INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

Vol. 16 No. 7 (2024) 1-11
https://publisher.uthm.edu.my/ojs/index.php/ijie

IJIE

Characterization of Weathered and Intact Limestone with FTIR Analysis in Batu Caves, Malaysia

Hamasa Kambakhsh[1,2], Nik Norsyahariati Nik Daud[1,3]*, Saifullah Inanch[3,2]

[1] *Department of Civil Engineering, Faculty of Engineering,*
Universiti Putra Malaysia, 43400 Serdang, Selangor, MALAYSIA
[2] *Department of Geology and Mine, Faculty of Engineering,*
Faryab University, Faryab, AFGHANISTAN
[3] *Housing Research Centre (HRC), Faculty of Engineering,*
Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, MALAYSIA

*Corresponding Author: niknor@upm.edu.my
DOI: https://doi.org/10.30880/ijie.2024.16.07.001

Article Info

Received: 24 July 2024
Accepted: 5 October 2024
Available online: 27 November 2024

Keywords

Batu Caves, calcium carbonate, weathered limestone,FTIR analysis

Abstract

This paper explores the complex geological processes involved in the weathering of limestone in Batu Caves, Malaysia. Batu Caves is well-known for its formations that hold cultural and geological importance. Limestone, consisting mostly of calcium carbonate, experiences weathering processes that are impacted by environmental conditions, necessitating a thorough investigation. The study used Fourier-transform infrared spectroscopy (FTIR) to thoroughly analyse six limestone samples from Batu Caves. The FTIR analysis provides essential information on the mineral composition of limestone. Three key objectives guided our investigation: i) to discern the physical properties of both intact and weathered limestone, ii) to scrutinize the wave spectrum through FTIR analysis, and iii) to elucidate the intricate relationship between physical and chemical properties during the weathering process. The FTIR findings provide significant insights into the mineral compositions of weathered limestone in Batu Caves. Within the cave, feldspar, calcite, and dolomite were identified, while beyond the cave's confines, distinct peaks indicated the presence of calcite, dolomite, clay minerals, and magnesium-rich chlorite. Noteworthy peaks at 3440.51 cm^{-1} and 3746.26 cm^{-1} confirmed the existence of clay minerals and chlorite, enriching our understanding of geological changes resulting from weathering. Overall, the FTIR analysis improves our understanding of Batu Caves's geological past by revealing the intricate connections between limestone and environmental elements. Additionally, this study examined the electrical and electronic properties of both intact and weathered limestone. Intact limestone exhibited low electrical conductivity, in the range of 10^{-8} to 10^{-6} S/m, due to its low porosity and insulating properties of calcium carbonate. Weathered limestone, with increased porosity and moisture content, showed significantly higher conductivity, ranging from 10^{-3} to 10^{-6} S/m.The results highlight the susceptibility of limestone formations to weathering.Key points of comparison include changes in mineral composition, with weathered limestone showing the introduction of clay minerals and magnesium-rich chlorite. Increased porosity in weathered limestone leads to greater moisture retention, which directly impacts its electrical properties, resulting in elevated conductivity. These differences highlight the significant effects of weathering on limestone's structure and function. The ramifications transcend mere scientific curiosity, underscoring the imperative for comprehensive conservation endeavours aimed at safeguarding this emblematic natural and cultural legacy for posterity.

1. Introduction

Limestone is mainly a sedimentary rock comprising calcium carbonate ($CaCO_3$) in the mineral form known as calcite. This rock typically originates in clear, warm, and shallow marine environments. This geological formation typically consists of organic sedimentary rock slowly accumulating shells, corals, algae, and feces. Additionally, this rock can be classified as a chemical sedimentary rock since it is created through the precipitation of calcium carbonate from bodies of water, such as lakes or oceans [1]. The weathering of limestone occurs when rainwater containing a mild carbonic acid reacts with limestone. Whenever it rains, limestone dissolves. Weathering is a mechanism that includes the physical, chemical, and biological breakdown of rock [2].

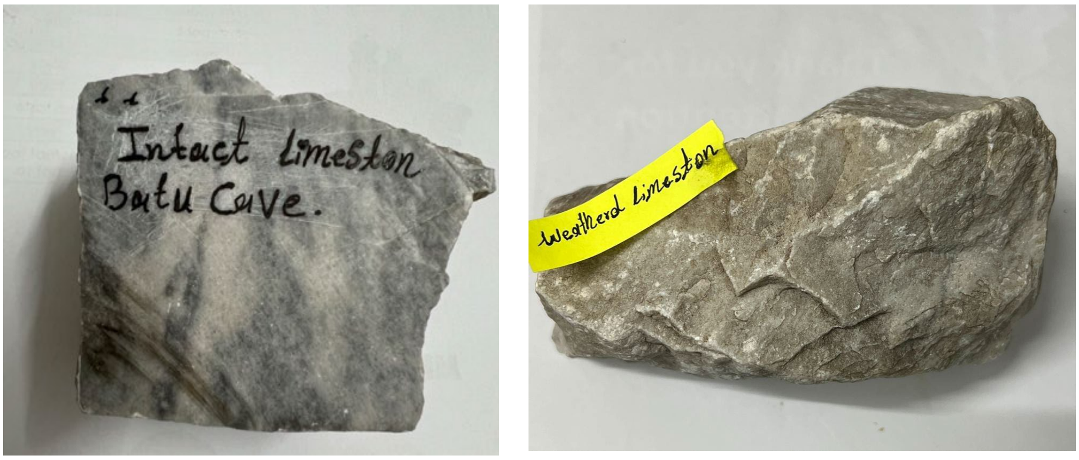
Fourier-transform infrared spectroscopy (FTIR), known for its exceptional accuracy in detecting chemical compositions and structural alterations, a very effective technique, to analyse and identify tiny alterations in the structural composition of limestone formations. Several research studies have been done on the physical, chemical, and mineralogical characteristics of limestone in the past. The characteristics of mineral changes in limestone composition have been investigated using FTIR techniques. FTIR bands at 1419, 874.08 cm^{-1} and 712.20 cm^{-1} indicate the presence of calcite. Weathering changes these compounds and leads to cracks and holes in the limestone. This study emphasizes the need to understand the complex properties of limestone and highlights the effect of weathering on calcite and its implications for long-term suitability in construction and industrial applications [3].

This research aims to provide a comprehensive understanding of the changes that occur in the physical properties and chemical composition of limestone due to weathering processes in the distinctive geological setting of Batu Caves. In order to achieve the aim, three objectives are outlined, i) to determine the physical properties of intact and weathered limestone, ii) to analyse the wave spectrum of intact and weathered limestone using the FTIR machine and iii) to establish the relationship of physical and chemical properties of intact and weathered limestone in weathering process.

2. Limestone Formation in Batu Caves, Malaysia

The Batu Caves, located in Selangor near Kuala Lumpur, Malaysia are renowned for their distinctive limestone formations of cultural and geological significance [4]. These limestone formations, predominantly composed of calcium carbonate, have been shaped over millions of years by various geological processes, resulting in amazing caverns, stalactites, and stalagmites. In addition to their geological significance, the Batu Caves is also a significant Hindu religious site, with numerous temples and shrines nestled within the caverns [5].

Batu Caves is a geographically distinct limestone hill, characterized by its dome shape, situated at coordinates 3.2379° N and 101.6840° E, with an elevation of roughly 390 meters above sea level It is positioned around 11 kilometers northeast of Kuala Lumpur, as documented [6]. The comprehension of the delicate relationship between weathered and intact limestone structures in Batu Caves exemplifies the complex interplay among geology, environment, and human culture. Although the limestone formations found in Batu Caves are undoubtedly impressive, they are not immune to the gradual effects of weathering processes. The limestone has undergone slow changes in its composition and structure as a result of the effects of rain, humidity, and the continuous passage of time. The aforementioned alterations have significant ramifications, not alone for geological research, but also for the conservation and administration of this renowned location, where the amalgamation of natural aesthetics and cultural legacy is evident [7]. Fig. 1 shows the weathering prosses of limestone in Batu Caves, Kuala Lumpur.



(a) **(b)**

Fig. 1 *Samples retrieved from Batu Caves site in Gombak, Selangor area (a) Intact limestone and (b) weathering limestone*

2.1 Chemical and Mineralogical Composition of Limestone

The complex chemical and mineralogical composition of limestone, a sedimentary rock of significant geological significance, is principally dominated by calcium carbonate, which gives it its unique characteristics. This mineral, which is mostly found as calcite, adds to the special qualities of the rock. But the composition of limestone is not restricted to calcite alone; other minerals have also been detected, especially in warm, shallow marine settings, such as dolomite, feldspar, and magnesium-rich chloride [8].

Limestone is formed by a series of complex chemical reactions that take place in clear, shallow marine settings. Because weathering is so prevalent in these environments, minerals change, which is an important part of how limestone has evolved geologically. In this case, weathering performs two functions: it determines the composition of limestone and initiates the breakdown of calcium carbonate in sedimentary structures [9]. The development and change of this sedimentary rock are significantly impacted by weathering, as demonstrated by this study in Batu Caves, which frequently contains limestone compounds [10]. Chemical weathering involves the transformation of certain minerals into different minerals. An instance of this occurs when feldspar undergoes alteration, specifically by hydrolysis, resulting in the formation of clay minerals. Conversely, several minerals have the ability to fully dissolve, causing their constituents to enter into a solution. For example, calcite ($CaCO_3$) is soluble in acidic liquids [11].

$$CaAl_2Si_2O_8 + H_2CO_3 + \frac{1}{2}O_2 \rightarrow Al_2Si_2O_5(OH)_4 + Ca^{2+} + CO_3^{2-} \tag{1}$$

(plagioclase + carbonic acid → kaolinite + dissolved calcium + carbonate ions)

The geological significance of limestone essentially stems from the dynamics of its composition, which are shaped by the interaction of minerals and weathering processes in warm, shallow marine environments. Comprehending these complex mechanisms offers a significant understanding of the geological past contained in limestone formations, particularly in the specific setting of caves. Limestone's geological story, told via the language of minerals and weathering, reveals the constantly changing fabric of Earth's geological processes.

2.2 Susceptibility of Limestone to Weathering Processes

The susceptibility of limestone to weathering pertains to its proneness and sensitivity to environmental processes that result in its disintegration and modification over a period of time. Limestone, a sedimentary rock consisting mainly of calcium carbonate, undergoes diverse geological alterations driven by external causes. The susceptibility is determined by factors such as local conditions, climatic components, and human activities [12].

Various factors, including climatic variables such as water erosion, wind erosion, temperature variations, and biological processes such as plant growth, influence the susceptibility of limestone. Human activities, particularly those that affect the nearby environment, also contribute to the erosion of limestone. Comprehending the vulnerability of limestone is essential for evaluating the possible hazards to structures constructed from this rock, such as historical sites and structures [13].

Weathering occurs as a result of chemical decomposition, in which minerals in limestone break down into different compounds under the influence of chemical agents such as carbon dioxide, water, oxygen, and organic acids. This process is expedited in areas with elevated temperatures and humidity levels. Chemical weathering of limestone can lead to the formation of cavities, fissures, seams, and fractures, which can ultimately compromise its structural stability. Limestone's susceptibility to weathering involves the complex and ever-changing mechanisms that cause its alteration over long periods. It is crucial to acknowledge and comprehend this vulnerability in order to effectively conserve natural limestone regions and protect historically significant structures [14]. Equation 2 shows the chemical reactions involved in the process [15].

$$CaCO_3 + H_2O + CO_2 \rightarrow Ca\,(HCO_3)_2 \tag{2}$$

(Limestone + Water + Carbon Dioxide → Calcium Bicarbonate)

3. Materials and Methodology

3.1 Selection of Samples

During this investigation, a rigorous selection process was conducted to obtain a total of six samples of limestone so that analyses obtained are close to reality, as well as several samples for a more complete understanding of geological features such as heterogeneity in rock composition, structure, and mineralogy, reliable inferences about the texture of the steady area, and we can make an average of the data that enable greater knowledge. The process of taking limestone samples according to the C-50 standard was selected from the areas that were physically deformed [16].

The provided samples were carefully categorized into two distinct groups. The first group consisted of three specimens of worn limestone taken from the exterior of Batu Caves. The second group comprised three intact limestone samples obtained inside the cave. In the Batu Caves area, three techniques were used to identify limestone, i) visual inspection: Geologists look at the color and texture of limestone and examine the fossils within the limestone, which can provide information about the depositional history and age of the rock ; ii), the limestone scratch test method easily scratches the limestone surface with a pointed object [17] and iii) method of boiling, the use of vinegar or acetic acid (CH_3COOH), was sprinkled on the surface of the stone, and after 2-3 minutes, the surface of the limestone is boiled and produces bubbles that confirm its limestone nature [18]. Adopting these well-balanced techniques facilitated the achievement of a full depiction of the limestone formations in Batu Caves, enabling a meticulous investigation.

3.2 Samples Preparation

The preservation and identification of samples were prioritized, thus necessitating the placement of all samples collected from the cave into a designated container. Each sample was carefully labelled to ensure that the limestone sample remains unaltered and undergoes no transformations upon arrival at the laboratory to analyses.

The first step to do is washing process, limestone samples need to be cleaned up to eliminate any superficial impurities and pollutants. The process is important for ensuring that the subsequent examinations were carried out on unadulterated material (Fig. 2a). Following thorough preparation, the samples underwent a finely regulated drying procedure. The procedure involved subjecting the samples to a constant temperature of 110˚C for a continuous period of 24 hours. The drying method was conducted in accordance with the prescribed guidelines specified in ASTM D5731 [19], which guarantees the uniformity and dependability of the sample preparation process (Fig. 2b).

(a) **(b)**

Fig. 2 *Limestone samples in the laboratory for characteristic testing (a) washing; and (b) drying process*

Then the limestone samples were subjected to reducing their particle size to achieve a uniform and granular state, which would aid in conducting further analyses. The reduction process entailed applying mechanical force using crushing and grinding techniques to attain a consistent distribution of particle sizes in the samples. To achieve a more precise particle size, the limestone samples that had been crushed and ground were meticulously placed into a sieve with a specified aperture size of 300μm.The purpose of this sieving operation was to maintain the uniformity of the particle size distribution and eliminate any data points that deviated significantly from the norm. This was done to improve the precision and reliability of the subsequent analytical methods as shown in (Fig. 3a).

After completing the sample preparation process, which involves cleaning, drying, and sieving; three intact limestone samples from inside the cave and three weathered limestone samples from outside the cave were relocated and labeled in separate bottles for forthcoming investigation (Fig. 3b).

(a) **(b)**

Fig. 3 *Limestone sample preparing process (a) particle size reduction using appropriate tools - crushing and sieving of limestone samples; (b) labelled limestone samples for characteristic testing*

3.3 Testing Program

The testing program was planned to carry out respective tests in order to observe the changes that occur in the physical properties and chemical composition of limestone due to weathering processes. [20], ii) Texture: Limestone has a diverse range of textures, spanning from finely-grained too coarsely crystalline. The texture of this material affects its appropriateness for various applications [21], iii) Durability: Limestone exhibits exceptional durability and longevity, rendering it highly ideal for a wide range of construction and architectural purposes [22], and iv) Hardness: Limestone exhibits a very low level of hardness on the Mohs scale of mineral hardness, measuring around 3. Consequently, it is highly malleable and may be readily sculpted and molded for artistic and ornamental applications [23].

The primary analytical approach utilized in this work was Fourier-transform infrared (FTIR) analysis, widely recognized for its accuracy in determining chemical compositions and structural alterations. The investigation utilized the FTIR equipment brand Perkin Elmer, serial number 70704, PODL04021914, as shown in Fig. 4, which enables data gathering with a high resolution of 0.5 cm^{-1}. The chemical characteristics of the limestone samples were assessed by Fourier transform infrared (FTIR) analysis, which covered a wide spectral range ranging from 400 to 4000 cm^{-1} wavenumbers. The utilization of this analytical methodology offers a full understanding of the molecular composition and structural attributes of the limestone specimens, facilitating a thorough evaluation of the weathered and Intact limestone within Batu Caves.

Fig. 4 *Indicates the Fourier Transform Infrared Spectroscopy (FT-IR) analyser*

4. Results and Discussion

Table 1 displays the findings of the mineral and chemical composition of limestone of this study. The limestone utilized in this investigation consisted of 97.93% calcium carbonate ($CaCO_3$) and 0.87% magnesium oxide (MgO). This suggests that the research effort utilized limestone with a high purity level, consisting of over 97% calcium carbonate [24].

Table 1 *Limestone's chemical and minerals composition*

Oxide	Wt (%)	Oxide	Wt (%)
MigO	0.87	MnO	0.03
Al_2O_3	0.16	Fe_2O_3	0.05
SiO_2	0.86	NiO	0.01
P_2O_5	0.02	CuO	0.01
SO_3	0.01	SrO	0.04
K_2O	0.03	CO_2	41.57
CaO	56.36	-	-

The infrared spectrum analysis of absorption or emission of weathered limestone samples taken from Batu Caves in Malaysia has found significant new information regarding the mineral compositions of these formations. Fig. 5 and Fig. 6 were contributed to the advancement of present knowledge on the mineral composition of the limestone found in Batu Caves.

In Fig. 5, the presence of feldspar in the limestone samples from inside the cave is most consistent with the prominent peak observed at 711.9 cm^{-1}. The spectral range from 873.1 to 1400 cm^{-1} emphasizes the importance of calcite as a basic component in minerals [25]. In addition, the identification of dolomite in the spectral region of 2758.97- 3064.77 cm^{-1} increases the understanding of the complex mineralogical composition in limestone. Dolomite was discerned within the 2758.96 cm^{-1}. Additionally, calcite and dolomite peaked at around 3064.77cm^{-1}. The presence of dolomite and feldspar in the samples inside the limestone sign is intact and protected from the weathering process [26].

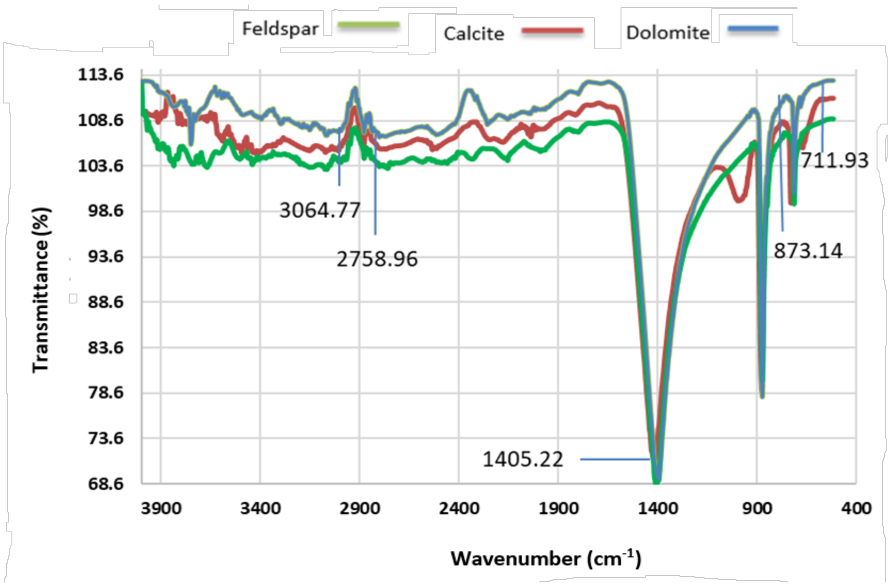


Fig. 5 *FTIR spectrogram showing a spectrum analysis of limestone inside from inside the cave*

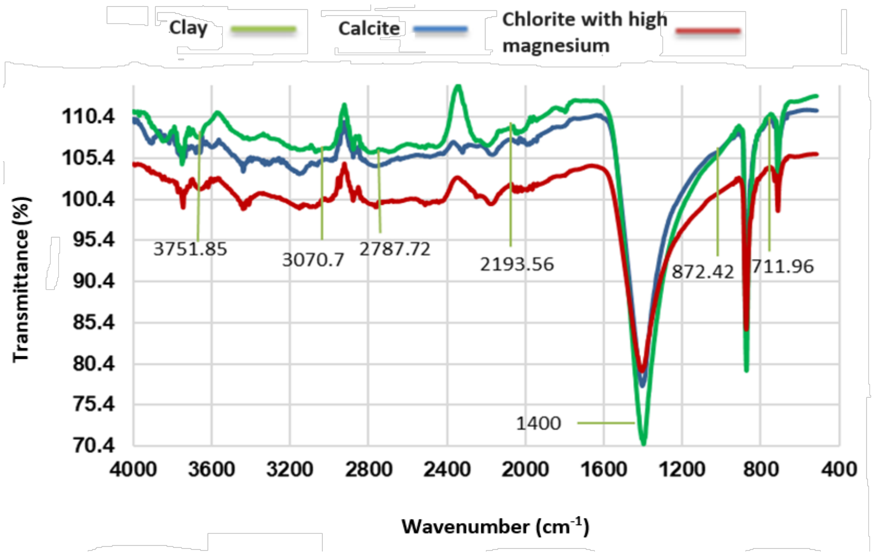


Fig. 6 *FTIR spectrogram showing a spectrum analysis of weathered limestone from outside the cave*

In Fig. 6, the limestone samples collected from outside the cave exhibit two distinct peaks that differ from those obtained inside the cave. The spectral range from 872.42 to 1400 cm-^{1} emphasizes the importance of calcite as a key component in minerals. The presence of dolomite was identified in the spectral range of 2787 to 2293.5 cm-^{1} [27]. The wave number range of 3440 to 3070.7 cm-^{1} indicates the presence of clay minerals, whereas the peak observed at 3751 cm-^{1} specifically indicates the presence of magnesium-rich chlorite [28]. In fact, the FTIR analysis's discovery of distinct peaks at particular wave numbers is a strong indicator of the authenticity of the samples of weathered limestone from outside the cave.

The presence of specific minerals and chemicals that have emerged as a result of weathering processes is directly related to the presence of these distinctive peaks. First, the wavenumber at 3440.51 cm^{-1} provides compelling evidence that the weathered limestone contains clay minerals. This peak represents the distinctive molecular vibrations that are characteristic of clay minerals and serves as an indicator of their formation. Clay minerals are frequently the result of chemical reactions and changes in limestone brought about by environmental factors such as precipitation, indicating that they play a crucial role in the geological changes that result from weathering.

Second, the characteristic peak at 3746.26 cm $^{-1}$ indicates the existence of chlorite, which is rich in magnesium. Chlorite, a mineral found in metamorphic rocks, is peculiar to this summit, indicating that it first appeared inside the weathered limestone. Chlorite's presence, which has a distinctive vibrational signature in the FTIR spectrum, adds to our understanding of the complex geological processes in gradually creating these distinctive limestone structures.

Table 2 *FTIR analysis summary*

Mineral/Component	Peak Wavenumber (cm^{-1})	Location (Inside/Outside Cave)
Feldspar	711.9	Inside
Calcite	873.14	Inside/Outside
Dolomite	2758.96	Inside/Outside
Calcite, Dolomite	3064.77	Inside/Outside
Clay Minerals	3440.51	Outside
Magnesium-rich Chlorite	3746.26	Outside

Table 2 presents a thorough overview of the FTIR (Fourier Transform Infrared) investigation. The comprehensive Fourier Transform Infrared (FTIR) study conducted has not only validated the prevalence of calcite and feldspar in the weathered limestone samples obtained from Batu Caves but has also revealed the subtle occurrence of dolomite, clay minerals, and chlorite with high magnesium content. The aforementioned discoveries collectively enhance our comprehension of the complex geological processes that have influenced the development of the limestone formations in Batu Caves over history.

4.1 Spectrum Analysis of Intact and Weathered Limestone

Intact Limestone: Internal stones are usually protected from direct exposure to environmental factors such as rain, temperature fluctuations, wind, and biological activity. As a result, the FTIR spectrum of internal stones often resembles that of intact limestone, with strong, well-defined absorption bands corresponding to minerals like calcite, dolomite, and feldspar. exhibits prominent peaks around 873 cm^{-1}, 1400 cm^{-1}, and 711 cm^{-1}, which are associated with the vibrational modes of the carbonate ions.

The transmittance percentage in the FTIR spectrum for internal stones typically remains high, ranging from 85% to 98%, indicating that the stone has retained much of its original composition and structure. The absence of significant shifts in peak positions or the appearance of new bands suggests minimal alteration or contamination. This stability in the FTIR spectrum reflects the fact that internal stones are less affected by weathering processes and thus maintain a more homogenous and pure mineral composition.

Weathered Limestone: In contrast, outer stones are exposed to environmental factors that can cause significant changes in their mineralogical composition. Weathering processes such as dissolution, oxidation, and the formation of secondary minerals clays, gypsum, iron oxides can introduce new absorption bands in the FTIR spectrum. weathered limestone show peaks corresponding to dolomite in the range of 2787-2293 cm^{-1}, as well as peaks indicating the presence of clay minerals and chlorite.

The transmittance percentage in the FTIR spectrum of outer stones is typically lower, ranging from 76% to 82%, reflecting the increased absorption of infrared light due to the presence of impurities and secondary minerals. This decrease in transmittance is often accompanied by broader, less-defined peaks, indicating a more heterogeneous structure with altered mineral content.

4.2 Electrical and Electronic Properties of Intact and Weathered Limestone

The electrical and electronic properties of limestone are primarily related to mineral composition, structural configuration, moisture content and the presence of impurities. These characteristics in limestone experienced significant changes during the weathering process, which caused changes in the chemical and physical characteristics of limestone. A comprehensive analysis of the electrical and electronic properties of intact and weathered limestone was discussed here.

4.2.1 Electrical and Electronic Properties of Intact Limestone

Based on the result of FTER analysis, intact limestone showed low electrical conductivity, which is mostly due to low porosity and insulating properties of calcium carbonate. The absence of free ions or mobile charge carriers in pure calcite makes it an ineffective conductor of electricity, making it valuable as an insulating material in various engineering applications. The electrical conductivity of dry and intact limestone is in the range of 10^{-8}-10^{-6} S/m.

4.2.2 Electrical and Electronic Properties of Weathered Limestone

Weathered limestone has experienced a wide range of chemical, physical and biological transformations in the Batu area, which significantly affected its electrical and electronic properties, created impurities, increased porosity, absorbed moisture and closed pores. filled with water and significantly affected the behavior of materials in electric fields and increased electrical conductivity in limestone from 10^{-3} – 10^{-6} S/m. Based on this, the more weathered and humid the limestone is, the higher its conductivity.

4.3 Comparison of Intact and Weathered Limestone

Comparison between intact and weathered limestone reveals significant differences in mineral composition, structural stability, and electrical properties. Intact limestone remains homogeneous with high purity, low porosity and low conductivity. In contrast, weathered limestone shows altered mineralogy, increased porosity, and higher conductivity, which reflects environmental exposure and metamorphism, which we briefly present in the table below.

Table 3 *Comparison summary of intact and weathered limestone*

Category	Intact Limestone	Weathered Limestone
Mineral Composition	Predominantly composed of calcite, dolomite, and feldspar.	Contains calcite, dolomite, clay minerals, and magnesium-rich chlorite.
Chemical Composition	97.93% $CaCO_3$, 0.87% MgO, minimal impurities (Al_2O_3, SiO_2**)**	Similar basic composition but includes additional weathering products like clay and chlorite
FTIR Spectrum Analysis	Strong, well-defined peaks at 873 cm^{-1}, 1400 cm^{-1}, and 711 cm^{-1} indicating stable, intact composition. Transmittance: 85%–98%.	Broader, less-defined peaks indicating heterogeneity and alterations. Key peaks: 2787–2293 cm^{-1} (dolomite), 3440–3070 cm^{-1} (clay minerals), 3746 cm^{-1} (chlorite). Transmittance: 76%–82%.
Electrical and Electronic Properties	Low conductivity due to low porosity and the insulating nature of calcium carbonate (10^{-8}–10^{-6} S/m).	Higher conductivity due to increased porosity, moisture, and impurities (10^{-3}–10^{-6} S/m)

4.4 Key Points of Comparison

Mineralogy and Chemical Composition: Intact limestone retains a more homogeneous structure, dominated by calcite, dolomite, and feldspar. Weathered limestone, on the other hand, shows signs of chemical alteration, with the introduction of clay minerals and chlorite, likely due to exposure to environmental conditions such as moisture, oxidation, and biological activity.

FTIR Spectrum Analysis: The FTIR spectra reflect these compositional changes. Intact limestone shows high transmittance with well-defined peaks, indicating purity and stability. In contrast, weathered limestone exhibits lower transmittance, broader peaks, and additional absorption bands, highlighting the increased heterogeneity and altered mineral structure due to weathering.

Electrical and Electronic Properties: The weathering process significantly impacts the electrical properties of limestone. Intact limestone has low conductivity due to its insulating properties, while weathered limestone, with its increased porosity and moisture content, shows much higher conductivity, indicating a substantial change in its physical characteristics.

This comparison underscores the impact of weathering on limestone, transforming its structural, mineralogical, and electrical properties. These findings are critical for understanding the long-term stability of limestone formations and informing conservation efforts, particularly in regions of cultural and geological significance like Batu Caves.

5. Conclusion

This study has significantly contributed to the understanding of the overall transformation of weathering processes on limestone in the specific geological environment of Batu Caves. Findings revealed varying susceptibilities to weathering-induced degradation among minerals like feldspar, calcite, dolomite, clay minerals, and magnesium-rich chlorite. Notably, feldspar transforms into clay minerals via water reactions, while calcite dissolves under acidity, and dolomite may alter. Clay minerals erode, impacting structural integrity. Based on the results, the limestone formations within Batu Caves are significantly affected by weathering due to the presence of clay minerals that are prone to erosion. The erosion presents a significant peril to the overall integrity of these formations.

Additionally, this study examined the electrical and electronic properties of both intact and weathered limestone. Intact limestone exhibited low electrical conductivity, in the range of 10^{-8} to 10^{-6} S/m, due to its low porosity and the insulating properties of calcium carbonate. Weathered limestone, with increased porosity and moisture content, showed significantly higher conductivity, ranging from 10^{-3} to 10^{-6} S/m. Key points of comparison include changes in mineral composition, with weathered limestone showing the introduction of clay minerals and magnesium-rich chlorite. Increased porosity in weathered limestone leads to greater moisture retention, directly impacting its electrical properties, resulting in elevated conductivity. These differences highlight the significant effects of weathering on limestone's structure and function.

In conclusion, the extensive investigation carried out in this work highlights the vulnerability of the limestone formations in Batu Caves to erosive weathering mechanisms. Collectively, these findings enhance our understanding of the intricate interplay between ambient factors and geological forces that have shaped the limestone formations of Batu Caves over time. Moreover, they emphasize the need for strategies to safeguard these geological marvels for future generations, as they have implications for the preservation and administration of this iconic natural and cultural heritage. Thus, the FTIR analyses have been instrumental in deciphering Batu Caves's geological history, casting light on its past and proposing strategies for its future conservation

Acknowledgement

The authors would like to acknowledge and thank the Civil Engineering Department, Engineering Faculty, Universiti Putra Malaysia, Malaysia.

Conflict of Interest

The authors, Hamasa Kambakhsh, Nik Norsyahariati Nik Daud, and Saifullah Inanch - declare no conflicts of interest related to the publication. Hamasa Kambakhsh has dual affiliations with the Department of Geology and Mine at Faryab University, Afghanistan, and the Department of Civil Engineering at Universiti Putra Malaysia. Nik Norsyahariati binti Nik Daud is affiliated with the Department of Civil Engineering at Universiti Putra Malaysia and serves as the corresponding author. There are no financial or personal relationships that could be perceived as conflicts of interest. For further correspondence, please contact Nik Norsyahariati binti Nik Daud at niknor@upm.edu.my.

Author Contribution

The authors affirm their contributions to the paper as follows: ***Study conception and design*** *were led by Hamasa Kambakhsh and Nik Norsyahariati Nik Daud;* ***Data collection:*** *Hamasa Kambakhsh;* ***Analysis and interpretation of results****: Hamasa Kambakhsh, Nik Norsyahariati Nik Daud and Saifullah Inanch;* ***Draft manuscript preparation****: Hamasa Kambakhsh, Nik Norsyahariati Nik Daud and Saifullah Inanch. This delineation of individual contributions underscores the collaborative effort and ensures transparency regarding each author's involvement in the research process.*

References

[1] F. B. Fatoye and Y. B. Gideon, "Geology and Occurrences of Limestone and Marble in Nigeria," *Journal of Natural Sciences Research www*, vol. 3, no. 11, pp. 2225–921, 2013.

[2] N. J. Aminuddin and N. I. M. Pauzi, "Scatter-plot analysis of microcracks pattern behaviour of weathered limestone at Batu Caves, Malaysia," *Electronic Journal of Geotechnical Engineering*, vol. 16 N, no. August, pp. 1639–1650, 2011.

[3] R. S. Hwidi, T. N. Tengku Izhar, and F. N. Mohd Saad, "Characterization of Limestone as Raw Material to Hydrated Lime," *E3S Web of Conferences*, vol. 34, no. March, 2018, doi: 10.1051/e3sconf/20183402042.

[4] D. G. Price, "Weathering and weathering processes," *Quarterly Journal of Engineering Geology*, vol. 28, no. 3, pp. 243–252, 1995, doi: 10.1144/gsl.qjegh.1995.028.p3.03.

[5] A. Kumar, "Pewter industry and tin mining in Malaysia; and the Batu Caves of Kuala Lumpur.," *Earth Science India*, vol. VIII, no. May, pp. 1–13, 2015.

[6] T. Lim, R. Stewardship, and C. Sdn, "Conservation status of the Batu Caves trapdoor spider (Liphistius batuensis Abraham (Araneae , Mesothelae)): A preliminary survey," no. January 2009, 2019.

[7] D. Dodge-wan, "Elongated tufaceous stalagmites in the entrance of Batu Caves," 2015, doi: 10.1007/s13146-014-0230-5.

[8] Y. Chen, C. Zou, M. Mastalerz, S. Hu, C. Gasaway, and X. Tao, "Applications of micro-fourier transform infrared spectroscopy (FTIR) in the geological sciences—A Review," *International Journal of Molecular Sciences*, vol. 16, no. 12, pp. 30223–30250, 2015, doi: 10.3390/ijms161226227.

[9] R. S. Hwidi, T. N. Tengku Izhar, and F. N. Mohd Saad, “Characterization of Limestone as Raw Material to Hydrated Lime,” *E3S Web of Conferences*, vol. 34, pp. 1–7, 2018, doi: 10.1051/e3sconf/20183402042.

[10] W. H. Abdullah, *National geoscience conference 2019 (ngc 2019) 1*, vol. 45, no. 3. 2019.

[11] G. Yuan *et al.*, “A review of feldspar alteration and its geological significance in sedimentary basins: From shallow aquifers to deep hydrocarbon reservoirs,” *Earth-Science Reviews*, vol. 191, no. October 2017, pp. 114–140, 2019, doi: 10.1016/j.earscirev.2019.02.004.

[12] H. R. G. K. Hack, “Susceptibility to weathering; overview,” *Ingeokring Newsletter (Dutch association of engineering geologists and geo engineers).*, no. December, pp. 4–16, 2021, [Online]. Available: https://www.researchgate.net/profile/Henri_Hack/publication/347934689_Susceptibility_to_weathering_overview/links/5fe87d7f299bf140884b3683/Susceptibility-to-weathering-overview.pdf

[13] J. Zha, S. Wei, C. Wang, Z. Li, Y. Cai, and Q. Ma, “Weathering mechanism of red discolorations on Limestone object: a case study from Lingyan Temple, Jinan, Shandong Province, China,” *Heritage Science*, vol. 8, no. 1, pp. 1–12, 2020, doi: 10.1186/s40494-020-00394-z.

[14] C. Alves, C. Figueiredo, A. Maurício, and L. Aires-Barros, “Salt weathering of limestones: susceptibility of petrographical features (SEM study),” *Microscopy and Microanalysis*, vol. 19, no. S4, pp. 113–114, 2013, doi: 10.1017/s1431927613001189.

[15] M. Samari, F. Ridha, V. Manovic, and A. Macchi, “Direct capture of carbon dioxide from air via lime-based sorbents,” pp. 25–41, 2020.

[16] S. Practice, “Standard Practice for Sampling , Sample Preparation , Packaging , and Marking of,” *Test*, vol. 00, no. January 2001, pp. 1–11, 2006.

[17] S. Müller, “LIMESTONE,” no. May, pp. 0–29, 2021.

[18] N. Jiang, P. Guo, H. Zhang, F. Lu, and J. Liu, “Mechanical behavior of a new similar material for weathered limestone in karst area : An experimental investigation,” 2023.

[19] M. Razali and M. Herman Jamal, “Quantitative Weathering Assessment of Rock Slope using CIELAB Color Space and Image Analysis Technique,” *Research Square*, 2021, [Online]. Available: https://doi.org/10.21203/rs.3.rs-937366/v1

[20] A. E. Sujianto and C. Nas, “Feasibility Analysis of Limestone Industry Development as a Leading Mining Product of Rembang Central Java District,” vol. 24, no. 09, pp. 4448–4459, 2020.

[21] G. Society and L. Special, “Differences in texture , physical properties and microbiology of weathering crust and host rock : A case of the porous limestone of Budapest (Hungary) Differences in texture , physical properties and microbiology of weathering crust and host rock : a case study of the porous limestone of Budapest (Hungary),” no. December 2014, 2007, doi: 10.1144/GSL.SP.2007.271.01.25.

[22] A. Sanda Bawa, M. Sani OUSMANE, O. Sanda Mamane, A. Chaibou Yacouba, and I. Natatou, “XRD and Infrared study of limestone from Chadawanka (Tahoua, Niger),” *J. Mater. Environ. Sci*, vol. 2021, no. 5, pp. 664–672, 2021.

[23] S. Ghorbani, S. H. Hoseinie, E. Ghasemi, T. Sherizadeh, and C. Wanhainen, “A new rock hardness classification system based on portable dynamic testing,” *Bulletin of Engineering Geology and the Environment*, vol. 81, no. 5, 2022, doi: 10.1007/s10064-022-02690-3.

[24] C. K. Onn and E. W. Teo, “Checklist of the herpetofauna of Batu Caves , Selangor , Malaysia,” no. May, 2023.

[25] D. Biondino *et al.*, “A multidisciplinary approach to investigate weathering processes affecting gneissic rocks (Calabria, southern Italy),” *Catena*, vol. 187, no. September 2019, p. 104372, 2020, doi: 10.1016/j.catena.2019.104372.

[26] G. Jozanikohan and M. N. Abarghooei, “The Fourier transform infrared spectroscopy (FTIR) analysis for the clay mineralogy studies in a clastic reservoir,” *Journal of Petroleum Exploration and Production Technology*, vol. 12, no. 8, pp. 2093–2106, 2022, doi: 10.1007/s13202-021-01449-y.

[27] D. Radulović, A. Terzić, L. Pezo, L. Andrić, and I. Grigorova, “The chemometric study of limestone physico-chemical properties and thermal behavior for application in construction composites,” *Science of Sintering*, vol. 49, no. 3, pp. 247–261, 2017, doi: 10.2298/SOS1703247R.

[28] L. V. and E. PLEVOVÁ, “low temperature bellow 400°C:,” *Acta Geodyn. Geomater*, vol. 2, no. 2, pp. 167–175, 2005.