Characterization of Weathered Limestone Rocks and the Correlation with the Engineering Properties through Ultrasonic Pulse Velocity (UPV) Testing

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Abstract. This study examines the application of non-destructive techniques, particularly ultrasonic pulse velocity (UPV), for evaluating the structural soundness and deterioration patterns of limestone. Comprehending the mechanical and physical features of limestone is crucial for maximizing its utilization, considering its vital role in the cement industry and building. The study quantifies ultrasonic pulse velocity (UPV) in different limestone specimens using varying transducer frequencies to analyze these features and evaluate the degree of weathering. The research highlights the efficacy of UPV as a cost-effective and uncomplicated tool by examining the elements that influence velocity fluctuations and establishing statistical correlations. The major findings emphasize the usefulness of UPV in forecasting limestone qualities and tracking the course of weathering. This provides a viable alternative to the more difficult techniques of extracting specimens for mechanical evaluation. This study enhances the broader application of non-destructive testing in geotechnical engineering by offering insights that improve the efficiency and sustainability of limestone use in building and cement manufacture.

Keywords: Limestone Characterization, Non-Destructive Testing, Rock Integrity Assessment, Tropical Weathering, Ultrasonic Pulse Velocity.

1.0 Introduction

Non-destructive testing (NDT) is a highly adaptable and essential method employed in diverse industries to analyze material properties, identify flaws, and evaluate buildings without inflicting any harm. NDT procedures, such as the rebound hammer and pull- out

R. Ramli and M. Zakaria (eds.), *Proceedings of the International Conference on Science Technology and Social Sciences – Physics, Material and Industrial Technology (ICONSTAS-PMIT 2023)*, Advances in Engineering Research 238,
https://doi.org/10.2991/978-94-6463-500-3_3

test, were primarily employed in the civil engineering sector to evaluate the characteristics of newly poured concrete. As the field progressed, it became clear that there was a need to assess older structures and materials. This led to the adoption of non-destructive testing (NDT) procedures in the construction industry by the 1970s. These methods have subsequently broadened their initial focus and are now used in diverse geotechnical contexts, such as evaluating natural rock formations like granite and limestone.

The utilization of Non-Destructive Testing (NDT) in geotechnical contexts has great importance when evaluating rocks, as natural rocks are widely employed in construction and engineering endeavors. Conventional testing techniques for assessing rock characteristics can incur significant expenses and require a substantial amount of time. Non-destructive testing (NDT) provides a cost-efficient and effective option, particularly beneficial considering the accessibility of resources and support from academic faculties for these investigations. This methodology enables thorough assessments without the requirement for damaging tests, guaranteeing the soundness of the material or structure being evaluated.

One particular obstacle that NDT tackles in this situation is the erosion of rocks, which results in the deterioration of their physical characteristics and strength metrics [1]. Limestone presents distinct challenges because of its vulnerability to weathering and the intricacies associated with its management, which can result in both financial and time-related burdens. Precisely characterizing the weathering characteristics of limestone is essential for comprehending its structural and technical properties. Non-destructive testing (NDT) offers a method to accurately assess these alterations, providing valuable information about the enduring effectiveness and resilience of limestone in different uses. NDT is essential for geotechnical evaluations since it provides significant data to guide engineering decisions and assure the safety and reliability of structures made of rock [2].

This study intends to fulfill three important objectives by applying non-destructive testing (NDT) in the geotechnical area, specifically for examining the weathering behavior of limestone. The primary objective is to establish the parameters of the Ultrasonic Pulse Velocity (UPV) test as a non-destructive testing (NDT) method for assessing the characteristics of worn limestone samples. This entails determining the optimal utilization of UPV for accurately evaluating the extent of weathering and its influence on the material. The primary objective of the study is to ascertain the engineering characteristics and durability of tropical weathered limestone specimens, thereby gaining a comprehensive comprehension of the impact of weathering on the structural soundness of limestone. Ultimately, the goal is to evaluate the relationship between non-destructive testing (NDT) results, specifically those obtained from ultrasonic pulse velocity (UPV) tests, and the engineering characteristics of tropical weathered limestone. This correlation will contribute to the validation of NDT as a dependable technique for forecasting the engineering capabilities of weathered limestone. It provides a cost-efficient and effective substitute for conventional destructive testing methods.

2.0 Literature Review

Limestone is notable not just for its visual attractiveness but also for its essential role as a primary resource in the cement industry. Integrating limestone into cement production has the potential to greatly reduce manufacturing costs. Cement, an essential ingredient in construction, especially for reinforced concrete, is widely used in the construction industry. The composition of major cement kinds, such as Ordinary Portland Cement (OPC) and Pozzolanic Portland Cement (PPC), is predominantly influenced by limestone. Although limestone is prone to eventual corrosion, it displays exceptional resilience, guaranteeing the long-term stability and integrity of erected buildings [3].

The investigation of limestone's characteristics and its utilization in cement manufacturing encompasses many approaches to quantify and guarantee the precision of pertinent parameters. Bery and Saad's [4] research emphasizes the use of critical metrics such as Standard Penetration Test (SPT) N-Values, friction angle, velocity index, and density. These parameters are essential for comprehending the mechanical behavior and stability of limestone in diverse applications. Altindag [5] highlights the significance of quantifying density, porosity, grain size, and Uniaxial Compressive Strength (UCS) as they offer a thorough understanding of the structural characteristics of the material.

Based on previous data, most of these studies incorporate both laboratory and field testing to confirm the strength and dependability of the findings. Laboratory testing provides the advantage of controlled settings and accurate measurements, whereas field tests offer the advantage of real-world applicability and validation. Non-Destructive Testing (NDT) procedures, such as the Ultrasonic Pulse Velocity (UPV) test, are crucial in this research. Non-destructive testing (NDT) is used to guarantee the distinctiveness and precision of outcomes, providing a non-intrusive method to evaluate the interior composition and characteristics of limestone without inflicting any harm.

The application of non-destructive testing (NDT) to study limestone is especially important in the fields of architecture and geotechnical engineering. The wide range of naturally occurring rocks, such as granites and limestones, are widely used in various fields because of their strong structure and pleasing appearance. Non-destructive testing (NDT) techniques offer vital insights into the integrity and durability of these materials, enabling informed decisions in construction and material selection. Non-destructive testing (NDT) plays a crucial role in evaluating the weathering characteristics and mechanical properties of limestone. This assessment helps in maximizing its utilization in cement manufacturing and building, leading to improved efficiency and sustainability in these sectors. This literature review emphasizes the crucial importance of non-destructive testing (NDT) in enhancing our comprehension of limestone and its various uses. It highlights the collaborative relationship between conventional testing methods and contemporary non-destructive techniques in the fields of geotechnical.

3.0 Methodology

The research technique used in this work, including data collection, sample preparation, rock testing [6], and data analysis, is clearly explained in Figure 1 below.

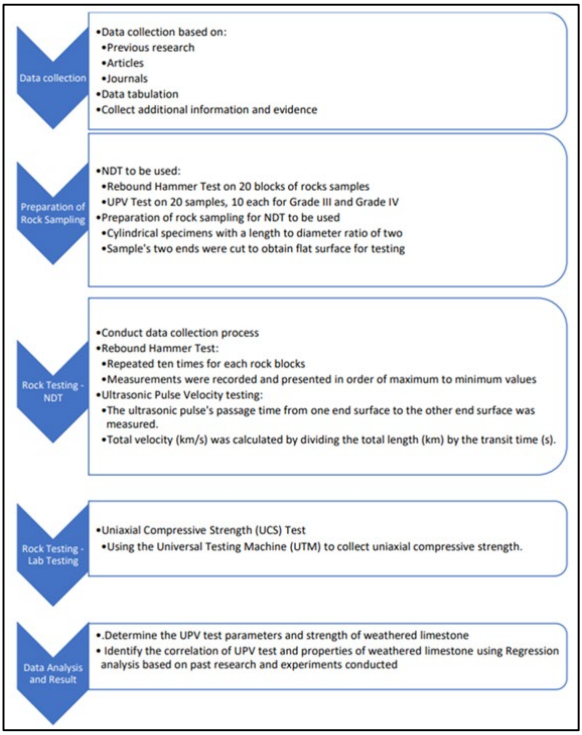

Fig. 1. Research flowchart.

4.0 Findings and Discussion

Based on the information provided in Table 1, a set of 20 rock block samples were subjected to Rebound Hammer Tests in order to determine their grade classification [7]. Rock blocks with an average reading between 30 and 39 are classified as Grade III, whereas those with an average reading between 20 and 29 are labeled as Grade IV. Grade III weathered limestone accounts for the majority of the rock block samples, at 65%, while the remaining samples are classified as Grade IV weathered limestone.

Table 1. Rebound hammer values on rock samples.

Sample	Rebound Count										Average R Value	Grade Classification
	1	2	3	4	5	6	7	8	9	10		
A	10	32	14	26	12	20	36	28	22	18	20.8	IV
B	20	26	22	14	28	24	12	28	32	26	22.9	IV
C	30	22	32	18	26	28	22	32	20	28	25.8	IV
D	40	22	18	32	40	22	26	22	20	20	26.2	IV
E	30	32	20	36	30	10	20	46	24	14	26.2	IV
F	32	38	30	32	26	28	18	30	28	30	29.4	IV
G	38	40	32	30	26	30	22	24	24	28	31.4	IV
H	32	12	20	12	46	42	46	42	24	38	32.8	III
I	40	30	40	38	30	36	26	28	30	30	32.4	III
J	32	24	34	32	46	26	36	40	30	24	33.0	III
K	20	38	32	22	26	40	44	42	32	44	34.3	III
L	25	52	25	40	35	38	35	40	42	46	34.8	III
M	42	28	46	28	40	42	20	36	36	30	36.6	III
N	26	28	40	36	36	42	38	40	40	40	36.6	III
O	40	42	28	38	40	30	40	48	30	32	36.8	III
P	12	36	42	40	26	30	44	36	34	40	37.6	III
Q	38	42	42	36	40	40	32	40	32	38	38.0	III
R	30	44	40	40	44	32	30	36	44	44	38.4	III
S	36	34	52	50	38	48	36	32	40	20	38.6	III
T	26	29	50	42	49	44	36	42	42	32	39.2	III

4.1 Properties of Limestone Rock Samples (20 nos.)

Table 2 displays the dimensions of cored rock samples, together with their grade classification. The table includes 10 samples of Grade III and 10 samples of Grade IV. The weights corresponding to these samples are also given. Figures 2 and 3 show the completed cored samples after the coring and cutting procedures, demonstrating that they are now prepared for testing.

Table 2. Properties of limestone coring samples.

Sample	Diameter, D (mm)	Length, L=2D (mm)	Weight (g)	Grade Classification
1	55.0	110.0	554.0	III
2	55.0	110.0	700.4	III
3	55.0	110.0	778.8	III
4	55.0	110.0	530.5	III
5	55.0	110.0	778.8	III
6	55.0	110.0	548.8	III
7	55.0	110.0	773.6	III
8	55.0	110.0	601.1	III
9	55.0	110.0	614.2	III
10	55.0	110.0	527.9	III
11	55.0	110.0	745.8	IV
12	55.0	110.0	749.6	IV
13	55.0	110.0	729.6	IV
14	55.0	110.0	731.9	IV
15	55.0	110.0	751.9	IV
16	55.0	110.0	641.9	IV
17	55.0	110.0	639.0	IV
18	55.0	110.0	616.6	IV
19	55.0	110.0	680.9	IV
20	55.0	110.0	662.7	IV

Fig. 2. The grade III cored samples of tropically weathered limestone.

Fig. 3. The grade IV cored samples of tropically weathered limestone.

4.2 Parameters of UPV Test as NDT Approach of Weathered Rock of Limestone Samples

Based on the results obtained in Table 4.3, the result obtained for UPV test for all cored samples are recorded in us which then converted to km/s.

Table 3. The result of UPV test for each cored samples.

Sample	Grade Classification	Length, L (mm)	UPV Test Reading, t (μs)	P-wave velocity, v (km/s)
1	III	110.0	21.7	5.067
2	III	110.0	22.0	5.000
3	III	110.0	20.8	5.278
4	III	110.0	20.9	5.270
5	III	110.0	21.7	5.063
6	III	110.0	22.0	5.001
7	III	110.0	21.3	5.169
8	III	110.0	22.0	5.001
9	III	110.0	22.2	4.964
10	III	110.0	21.5	5.110
11	IV	110.0	19.7	5.584
12	IV	110.0	20.0	5.500
13	IV	110.0	20.3	5.419
14	IV	110.0	20.5	5.366
15	IV	110.0	22.3	4.933
16	IV	110.0	19.8	5.556

17	IV	110.0	16.5	6.667
18	IV	110.0	17.3	6.358
19	IV	110.0	18.2	6.044
20	IV	110.0	18.7	5.882

4.3 Engineering Properties and Strength of Tropical Weathered Limestone Samples

The engineering properties of tropical weathered limestone samples, particularly their uniaxial compressive strength, are determined using a universal testing machine. This equipment is capable of applying loads of up to 500 KN and incorporates servo control features, enhancing the testing procedure's ease and relevance. Specifically designed for uniaxial compression strength testing, the machine allows for adjustable-rate loading to accommodate experimental requirements.

Tables 4 and 5 present individual and average values of uniaxial compressive strength for Grade III and Grade IV tropically weathered limestones. Notably, the results indicate a decrease in the average uniaxial compressive strength of limestone as the weathering grade increases. The estimated strength of limestone experiences a reduction of 3.5% as weathering grades progress from Grade III to Grade IV. Based on the results obtained in Table 4.3, the result obtained for UPV test for all cored samples are recorded in us which then converted to km/s.

Table 4. The results of UCS test on each cored samples (GRADE III).

Sample	Grade	Diameter, D (mm)	Length, L=2D (mm)	Weight (g)	UCS (MPa)	Average UCS (MPa)
1	III	55.0	110.0	554.0	40.16	
2	III	55.0	110.0	700.4	55.34	
3	III	55.0	110.0	778.8	49.68	
4	III	55.0	110.0	530.5	60.02	
5	III	55.0	110.0	778.8	64.81	
6	III	55.0	110.0	548.8	47.06	49.558
7	III	55.0	110.0	773.6	35.67	
8	III	55.0	110.0	601.1	39.97	
9	III	55.0	110.0	614.2	57.11	
10	III	55.0	110.0	527.9	45.67	

Table 5. The results of UCS test on each cored samples (Grade IV).

Sample	Grade	Diameter, D (mm)	Length, L=2D (mm)	Weight (g)	UCS (MPa)	Average UCS (MPa)
1	IV	55.0	110.0	745.8	48.28	
2	IV	55.0	110.0	749.6	45.69	
3	IV	55.0	110.0	729.6	44.89	
4	IV	55.0	110.0	731.9	49.38	
5	IV	55.0	110.0	751.9	65.19	
6	IV	55.0	110.0	641.9	30.59	47.838
7	IV	55.0	110.0	639.0	52.53	
8	IV	55.0	110.0	616.6	39.05	
9	IV	55.0	110.0	680.9	69.11	
10	IV	55.0	110.0	662.7	33.36	

4.4 Relation Between UPV Testing and Mechanical Properties of Weathered Limestone

Utilizing the values obtained from UPV and UCS tests, the correlation between UPV tests and the mechanical properties of weathered limestone samples is now explored [8]. To illustrate the relationship between UPV and UCS, a regression analysis is conducted. By plotting velocity (km/s) against uniaxial compressive strength (MPa) and determining the equation of the best-fit line along with the correlation coefficient (R^2), insights into whether UPV test parameters can effectively determine the uniaxial compressive strength of the samples are gained [9].

In this study, the results of UPV test values and UCS test values, sorted by Grade III and Grade IV, are presented in Tables 6 and 7, respectively. Figure 3, Figure 4, and Figure 4.5 depict the linear correlation between UPV values and uniaxial compressive strength through scatter graphs. This analysis aims to assess the capability of UPV test parameters in predicting the uniaxial compressive strength of the samples.

Table 6. UPV and UCS test values (Grade III).

Sample	Grade	P-Wave velocity, v (km/s)	Uniaxial Compressive Strength, UCS (MPa)
1	III	5.067	40.16
2	III	5.000	55.34
3	III	5.278	49.68
4	III	5.270	60.02
5	III	5.063	64.81
6	III	5.001	47.06

7	III	5.169	35.67
8	III	5.001	39.97
9	III	4.964	57.11
10	III	5.110	45.67

Table 7. UPV and UCS test values (Grade IV).

Sample	Grade	P-Wave velocity, v (km/s)	Uniaxial Compressive Strength, UCS (MPa)
1	III	5.584	48.28
2	III	5.500	45.69
3	III	5.419	44.89
4	III	5.366	49.38
5	III	4.933	65.19
6	III	5.556	30.59
7	III	6.667	52.53
8	III	6.358	39.05
9	III	6.044	69.11
10	III	5.882	33.36

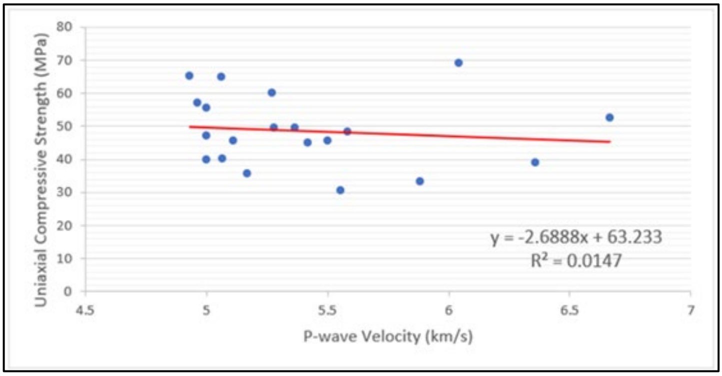

Fig. 4. Correlation between uniaxial compressive strength and pulse velocity of weathered limestone.

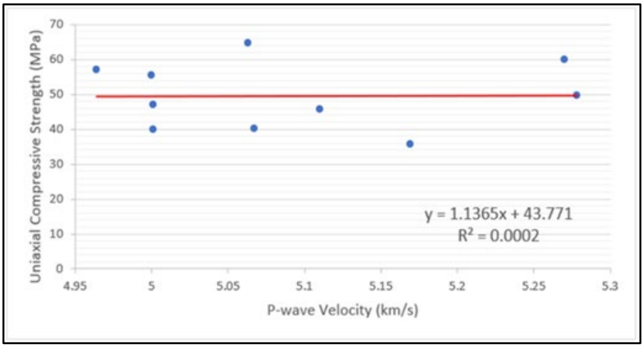

Fig. 5. Correlations between Uniaxial Compressive Strength and Pulse Velocity of Weathered Limestone (Grade III only).

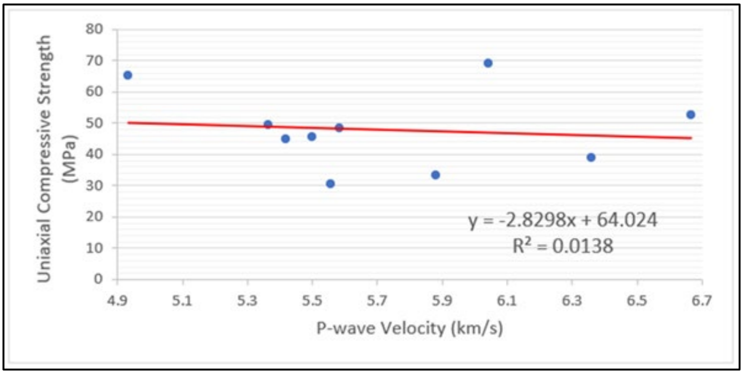

Fig. 6. Correlation between uniaxial compressive strength and pulse velocity of weathered limestone (Grade IV only)

In figure 4, a linear correlation between uniaxial compressive strength and ultrasonic pulse velocity is depicted, yielding a correlation coefficient (R^2) of 0.0147. The scattered values indicate a weak relationship between these two tests, suggesting that ultrasonic pulse velocity cannot be reliably considered a definitive method for predicting the uniaxial compressive strength of weathered limestone due to the observed weak association.

Moving to Figure 5, there is almost no correlation between the two tests, particularly for Grade III tropically weathered limestone, with a correlation coefficient of $R^2 = 0.0002$. This lack of correlation may be attributed to the low-grade weathered limestone, which exhibits random scatter values likely influenced by increased porosity. This porosity can directly impact the uneven p-wave velocity and uniaxial compressive strength, resulting in a wide range of outcomes [10].

Figure 6, on the other hand, reveals a slight but weak correlation between the two tests, specifically for Grade IV tropically weathered limestone, with a correlation coefficient of $R^2 = 0.0138$. Higher-grade weathered limestone samples exhibit less random scatter compared to Grade III samples.

Despite some disparities between the findings of this study and previous research, it is essential to acknowledge that the types of rocks used and the testing procedures employed contribute to the variability in outcomes. Numerous studies have demonstrated a strong connection between non-destructive tests (NDTs) and rock mechanical characteristics, emphasizing the complexity of the relationship [11].

5.0 Conclusion & Recommendation

To summarize, the study effectively accomplished its goals, which were to collect Ultrasonic Pulse Velocity (UPV) data for weathered limestone using non-destructive testing (NDT), determine engineering properties and strength through Rebound Hammer and Uniaxial Compressive Strength tests, and investigate the relationship between NDT and engineering properties. The data obtained, provided in tabular and graphical formats, clearly illustrates the achievement of these aims.

However, the correlation study revealed an unexpected finding: there is a weak connection between the UPV test parameters and the findings of the Uniaxial Compressive Strength (UCS) test. Hence, it was deduced that non-destructive testing (NDT), particularly ultrasonic pulse velocity (UPV) testing, may not be dependable in forecasting the engineering characteristics of worn limestone. Preliminary forecasts made during the analysis of the site, which involved a straightforward and economical evaluation, were considered to be more reliable in comparison to non-destructive testing (NDT) projections. The result highlights the necessity for further comprehensive and meticulous investigation to tackle this constraint.

In order to improve the quality of future research, a number of recommendations are suggested. Firstly, it is recommended to obtain improved equipment, particularly for the Universal Testing Machine (UTM), in order to collect additional data, such as strain, for theproduction of stress-strain curve results. It is advisable to carefully arrange the collection of samples according to a timetable in order to minimize deficiencies and assure precise data by enabling comparisons between samples. Furthermore, it is imperative to rectify any equipment shortcomings in UPV testing, such as the utilization of faulty laboratory apparatus. The recommendation is to utilize conventional equipment in order to adhere to established practices in the field of geology, so minimizing any inconsistencies in variables such as frequency and gain that may affect the accuracy of the data.

Acknowledgement. This publication expresses appreciation for the backing received from the Malaysian Government through the Geran Penyelidikan Khas UiTM at the Rock Mechanics Laboratory UiTM. The authors are thankful for the invaluable contributions and support provided by final year students, laboratory staff, and technicians who played a crucial role in conducting this research.

Conflict of Interest. The authors have no competing interests to declare that are relevant to the content of this article.

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