COMPREHENSIVE STUDY ON LIMESTONE WEATHERING GRADE AND RISK POTENTIAL IN BATU CAVES, MALAYSIA

(Date received: 06.12.2023/Date accepted: 24.01.2024)

Hamasa Kambakhsh[1], Nik Norsyahariati Nik Daud[2*]

[1]*Department of Geology and Mine, Faculty of Engineering, Faryab University, Faryab, Afghanistan*

[1,2]*Department of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia*

[2]*Housing Research Centre (HRC), Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*

[*]*Corresponding author: niknor@upm.edu.my*

The limestone formations within Batu Caves, situated in the Selangor region, represent a significant geological phenomenon in Malaysia, capturing the attention of engineers due to their distinctive karst features. The assessment entails a comprehensive review of geological characteristics, currently employed categorization frameworks, assessment approaches, and the possible ramifications for the construction industry, infrastructure advancement, and the natural surroundings. This study aims to enhance the collective comprehension of limestone weathering and its impact on risk assessment due to weathered processes. The insights gained from the distinctive circumstances surrounding Batu Caves possess the capacity to guide optimal approaches and tactics for addressing the consequences of limestone weathering. The Batu Caves attracts a substantial number of tourists annually. Consequently, it is subject to significant levels of human activity and encounters high traffic volumes. Moreover, Batu Caves encompasses an assemblage of Hindu temples and shrines, setting it apart from numerous other limestone formations due to its cultural and religious significance. The impact of urban environments on weathering processes differs significantly from that observed in limestone formations found in other geographical areas. Based on the geological landscape of Batu Caves, effects reveal moderate stability in sections 1, 3, and 8, while sections 6 and 7 pose an elevated risk of limestone collapse. These sections have lost their stability due to weathering activity and require an emphasis on effective risk-reduction measures to preserve the cave. The parts assessed as risk areas need risk reduction techniques such as taking nets, giving solid foundations, and installing danger signs to protect people who come to the area. This analysis provides a deeper understanding of limestone weathering in Batu Caves, emphasizing the need for efficient risk mitigation techniques to address weathering issues. This could lead to preserving Batu Cave's geological significance and potentially global applications for limestone-rich places. The study contributes to engineering, construction, and environmental conservation by providing valuable resources for decision-making.

Keywords: Batu Caves, Classification, Limestone, Rock-fall, Weathering Grade

1.0 INTRODUCTION

The geological marvels of Batu Caves in Malaysia have long attracted the attention of scientists, explorers, and enthusiasts from all over the globe (Price, 1995). A dynamic interplay exists between the natural environment and engineering considerations amidst the awe-inspiring limestone formations and rich cultural heritage (Zabidi and De Freitas, 2011). This discussion centers on weathering grade, a multidimensional phenomenon that modifies rock properties in response to changing environmental conditions.

The concept of weathering limestone in Batu Caves Malaysia has differing definitions among authors. However, the broader concept entails a cascade of alterations in rock properties resulting from exposure to the ever-changing trinity of physical, chemical, and biological environmental factors (Dearman, 1975). The classification of weathering is of the utmost importance from an engineering perspective (Norbury *et al.*, 1995). This categorization is essential for comprehending the myriad effects of weathering on the engineering properties of limestone (Dearman, 1975), including material-scale attributes such as rock strength, compressibility, and consolidation characteristics, as well as mass-scale characteristics such as fractures, discontinuities, and permeability (Farah, 2011).

Nevertheless, navigating the domain of weathering classification is not an easy task. In addition, the story does not end with construction; ongoing weathering, influenced by the new environment to which the rock mass is exposed, may continue after construction (Durgin, 2020). Researchers, engineers, and geologists have attempted to address this complexity, resulting in classifications and guidelines encapsulated in various codes and documents, such as those by the International Society and Engineering Group of the Geological Society for Rock Mechanics Conservancy in Batu Caves (Kiew *et al.*, 2023). In this paper, various aspects of weathering classification guidelines and their profound engineering implications were thoroughly examined.

From the findings, the complex relationship between geological processes, weathering gradation, and engineering considerations by synthesising the efforts of experts and the insights gained from these guidelines will be cleared.

1.1 Batu Caves' Geological Background

The Batu Caves are 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 (Lim, Stewardship and Sdn, 2019). The geological composition of the Batu Caves mostly consists of Silurian limestone, a rock formation dating back about 400 million years to the Paleozoic epoch. Following the initial deposition of the rock, it underwent a series of geological transformations, including uplift, compression, heating, and folding, which took place millions of years later during the Triassic period, approximately 200 million years ago. However, it is plausible that these processes commenced as early as the Devonian-Carboniferous period, around 300 million years ago. The majority of the limestone underwent a transformation into crystalline marble and then underwent uplift, resulting in the formation of the mountain ranges (Zabidi and Freitas, 2006). The caves likely were created during the late Mesozoic era, specifically the Cretaceous or Tertiary period, approximately 60-120 million years in the past. It might be posited that the caverns possess an approximate age of 100 million years. Presently, Batu Caves stands as a solitary hill, exemplifying a karst topography referred to as karst expanding (Anon, 1978). Figure 1 shows the geological map of Batu Caves in the north of Kuala Lumpur.

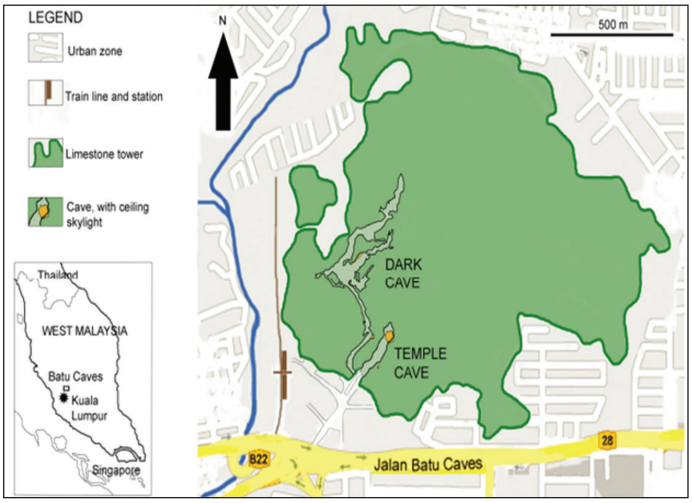

Figure 1: The above map illustrates the geological positioning of the Temple Cave located within the Batu Caves karst tower in the Gombak area north of Kuala Lumpur (Wan, 2015)

1.2 The Limestone Formation of Batu Caves

The limestone formation of Batu Caves exemplifies the intricate connections between geological processes and the passage of time. The place exhibits the exceptional artistic abilities of nature, featuring visually striking stalactites, stalagmites, and intriguing formations within the Cave (Dodge-wan, 2015). Every curve, contour, and crack present in the limestone is a testament to the ancient history of the Earth, intricately imprinted inside the very structure of the Cave. Limestone is a sedimentary rock composed of calcite minerals, chemically known as calcium carbonate ($CaCO_3$). Dolomite [$CaMg\ (CO_3)$] is another prevalent mineral found in limestone (Chowdhury, Punuru and Gauri, 1990). Frequently encountered impurities inside limestone are characterized by its microcrystalline, cryptocrystalline quartz, amorphous silica composition (SiO_2), clay, organic debris, and iron oxides. Limestone exhibits a distinctive characteristic as it possesses solubility even in mildly acidic aqueous environments, including carbonic acid from dissolving carbon dioxide in water (Tan, 2002). Figure 2. The geological map of Selangor, Kuala Lumpur Limestone Formation (Zabidi and De Freitas, 2013).

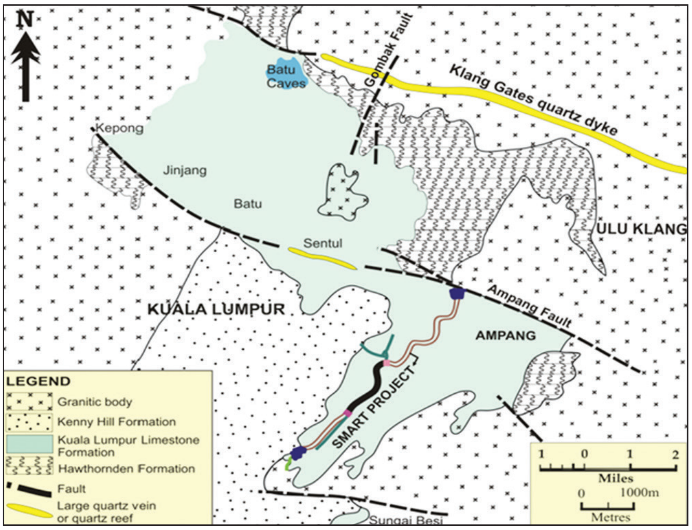

Figure 2: A simplified version of the geological map of Selangor, Kuala Lumpur Limestone Formation (Tunnel, 2013)

2.0 WEATHERING OF LIMESTONE

Weathering refers to how minerals undergo chemical and physical breakdown due to various physical, chemical, and biological mechanisms (Hack, 2020). Weathering impacts not just the overall structure of solid rock but also the composition and characteristics of any fractures or gaps within the rock formation (Tating, Hack and Jetten, 2015). The weathering process is influenced by various local conditions, including the prevailing climate, the land surface, and groundwater characteristics (White and White, 2018). Local variables, including temperature and water availability, highly affect the rates at which these processes occur (Gurocak, 2014). The parameters that play a role in the weathering mechanism of Batu Caves limestone are shown in Table1.

Table 1: Various parameters cause weathering in Batu Cave (Dans and Royaume, 1974)

Environmental factors	Time year	Rock Properties	Response	Source
Temperature	Varying	Mineralogical composition	Discoloration	(González-Gómez *et al.,* 2015)
Moisture	Geological Time	Fabric and grain structure	Decomposition	(Hajna, Hajna and Gabrovsek, 2002)
Chemical fluids	Different	Structural defects	Disintegration	(Scrivano and Gaggero, 2020)

2.1 Weathering Process

The amount of weathering depends not only on environmental conditions and rock properties but also on the combination of these factors, the duration of exposure to weathering, and the classification of environmental cycles (Waragai, 2016). Limestone formations in Batu Caves, Selangor, Malaysia are shaped by various weathering processes. Physical, chemical, and biological processes of weathering have been observed in the Batu Caves (Biondino *et al.,* 2020). Here are the specific mechanisms of weathering that affect the limestone in Batu Caves (Hack, 2019).

2.1.1 Physical Weathering

Disintegration: Limestone in Batu Caves disintegrates (Fig. 3a) as a result of physical forces such as the expansion and contraction of rock induced by temperature variations, resulting in the formation of cracks and fissures (Lee *et al.,* 2023). In regions with periodic freezing and thawing cycles, water can permeate limestone, freeze, and expand, exerting pressure on the rock and causing its fragmentation (Camuffo, 1995).

2.1.2 Chemical Weathering

Carbonation: Atmospheric carbon dioxide (CO_2) combines with water to form carbonic acid (H_2CO_3) (Price and Velbel, 2003). This weak acid reacts with the calcium carbonate ($CaCO_3$) in limestone, resulting in the dissolution of the calcium carbonate and the formation of calcium bicarbonate ($Ca\ (HCO_3)_2$) (Rau *et al.,* 2007). The example of carbonation weathering is shown in Fig. 3b. Equation 1 shows the chemical reactions involved in the process (Nur Lyana *et al.,* 2016).

$$CaCO_3 + H_2O + CO_2 = Ca\ (HCO_3)_2 \qquad \text{Equation (1)}$$

(Limestone + Water + Carbon Dioxide
= Calcium Bicarbonate)

2.1.3 Biological Weathering

Plant roots can grow into fissures and crevices in limestone and exert pressure as they expand as shown in Fig. 3c (Finlay *et al.,* 2020). The limestone structures in the field of engineering are generally estimated to range from 50 to 100 years. During this duration, several trees and plants will reach their complete maturity, both in terms of above-ground growth and below-ground root development (Dontsova, Chorover and Balogh-Brunstad, 2020). As a consequence, these plants can exert considerable force through root wedging, leading to serious damage to the structures (Price, 1995).

Figure 3: The photos of a) Physical, b) Chemical (Kumar, 2015) and c) Biological weathering (Grismer et al., 2014) limestone in Batu Caves Malaysia

2.2 Classification of Limestone Weathering in Batu Caves

Limestone weathering classification systems are helpful in evaluating the grade of weathering in limestone formations (Bissell and Chilingar, 1967). These systems are intended to classify levels of degradation based on various criteria (Vivoda Prodan *et al.,* 2017). Several existing classification systems can provide insight into the weathering grade of Batu Caves Limestone, classified as a carbonaceous rock, which undergoes weathering according to the categorisation depicted in Table 2 (Fernandes Leao, 2018). The weathering grade in Batu Caves are classified into five categories: Grade I refer to fresh limestone, with a grain size range of 0.1 – 0 mm, and it is not weathered. The grain size range for Grade II was between 0.1 - 0.2mm. Grade III to IV exhibited a grain size of 0.15mm, while grade IV to V ranged from 0.1 - 0.12mm. Grade V to VI displayed a grain size of 0.11mm, with smaller grain sizes observed in Grade VI.

Table 2: Classification weathering grade of limestone Batu Caves (Aminuddin and Pauzi, 2011)

Grade of Weathering	Term (Year)	Grain Size (mm)	Schmidt Hammer (N)
I	Fresh intact	0.1 – 0.	12-22
II	Slightly weathered	0.1 – 0.2	12-20
III	Moderately weathered	0.15	11-18
IV	Highly weathered	0.11	10-16
V	Completely weathered	0.11	6-15

Based on the observations, it can be inferred that there is a negative correlation between weathering grade and grain size, indicating that as the weathering grade increases, the grain sizes decrease as a result (Aminuddin and Pauzi, 2011).

The utilization of the limestone rock's weathering grade knowledge served as a means to guide the collection of samples representing various degrees of weathering (Regmi *et al.,* 2014). There is a positive correlation between the elevation of the limestone and the extent of weathering (Budakci and Karmanglu 2014). This can be attributed to the fact that the upper regions of the Batu Caves see greater levels of precipitation in comparison to the lower regions (Pauzi *et al.,* 2011).

The specimens were categorised into several weathering grades in the provided table 2 based on qualitative factors such as colour, surface texture, and friability (Chala, Science and Rao, 2021). The classification process did not consider the specific location or depth of the specimens, but rather focused only on their weathering state. The process entails visually and field-evaluating many elements, such as modifications in coloration, shifts in mineral composition, variations in texture, the presence of fractures, and other characteristics associated with weathering. The aforementioned classification system offers a qualitative depiction of the extent of weathering, rendering it advantageous for expeditious evaluations in the field or for assessing the appropriateness of rocks and helping to identify the risk area. However, it does not furnish comprehensive insights into the underlying geological mechanisms or the disparities in weathering across various depths within the formation (Budakci and Karamanoglu 2014).

3.0 MECHANISMS FOR DETERMINING THE WEATHERING GRADE OF LIMESTONE

The evaluation of limestone weathering intensity commonly utilizes a set of three core methodologies, encompassing the following methods (Shah *et al.,* 2022).

3.1 Laboratory Techniques for Determining the Weathering Grade

Laboratory methodologies employed for assessing the weathering grade of rocks and geological specimens offer enhanced precision and quantitative data in contrast to visual evaluations conducted in the field. These procedures frequently encompass a range of analytical methodologies utilised to evaluate the mineralogical, chemical, and physical alterations linked to weathering phenomena. Several laboratory approaches are commonly employed to assess the weathering grade (Razali *et.al,* 2021).

3.2 Compressive Strength Analysis

The Uniaxial Compressive Strength (UCS) and elasticity modulus (E) are significant quantities extensively employed in geotechnical and rock engineering endeavors. The strength characteristics are determined by standardized unconfined compressive strength (UCS) testing (Aboutaleb *et al.,* 2017). The testing process is standardized by the American Society for Testing and Materials (ASTM, Materials n.d. 1984). The investigation of compressive strength is a crucial mechanical examination employed to assess the capacity of limestone to endure axial loads or pressures exerted in a linear direction. The examination holds significant importance in evaluating the structural integrity of the rock and its ability to withstand compression, so it serves as a beneficial instrument for comprehending the limestone's capacity to bear vertical stresses The aforementioned test has been extensively employed in numerous research investigations to examine the compressive strength of limestone. Presented below in Table 3 are some instances of research projects that have employed this particular test, along with their respective findings.

3.2.1 Slake-Durability Test

The primary aims of the slaking durability test encompass the anticipation of the long-term durability of the rock specimens, the determination of weathering and degradation attributes specific to each rock type, and the evaluation of the influence of water on rock deterioration. The test technique and data reduction followed a methodology comparable to the standard practise outlined in ASTM D4644 (Khattab and Othman, 2012). This test has been extensively employed in numerous research papers to examine the Slake-Durability Test of weathered limestone.

The following are instances of research endeavours that have employed durability tests to identify weathering impact on limestone. The following examples of research initiatives that have utilized this specific test, along with their corresponding results, are provided in Table 4.

3.2.2 X-Ray Fluorescence (XRF) and SEM Analyses

This analysis is the prescribed method for the conclusive detection of chemical assessments of weathered limestone, as per the guidelines outlined in ASTM C1271(Morner, no date).This method is a highly robust analytical technique that demonstrates significant efficacy in the evaluation of weathered limestone. X-ray fluorescence (XRF) analysis offers a quantitative assessment of the elemental composition of limestone (Hwidi, Tengku Izhar and Mohd Saad, 2018a). The test in evaluation has been widely utilized in a multitude of study publications to investigate the Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) analysis of weathered limestone. Table 5 illustrates this research's attempts to utilize tests to assess the effects of weathering on limestone.

3.2.3 Fourier Transform Infrared (FTIR) Analysis

The limestone functional group and chemical component analysis was conducted using a Perkin Elmer 2000 Fourier transform infrared spectrometer by the ASTM E1252-98 standard (Akbar, Aziz and Adlan, 2021). The potential could offer significant insights into the chemical transformations in worn limestone specimens. The assessment of weathering extent

Table 3: A succinct overview of previous research on limestone using the compressive strength test

Title	Findings	Discussion	Citation
The effect of weathering on pore geometry and compressive strength of selected rock types from Turkey.	The mechanism of weathering significantly affects the porosity of limestone, leading to faster destruction and lower strength under uniaxial pressure.	Weathering exerts a deleterious influence on rocks, increasing porosity and decreasing compressive strength. Consideration of weathering effects is crucial in engineering.	(Dontsova, Chorover and Balogh-Brunstad, 2020)
Effects of weathering on some physical and mechanical properties of Ewekoro Limestone South-western Nigeria.	Mechanical properties of limestone, including uniaxial compressive strength, point load strength, tensile strength, and Schmidt hardness number, are reduced by weathering.	Weathering's impact on structural stability underscores the importance of considering regional climate in limestone applications.	(Budakçi and Karamanoğlu, 2014)
Study of the limestone strength weakening mechanism at the eastern margin of the Kangdian Palaeouplife in Southwest China.	Uniaxial compressive strength of deeply weathered rock mass is significantly lower compared to fresh and weakly weathered rock mass. Reductions range from 74% to 84% and 65% to 68% under natural conditions, further reduced in the saturated state.	Weathering causes substantial reductions in rock mass strength, emphasizing the need to consider weathering effects in engineering.	(Tang, Wang and Xiang, 2021)

and characteristics, as well as the identification of environmental factors impacting limestone deterioration, can be achieved through a comparative analysis of the Fourier Transform Infrared (FTIR) spectra of weathered samples and pure limestone spectra (Horn *et al.*, 1994). The test indicated above has been widely utilized in several research studies to investigate the FTIR analyses of limestone. Table 6 provides some examples of research studies that have used this particular test, along with their conclusions and analysis.

Table 4: Highlights the research that has used slake durability testing to determine how weathering affects limestone

Title	Findings	Discussion	Citation
Complex weathering effects on durability characteristics of building stone.	The research assesses and compares the durability properties of limestone using the conventional sodium sulfate salt crystallization test and a modified laboratory weathering simulation. The method involves both sodium sulfate (Na2SO4) salt weathering and freeze-thaw cycles, introducing intricacy to the collapse process and diminishing limestone's endurance. Structural aspects are found to be relatively insignificant, and mineralogy variations influence weathering characteristics.	The methodology involving salt weathering and freeze-thaw cycles emphasizes the impact of mineralogical variations on weathering patterns.	(Warke and Smith, 2007)
Slake durability test on Lower Oligocene limestone from Al Ain City, United Arab Emirates.	The study evaluates rock resistance to weathering using the stain durability test, revealing limestone's loss of durability due to weathering and climatic effects. Fine fractures and increased pore size are observed.	The study highlights the susceptibility of limestone to weathering and climatic effects, leading to structural degradation.	(Arman and El Tokhi, 2016)
Role of petrography in durability of limestone used in construction of Persepolis complex subjected to artificial accelerated ageing tests.	The study investigates the physical and mechanical properties of limestone and the impact of weathering processes such as freeze-thaw, thermal shock, and salt crystallization. Petrographic examinations reveal the impermeable and non-porous nature of the rock, with substantial diagenesis under pressure and clay-filled fractures. Degradation is associated with repetitive freezing and thawing cycles, salt crystallization cycles, and thermal shock.	Petrographic studies underscore the importance of evaluating durability through freeze-thaw cycles, salt crystallizations, and heat stress-induced diagenetic cracks.	(Torabi-Kaveh *et al.,* 2019)

Table 5: The efforts of prior research to assess the effects of weathering on limestone using X-ray fluorescence (XRF) and scanning electron microscopy (SEM) analysis are detailed

Title	Findings	Discussion	Citation
Accelerated weathering tests on two highly porous limestone.	The primary determinant of weathering in limestone monuments is desiccation and rehydration, leading to structural damage or material loss. Absorption-drying cycles with pure water and NaCl solutions simulate weathering, influencing two limestone samples based on overall porosity, cycle quantity, salt solution concentration, and mineralogical composition.	The study demonstrates the impact of weathering on limestone through absorption-drying cycles and salt solutions, emphasizing the importance of mineralogical composition.	(Přikryl *et al.,* 2007)
Weathering effects in an urban environment: a case study of Tuffeau, a French porous limestone.	Structural and mineralogical alterations in suburban limestone are attributed to shifts in environmental circumstances. Macroscopic approaches and microstructure investigation using SEM and XRD validate the significant influence of the weathering process on rock alteration.	The study highlights the substantial influence of weathering on Tuffeau limestone in urban environments, providing insights into characteristic coupling and microstructural changes.	(Beck and Al-Mukhtar, 2010)
Weathering mechanism of red discolorations on Limestone object: a case study from Lingyan Temple, Jinan, Shandong Province, China.	Red color alteration during limestone weathering is attributed to the carbonic acid weathering process, transforming cotenorite and iron into red iron oxides. XRD, Raman, FTIR, SEM, and chelating agent investigations provide insights into the alteration mechanism.	The study elucidates the weathering process leading to red color change in limestone, emphasizing the chemical reactions and physical adhesion involved.	(Zha *et al.,* 2020)

Table 6: Selection of research projects that have utilised FTIR testing, with their respective findings and analyses

Title	Findings	Discussion	Citation
Characterization of limestone as raw material to hydrated lime.	The research focuses on physical, chemical, and mineralogical characteristics of limestone. Morphological features are investigated using XRF, XRD, and FTIR techniques. FTIR bands at 1419, 874.08, and 712.20 cm-1 indicate the presence of calcite. Weathering alters these compounds, leading to fissures and cavities in limestone.	The study emphasizes the need to comprehend limestone's complex characteristics, highlighting the impact of weathering on calcite and its implications for long-term suitability in construction and industrial uses.	(Hwidi, Tengku Izhar and Mohd Saad, 2018b)
Influence of fungi in the weathering of limestone of Mayan monuments.	FTIR reveals alterations in the chemical composition of eroded limestone due to fungal activity, leading to surface degradation and the conversion of calcite to gypsum. Organic acid-producing fungi facilitate calcium release, contributing to limestone building degradation in high humidity and severe weathering environments.	The study highlights the crucial role of fungi in limestone weathering, emphasizing the conversion of calcite to gypsum and the release of calcium. This knowledge is vital for conservationists and archaeologists to mitigate the impact on cultural heritage sites.	(De la Rosa–García *et al.,* 2011)
The characteristics of limestone and anthracite coal as filter media in treating pollutants from groundwater.	FTIR spectrum analysis demonstrates limestone's notable cation exchange capacity. Hydrophilic functional groups on limestone facilitate water absorption, leading to pore saturation, dissolution of minerals like chalk, and limestone deformation and destruction.	The study emphasizes limestone's potential in treating groundwater pollution through cation exchange but also highlights its vulnerability to mineral dissolution and deformation caused by water absorption. This knowledge is crucial for sustainable groundwater remediation.	(Akbar, Aziz and Adlan, 2021)

Table 7: Research studies that utilised field-based assessment techniques and their conclusions and analyses

Title	Findings	Discussion	Citation
Field testing of rock hardness and its relationship to limestone dissolution in Guilin, Southern China.	Field-based evaluation was conducted to assess the topography of limestone formations, obtaining data on the state of limestone rocks at their surfaces. The study included a review of karst slope profiles to differentiate between severe and shallow weathering, involving thorough examination of damaged surfaces and worn-out components.	In this research, the state of limestones in different processes and the distinction between severe and shallow weathering, including a complete examination of the damaged surfaces and worn parts have been discussed.	(Tang, 1998)
Assessment of limestone caves in Dabong, Kelantan using systematic studies for potential geoheritage sites.	Field-based assessment techniques were employed to categorize strata created throughout different geological epochs based on grain colour and composition. Higher layers show evidence of compositional degradation, appearing lighter in colour than the lowest strata, indicating relative geological freshness. This realization was possible due to careful field observations.	Field-based assessment techniques were crucial in understanding the target area, providing valuable insights into the complex interplay between geological processes and limestone dissolution. The study identified potential geoheritage sites and emphasized the importance of field observations in making such diagnoses.	(Sulaiman *et al.,* 2020)
Assessment of rockfall potential of limestone hills in the Kinta Valley.	The study emphasises the management strategies to reduce the possible risks caused by these limestone hills for human safety and property.	With time, mechanical weathering, root growth and carbonate rock dissolution can increase the susceptibility to rock fall and cause limestone hills to loosen.	(Simon *et al.,* 2015)

3.3 Field-Based Assessment Techniques

The United States Geological Survey (USGS) provides comprehensive advice and standards for the execution of geological fieldwork and surveys, encompassing various mapping techniques and methodologies for data collecting (Lide, 1982). This method refers to the evaluation techniques conducted in area settings rather than controlled laboratory environments. These methods involve observing and measuring phenomena like changes in colour, fracture, rift, and slip-in study areas (Emry, Goldstein and Franseen, 2012).

3.4 Comparative Analysis of Assessment Techniques

In order to determine the weathering grade of limestone in Batu Caves, it is necessary to conduct a comparison analysis for the selection of an appropriate evaluation method (Mallick, Choudhary and Budi, 2020). This section presents a comparative analysis and interpretation of the results obtained from different evaluation methods while appropriately considering the potential consequences of regional geographic disparities (Luquot, Hebert and Rodriguez, 2016).The selection of an appropriate methodology for effectively evaluating the degree of weathering in limestone in Batu Caves holds significant significance, requiring careful deliberation of the surrounding environmental factors and prevailing conditions (Martinez and Horvath, 2023). Table 8. A comparative analysis table is provided for evaluation processes specifically designed for weathered limestone.

The descriptions and practical applications of three evaluation methods for weathered limestone are detailed in this table 8, which also presents a comparative analysis of the methods. The method selected is contingent upon the particular research aims, available resources, and environmental circumstances in the area under investigation.

4.0 EVALUATION OF RISK ASSESSMENTS AND THE REPERCUSSIONS

Assessing the risks associated with eroded limestone is necessary to ensure the safety and protection of Batu Caves. Weathered limestone can cause many troubles such as loss of structural integrity and rock fall due to erosion and weathering (Fu *et al.,* 2020). Risk assessment is critical to understanding and minimizing potential consequences. Below is a summary of the evaluation method and its implications for weathered limestone:

4.1 Risk Assessment Identification in Batu Caves

The assessment process entails a thorough examination of the potential hazards associated with the degraded limestone conditions in Batu Caves. Special consideration is given to areas within the cave susceptible to rock falls, primarily focusing on the entrance gate and sections affected by weathering. Detailed observations have identified cracks in the soil, and the intrusion of tree roots further exacerbates the situation. These factors collectively contribute to an increased risk of rock falls and structural instability, posing a significant threat to the integrity of the cave and potentially causing extensive damage. The assessment aims to provide a comprehensive understanding of these risks, allowing for informed decision-making and the implementation of necessary preventive measures to ensure the safety and preservation of Batu Caves (Mohamed *et al.,* 2021).

5.0 EFFECTS OF WEATHERING ON MECHANICAL PROPERTIES OF LIMESTONE

The assessment of the degree of limestone weathering in Batu Caves holds significant consequences for the mechanical characteristics of the limestone formations (Naeem *et al.,* 2014). Comprehending these impacts is of utmost importance in evaluating the corresponding dangers (Metcalfe, 2018). Effects of weathering on mechanical properties in Batu caves limestone, according to the dimensions of the cave, it can be determined that Sections 4 and 8 of Gua Damai exhibit stability, whereas Sections 1, 2, 3, 5, 6, and 7 necessitate additional support.

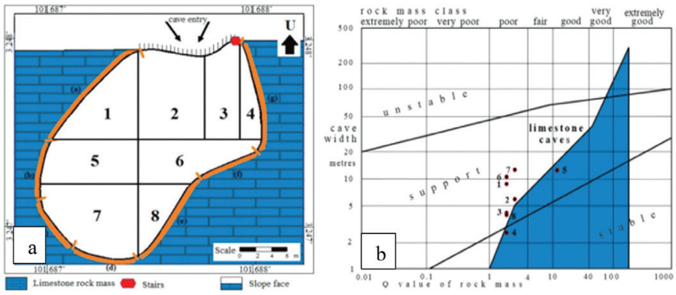

Figure 4 (a): The cave walls and cavity of Batu Caves, Selangor, Malaysia, were labelled into seven distinct pieces as a to g. Additionally, the cave cavity was separated into eight sections numbered 1 to 8, based on their relative orientations on the cave walls.

Figure 4 (b): The stability evaluation of Batu Caves, Selangor, Malaysia. The diagram illustrates that Section 4 exhibits stability, whereas Sections 1, 2, 3, 5, 6, 7, and 8 necessitate additional support.

Figure 4 (a) and (b) clearly shows the strong parts and the dangerous area that needs support (Goh *et al.,* 2018).

In Figure 4 (a), the cave exhibits the highest degree of stability in Section 4, with Sections 5 and 2 following closely behind. Sections 1, 3, and 8 exhibit a moderate level of stability, but Sections 6 and 7 have a low level of stability (Goh *et al.,* 2018).

Table 8: Comparative analysis table outlining assessment procedures for weathered limestone

Evaluation Method	Description	Applicability	Reference
Visual Inspection	Observing limestone surfaces directly for weathering indicators, such as colour shifts, fractures, erosion, and surface roughness. Requires fieldwork and visual expertise.	Appropriate for preliminary evaluations and expedited data collection in the field, it offers detailed information regarding the state of surface conditions.	(Lee *et al.,* 2023)
Laboratory Analysis	Gathering limestone samples for thorough examination utilizing methods such as XRD, XRF, and FTIR to evaluate mineral composition and modification offers numerical information.	Provides accurate information regarding the mineral composition and chemical transformations.	(Irfah and Pauzi, 2014)
Geophysical Surveys	Non-destructive technologies such as ground-penetrating radar (GPR), electrical resistivity and a Seismic Refraction Survey for Site Investigation are used to examine subsurface conditions and assess structure integrity.	It is ideal for assessing subsurface characteristics and detecting structural changes, and it is helpful in scenarios where direct access to the limestone is limited.	(Roslan *et al.,* 2019)

Table 9: Classification of susceptibility based on (Slope Mass Rating) SMR value (Romana, Tomás and Serón, 2015)

SMR Value	Class No	Rock Mass Description	Stability	Failures	Probability	Susceptibility Classification
0-20	V	Very bad slope	Completely unstable	Big planar or soil like circular	0.9	High susceptibility
21-40	IV	Bad slope	Unstable	Planar or big wedges	0.6	//
41-60	III	Normal slope	Partially stable	Planar along some joint	0.4	Moderate susceptibility
61-80	II	Good slope	Stable	Some blocks failures	0.2	Low susceptibility
81-100	I	Very good slope	Completely unstable	No failures	0	//

6.0 SLOPE MASS RATING (RSM) THRESHOLDS FOR SLOPE FAILURE SCENARIOS IN BATU CAVES

The slope mass rating (RSM) technique was employed to evaluate the stability of the rock slope. The SMR approach utilizes many components to assess the overall strength of a rock mass (Tomás *et al.,* 2012). Below is a detailed analysis of each element:

6.1 Uniaxial Compression Strength (UCS)

This test includes measuring the rock's ability to withstand stress when compressed along a single axis. The Uniaxial Compressive Strength (UCS) is a vital measure for assessing the rock's ability to resist compressive pressures.

6.2 Rock Quality Designation (RQD)

Rock Quality Designation (RQD) is a metric used to evaluate the level of preservation of rock core samples. It offers data on the quality of the rock formation and aids in assessing the overall state of the rock.

6.3 Compressive Strength Uniaxial

This reiterates the prior assertion that the uniaxial compressive strength of the rock is a critical determinant in assessing the stability of a slope (Lai *et al.,* 2018).

The slope stability of the Batu cave wall was investigated using RSM technique, which included uniaxial compressive strength (UCS) analysis, rock quality determination (RQD), discontinuity spacing and discontinuity conditions.

As a result of the Batu Caves research, different stability categories and experimentally determined slope mass rating (SMR) threshold values are associated with distinct failure scenarios. The following order is detailed in Table 9 and the text (Goh *et al.,* 2016).

The table 9 presented above serves as a concise and informative tool for evaluating the stability and vulnerability of rock slopes, utilising their SMR values. This resource facilitates the process of decision-making and risk assessment in the fields of geology and engineering.

The SMR value 0–20 is classified as weathered grade V, indicating a very bad quality slope. The geological conditions of the area are characterized by a state of total instability, exhibiting a pronounced vulnerability to rock failures, particularly those of significant magnitude involving planar formations or circular failures resembling soil-like behaviour (Triana and Hermawan 2020).

According to the standardised slope classification system, slopes falling within the range of SMR 21–40 are categorized as IV, indicating poor slope quality. The slope exhibits an unstable nature, characterised by a likelihood of failures associated with planar or large wedges. The table does not provide a specific likelihood (Goh *et al.,* 2016).

The SMR 41–60 range falls within the classification of III, which denotes a normal slope. The system exhibits a certain degree of stability, while it is prone to instability to a significant extent, particularly in relation to planar breakdowns occurring at certain joint (Albar and Mohd-Nordin, 2022).

The SMR 61–80 range is classified as weathered grade II, indicating a favourable slope quality. The slope exhibits a state of relative stability, although there is a potential for localized block collapses. The vulnerability to instability is minimal (Goh *et al.,* 2018).

Within the SMR 81–100 range, the designated categorization is denoted I, which signifies a high-quality slope characterized as very good. The system is characterized as highly stable, exhibiting no anticipated instances of breakdown (Romana, Tomás and Serón, 2015).

7.0 STRATEGIES FOR RISK MITIGATION

Geological catastrophes are unpredictable temporal occurrences. The attempt to reduce the risk associated with weathered limestone in Batu Caves necessitates implementing effective stabilisation techniques. These techniques are essential for improving limestone formations' structural integrity and durability. A prominent and precipitous limestone incline renders rock stabilisation measures unfeasible (Lem, 2021). Nevertheless, the stabilisation process effectively removes loose stone blocks from the rock's surface for smaller banks (Simon *et al.,* 2015). The primary emphasis of mitigation strategies on rock fall dangers is directed towards Disaster risk reduction measures for development in the Near area, which can be effectively applied through mitigation strategies (Youssef and Maerz, 2009). Implementing rock fall mitigation measures involves the construction of several protective structures, including trap trenches, rock barriers, stone fences, and wire mesh installations (Onn and Teo, 2023). In this particular setting, developing comprehensive strategies to mitigate risks is imperative. These strategies should comprise diverse preventive, protective, and adaptive measures. Table 10 offers a succinct summary of the different approaches that can be used to reduce the risk that comes with limestone weathering at Batu Caves.

8.0 ENVIRONMENTAL IMPLICATIONS

Most critical environmental ramifications result from the limestone's weathering in Batu Caves, especially regarding the impact on regional ecosystems. Reviewing the locations where

Table 10: The strategies for risk mitigation in Batu Caves

Strategy	Description	Reference
Regularly Observation and Evaluation	In order to analyse limestone formations, cave structures, and weathering patterns, it is imperative to establish systematic monitoring and evaluation programs. These programs should encompass various activities such as geological and structural inspections.	(Geoguide 4: Guide to Cavern Engineering, 2017)
Management of the Environment	To protect the cave environment, pay attention to things around it, such as water infiltration, reducing pollution and controlling tourist activities that cause weathering.	(Cave and Karst Management Plan / Environmental Assessment Mammoth Cave National Park, 2019)
Providing information	Batu Caves is at risk from limestone weathering, so it's important to inform visitors and the local community about this issue.	(Kiew, Nuratiqah and Zubaid, 2023)
The oversight and Zoning	Creating regulations and zoning to manage human activities, restricting access to dangerous areas by installing signs.	(Rahman and Kiew, 2018)
Engineering and Infrastructure Solutions	Creating engineering solutions to protect against atmospheric agents, such as barriers, drainage systems, or protective coatings for limestone surfaces and catching nets in the path of rock falls.	(Quilter, 2020)

water runs from above the slope and the mechanical weathering of roots, There was evidence of vegetation and exposed cracks that may be impacted by rock (Tan, 2002). In Batu Caves, limestone weathering grade from grade 1 to the slopes fell under the class III to IV range. Grade V is a high risk for visitors and those who come to the temple for pilgrimage (Goh *et al.,* 2017). The environmental consequences of Batu Caves that occur due to weathering are as follows:

8.1 Loss of Vegetation

The process of limestone weathering has been observed to have adverse effects on flora. The process of soil alteration results in changes to soil pH and nutrient concentrations, rendering it less conducive for the growth and development of certain plant species. The depletion of flora within the cave not only has implications for its visual appeal, but also has the potential to disrupt the availability of sustenance and the habitats of indigenous fauna (Haule *et al.,* 2016).

8.2 Loss of Habitat

Can potentially occur as a consequence of the degradation of limestone formations. Cave and limestone formations frequently serve as vital habitats for bats and invertebrates, among other species. Disruptions to these habitats may lead to the seclusion of populations and a decline in genetic diversity, thereby heightening the vulnerability to local extinctions (Nordin *et al.,* 2021).

8.3 Challenges to Stability

The results of the study pertaining to weathering grades and risk potential emphasize the pressing issue of cave stability. The structural soundness of the cave system is compromised, thereby increasing the likelihood of rock fall occurrences and cave collapses. Consequently, this poses a significant hazard to the safety of visitors and the conservation of the distinctive characteristics of the caves (Goh *et al.,* 2018).

8.4 Tourism Effect on the Economy

The Batu Caves holds significant prominence as a prominent tourist destination, and the potential deterioration of its ecosystem has the potential to adversely affect the local tourism sector. Economic losses for the region can ensue as a result of reduced visitors either from safety concerns or unappealing aesthetics (Zulkifli and Yalumalai, 2018).

9.0 DIRECTIONS FOR FUTURE RESEARCH

In future research in Batu Caves, two techniques are proposed to investigate and apply complex methods for limestone weathering processes.

9.1 Remote Sensing Technologies

Within the domain of prospective investigations in Batu Caves, the application of remote sensing technology emerges as a highly interesting route. The utilization of these sophisticated instruments might greatly augment our comprehension of the mechanisms involved in limestone weathering and their ramifications on the environment within the cave. The following are important factors to take into account while considering this approach:

9.1.1 LiDAR- Stands for 'Light Detection and Ranging

The utilisation of sophisticated and contemporary cartographic technology plays a pivotal role in evaluating the stability and deformation characteristics of rock slopes. Rockfalls are a common geological hazard that occurs on steep slopes, often leading to significant impacts on economic, human life, and environmental aspects. The commencement of rock-fall processes in a tropical setting is influenced by a mix of climatic, topographic, and vegetation factors. The rock-mass properties, namely the characteristics of discontinuities such as joints, bedding planes, and fractures, play a crucial role in identifying potential unstable blocks that can trigger rock-fall events (Razak *et al.,* 2014).

9.1.2 Particulars and Accuracy

Light Detection and Ranging, or LiDAR, is a remote sensing technology that creates highly accurate three-dimensional representations of the Earth's surface by measuring distances with laser pulses. When assessing limestone slopes, LiDAR technology offers exceptional levels of accuracy and specificity. With remarkable precision, it is capable of capturing the intricate features that comprise the slope's topography. It is critical to have this level of specificity in order to identify prospective factors that may cause the instability of limestone (Reutebuch, Andersen and McGaughey, 2005).

9.1.3 The Utilisation of Visualisation and Modeling

LiDAR data-generated three-dimensional models provide significant insights into the granite slope's geometry and spatial relationships. Engineers and geologists can use this information to generate comprehensive geotechnical models and simulations that evaluate the geological mass's potential behaviour under various circumstances, including extreme weather events (Cucchi *et al.,* 2023).

The utilisation of LiDAR technology serves a dual purpose in the evaluation of potential hazards and the development and execution of efficient measures to minimise their impact. By acquiring a comprehensive comprehension of the topography and the presence of potentially unstable rock formations, engineers are able to devise methodologies for the stabilisation of slopes, implementation of preventive measures, and establishment of early warning systems. These procedures aim to mitigate the adverse effects caused by occurrences of rock fall (Abdulwahid and Pradhan, 2017).

10.0 CONCLUSION

This review article provides an overview of the classification of the degrees of limestone weathering in Batu Caves and the challenges caused by the effect of weathering and proposes to address these challenges. Based on the outcomes of the prior investigation, it was determined that sections 1, 3, and 8 exhibit moderate stability with weathering grades of 3 and 4, whereas sections 6 and 7 display low stability with a weathering grade of 6, indicating a high-risk zone prone to potential limestone rockfall hazards. This review serves to deepen our understanding of the process of limestone weathering in Batu Caves and its wide-ranging ramifications for the fields of engineering, construction, and environmental protection. The findings obtained from this research provide essential guidance, informing the most effective strategies for mitigating the effects of weathering, conserving the geological significance of Batu Caves, and imparting important knowledge for the protection of limestone-rich locations globally.

ACKNOWLEDGMENTS

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

REFERENCES

[1] Abdulwahid, W.M. and Pradhan, B. (2017). Landslide Vulnerability and Risk Assessment for Multi-Hazard Scenarios Using Airborne Laser Scanning Data (Lidar), Landslides, 14(3), Pp. 1057–1076. https://doi.org/10.1007/S10346-016-0744-0.

[2] Aboutaleb, S., Bagherpour, R., Behnia, M., and Aghababaei, M. (2017). Combination of the Physical and Ultrasonic Tests in Estimating the Uniaxial Compressive Strength and Young's Modulus Of Intact Limestone Rocks, Geotechnical and Geological Engineering, 35(6), Pp. 3015–3023. https://doi.org/10.1007/S10706-017-0281-1.

[3] Akbar, N.A., Aziz, H.A., and Adlan, M.N. (2021). The Characteristics of Limestone and Anthracite Coal as Filter Media in Treating Pollutants from Groundwater, International Journal of Environmental Science and Development, 12(2), Pp. 58–62. https://doi.org/10.18178/IJESD.2021.12.2.1318.

[4] Albar, A. and Mohd-Nordin, M.M. (2022). Slope Mass Rating (SMR) Classification for Rock Slope Stability and Geohazard Vulnerability Assessment, International Journal of Integrated Engineering, 14(5), Pp. 57–65. https://doi.org/10.30880/Ijie.2022.14.05.006.

[5] Aminuddin, N.J. and Pauzi, N.I.M. (2011). Scatter-Plot Analysis of Microcracks Pattern Behaviour of Weathered Limestone at Batu Caves, Malaysia, Electronic Journal of Geotechnical Engineering, 16 N(August), Pp. 1639–1650.

[6] Ali Shah, S.Y., bin, D., Obaidullah, Hussain. J., Hussain, K., Asghar, A., Hussain, H., and Rahman, A.U. 2022). Physio-Mechanical Properties and Petrographic Analysis of Nikanaighar Limestone KPK, Pakistan. Open Journal of Civil Engineering, 12(02), Pp. 169–188. https://doi.org/10.4236/Ojce.2022.122011.

[7] Arman, H. and El Tokhi, M. (2016). Slake Durability Test on Lower Oligocene Limestones from Daniel United Arab Emirates, Journal of Earth Science & Climatic Change, 7(6). https://doi.org/10.4172/2157-7617.1000356.

[8] Quilter, D. (2020). Ipoh & Gopeng. Risk Assessment – 2020.

[9] Beck, K. and Al-Mukhtar, M. (2010). Weathering Effects in an Urban Environment: A Case Study of Tuffeau, a French Porous Limestone, Geological Society Special Publication, 331(March 2010), Pp. 103–111. https://doi.org/10.1144/SP331.8.

[10] Biondino, D., Borrelli, L., Critelli, S., and Muto, F. (2020). A Multidisciplinary Approach to Investigate Weathering Processes Affecting Gneissic Rocks (Calabria, Southern Italy), Catena, 187(September 2019), P. 104372. https://doi.org/10.1016/J.Catena.2019.104372.

[11] Bissell, H.J. and Chilingar, G. V. (1967). Chapter 4 Classification of Sedimentary Carbonate Rocks, Developments In Sedimentology, 9 (PART A), Pp. 87–168. https://doi.org/10.1016/S0070-4571(08)71112-9.

[12] Budakçi, M. and Karamanoğlu, M. (2014). Effects of Weathering on Some Physical Properties of Wood, Kastamonu University Journal of Forestry Faculty, 14(1), P. 37. https://doi.org/10.17475/Kuofd.87880.

[13] Camuffo, D. (1995). Physical Weathering of Stones, Science of the Total Environment, 167(1–3), Pp. 1–14. https://doi.org/10.1016/0048-9697(95)04565-I.

[14] Cave and Karst Management Plan/Environmental Assessment Mammoth Cave National Park (2019), (July).

[15] Chala, E.T., Science, A.A., and Rao, S.K. (2021). Evaluation of Weathered Rock Mass Strength and Deformation Using Evaluation of Weathered Rock Mass Strength and Deformation Using Weathering Indices, (September). https://doi.org/10.1088/1755-1315/833/1/012194.

[16] Chowdhury, A.N., Punuru, A.R., and Gauri, K.L. (1990). Weathering of Limestone Beds at the Great Sphinx, Environmental Geology and Water Sciences, 15(3), Pp. 217–223. https://doi.org/10.1007/BF01706413.

[17] Cucchi, L., Gioia,C., Paonni, M., and Senni, T. (2023). Galileo High Accuracy Service: An Automotive Test, Pp. 122–126. https://doi.org/10.1109/metroautomotive57488.2023.10219123.

[18] Dearman, W.R. (1974). Weathering Classification in the Characterisation of Rock for Engineering Purposes in British Practice. Bulletin of the International Association of Engineering

Geology - Bulletin de l'Association Internationale de Géologie de l'Ingénieur.

[19] Dearman, W.R. (1975). Weathering Classification in the Characterisation of Rock: A Revision, Bulletin of the International Association of Engineering Geology, 14(1), Pp. 123–127. https://doi.org/10.1007/BF02634744.

[20] De la Rosa–García, S.D.CM., Ortega–Morales, O., Claire Gaylarde, C., Beltrán–García, M., Quintana–Owen, P., Reyes–Estebanez, M. (2011). Influence of Fungi in the Weathering of Limestone of Mayan Monuments Autor Para Correspondencia: B.O. Ortega-Morales Beortega@Uacam.Mx Original, 33(October 2010), Pp. 43–51.

[21] Dodge-Wan, D. (2015). Elongated Tufaceous Stalagmites in the Entrance of Batu Cave. https://doi.org/10.1007/S13146-014-0230-5.

[22] Dontsova, K., Chorover, J. and Balogh-Brunstad, Z. (2020). Plants as Drivers of Rock Weathering, Biogeochemical Cycles: Ecological Drivers and Environmental Impact, Pp. 33–58. https://doi.org/10.1002/9781119413332.Ch2.

[23] Durgin, P.B. (2020). Landslides and the Weathering of Granitic Rocks, (January 1977). https://doi.org/10.1130/REG3-P125.

[24] Emry, R., Goldstein, R.H. and Franseen, E.K. (2012).Technical paper - A First-Cut Field Method to Evaluate Limestone Aggregate Durability, (September).

[25] Fernandes Leao, M. (2018). Characterization of Weathered Soft Rock Mass by Index Tests, International Journal of Paleobiology & Paleontology, 1(1). https://doi.org/10.23880/Ijpbp-16000104.

[26] Finlay, R.D., Mahmood, S. Rosenstock, N., Bolou-Bi, E.B., Köhler, S.J., Fahad, Z., Rosling, A., Wallander, H., Belyazid, S., Bishop, K., and Lian, B. (2020). Reviews and Syntheses: Biological Weathering and Its Consequences at Different Spatial Levels - From Nanoscale To Global Scale, Biogeosciences, 17(6), Pp. 1507–1533. https://doi.org/10.5194/Bg-17-1507-2020.

[27] Fu, S., Chen, L., Woldai, T., Yin, K., Gui, L., Du, J., Zhou, C., Xu, Y., and Lian, Z. (2020). Landslide Hazard Probability and Risk Assessment at the Community Level: A Case of Western Hubei, China, Natural Hazards and Earth System Sciences, 20(2), Pp. 581–601. https://doi.org/10.5194/Nhess-20-581-2020.

[28] Lai, G.T., Mohd Razib, A.M., Mazlan, N.A., Rafek, A.G., Serasa, N.A.S., Mohamed, T.R. (2016). Rock Slope Stability Assessment Using Slope Mass Rating (SMR) Method: Gunung Lang Ipoh Malaysia, Scholars Journal of Engineering and Technology (SJET), 4(May), Pp. 185–192.

[29] González-Gómez,W.S., Quintana, P., May-Pat, A., Avilés, F., May-Crespo, J., and Alvarado-Gil, J.J. (2015). Thermal Effects on the Physical Properties of Limestones from the Yucatan Peninsula, International Journal of Rock Mechanics and Mining Sciences, 75, Pp. 182–189. https://doi.org/10.1016/J.Ijrmms.2014.12.010.

[30] Grismer, L.L., Wood Jr, P.L., Onn, C.K., Anuar, S., and Muin, M.A. (2014). Cyrts in the City: A New Bent-Toed Gecko (Genus Cyrtodactylus) is the only Endemic Species of Vertebrate from Batu Caves, Selangor, Peninsular Malaysia. Zootaxa, 3774(4), Pp. 381–394. https://doi.org/10.11646/Zootaxa.3774.4.6.

[31] Gurocak, Z. (2014). Effect of Weathering on the Geomechanical Properties of the Miocene Basalts in Malatya, Eastern Turkey. https://doi.org/10.1007/S10064-005-0005-2.

[32] Hack, H.R. (2020). Susceptibility to Weathering; Overview. (December).

[33] Hack, H.R.G.K. (2019). Weathering, Erosion, and Susceptibility to Weathering. Soft Rock Mechanics and Engineering, Pp. 291–333. https://doi.org/10.1007/978-3-030-29477-9_11.

[34] Hajna, N.Z., Hajna, N.Z., and Gabrovsek, F. (2002). Chemical Weathering of Limestones and Dolomites in a Cave Environment. Evolution of Karst: From Prekarst to Cessation, (January 2003), Pp. 347–356.

[35] Haule, H., Ringo, J.E., Luvinga, K., Kawonga, S., Mayengo, G., and Morsardi, L. (2016). Effects of Limestone Mining on Deforestation and Land Degradation in Mbeya Region, Tanzania. International Journal of Modern Social Sciences, 5(2), Pp. 117–132. _On_Deforestation_And_Land_Degradation_In_Mbeya_Region_Tanzania.

[36] Horn, B.A., Qiu, J., Owen, N.L., and Feist, W. (1994). FT-IR Studies of Weathering Effects in Western Redcedar and Southern Pine. Applied Spectroscopy, 48(6), Pp. 662–668.

[37] Hwidi, R.S., Tengku Izhar, T.N., and Mohd Saad, F.N. (2018a). Characterization of Limestone as Raw Material to Hydrated Lime. E3S Web of Conferences, 34(January). https://doi.org/10.1051/E3sconf/20183402042.

[38] Hwidi, R.S., Tengku Izhar, T.N. , and Mohd Saad, F.N. (2018b). Characterization of Limestone as Raw Material to Hydrated Lime. E3S Web of Conferences, 34(March). https://doi.org/10.1051/E3sconf/20183402042.

[39] Irfah, N. and Pauzi, M. (2014). Scatter-Plot Analysis of Microcracks Pattern Behaviour of Weathered Limestone at Batu Caves , Malaysia.(June 2011).

[40] Khattab, S.I.A., and Othman, H.M.S. (2012). Durability & Strength of Limestone Used in Building, ءانبلا يف ةمدختسملا ةيسلكلا ءانبلا راجحأ ةموميدو ةناتم نامثع حلاص دملم ليد ر’ Pp. 3–6.

[41] Kiew, R., Nuratiqah, A.R. and Zubaid, A. (2023). Malaysian Cave and Karst Conservancy Batu Caves Scientific Expedition 2019, 75(1), Pp. 1–13.

[42] Kumar, A. (2015). Pewter Industry and Tin Mining in Malaysia; and the Batu Caves of Kuala Lumpur. Earth Science India, VIII(May), Pp. 1–13.

[43] Goh, T.L., Wong, J.M., Abdul Ghani, R., Serasa, A.S., Mazlan, N.A., Mohd Razib, A.M., Hussin, A., Lee, K.E., and Mohamed, T.R. (2018). Stability Assessment of Limestone Cave: Batu Caves, Selangor, Malaysia. Sains Malaysiana, 47(1), Pp. 59–66.

[44] Lee, A.K.Y., Razali, M., Mohamad Ismail, M.A., Yusoff, I.N., Nagendran, S.K., Zainal, Z., Tobe, H., Date, K., Yokota, Y. (2023). Preliminary Analysis of Rock Mass Weathering Grade Using Image Analysis of CIELAB Color Space with the Validation of Schmidt Hammer : A Case Study. Physics and Chemistry of the Earth, 129(August 2022), P. 103291. https://doi.org/10.1016/J.Pce.2022.103291.

[45] Lem, K. and Gelongsoran, J. (2021). Penilaian Komprehensif Kestabilan Cerun Batuan Menggunakan Kaedah Had. (December).

[46] Lide, D.R. (1982). Assuring Data Quality. (December), P. 2. https://doi.org/10.1007/978-1-4302-0528-9_9.

[47] Lim, T.W. and Yussof, S.S. (2019). Conservation Status of the Batu Caves Trapdoor Spider (Liphistius Batuensis Abraham (Araneae, Mesothelae)): A Preliminary Survey. (January 2009).

[48] Luquot, L., Hebert, V., and Rodriguez, O. (2016). Calculating Structural and Geometrical Parameters by Laboratory Measurements and X-Ray Microtomography : A Comparative Study Applied to a Limestone Sample Before and After a Dissolution Experiment. Pp. 441–456. https://doi.org/10.5194/Se-7-441-2016.

[49] Mallick, M.K., Choudhary, B.S. and Budi, G. (2020). Geological Reserve Estimation of Limestone Deposit: A Comparative Study Between ISDW and OK. Modelling, Measurement And Control C, 81(1–4), Pp. 72–77. https://doi.org/10.18280/Mmc_C.811-413.

[50] Martinez, D.M. and Horvath, A. (2023). Comparative Environmental Assessment of Limestone Calcined Clay Cements and Typical Blended Cements Comparative Environmental Assessment of Limestone Calcined Clay Cements and Typical Blended Cements.

[51] Annual Book of ASTM Standards ASTM.

[52] Metcalfe, I. (2018). Persatuan Geologi Malaysia Warta Geologi.

[53] Mohamed, Z., Rafek, A.G., Mingwei, Z., Yanlong, C., Lai, G.T., Azahari, K., and Mohamad, Z. (2021). Leveraging on Multidisciplinary Expertise for Landslide Disaster Risk Reduction and Management: A Case Study of A Limestone Hill Rockfall Hazard Assessment, Batu Caves, Selangor, Malaysia. Sains Malaysiana, 50(8), Pp. 2179–2191. https://doi.org/10.17576/Jsm-2021-5008-04.

[54] Morner, B. (No Date). Chemical Analysis of Limestone / Calcium Oxide Material. Bowser Morner [Preprint].

[55] Naeem, M., Sadiq, R.A., Anwar, M., and Perveiz, K. (2014). Mechanical Properties and Petrographic Characteristics of Margala Hill Limestone and Lockhart Limestone of Rumli Area, Islamabad Pakistan. Acta Geodaetica Et Geophysica, 49(4), Pp. 441–454.

[56] Nordin, J., Chew, T.H, Lim, L.S., and Shamsir, M.S.(2021). Temporal Changes of Bat Diversity in the Urban Habitat Island of Batu Caves, Malaysia. IOP Conference Series: Earth and Environmental Science, 736(1). https://doi.org/10.1088/1755-1315/736/1/012051.

[57] Lyana, K. N., Shah, A., Hazizan, and M., Hareyani, Z. (2016). Effect of Geological Condition on Degree of Fragmentation in a Simpang Pulai Marble Quarry. Procedia Chemistry, 19 (December), Pp. 694–701.

[58] Geoguide 4: Guide to Cavern Engineering. Civil Engineering and Development Department. P. 93. http://www.Cedd.Gov.Hk/Eng/Publications/Geo/Doc/Eg7_2017.09.18.Pdf.

[59] Onn, C.K. and Teo, E.W. (2023). Checklist of the Herpetofauna of Batu Caves , Selangor , Malaysia. (May).

[60] Mohd Pauzi, N.I., Omar, H., Kim Huat, B., Misran, H., and Md Yusoff, Z. (2011). Microcrack Pattern Propagations and Rock Quality Designation of Batu Caves Limestone. Electronic Journal of Geotechnical Engineering, 16 F(January), Pp. 591–604.

[61] Price, D.G. (1995). Weathering and Weathering Processes. Quarterly Journal of Engineering Geology, 28(3), Pp. 243–252.

[62] Price, J.R. and Velbel, M.A. (2003). Chemical Weathering Indices Applied to Weathering Profiles Developed on Heterogeneous Felsic Metamorphic Parent Rocks, 202, Pp. 397–416. https://doi.org/10.1016/J.Chemgeo.2002.11.001.

[63] Přikryl, R., Melounová, L.,Varilova, Z.,Weishauptová, Z. (2007). Spatial Relationships of Salt Distribution and Related Physical Changes of Underlying Rocks on Naturally Weathered Sandstone Exposures (Bohemian Switzerland National Park, Czech Republic). Environmental Geology, 52(2), Pp. 283–294. https://doi.org/10.1007/S00254-006-0532-6.

[64] Rahman, R.A. and Kiew, R. (2018). Strategy to Conserve Maximum Biodiversity of Limestone Flora in Peninsular Malaysia. Sibbaldia: The International Journal of Botanic Garden Horticulture, (16), Pp. 57–66. https://doi.org/10.24823/Sibbaldia.2018.247.

[65] Rau, G.H., Knauss, K.G., Langer, W.H., and Caldeira, K. (2007). Reducing Energy-Related CO2 Emissions Using Accelerated Weathering of Limestone. Energy, 32(8), Pp. 1471–1477.

[66] Razak, K.A., Che Hasan, R., Aitin, A., Sheng, L.C., Mohamed, Z., A'zad, Q., and Abu Bakar, R.(2014). Hyperspatial Resolution of Ground Based Remote Sensing for Natural Limestone Characterization: A Critical Input for Rock Slope Hazard Assessment in the Tropics. 35th Asian Conference on Remote Sensing 2014, ACRS 2014: Sensing For Reintegration of Societies, Pp. 2–7.

[67] Razali, M., Jamal, M.H., Mohamad Ismail, M.A., Yusoff, I.N., Nagendran, S.K., Zainal, Z., Zainuddin, N.E., Tobe, H., Miyoshi, T., Date, K., and Yokota, Y.(2021). Quantitative Weathering Assessment of Rock Slope Using CIELAB Color Space and Image Analysis Technique. Research Square [Preprint].

[68] Regmi, A.D., Yoshida, K., Dhital, M.R. and Pradhan, B. (2014). Weathering and Mineralogical Variation in Gneissic Rocks and Their Effectin Sangrumba Landslide, East Nepal. Environmental Earth Sciences, 71(6), Pp. 2711–2727. https://doi.org/10.1007/S12665-013-2649-8.

[69] Reutebuch, S.E., Andersen, H.E., and Mcgaughey, R.J. (2005). Light Detection and Ranging (LIDAR): An Emerging Tool for Multiple Resource Inventory. Journal of Forestry, 103(6), Pp. 286–292.

[70] Romana, M., Tomás, R. and Serón, J.B. (2015). Slope Mass Rating (SMR) Geomechanics Classification: Thirty Years Review.13th ISRM International Congress of Rock Mechanics, 2015-MAY(May), Pp. 1–10.

[71] Roslan, R., Che Omar, R., Baharuddin, I.N.Z., Abdul Wahad, W., and Buslima, F.S. (2019). Integration of Resistivity and Seismic Data to Determine the Cavity at Teluk Apau, Langkawi: An Evaluation. International Journal of Engineering and Advanced Technology, 9(1), Pp. 2295–2300. https://doi.org/10.35940/Ijeat.A2706.109119.

[72] Scrivano, S. and Gaggero, L. (2020). An Experimental Investigation into the Salt-Weathering Susceptibility of Building Limestones. Rock Mechanics and Rock Engineering, 53(12), Pp. 5329–5343. https://doi.org/10.1007/S00603-020-02208-X.

[73] Simon, N., Abdul Ghani, M.F., Hussin, A., Goh, T.L., Rafek, A.G., S., Noraini, S., Taalab, M., and Lee, K.E. (2015). Assessment of Rockfall Potential of Limestone Hills in the Kinta Valley. Journal of Sustainability Science and Management, 10(2), Pp. 24–34.

[74] Sulaiman, N., Sulaiman, N., Mohd Shariffuddin, S.I., Mohd Raflis, S.B., and Ibnu Hassim, R. (2020). Assessment of Limestone Caves in Dabong, Kelantan Using Systematic Studies for Potential Geoheritage Sites. IOP Conference Series: Earth and Environmental Science, 549(1). https://doi.org/10.1088/1755-1315/549/1/012021.

[75] Tan, B.K. (2002). Environmental Geology of Limestone in Malaysia. Igcp, Pp. 54–67.

[76] Tang, M., Wang, Y., and Xiang, C. (2021). Study of the Limestone Strength Weakening Mechanism at the Eastern Margin of the Kangdianpalaeouplife in Southwest China. IOP Conference Series: Earth and Environmental Science, 861(6). Https://doi.org/10.1088/1755-1315/861/6/062035.

[77] Tang, T. (1998). Field Testing of Rock Hardness and Its Relationship to Limestone Dissolution in Guilin, Southern China. Middle States Geographer, 31(I), Pp. 15–22.

[78] Tating, F., Hack, R., and Jetten, V. (2015). Weathering Effects on Discontinuity Properties in Sandstone in a Tropical Environment: Case Study at Kota Kinabalu, Sabah Malaysia. Bulletin of

Engineering Geology and the Environment, 74(2), Pp. 427–441. https://doi.org/10.1007/S10064-014-0625-5.

[79] Goh, T.L, Mohd Razib, A.M., Mazlan, N.A., Rafek, A.G., Serasa, A.S., Simon, N., Surip, N., Lee, K.E., and Mohamed, T.R. (2017). Rock Slope Stability Assessment of Limestone Hills, Southern Kinta Valley, Ipoh, Perak, Malaysia. Geological Behavior, 1(2), Pp. 05–09. https://doi.org/10.26480/Gbr.02.2017.05.09.

[80] Tomás, R., Cuenca, A., Cano, M., Garcia- Barba, J. (2012). A Graphical Approach for Slope Mass Rating (SMR). Engineering Geology, 124(1), Pp. 67–76. https://doi.org/10.1016/J.Enggeo.2011.10.004.

[81] Torabi-Kaveh, M., Heidari, M., Mohseni, H., Ménendez, B. (2019). Role of Petrography in Durability of Limestone Used in Construction of Persepolis Complex Subjected to Artificial Accelerated Ageing Tests. Environmental Earth Sciences, 78(10). https://doi.org/10.1007/S12665-019-8308-Y.

[82] Zabidi, H., and De Freitas, M.H. (2013). Geospatial Analysis in Identifying Karst Cavity Distribution: The SMART Tunner, Malaysia. Pp. 125–133. https://doi.org/10.1007/S13146-013-0148-3.

[83] Prodan, M.V., Mileusnić, M., Arbanas, S.M, and Arbanas, Ž. (2017). Influence of Weathering Processes on the Shear Strength of Siltstones From a Flysch Rock Mass Along the Northern Adriatic Coast of Croatia. Bulletin of Engineering Geology and the Environment, 76(2), Pp. 695–711. https://doi.org/10.1007/S10064-016-0881-7.

[84] Waragai, T. (2016). The Effect of Rock Strength on Weathering Rates of Sandstone Used for Angkor Temples in Cambodia. Engineering Geology, 207, Pp. 24–35. https://doi.org/10.1016/J.Enggeo.2016.04.006.

[85] Warke, P.A. and Smith, B.J. (2007). Complex Weathering Effects on Durability Characteristics of Building Stone. Geological Society Special Publication, 271, Pp. 211–224. https://doi.org/10.1144/GSL.SP.2007.271.01.21.

[86] White, W.B. , and White, E.L. (2018). Karst Geomorphology. Pp. 45–62.

[87] Youssef, A.M.. and Maerz, N.H. (2009). Slope Stability Hazard Assessment and Mitigation Methodology Along Eastern Desert Aswan-Cairo Highway, Egypt. Journal of King Abdulaziz University, Earth Sciences, 20(2), Pp. 161–181. https://doi.org/10.4197/Ear.20-2.8.

[88] Zabidi, H., and Freitas, M.H.D.E. (2006). Structural Studies for the Prediction of Karst in the Kuala Lumpur Limestone. 10th Congress of the International Association for Engineering Geology and the Environment – Engineering Geology for Tomorrow's Cities, (264), Pp. 1–7.

[89] Zha, J., Wei, S., Wang, C., Li, Z., Cai, Y., and Ma, Q.(2020). Weathering Mechanism of Red Discolorations on Limestone Object: A Case Study From Lingyan Temple, Jinan, Shandong Province, China. Heritage Science, 8(1), Pp. 1–12. https://doi.org/10.1186/S40494-020-00394-Z.

[90] Zulkifli, Z. and Yalumalai, R. (2018). Analysis of the Impact of Tourism Development on Economic and Social Culture Community Aspects. Sumatra Journal of Disaster, Geography and Geography Education, 2(2), Pp. 30–34. https://doi.org/10.24036/Sjdgge.V2i2.150.

PROFILES

HAMASA KAMBAKHSH graduated with Bachelor of Geology and Mining from Jawzjan University, Afghanistan. She is a geologist, dedicated Researcher, and esteemed Senior Lecturer of Engineering Faculty at the Faryab University, Afghanistan. Currently, she is pursuing a Master's degree in Engineering (Geology and Geotechnical) at Universiti Putra Malaysia (UPM). Her research interests are geological and environmental engineering.
Email address: h.kambakhsh1989@gmail.com

NIK NORSYAHARIATI NIK DAUD (PhD) is a senior lecturer of Civil Engineering at the Universiti Putra Malaysia (UPM), Malaysia. She is a registered Graduate Engineer under the Board of Engineers Malaysia (BEM) and Institution of Engineers Malaysia (IEM). She also served as the Head of Geotechnical and Geological Engineering Unit and Head of Soil Mechanics Laboratory at the department. She has several publications and awards in both national and international levels. Her research interests are geotechnical engineering and environmental geotechnics.
Email address: niknor@upm.edu.my