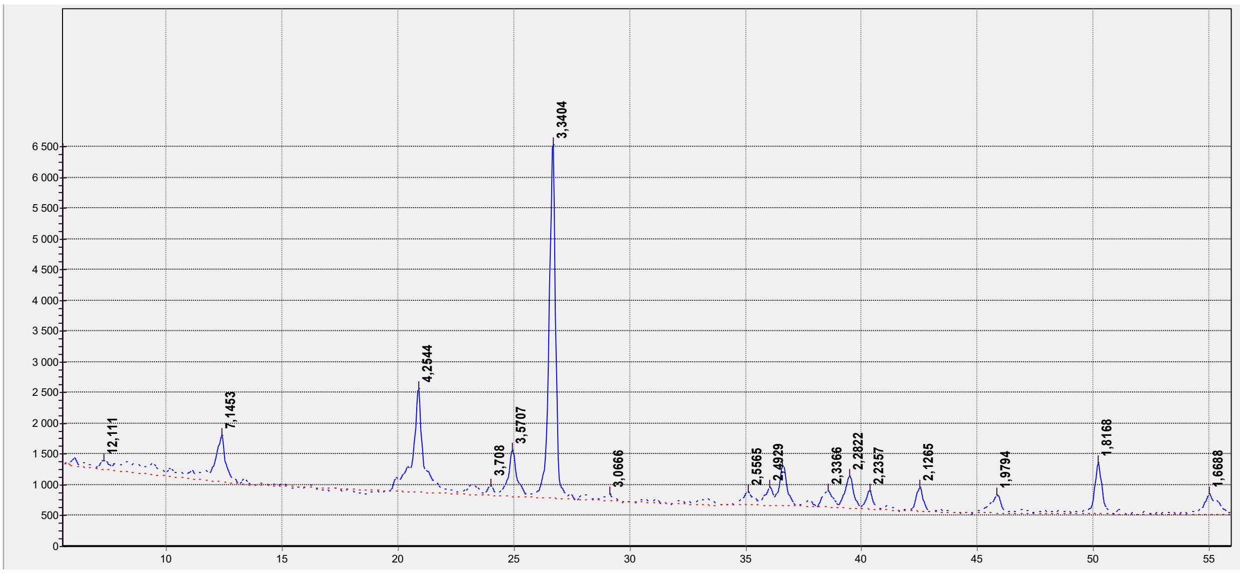

Figure 7. Result of Sioni XRD analysis.
Source. GTU (2024)

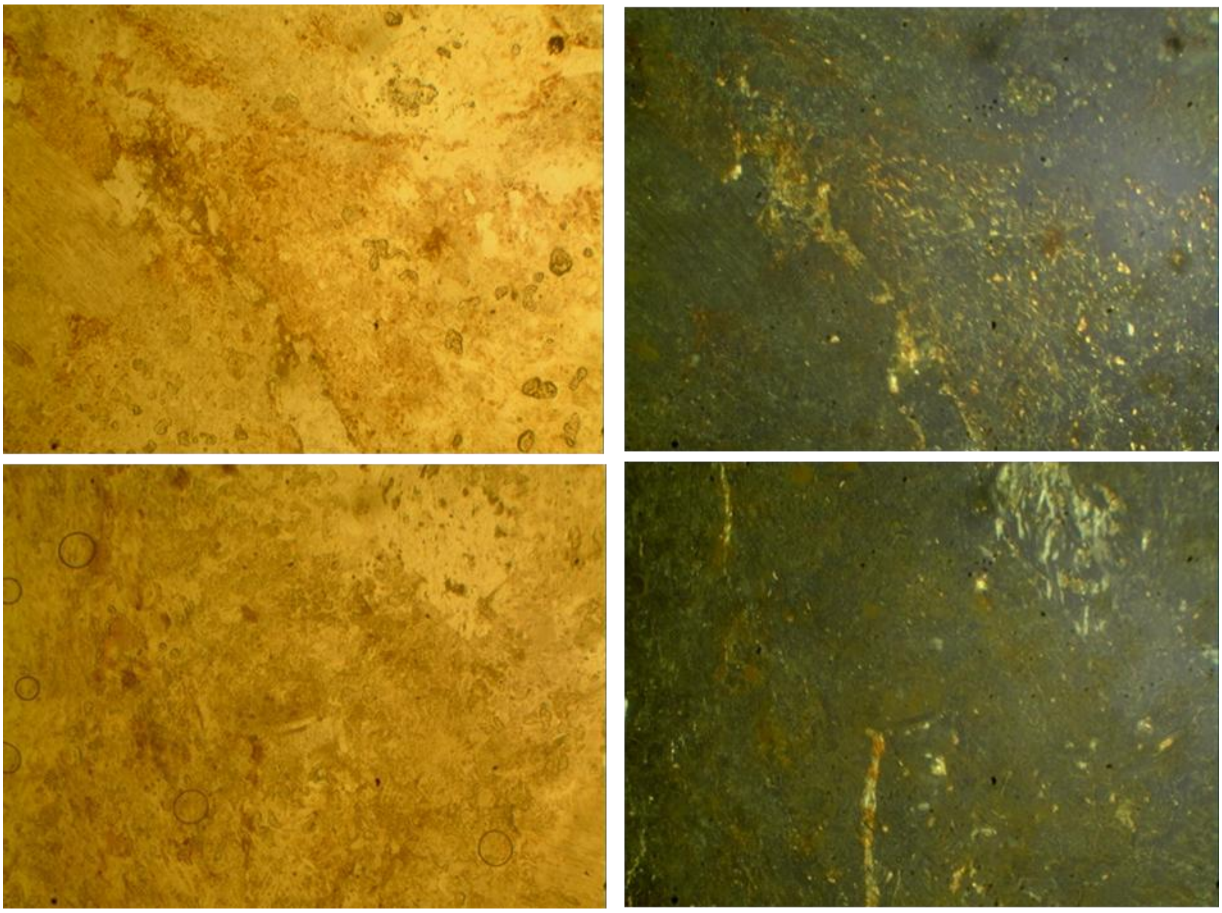

Figure 8. Result of Sioni Petrographic analysis (left: single Nicol (-); right: crossed-Nicols (+)).
Source. GTU (2024)

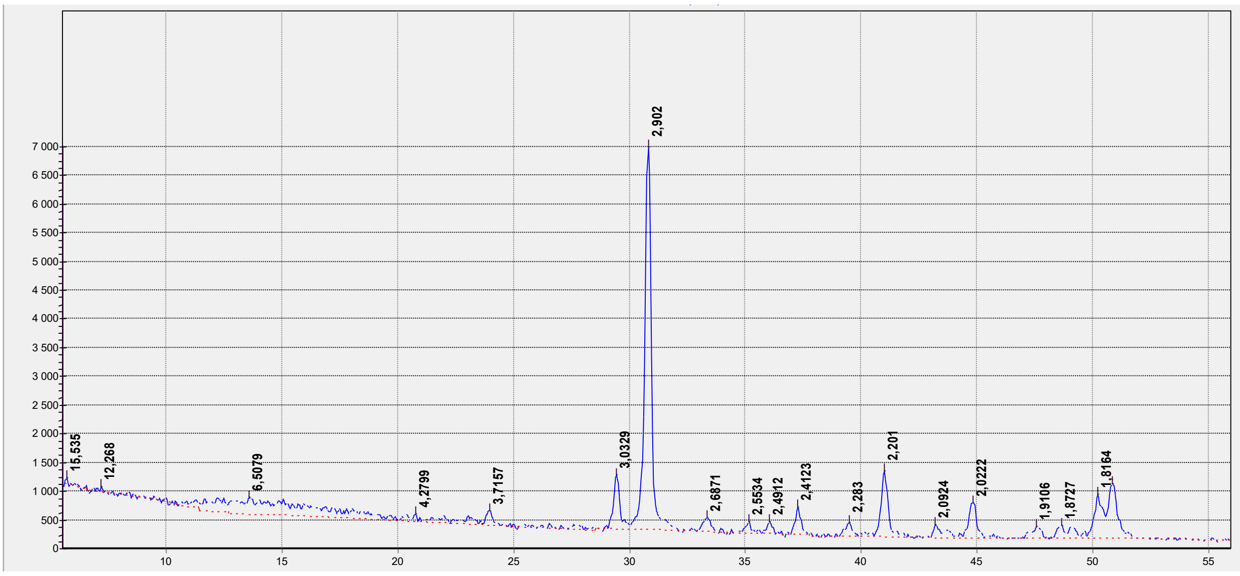

Figure 9. Result of Barakoni XRD analysis.
Source. GTU (2024)

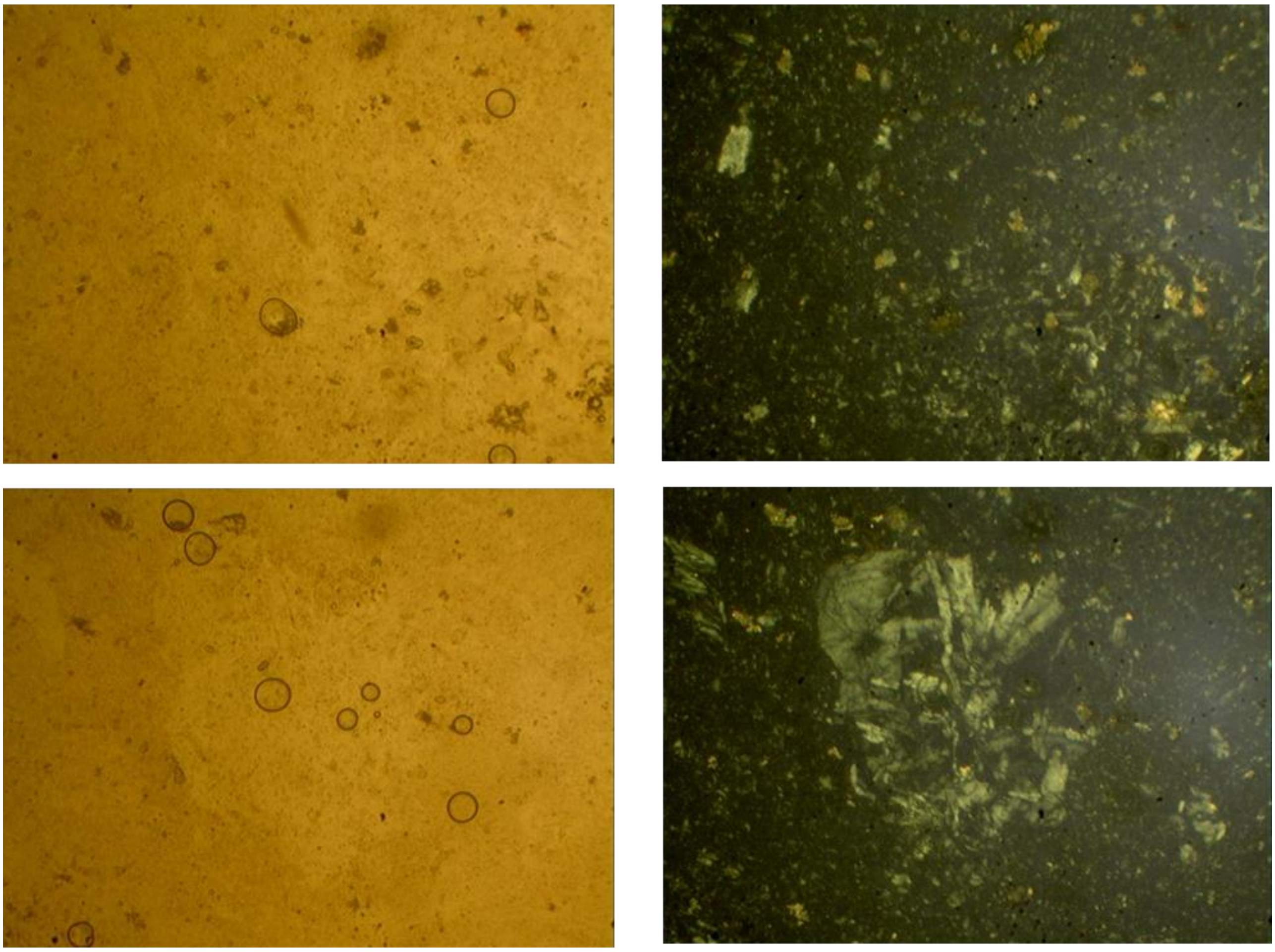

Figure 10. Result of Barakoni Petrographic analysis (left: single Nicol (-); right: crossed-Nicols (+)).
Source. GTU (2024)

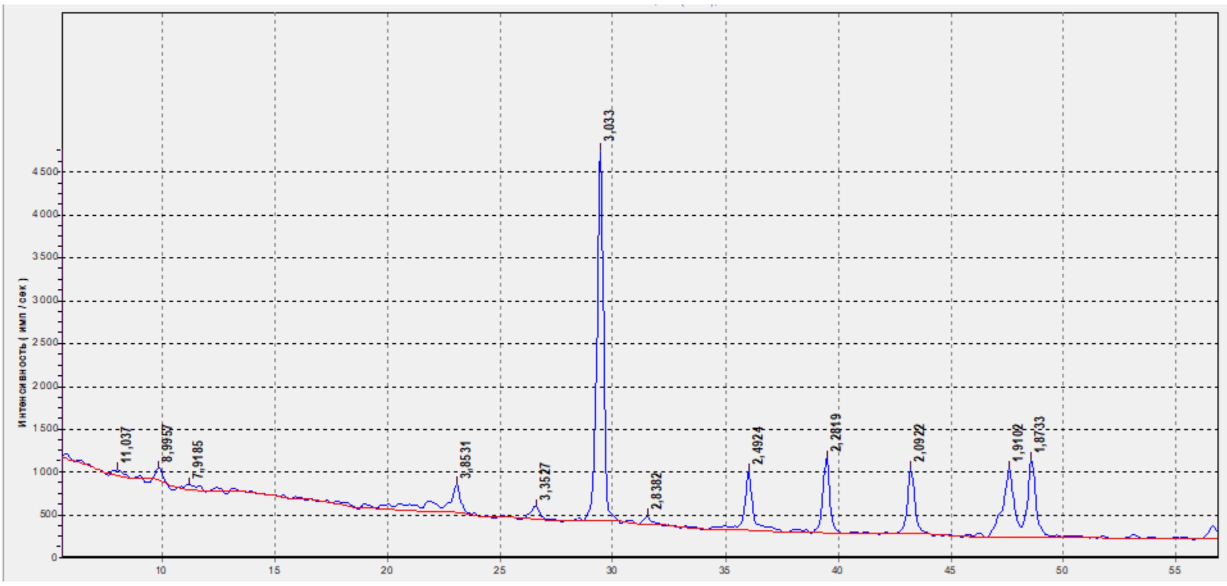

Figure 11. Result of Nikortsminda XRD analysis.
Source. GTU (2024)

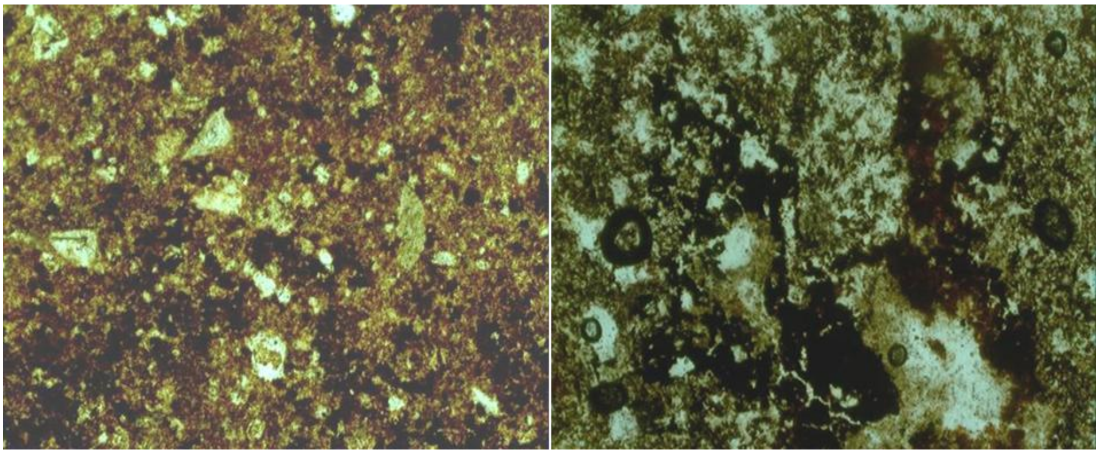

Figure 12. Result of Nikortsminda Petrographic analysis (single Nicol (-)).
Source. GTU (2024)

Anchiskhati Basilica's tuff was found to contain approximately 25% quartz, along with significant amounts of feldspar, clay minerals (including kaolinite), and traces of mica. These constituents indicate high susceptibility to chemical weathering and physical disintegration when exposed to fluctuating moisture conditions (**Figure 5**). Sioni Cathedral's yellowish tuff includes approximately 40% quartz and shows signs of kaolinite and Na-montmorillonite, suggesting a material highly vulnerable to moisture retention and swelling-related stresses (**Figure 7**). Barakoni Church's dolomitic and calcitic stone showed relatively low resistance to acid exposure, indicating vulnerability to acid rain and carbonic acid infiltration (**Figure 9**). Nikortsminda Cathedral's sandstone showed clinoptilolite content, which promotes degradation in architectural contexts due to increased capillarity (**Figure 11**).

2.3. Physical-Mechanical Characterization

Laboratory testing was conducted to determine four key parameters: bulk density, true density, water absorption, and porosity. Results were compared with published reference standards for similar stone types to determine the extent of degradation (**Table 1**). Samples of building stone from the churches studied were also tested for dry compressive strength, as well as for strength reduction due to exposure to an aggressive environment for 12 months after exposure (**Table 2**). The water resistance of building stone (reduction in strength compared to dry strength) according to GOST 9479-2011 (Stone blocks for architectural, construction, memorial, and other types of products. Technical conditions) should not exceed 30%. Rainwater and groundwater collected from the church grounds were used as aggressive media.

Anchiskhati samples demonstrated a 5% increase in porosity and a 28% decrease in compressive strength compared to standard values. Water absorption had also slightly increased. Sioni samples showed a 12.5% increase in porosity and a 5% rise in water absorption. Their compressive strength had declined by 28%, indicating significant loss of structural integrity. Barakoni samples had the highest porosity values-up to 22.5% in wall base samples-and water absorption rates exceeding 12%, suggesting severe long-term deterioration. Nikortsminda samples showed a 33% increase in porosity and a 29% reduction in mechanical strength, indicating a progressive weakening of the sandstone structure.

These values were corroborated by polarizing microscope imaging, which revealed widespread microfractures and mineral surface erosion.

Table 1. Results of physical-mechanical analysis of Anchiskhati, Sioni, Barakoni, and Nikortsminda churches construction materials.

Sample	Bulk density, g/cm3	True density, g/cm3	Water absorption,%	Porosity,%
Anchiskhati	2.13 - 2.16	2.54 - 2.55	9.79 -10.99	15.0 - 16.5
Sioni	2.33 - 2.35	2.62 - 2.76	2.20 - 5.52	12.41 - 14.86
Barakoni	2.17 - 2.29	2.73 - 2.80	11.65 - 12.44	16.12 - 22.50
Nikortsminda	2.26	2.56	7.79	11.72

Table 2. The influence of aggressive environments on the physical and mechanical strength of building stone.

Sample	Initial average strength value, kg/cm²	Average strength after exposure to rainwater, kg/cm²		Average strength after exposure to groundwater, kg/cm²	
		strength	strength decline %	strength	strength decline %
Anchiskhati	398.9	272.3	31.7	217.5	45.5
Sioni	353.7	226.1	36.0	191.1	54.0
Barakoni (wall)	236.7	187.1	21.0	*	*
Barakoni (plinth)	301.3	205.0	32.0	*	*
Nikortsminda	514.7	328.9	36.1	*	*

Note: *Groundwater sampling was unavailable for Barakoni and Nikortsminda.

2.4. Meteorological and Environmental Data

To contextualize the degradation processes, meteorological data from the past three decades were reviewed, including average temperature, humidity, wind speed, and annual precipitation for both Tbilisi and Racha regions. In addition, atmospheric deposition samples, including rainfall and surface runoff, were collected and analyzed for pH and ionic composition to determine the presence of acidifying agents such as sulfur and nitrogen oxides.

The combined mineralogical, mechanical, and climatic data provide a comprehensive methodology for understanding the mechanisms of stone decay under both natural and anthropogenic pressures. These insights will be critical in developing conservation strategies tailored to the material-specific vulnerabilities of each monument.

3. Results

The comprehensive analysis of stone samples collected from the four selected historical churches revealed significant signs of material degradation, most likely induced by long-term exposure to environmental factors, particularly moisture, atmospheric pollutants, and climatic fluctuations. The data obtained through physical-mechanical tests and mineralogical characterization allow us to draw several key conclusions regarding the state of preservation and environmental vulnerability of these architectural heritage sites.

3.1. Physical and Mechanical Properties

The results of the physical-mechanical testing, as summarized in **Table 1**, indicate increased porosity and water absorption in all studied samples, alongside a notable reduction in bulk material strength. These changes are strong indicators of material degradation, commonly associated with aging, repeated wet-dry cycles, freeze-thaw actions, and pollutant-induced chemical reactions.

Anchiskhati Basilica's yellowish tuff displayed increased porosity values (up to 16.5%) and a water absorption rate of nearly 11%, exceeding typical thresholds for structural tuff. This is consistent with polarizing microscope observations showing surface damage and microcracks, which suggest progressive weathering. Similarly, Sioni Cathedral's tuff samples exhibited 12.5% porosity and 5.5% water absorption. Both sites showed a strength reduction of around 28% compared to reference standards, suggesting significant deterioration (Melikidze,1967; State Committee of the Council of Ministers of the USSR, 1962).

In the case of Barakoni Church, located in the Racha region, the deterioration appears more severe. The lower wall segments, in particular, demonstrated the highest porosity recorded in this study (22.5%) and water absorption up to 12.44%. These values point to a compromised structural condition and suggest a high susceptibility to environmental moisture, particularly given the church's proximity to the Shaori Reservoir and increasing regional humidity levels. The presence of dolomite and calcite, both sensitive to acid rain and freeze-thaw conditions, further exacerbates the vulnerability of Barakoni's building material.

Nikortsminda Cathedral, also in Racha, presents similarly concerning results. The porosity of its stone samples reached 33% - the highest of all the samples studied - while the porosity decreased by approximately 29%. Mineralogical analysis showed the presence of clinoptilolite, a natural zeolite with strong water-retention capacity. While such materials may offer certain structural benefits, their enhanced capillarity under wet conditions promotes internal stress and eventual breakdown through salt crystallization and freeze-thaw cycles.

3.2. Environmental Influence and Material Sensitivity

The results confirm that the building materials used in these historical churches - especially tuff, calcitic sandstone, and dolomitic rocks - are inherently sensitive to moisture and vulnerable to environmental weathering. This sensitivity is amplified by current climatic trends observed in various regions of Georgia. For instance, in the Racha region, statistical meteorological data over the past three decades indicate an upward trend in annual precipitation and relative humidity. These shifts in local climate parameters likely contribute to the material degradation observed in Barakoni and Nikortsminda, especially in the form of increased porosity and water absorption.

Moreover, many of the construction materials, particularly those of carbonate origin, are prone to surface salt crystallization, a process driven by capillary rise and evaporation. The recurrent deposition and crystallization of soluble salts within the stone matrix leads to microfracturing and eventual surface exfoliation, further weakening structural cohesion.

The correlation between material sensitivity and environmental exposure is evident: materials such as tuff with high quartz and feldspar content (Anchiskhati and Sioni), and carbonate-rich stones (Barakoni and Nikortsminda), are particularly prone to degradation in the presence of variable humidity, acidic precipitation, and polluted urban air. Given that most of these buildings are exposed to both natural weathering and anthropogenic impacts (e.g., urban emissions, acid rain), the observed deterioration can be attributed to a multifactorial set of stressors.

3.3. Preservation Challenges and Strategic Considerations

The evidence suggests that the long-term survival of these centuries-old monuments depends on how effectively such environmental and material risks are addressed. As climate models predict continued warming, increased precipitation, and more frequent extreme weather events, it is imperative that tailored conservation strategies be developed and implemented.

The present study highlights the necessity of site-specific interventions based on detailed mineralogical and environmental assessments. For example, protective surface treatments might be used to reduce water ingress and mitigate surface erosion. However, such interventions must be carefully designed to avoid altering the visual or structural integrity of these monuments. Conservation treatments should be reversible, breathable, and compatible with the original stone material.

Future work will involve the proposal of state-level recommendations aimed at protecting these cultural monuments from progressive degradation. These recommendations will include the selection and application of environmentally compatible stone consolidants and water repellents, as well as architectural modifications-such as improved drainage systems and protective eaves-to shield vulnerable areas from indirect rainfall and runoff.

In addition, ongoing climate monitoring and non-invasive diagnostic techniques such as ground-penetrating radar (GPR), infrared thermography, and moisture mapping will be employed to detect early signs of decay and assess the long-term performance of conservation treatments.

This study demonstrates the clear relationship between environmental conditions and the deterioration of historic Georgian churches. It emphasizes that increased humidity, acid rain, freeze-thaw dynamics, and salt weathering are the dominant factors affecting the integrity of traditional stone materials. Effective conservation must therefore incorporate not only a deep understanding of material science but also the evolving context of local climate dynamics. Only through integrated, interdisciplinary, and preventive approaches can the architectural and cultural value of these irreplaceable monuments be preserved for future generations.

3.4. International Parallels of the Current Study

The degradation mechanisms observed in Georgian ecclesiastical monuments mirror those widely documented in global heritage conservation literature, especially regarding the roles of moisture sensitivity, salt crystallization, and climatic stressors.

Salt weathering is a primary degradation driver. Alves et al. (2021) emphasize how comparative laboratory studies reveal salt crystallization-induced deterioration in porous stones like tuff and limestone, paralleling increased porosity and moisture absorption in Barakoni and Nikortsminda monuments. Similarly, Espinosa-Marzal et al. (2011) explain the chemo-mechanics of sodium sulfate crystallization in limestone, describing internal micro-fracturing consistent with the weakening observed in Georgian monuments' carbonate/calcite structures.

Mixed sulfate attacks are also significant. Cardell et al. (2008) characterize microstructural damage in limestone exposed to mixed sulfate solutions using techniques like petrography and XRD methods mirrored in our study. They outline reaction products and decay morphologies that resemble those observed in Barakoni's dolomitic stones. Importantly, Barakoni Church is located near the former Uravi arsenic mining and processing site in Racha. Uravi is known for its arsenopyrite (FeAsS)-rich ore deposit, and decades of mining and waste disposal have elevated arsenic and sulfate levels in surrounding soils, watercourses, and groundwater (Shavliashvili, 2023; Shavliashvili et al., 2025). Oxidative weathering of arsenopyrite releases sulfate ions, which can contribute to aggressive salt crystallization cycles on carbonate building stones. Taken together, the proximity of this sulfur- and arsenic-rich contamination source and the mineralogical vulnerability of Barakoni's stone may accelerate degradation via sulfate-induced stress and salt crystallization – amplifying the microstructural damages described by Cardell et al. (2008).

In terms of environmental modeling, Cappai et al. (2024) use infrared thermography alongside environmental and accelerated ageing data to assess decay kinetics in porous stone, a promising approach for future monitoring of stone condition of Georgian historical monuments affected by climate-induced deterioration.

Groundwater-driven decay is another critical factor. El-Gohary (2016) employed AAS, microscopy, and XRD to document salt-induced decay in the Edfu Temple associated with rising damp from groundwater. This mechanism aligns with observations at Barakoni, where reservoir-affected moisture may exacerbate structural degradation (Sass & Heil, 2024).

Complicated salt mixtures are explored by Godts et al. (2023), who reveal how co-crystallizing salts form internal stresses amplifying stone deterioration, helpful for interpreting mixed salt effects within Georgian stone matrices.

Extreme climate vulnerability is analyzed by Cacciotti et al. (2024), offering a framework for assessing heritage under climate change, supporting our interdisciplinary methodology that integrates mineralogical testing with climatic datasets.

Urban atmospheric stressors, such as acidification and pollution, are discussed by Basu et al. (2023), who illustrate how urban environments and climate change contribute to stone decay in London - comparable to Tbilisi's polluted conditions affecting Anchiskhati and Sioni.

Moisture-induced expansion of tuff and sandstone is substantiated by Wedekind et al. (2013) and Siegesmund et al. (2023), highlighting swelling processes in clays and zeolites, directly parallel to findings in Georgia's sandstone and tuff monuments.

Brick deterioration modeling in humid, flood-prone Venice, explored by Hernández Montes et al. (2023), shares common climatic sensitivity patterns observed in Georgian stone structures.

Conservation treatments for volcanic tuff are demonstrated by Özgünler & Karkas (2024), who affirm that breathable hydrophobic coatings can effectively reduce moisture ingress while preserving visual integrity, validating similar recommendations proposed for Georgian heritage sites.

Material durability assessment, such as performed by Shekofteh et al. (2019) at Pasargadae, confirms the efficacy of combined XRD, petrographic and physical-mechanical testing - a methodological parallel to our study approach.

Biological and bacterial interactions, as described by Elert et al. (2021) at Copán, stress bio-conservation factors in tropical humid climates, offering additional insight into microbial risks for Georgian sites under similar humidity conditions.

Chinese case studies on tuff weathering presented by Wu et al. (2022) reinforce the connection between environmental factors (rainfall, condensation, freeze–thaw) and stone decay, lending cross-cultural scientific support to observations in Georgian contexts.

Reviews on carbonate deterioration and conservation, like that of Yan and Wang (2024), highlight acid precipitation and pollution as critical threats to calcareous stones-consistent with observed degradation in Georgian stonework.

Collectively, these studies provide compelling international parallels to the decay phenomena documented in Georgia. They affirm that moisture retention, salt crystallization, freeze-thaw cycles, pollution, and climatic variability are universal challenges for porous stone heritages. Our integrated use of XRD, petrography, porosity and density testing, meteorological data analysis, and proposed conservation methods reflects international best practices and reinforces the scientific rigor of our regional adaptation.

4. Conclusion

The present study highlights the critical vulnerability of historic Georgian ecclesiastical architectural monuments, particularly the churches - Anchiskhati, Sioni, Barakoni and Nikortsminda, to environmental and anthropogenic degradation processes. Our material analyses (XRD, petrography, physical-mechanical assessments) reveal that construction materials, especially carbonate and zeolite-rich stones, exhibit high sensitivity to moisture and salt crystallization, both of which are exacerbated by ongoing climatic shifts such as increasing humidity, rainfall intensity, and freeze-thaw cycles.

Comparison with international literature confirms that these decay patterns are not isolated phenomena. Similar mechanisms of stone weathering - especially through salt crystallization and sulfation have been extensively documented across Mediterranean and Central European heritage structures (Alves et al., 2021; Espinosa-Marzal et al., 2011; Cardell et al., 2008). Moreover, the proximity of Barakoni Church to the arsenic-rich Uravi mining site adds a unique geochemical stressor to the stone decay processes in this region, echoing cases such as the Edfu Temple in Egypt where groundwater chemistry plays a destructive role (El-Gohary, 2016).

Given this convergence of environmental and geochemical pressures, the preservation of the architectural heritage of Georgia requires targeted, site-specific conservation strategies. Such strategies must be based on thorough material diagnostics and consider external pollution sources, regional climate trends, and stone mineralogy. Future research should emphasize interdisciplinary approaches, combining geological, chemical, and environmental analyses with conservation science.

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Ethics approval

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Conflict of interest:

The author(s) declare(s) that there is no competing interest.

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