Utilizing Wave Propagation to Correlate P-Waves Velocity with Engineering Characteristics of Tropical Weathered Limestone in Batu Caves, Selangor

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Abstract. Non-Destructive Testing (NDT) was used to assess the link between P-wave velocity and engineering parameters in weathered limestone near Batu Caves, Selangor. This study specifically investigated the relationship between ultrasonic pulse velocity (UPV) and rock uniaxial compressive strength, utilizing Rebound Number and Uniaxial Compressive Strength (UCS) as quantitative measures. Samples, categorized as Grade II to Grade IV tropical weathered limestone, underwent X-ray fluorescence (XRF) analysis for elemental composition. Results showed varying correlations, with Grade II limestone exhibiting a weak relationship (R2 = 0.048), while Grade III and IV displayed stronger correlations (R2 = 0.7777 and 0.9347, respectively).

Keywords: P-Waves Velocity, Ultrasonic Pulse Velocity (UPV), Uniaxial Compressive Strength (UCS), X-ray Fluorescence (XRF).

1.0 Introduction

Various research endeavors employ an extensive range of non-destructive techniques to probe into the quantitative behavior and performance of materials. Seismic-based methods, notably sensitive to geo-material physical properties, show relatively low sensitivity to geo-material chemistry and fluids. Seismic waves convey energy through the vibrational movement of soil particles in diverse directions. In the case of P-waves, particles vibrate parallel to wave propagation, while S-waves exhibit perpendicular vibration [1]. This study focuses on examining the P-wave velocities of tropical limestone in correlation with its engineering properties. During seismic surveys, P-wave speed is theoretically derived, with P-waves, or Primary waves, typically dominating readings before the onset of S-waves (Secondary). Malaysia's tropical climate makes limestone subjected to weathering a fitting specimen for testing. The investigation aims to establish correlations between non-destructive parameters,

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specifically P-wave velocity, and the engineering characteristics of limestone samples, a rock known for challenges in high-water content and weathered conditions.

2.0 Literature Review

Limestone stands out for its aesthetic appeal and serves as a crucial raw material in the cement industry. A successful integration of limestone in cement production has the potential to reduce manufacturing costs. Cement, a vital component in construction, especially for reinforced concrete, is utilized extensively in the building trades. Major cement types, including Ordinary Portland Cement (OPC) and Pozzolanic Portland Cement (PPC), rely on limestone. Despite eventual corrosion, limestone exhibits remarkable durability, ensuring the stability of constructed buildings.

This study employs diverse methodologies to measure and ensure the accuracy of relevant parameters. Various factors are assessed based on the nature of the study. Measurements such as Standard Penetration Test (SPT) N-Values, friction angle, velocity index, and density, as utilized in Bery and Saad's [2] research, provide valuable insights. Altindag [3] emphasizes the measurement of density, porosity, grain size, and Uniaxial Compressive Strength (UCS). Drawing from past data, a majority of these studies involve both laboratory and field testing. Non-Destructive Testing (NDT) is employed to ensure the uniqueness and accuracy of results. The diverse array of naturally occurring rocks, including granites and limestones, finds extensive application in architecture and geotechnical engineering.

3.0 Methodology

3.1 Study Area

Conducted within the rockfall-prone area of Batu Caves, the study focuses on a limestone region, as illustrated in Figure 1 on the geological map. Rock samples ranging from Grades II to IV were identified, and in-situ tests were undertaken to assess the weathering grade. The Rebound Hammer Test was employed to ascertain the extent of weathering.

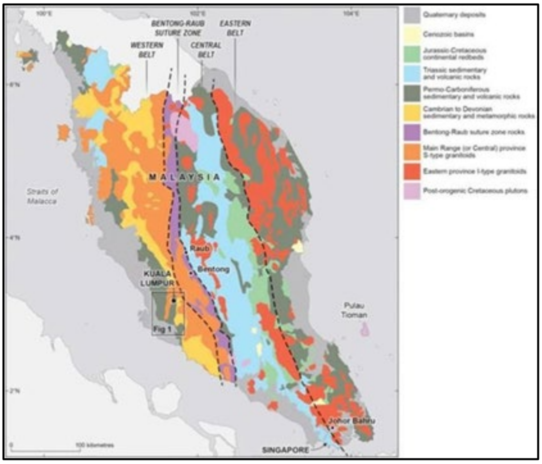


Fig. 1. Geological map of study area at Batu Cavs, Kuala Lumpur.

3.2 Preparations of Samples

Tropical weathering introduces diverse grades to limestone, influenced by local climate and geological factors. The rock is susceptible to significant weathering and alteration, leading to the formation of a thick, lateritic soil layer. Criteria for distinguishing weathering grades, such as appearance, mineralogy, and mechanical properties, may vary among studies. Figure 2 displays block samples used for rock testing.

Fig. 2. Limestone samples for rock testing

All samples for this study were gathered in Peninsular Malaysia at Batu Caves, Selangor, and categorized into Grades I to IV. Thirty cylindrical cored samples, ranging from Fresh Rock (Grade I) to Weathered Rock (Grade IV), were utilized, maintaining a length-to-diameter ratio of 1:2. Each grade is characterized by unique color and texture descriptions based on grain size, as seen in Figure 2.

Fig. 3. Coring of limestone sample.

Limestone coring involves extracting cylinder-shaped rock samples through drilling or cutting, a method employed for analysis to understand the physical and chemical characteristics. Geologists analyze core samples to glean insights into the rock's porosity, permeability, strength, and mineralogy, facilitating its potential engineering applications. Trimming of limestone cylinder samples adheres to ISRM specifications, ensuring dimensions of at least 38mm in diameter and 70mm in length, with a smooth, parallel, and perpendicular surface. Trimming details are presented in Figure 4, with the finalized product illustrated in Figure 5.

Fig. 4. Process of cutting cored limestone sample.

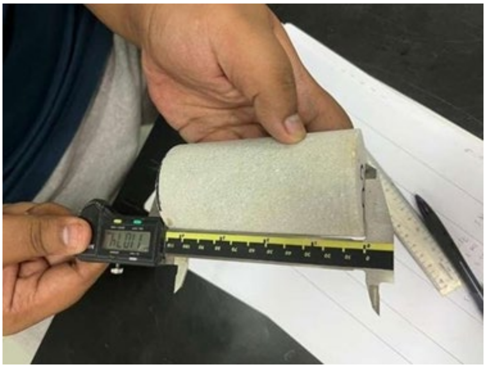


Fig. 5. Cylindrical sample is measured based on ISRM recommendation.

3.3 Uniaxial Compressive Strength (UCS) Test

Research indicates that reliable estimates of the uniaxial compressive strengths of rocks can be derived from transmitted sonic wave velocities [4]. This section employs the Uniaxial Compressive Test to assess the mechanical properties of the specimen. External loads are applied using a Universal Testing Machine (UTM-500). This method was chosen based on the availability of laboratory equipment capable of sustaining loads up to a maximum of 500 MPa. The Uniaxial Compressive Strength test follows the standard method outlined in the ISRM Suggested Method on Uniaxial Compressive Strength and Deformability of Rock Materials [5], as depicted in Figure 5. The results, specifically the maximum peak strength of each specimen, will be observed and analyzed.

3.4 Rebound Hammer Test

The Rebound Hammer test serves as a non-destructive technique to assess the compressive strength of a rock sample. When the plunger of the rebound hammer makes contact with the rock's surface, it causes a spring-controlled mass with constant energy to strike and rebound. The objective of the Rebound Hammer test is to establish a correlation between the rebound index and compressive strength, thereby determining the specimen's compressive strength. The rebound hardness value obtained from the Schmidt Hammer can provide a preliminary indication of the rock sample's weathering grades [6]. Conducted ten times per rock, the test results in an average rebound number for analysis.

3.5 Ultrasonic Pulse Velocity Test (UPV)

The Portable Ultrasonic Non-Destructive Digital Indicating Tester (PUNDIT) is a widely utilized technique for assessing the mechanical properties of rocks. Utilizing PUNDIT, the Ultrasonic Pulse Velocity (UPV) is determined by measuring the time, in microseconds, needed for an ultrasonic pulse to travel a known distance of rock core (path length, in millimeters) from a transmitter to a receiver. The transmission method is influenced by the surface accessibility of concrete elements and the characteristic being tested. Each sample undergoes three separate measurements, with the average value subsequently calculated. Alignment of each transducer with its neighboring end along the specimen is essential, as illustrated in Figure 5. The data, initially obtained in microseconds, is then converted to meters per second to derive the velocity (Vp).

3.6 X-Ray Fluorescence Test (XRF)

Non-Destructive Testing (NDT) can assess the chemical composition of a sample. For acceptance of data, the sample needs exposure to the XRF instrument for a duration of sixty seconds. Results are categorized based on their chemical composition. XRF analysis is performed on each rock sample to ascertain its engineering properties, providing the percentages of individual chemical compounds. Comparable to X-rays, XRF allows the non-destructive examination of solid samples. The testing procedure for limestone samples utilizing XRF is illustrated in Figure 6.

3.7 Regression Analysis

Utilizing regression analysis, researchers have harnessed a potent tool to explore the correlation between diverse properties of limestone samples and their physical characteristics. In a study conducted by Singh et al. [7], regression analysis was employed to investigate how the chemical composition, mineralogy, and texture of a limestone sample relate to its compressive strength, porosity, and permeability. To ascertain the R^2 value in a regression analysis for a rock sample, the initial step involves performing a regression analysis using an appropriate technique (e.g., linear regression) to model the connection between the rock sample's properties (mineralogy, chemistry, and texture) and a specific dependent variable of interest (such as strength, porosity, or permeability). R^2 serves as an indicator to assess the model fit for a set of quantitative dependent variables and their relationship to the dependent variable. The determination of an acceptable R^2 value is crucial for evaluating the adequacy and efficiency of the regression model. An ideal R^2 statistic should be dimensionless, possess well-defined values within a range indicating a perfect fit to a lack of fit ($0 \leq R2 \leq 1$), and be applicable to models with both random and non-random variables. Once the regression model is established, the R^2 value is employed to gauge the model's goodness of fit. A R^2 value close to 1 suggests a well-fitted model, while a value near 0 indicates a poor fit to the data.

4.0 Findings

Following the cutting and trimming phase of sample preparation, the samples were measured for weight, diameter, and height, and the volume and density parameters were calculated to determine the physical properties. Table 1 depicts the physical property information in its entirety. In addition, Table 2 contains the results of the Rebound Hammer test, which is used to determine the weathering grade.

Table 1. Results of physical properties of limestone sample tested.

No. of sample	Grade	Volume (m3)	Weight (kg)	Density (kg/m3)	No. of sample	Grade	Volume (m3)	Weight (kg)	Density (kg/m3)
1	II	0.000141	0.75	5352.484	16	III	0.000139	0.74	5317.885
2	II	0.000142	0.76	5339.07	17	III	0.000139	0.74	5331.218
3	II	0.000144	0.74	5152.651	18	III	0.000136	0.72	5309.487
4	II	0.000136	0.79	5773.869	19	III	0.000137	0.77	5637.513
5	II	0.000139	0.72	5206.991	20	III	0.000135	0.76	5585.927
6	II	0.000137	0.78	5690.791	21	III	0.000138	0.74	5382.04
7	II	0.000139	0.80	5743.847	22	III	0.000133	0.72	5375.291
8	II	0.000141	0.78	5565.946	23	III	0.000133	0.71	5382.725
9	II	0.000135	0.77	5751.25	24	III	0.000138	0.77	5572.9
10	III	0.000133	0.74	5572.046	25	IV	0.000136	0.71	5236.569
11	III	0.000135	0.72	5356.726	26	IV	0.000142	0.75	5257.249
12	III	0.000138	0.78	5646.843	27	IV	0.000130	0.73	5565.415
13	III	0.000139	0.74	5315.323	28	IV	0.000136	0.73	5351.008
14	III	0.000131	0.76	5775.704	29	IV	0.000136	0.74	5430.194
15	III	0.000133	0.72	5417.542	30	IV	0.000139	0.75	5397.648

Table 2. Results of rebound Hammer test.

No. of samples	Average strength (MPa)	Grade	No. of samples	Average strength (MPa)	Grade	No. of samples	Average strength (MPa)	Grade
9	20.8	IV	1	35	III	23	41	II
10	26.2	IV	2	33	III	25	41	II
13	25.8	IV	3	36.8	III	29	40.8	II
15	22.9	IV	4	39.8	III	32	43.6	II
19	29.2	IV	5	39.2	III	35	42.2	II

21	26.2	IV	6	38.4	III	36	43.4	II
27	29.4	IV	7	34.3	III	37	43.8	II
			8	34.3	III			
			11	31.4	III			
			12	33	III			
			14	37.6	III			
			16	31	III			
			17	36.6	III			
			18	32.8	III			
			20	30	III			
			22	39.6	III			
			24	30.4	III			
			26	32.4	III			
			28	38.6	III			
			30	30	III			
			31	36.8	III			
			33	38	III			
			34	39.8	III			

4.1 Uniaxial Compressive Strength (UCS) Test and Ultrasonic Pulse Velocity (UPV) Test

In a wide number of engineering applications, the uniaxial compressive strength of rocks is one of the mechanical properties of rocks that is applied the most frequently and is one of the most important. The availability of core samples of a high quality is required to calculate the UCS, even though this is not always achievable due to the presence of rocks that are fragile, fractured, and foliated. Figure 6 depicts the overall results of Uniaxial Compressive Strength (UCS) Test in this study.

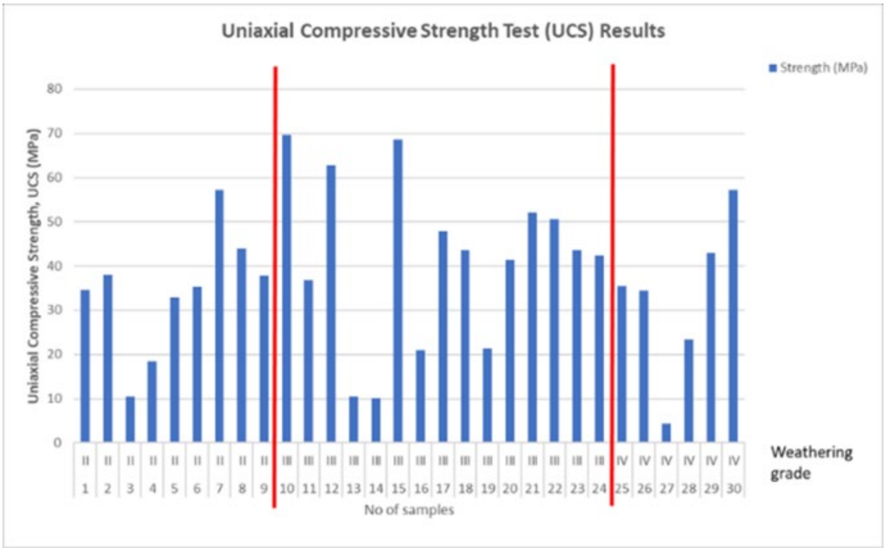


Fig. 6. Uniaxial Compressive Strength (UCS) test results.

In this section, the UPV data obtained in microsecond and need to be convert to velocity (Vp) in m/s as shown in Table 3 where descriptive statistics was shown. Only then it can be correlate with another data to determine the best deduction. In this test, the Vp can obtained by dividing reading in microsecond with length. Vp is described as P-Wave velocity where the objective of the study can be achieved here. Lower reading of UPV test give higher P-Wave velocity reading with the formula of Vp equals to Length over Time. Figure 7 indicates the results of Ultrasonic Pulse Velocity (UPV) Test for the overall samples tested in this study. Table 3 shows the descriptive data of Uniaxial Compressive Strength (UCS) and Ultrasonic Pulse Velocity Test (UPV) applied on the rock samples.

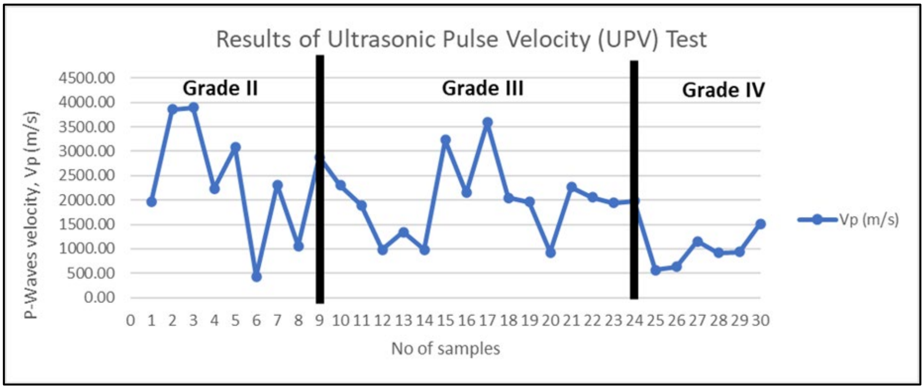


Fig. 7. Results of Ultrasonic Pulse Velocity (UPV) test.

Table 3. Descriptive statistics of Uniaxial Compressive Strength (UCS) and Ultrasonic Pulse Velocity Test (UPV).

Uniaxial Compressive Strength (UCS)		Ultrasonic Pulse Velocity (UPV) Test
Mean	37.5945	1902.784
Standard Error	3.13103877	176.9086
Median	37.8835	1959.0792
Mode	#N/A	#N/A
Standard Deviation	17.1494056	968.96832
Sample Variance	294.102114	938899.6
Kurtosis	-0.4205919	-0.458367
Skewness	-0.114673	0.4900795
Range	65.248	3457.8036
Minimum	4.378	434.19643
Maximum	69.626	3892
Sum	1127.835	57083.521
Count	30	30

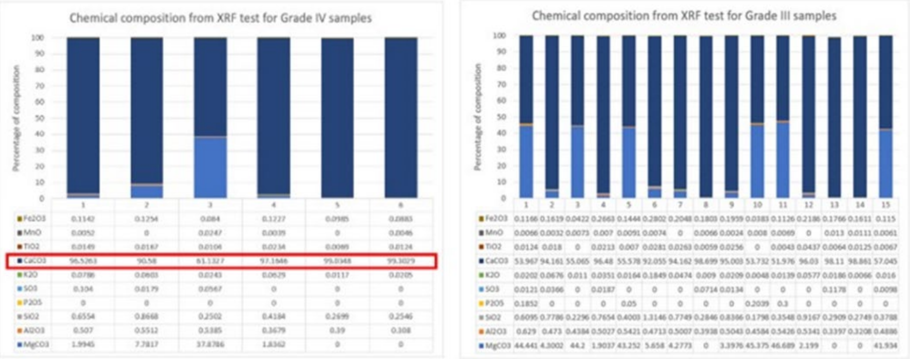
4.2 X-Ray Fluorescence (XRF) Test

The XRF data would be presented and, in a table, according by grade. Each grade would be differentiated by chemical composition. X-ray fluorescence (XRF) is a commonly used analytical technique for determining the elemental composition of solid samples, including limestone. The principle of XRF is based on the excitation of the sample by X-rays, which leads to the emission of secondary X-rays. These secondary X-rays are characteristic of the elements presents in the sample and can be used to identify and quantify them. Table 4 shows the chemical composition in percentage of Grade II Weathered Rock on Sample number 9. Based on the Grade II weathered rock, the highest chemical percentage is $CaCO_3$ (Calcium Carbonate) with 94.0049 %. It can also be deduced that this sample is an almost pure calcium carbonate. The chemical composition of the overall samples can be observed in Figure 8. Figure 4.3(a) indicates chemical composition for Grade IV samples, Figure 4.3(b) indicates chemical composition for Grade III samples while Figure 4.3(c) indicates chemical composition for Grade II samples respectively.

Table 4. Sample number 9 result from XRF testing.

Rock Type	Grade 2 Weathered Limestone (No. of sample = 9)
Elements	Chemical Composition (%)
$MgCO_3$	4.2612
$AI2O_3$	0.5446
SiO_2	0.9591
$P2O_5$	<LOD
SO_3	<LOD

K2O	<LOD
$CaCO_3$	94.0049
TiO_2	0.0258
MnO	0.0039
Fe_2O_3	0.1956

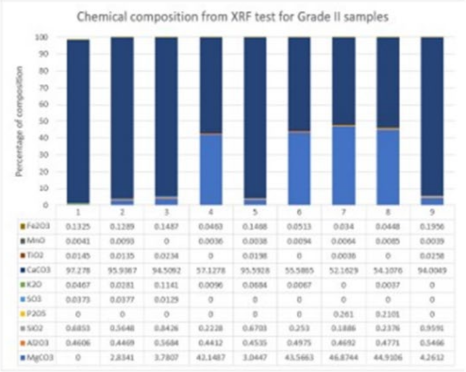


	1	2	3	4	5	6
■ Fe2O3	0.1142	0.1254	0.084	0.1227	0.0985	0.0883
■ MnO	0.0052	0	0.0247	0.0039	0	0.0046
■ TiO2	0.0149	0.0167	0.0106	0.0234	0.0089	0.0124
■ CaCO3	96.5263	90.58	61.1327	97.1646	99.0348	99.3029
■ K2O	0.0786	0.0603	0.0243	0.0629	0.0117	0.0205
■ SO3	0.104	0.0179	0.0567	0	0	0
■ P2O5	0	0	0	0	0	0
■ SiO2	0.6554	0.8668	0.2502	0.4184	0.2699	0.2546
■ Al2O3	0.507	0.5512	0.5385	0.3679	0.39	0.308
■ MgCO3	1.9945	7.7817	37.8786	1.8362	0	0

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
■ Fe2O3	0.1166	0.1619	0.0422	0.2663	0.1444	0.2802	0.2048	0.1803	0.1959	0.0383	0.1126	0.2186	0.1766	0.1611	0.115
■ MnO	0.0066	0.0032	0.0073	0.007	0.0091	0.0074	0	0.0066	0.0024	0.008	0.0069	0	0.013	0.0111	0.0061
■ TiO2	0.0124	0.018	0	0.0213	0.007	0.0281	0.0263	0.0059	0.0256	0	0.0043	0.0437	0.0064	0.0125	0.0067
■ CaCO3	53.967	94.161	55.065	96.48	55.578	92.055	94.162	98.699	95.003	53.732	51.976	96.03	98.11	98.861	57.045
■ K2O	0.0202	0.0676	0.011	0.0351	0.0164	0.1849	0.0474	0.009	0.0209	0.0048	0.0139	0.0577	0.0186	0.0066	0.016
■ SO3	0.0121	0.0366	0	0.0187	0	0	0	0.0714	0.0134	0	0	0	0.1178	0	0.0098
■ P2O5	0.1852	0	0	0	0.05	0	0	0	0	0.2039	0.3	0	0	0	0
■ SiO2	0.6095	0.7786	0.2296	0.7654	0.4003	1.3146	0.7749	0.2846	0.8366	0.1798	0.3548	0.9167	0.2909	0.2749	0.3788
■ Al2O3	0.629	0.473	0.4384	0.5027	0.5421	0.4713	0.5007	0.3938	0.5043	0.4584	0.5426	0.5341	0.3397	0.3208	0.4886
■ MgCO3	44.441	4.3002	44.2	1.9037	43.252	5.658	4.2773	0	3.3976	45.375	46.689	2.199	0	0	41.934

Figure 4.3(a): Chemical composition from XRF test for Grade IV samples

Figure 4.3(b): Chemical composition from XRF test for Grade III samples



	1	2	3	4	5	6	7	8	9
■ Fe2O3	0.1325	0.1289	0.1487	0.0463	0.1468	0.0513	0.034	0.0448	0.1956
■ MnO	0.0041	0.0093	0	0.0036	0.0038	0.0094	0.0064	0.0085	0.0039
■ TiO2	0.0145	0.0135	0.0234	0	0.0198	0	0.0036	0	0.0258
■ CaCO3	97.278	95.9367	94.5092	57.1278	95.5928	55.5865	52.1629	54.1076	94.0049
■ K2O	0.0467	0.0281	0.1141	0.0096	0.0684	0.0067	0	0.0037	0
■ SO3	0.0373	0.0377	0.0129	0	0	0	0	0	0
■ P2O5	0	0	0	0	0	0	0.261	0.2101	0
■ SiO2	0.6853	0.5648	0.8426	0.2228	0.6703	0.253	0.1886	0.2376	0.9591
■ Al2O3	0.4606	0.4469	0.5684	0.4412	0.4535	0.4975	0.4692	0.4771	0.5466
■ MgCO3	0	2.8341	3.7807	42.1487	3.0447	43.5663	46.8744	44.9106	4.2612

Figure 4.3 (c): Chemical composition from XRF test for Grade II samples

Fig. 8. Chemical composition from XRF test of the overall samples.

5.0 Discussion

The focus of this research has been on three main goals. The Non-Destructive Test (NDT) is used to categories the material by engineering properties and quality. The weathering grade of each rock can be determined using the Rebound Hammer test. The study will also use NDT to determine P-wave velocity and other engineering properties of tropical limestone. According to the methodology, P-wave velocity can be induced by the PUNDIT test, which is classified as NDT. X-Ray Fluorescence (XRF), UPV, and PUNDIT were classified as NDT because they preserved the original state of a cylindrical sample without destroying it.

Consequently, the research will look into the relationship between P-wave velocity and engineering properties of tropical limestone obtained through non-destructive and laboratory testing methods. The Uniaxial Compressive Strength test is referred to as laboratory testing in this context. The correlation can be found by generating the graph shown in Figure 9. The data was analyzed by grade, and the highest Regression, R^2 was 0.9347, which corresponds to grade IV. The next highest R^2 was 0.7777 on a grade II rock sample. Regression Analysis is used to show the correlation between the parameters involved. The regression was applied to a scattered graph of UPV vs UCS with a trendline.

Chemical composition for every rock is different and this can be seen in Figure 6. It can be deduced that different composition in rock does affect other engineering properties as well as P-waves velocity. In general, it is known that the mechanical properties of rocks are closely related to their chemical and mineralogical compositions, XRF is a powerful tool to understand the correlation between these properties. The chemical composition of a rock can be used to predict its P-wave velocity and other engineering properties, making XRF an important tool in geology, geophysics, and engineering.

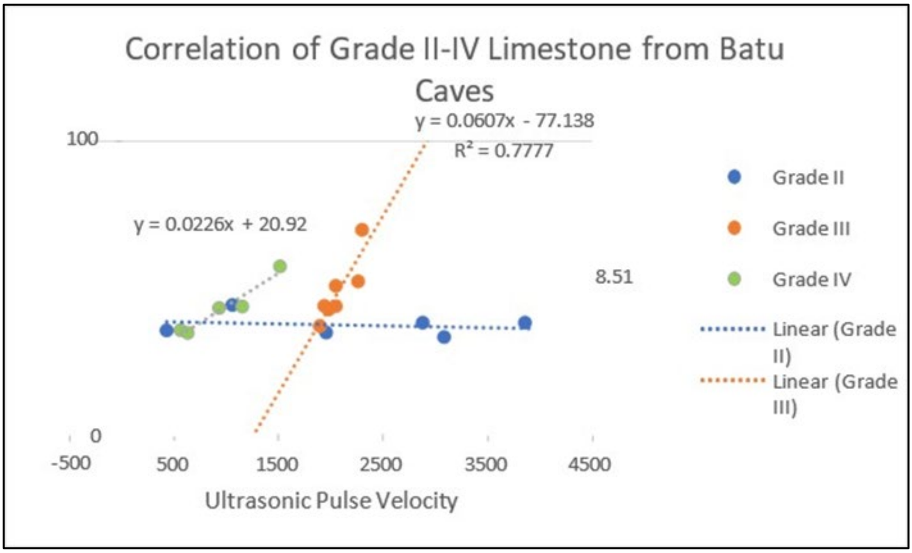


Fig. 9. Correlation of P-waves by UPV test based on classification group of Grade II, Grade III, and Grade IV limestone from Batu Caves.

6.0 Conclusion & Recommendation

The purpose of this research was, in part, to apply non-destructive testing techniques to tropical limestone in order to ascertain its P-waves velocity and other engineering properties in relation to its weathering grade. Using the formula Vp = L (Length) / T, P-waves can be measured and calculated with UPV Testing (Time). Through UPV Testing, P-waves can be measured and analyzed (Time). This research also explored and determined other engineering properties, such as Chemical Composition. This objective can be reached by using X- Ray Fluorescence (XRF) analysis. These tests were considered non-destructive because they had no effect on the samples.

In addition, the purpose of this research was to determine engineering properties and grade classification using Non-Destructive Test (NDT). This objective's non-destructive test is the Rebound Hammer Test. It was read 10 times and the average was calculated. Therefore, the obtained data are summarized in Table 2 and classified according to their weathering grade. Within Grades II through IV, a total of 30 samples were cored and categorized accordingly.

This study also aims to determine the relationship between the velocity of P-waves and the engineering properties of tropical limestone extracted from the Batu Caves using nondestructive and laboratory testing techniques. Since XRF and UPV tests were classified as NDT, Uniaxial Compressive Strength (UCS) tests were performed on each sample to determine its compressive strength. A scatter graph was created from the tabulated data as a whole. The scattered graph was then correlated, and the R value was calculated. The correlation was performed for each grade, with R2 values of 0.048, 0.7777, and 0.9347 for Grades II, III, and IV, respectively. Due to the fact that the Coefficient of Determination, R^2 of Grade II is low and far from the value of 1, it is reasonable to assume that there are errors or possible other factors affecting it. The equation for each regression is displayed in Figure 9. This study is significant because the correlation between Grades III and IV demonstrates a high degree of concordance, indicating a large number of numbers that are close to 1.

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