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# Evaluation on Weathering Degree of Limestone Artifacts Considering Water Absorption Characteristics

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***Abstract***

To realize the non-destructive detection of cultural relics, the limestone relics in Feilai Peak and Yue Temple area in Hangzhou, Chian were selected as inspection objects, and the relationship between the water absorption rate of limestone surface layer, ultrasonic longitudinal wave velocity and surface layer strength were investigated. The fitting model was established according to the variation characteristics among water absorption rate, ultrasonic longitudinal wave velocity, surface layer strength. The evaluation method of surface layer weathering level of limestone relics based on water absorption characteristics was also established based on the fitting model. Results show that the field test data of the superficial strength, longitudinal wave velocity and water absorption rate of limestone have an obvious negative correlation. The weathering grade evaluation method based on water absorption rate of rocks is derived from the field test data, and the rocks are classified into five grades: unweathered, slightly weathered, moderately weathered, strongly weathered and fully weathered. The corresponding water absorption rates range from 0-0.12%, 0.12-0.20%, 0.20-0.61%, 0.61-2.40% and >2.40%, respectively. The accuracy of the fitting results in the area around the seated statue of Luohan and the back of the Huangji tombstone are above 80%, so the weathering grade evaluation method is feasible. The weathering grade evaluation method is completely nondestructive and strictly conforms to the principle of minimum intervention. The conclusions obtained in this study can provide the reference for the subsequent conservation of limestone artifacts.

*Keywords:* Longitudinal wave velocity, Surface strength, Water absorption rate, Evaluation method

## 1. Introduction

Since the advantages of rock materials, especially the unique characteristics of good weather resistance and insensitivity to environmental changes, many of the early remains of human civilization that remain today were made of stone materials. Many of the early relics of human civilization left to this day were mainly made of stone, such as the cave temples and cliff statues in China. Most of these artifacts were in the open air, subject to temperature, humidity, atmosphere, wind, sunlight, acid rain erosion, and other natural weathering conditions. The body of the artifacts existed in varying degrees of surface deterioration. The surface weathering of these stone artifacts is the most common and the largest surface deterioration disease in terms of area [1-4].

There are many kinds of methods used to evaluate the weathering degree of stone relics. For example, judging the weathering degree of rocks according to their color, rock integrity, mineral composition, chemical composition, and hydrological properties, etc. [5-7]. However, most of these methods are qualitative rather than quantitative, which cannot obtain the accurate mechanical properties of rock surface and provide limited reference value for subsequent conservation work. Some scholars used rebound values, tensile strength, and chemical indices to quantitatively evaluate the weathering degree of engineering rocks [8-10]. However, the use of rebound and ultrasonic instruments for testing, although causing less impact, is not a completely nondestructive detection, rebound instrumentation will cause micro damage to the surface of the artifacts. Using ultrasonic instruments to accurately detect the wave velocity of stone artifacts will require coupling agent, and the coupling agent will cause pollution to the surface of stone artifacts. These micro letter damage and pollution to the cave temples, cliff statues and other stone artifacts caused by the damage should not be underestimated.

There are also many limestone cave temples and cliff statues in Zhejiang Province, China, which were mostly made of limestone and tuff. In view of this situation, this study used a completely nondestructive moisture meter to test the mechanical properties and water absorption characteristics of limestone artifacts in the field, relying on several stone heritage conservation projects. Based on this characteristic, the relationships among the water absorption rate of limestone surface layer, the longitudinal wave velocity and surface layer strength were investigated. The fitting model was established and an evaluation method of the surface weathering level of limestone artifacts based on water absorption characteristics was built based on this model. The final evaluation method can be more convenient, faster and completely non-destructive to determine the

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weathering degree of stone artifacts, and which can provide the reference for the subsequent conservation of artifacts.

## 2. State of the art

There are many studies on the variation characteristics of the various physical parameters of rocks, however, the relationships among the water absorption rate, strength and wave velocity during the weathering of rocks were studied little, and there is almost a gap in this aspect for limestone. Dagdelenler et al. developed a nonlinear model based on the physical and mechanical parameters of granites with different degrees of weathering, which could be used to evaluate the degree of weathering of granites [11]. Li et al. studied the effect of water content on the strength and deformation properties of siltstone and found that the strength and deformation parameters of siltstone were weakened to different degrees after water absorption, the strength of dry and saturated specimens varied regularly with the change of compaction pressure, and the relationships among them could be described by an exponential criterion. The link between rock strength and ultrasonic wave velocity was established [12]. Jiang et al. measured the mass, wave velocity and permeability of granite specimens from Maluangshan tunnel after high-temperature treatment, and they established a wave velocity-permeability model using the modified wave velocity porosity formula and Kozeny-Carman formula. The permeability at different temperatures and wave velocities could be obtained for a given wave velocity and corresponding permeability [13]. Bayram conducted freeze-thaw tests on nine limestone samples from different cold regions of Turkey and developed a statistical model to predict the percentage loss of uniaxial compressive strength for rocks deteriorated due to freeze-thaw cycles based on complete tests of impact strength, modulus of elasticity and water absorption values [14]. Qureshi & Towhata performed standard sliding durability tests on rock samples as well as artificial soft rocks with multiple cycles and also studied the strength and stiffness loss by reproducing mechanical weathering in the laboratory, and obtained the relationship between rock strength and S-wave velocity from the results of simulated weathering tests [15].

Many evaluation methods for the degree of rock weathering have been done, however, due to the preciousness of stone artifacts, these methods are not applicable to the weathering evaluation of stone artifacts. Phelipot-Mardele et al. conducted wear tests on fresh and artificially aged rocks and concluded that wear tests could accurately evaluate the degree of rock weathering [16]. Shi et al. studied the ratio of water absorption between weathered and fresh rock samples of sandstone and tuff as a way to quantitatively evaluate the weathering of rocks [17]. Hu et al. used the plagioclase solubility index as a new index to evaluate the weathering of granite [18]. Li et al. proposed a method to classify the weathering degree of granite based on slope characteristics by analyzing the coupling relationship between weathering degree and slope, in response to the problem that it was difficult to quickly classify the weathering degree of rocks by means of remote sensing technology [19]. Liu & Bai conducted a large number of experimental comparisons of various weathering degree rock formations and borehole core samples through experimental research, using rock field characteristics appearance observation, ultrasonic method and impact elastic wave method test methods, and they established an evaluation method containing the boundary of rock weathering degree division by impact elastic wave method [20]. Li et al. combined with the engineering geological conditions of a power plant, used wave velocity test, high-density resistivity method and geological radar test and other physical exploration methods to discern the overall distribution range of bedrock weathering degree and the distribution area of weak rock and soil layers, which truly and accurately reflected the degree of bedrock weathering [21]. Busthan et al. studied how to determine the landslide according to the geometry of slope, lithology and rock weathering grade, and hazard potential [22]. Deng et al. established a shear strength estimation model for tuffs under different weathering degrees through strength shear tests of rock samples with different weathering degrees to reveal the quantitative relationship between weathering degree and shear strength [23]. Gokceoglu et al. collected data on porosity, P-wave velocity and uniaxial compressive strength of granite and established a weathering degree prediction model for indirect determination of weathering degree of granite [24]. Arıkan et al. established a regression model by the pattern between porosity, indirect tensile strength, block punching strength and P-wave velocity for quantitative estimation of weathering grade of volcanic rocks [25]. Matsuzawa et al. established an evaluation based on the slump density of weathered rock formations to determine the weathering degree of rocks by geological survey, collapse site survey and detailed topographic analysis method [26].

There are also many scholars engaged in research targeting the evaluation methods of weathering degree of stone artifacts, although non-destructive detection methods are used, however, these evaluation methods are not completely nondestructive for reasons such as the coupling agent of ultrasonic detector can cause contamination to the surface of artifacts and rebound meter can cause minor damage to the surface of artifacts. Chen et al. proposed a method based on ultrasonic CT technology to method to assess the degree of weathering and stability of stone artifacts, applied to an ancient stone bridge in eastern China [27]. Ruedrich et al. evaluated the weathering of the Schlossbrücke marble statue in Berlin by ultrasonic measurements, and they found that some key parts of the statue had to be replaced [28]. Meng et al. developed a regression model for predicting the degree of weathering of stone artifacts based on terahertz (THz) spectra and ultrasonic wave velocities, which could determine the degree of weathering of large exposed stone artifacts [29].

In this study, a completely nondestructive, rapid, and low-cost moisture meter was used to conduct field tests on the mechanical properties and water absorption characteristics of limestone artifacts based on several stone artifact conservation projects, to investigate the relationships among the water absorption rate of limestone surface layers, the longitudinal wave velocity and surface layer strength, to establish a numerical fitting model and establish a weathering grade evaluation of limestone artifacts surface layers based on water absorption characteristics.

The rest of this study is organized as follows. Section 3 introduces the research methods and gives the test objects. Section 4 analyzes the field test results, the variation characteristics among the surface strength, longitudinal wave velocity, and water absorption rate of limestone. The evaluation method of surface weathering grade of limestone artifacts will be established and validated based on the water absorption characteristics of limestone, and finally, the conclusions are summarized in Section 5.

## 3. Methodology

Surface strength and ultrasonic wave velocity are the main indicators for evaluating the weathering degree of stony artifacts. Therefore, this study uses rebound meter, moisture meter and ultrasonic detector to select limestone artifacts from Feilai Peak and Yue Temple area in Hangzhou as the test objects, and to test the mechanical properties of limestone artifacts surface layer and water absorption performance. After the field test data being obtained, the relationships among the longitudinal wave velocity, intensity and water absorption rate of limestone relics with different weathering degrees were analyzed. According to the variation characteristics obtained from the field test data, a fitting model was established, and the fitting function that could more accurately reflect the relationship among the wave velocity, intensity and water absorption was obtained after fitting iterations. The weathering grade evaluation method based on the water absorption characteristics of limestone artifacts was established. The Fei Lai Feng area was tested and verified, and the results calculated from the field test data and the fitting model were compared to determine whether the weathering grade evaluation method was feasible according to the error size.

### 3.1 Detection method

#### 3.1.1 Surface strength testing

The HT-225A rebound meter was used for rock strength field sampling and testing. The product of the rebound value and the density of the rock is linearly related to the compressive strength of the rock, so as long as the rebound value and density are measured, the compressive strength of the rock can be estimated according to Fig. 1. The rebound value is taken as the average of the 16 values in a test area after removing the 3 maximum and minimum values.

#### 3.1.2 Surface water absorption detection

JC-50 moisture meter was used for rock surface moisture field testing. JC-50 moisture meter could get the water content of the rock surface by the size of the rock surface resistance, the surface absorption rate detected by the instrument in the surface refered to the range of no more than 1 cm. The field testing was divided into two times before and after sprinkling, the interval was about 10 min. The faster the moisture value increased before and after, it mean that the more loose the surface of the rock body, the higher the degree of weathering of the rock. The water content value of an area was obtained by averaging the 10 water content values after ten tests of the selected area. The average value of water content before and after sprinkling was subtracted to obtain the value of water absorption in the surface layer of the rock. In the field testing, the site temperature was between 20-30 ℃, the humidity was between 50-60%, and the weather was chosen to be cloudy as well as cloudy to avoid the influence of different temperature and humidity environment on the water absorption rate, and the same for other tests.

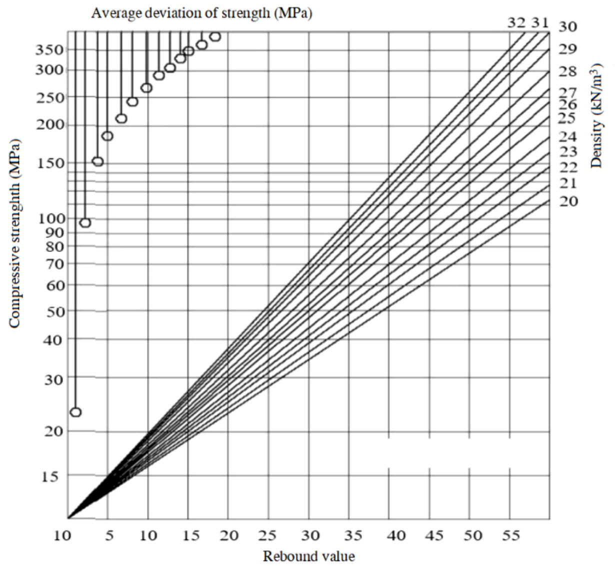



**Fig. 1.** Rock strength versus rebound value.

#### 3.1.3 Ultrasonic wave velocity detection

The method of determining the weathering degree of rocks based on ultrasonic wave velocity was already available in the Code for Geotechnical Investigation in China. Therefore, the weathering grade evaluation system of limestone artifacts established in this study correlated the water absorption rate with the longitudinal wave velocity to ensure the feasibility of the method.

Rock wave velocity detection adopted the RSM--SY7 ultrasonic detector, which fixed two probes to the rock surface to be tested with coupling agent at a certain distance, and measured the distance between the midpoints of the two transducers, and this value was the distance of the sound wave propagation in the rock. When the sonde was started, the time scale value corresponding to the first jump point of the waveform curve displayed on the fluorescent screen could be used as the time of arrival of the longitudinal wave, and the distance and time could be divided to obtain the wave speed value of the rock. In this test, the coupling agent was chosen to be butter. Considering that the coupling agent was not easy to remove, it would affect the surface of the artifact. Therefore, the coupling agent was chosen to be put into the film and then coupled to the rock surface to minimize the impact on the artifacts. Each area was detected three times with three different spacing of 50 mm, 100 mm and 150 mm using the flat measurement method, and the average value was taken as the longitudinal wave velocity value of the area.

### 3.2 Detection object

The test objects included the Li Gong Pagoda, Huang Ji tombstone, Yue Fei tomb in Yue Temple, Yue Temple stone statue life, and the material of the above stone relics were all limestone.

Fig. 2(a) is the Li Gong Pagoda, located at the entrance of Long Hong Cave in Fei Lai Peak of Lingyin, on the side of Chun Chong Ting, which is the place where Hui Li, the founder of Lingyin Temple, laid his bones. It was rebuilt in the eighth year of the Song Dynasty (975 AD) and destroyed in June of the fifteenth year of the Ming Dynasty (1587 AD) due to a flash flood, and was rebuilt in the eighteenth year of the monk Rutong. Fig. 2(b) shows the tombstone of Huang Ji, located in the middle of the tea field on the southeast side of the North Summit in Lingyin Scenic Area, which was erected in the 26th year of the Kangxi Emperor of the Qing Dynasty (1687). Fig. 2(c) is the tomb of Yue Fei, located at the west end of the tomb road. The tomb was reburied in the 32nd year of Shaoxing of the Southern Song Dynasty (1162) with rituals, and was rebuilt in the Republic of China with a concrete roof, which was destroyed in 1966. The present tomb was rebuilt in 1979 at the original site, restoring the original appearance of the historical sealing soil and planting grass. Fig. 2(d) shows stone elephants on both sides of the tomb path, north and south, in two pairs, from west to east, a pair of civil officials, a pair of warriors, a pair of military warriors, a pair of stone horses, a pair of stone sheep, and a pair of stone tigers. There are all relics of the Ming Dynasty.


(a) Li Gong Pagoda (b) Huang Ji tombstone

(c) Yue Fei tomb (d) Stone elephants

**Fig. 2.** Field test objects.

## 4. Results analysis and discussion

### 4.1 Analysis of surface layer strength and water absorption

Figs.3 and 4 show the test data of the surface strength and water absorption rate of the Polytechnic Tower and Huang Ji tombstone of Feilai Peak and the stone statue of Yue Temple Sheng and Yue Fei tomb. The test results of 35 areas of Feilai Peak and 15 areas of Yue Temple, a total of 50 areas. Figs. 5(a) and 5(b) are the testing point maps of Feilai Peak area, and Figs. 5(c) and 5(d) are the testing point maps of Yue Temple area.

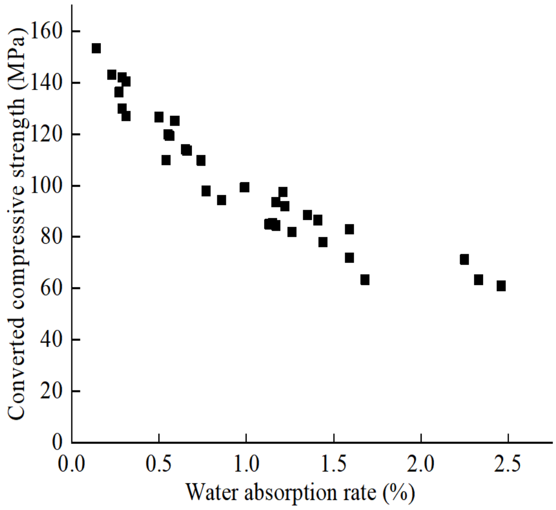



**Fig. 3.** Surface strength of cultural relics and water absorption rate relationship.

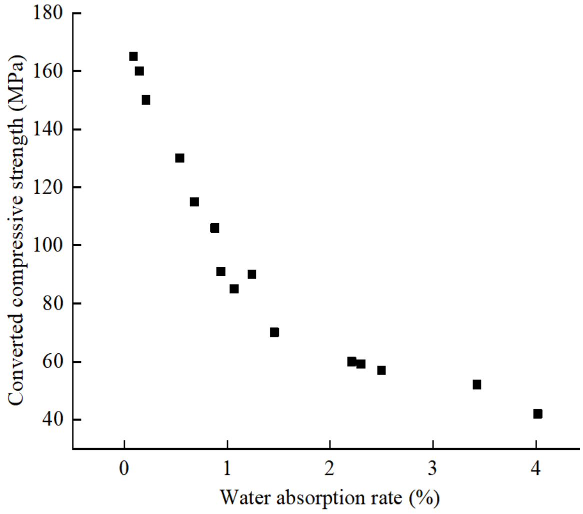
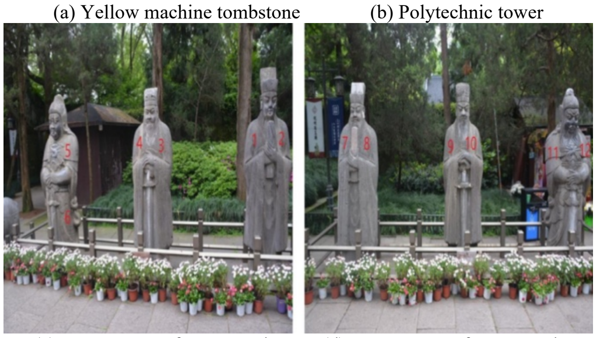



**Fig. 4.** Surface strength of cultural relics and water absorption rate relationship of Yue Temple.

(a) Yellow machine tombstone (b) Polytechnic tower



(c) Stone statue of Yue temple (d) Stone statue of Yue temple


(e) Yue Fei tomb of Yue temple

**Fig. 5.** On-site testing points.

After summing up the test data from the two areas, the change trend of the graph of limestone surface strength versus water absorption is obtained as Fig. 6, which is similar to the image of the function $y=1/x$. Establish the fitting function model $y=\frac{A}{x^B}+C$, the initial values of the fitting parameters A, B and C are taken as 1, and the fitting converges after 67 iterations by Levenber-Marquardt iterative algorithm to obtain the nonlinear fitting function Eq. (1). This method integrates the most rapid descent method and linearization method (Taylor series), which converges faster and reduces the computational effort. The coefficient of determination of the fit function $R^2$ = 0.952, the coefficient of determination can measure the effect of fitting the data, the closer $R^2$ is to 1, the effect of fitting is better.

$$y=\frac{122198}{x^{0.0002818}}-122104 \quad (1)$$

where, $x$ is the water absorption rate (%). $y$ is the converted compressive strength (MPa).

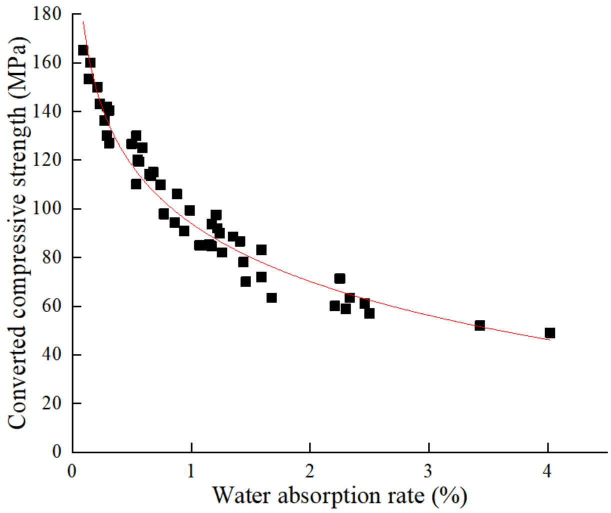



**Fig. 6.** The relationship between the strength of limestone surface layer and water absorption rate.

### 4.2 Analysis of ultrasonic wave velocity and water absorption

Figs. 7 and 8 show the detection data of ultrasonic wave velocity and water absorption rate of the Li Gong Pagoda of Feilai Peak, Huang Ji tombstone and Yue Temple stone statue of Sheng and Yue Fei tomb. The ultrasonic wave detection points are the same as the surface strength detection points.

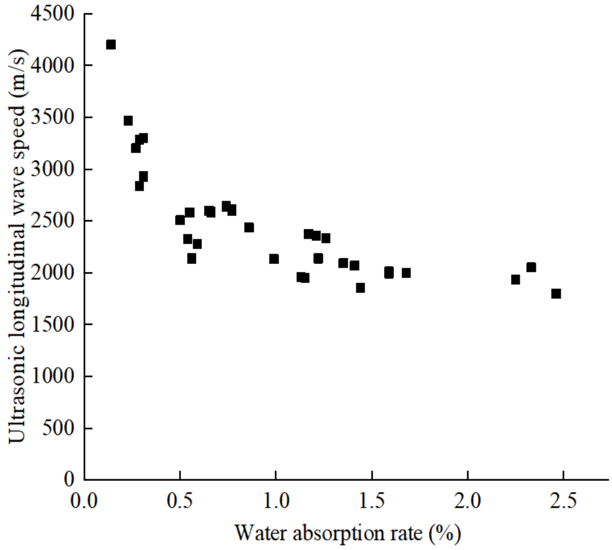



**Fig. 7.** Longitudinal wave velocity and water absorption rate of stone artifacts from Feilai Peak.

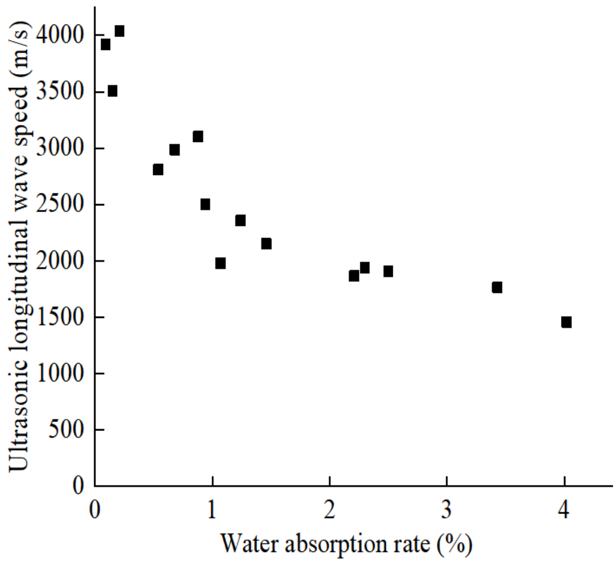



**Fig. 8.** Longitudinal wave velocity and water absorption rate of stone artifacts from Yue Temple.

The longitudinal wave velocity data were summarized to obtain the graph of the relationship between ultrasonic longitudinal wave velocity and water absorption in limestone in Fig. 9, which is similar to the image of the function $y=1/x$. The fitting function similar to Eq. (1) was established, and the fitting algorithm was the same as Eq. (1). After 26 iterations through the Levenber-Marquardt iterative algorithm, the nonlinear fitting function Eq. (2) was obtained, in which the coefficient of $R^2$ = 0.846.

$$V_p=\frac{2602.3}{x^{0.2273}}-285.1657 \quad (2)$$

where, $x$ is the absorption rate (%). $V_P$ is the longitudinal wave velocity in rock (m/s).

### 4.3 Evaluation method for the weathering level of limestone artifacts surface layer

#### 4.3.1 Surface layer strength-absorption rate evaluation

The group has completed a number of stone cultural relics conservation projects, such as Tongjun Mountain cliff carvings in Tonglu County, rock carvings in Shima Mountain in Rui'an City, Dasan Pagoda in Hangzhou City, Shaoxing Shiya Zen Temple, Hangzhou Tianlong City statue, Hangzhou Yanxia Cave statue and more than 10 other places.

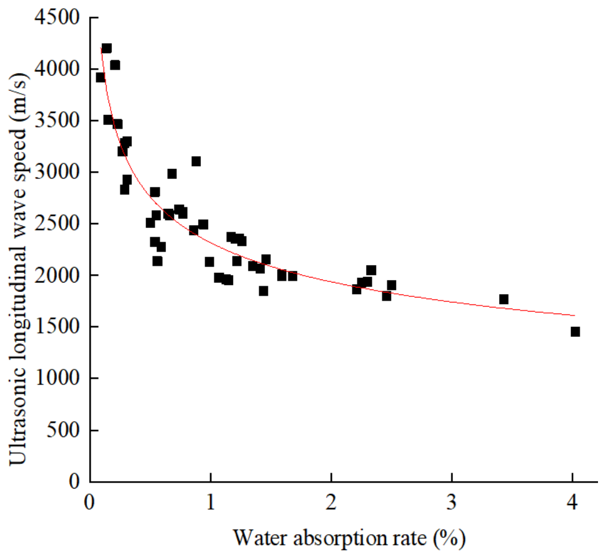



**Fig. 9.** Longitudinal wave velocity of limestone versus water absorption rate.

By testing the rebound values of these stone artifacts, collating them as well as analyzing them, and referring to the classification method of rock weathering based on ultrasonic wave velocity in the Code for Geotechnical Engineering Investigation in China, the evaluation method of weathering degree of limestone artifacts based on surface strength was established, when the ratio of surface strength of limestone artifacts to that of fresh limestone was 0.9-1.0, 0.8-0.9, 0.6-0.8, 0.4-0.6, and 0-0.4, respectively. Then the weathering degree is unweathered, slightly weathered, moderately weathered, strongly weathered,and fully weathered, respectively. The surface strength of fresh limestone is taken as the value of the limestone of the same material on the slope of Feilai Peak as Fig. 10, and the surface compressive strength of fresh limestone is 180 MPa obtained by rebound test after cutting off the weathering layer, and the range of water absorption rate corresponding to different weathering degrees can be obtained by the calculation of Eq. (1), as shown in Table 1.

#### 4.3.2 Longitudinal wave velocity and absorption rate evaluation

Referring to the classification method of rock weathering grade based on ultrasonic wave velocity in the Code for Geotechnical Investigation in China, the rocks are classified into five grades: unweathered, slightly weathered, moderately weathered, strongly weathered and fully weathered. The wave velocities of fresh limestone in Table 2 were obtained by selecting limestone of the same material on the slope of Feilai Peak after cutting away the weathered surface layer. The wave velocity ranges from 4167 m/s to 4762 m/s, and 4500 m/s is taken as the longitudinal wave velocity of the fresh limestone.

**Fig. 10.** Limestone rock sample.

**Table 1.** Evaluation method of weathering grade based on the strength of limestone surface layer.

| Weathering grade | Ratio of weathered rock surface strength to fresh rock surface strength | Corresponding strength range (MPa) | Corresponding limestone water absorption range (%) |
|---|---|---|---|
| Unweathered | 0.9-1.0 | 162-180 | 0-0.14 |
| Breeze-up | 0.8-0.9 | 144-162 | 0.14-0.23 |
| Moderately weathered | 0.6-0.8 | 108-144 | 0.23-0.67 |
| Strong weathering | 0.4-0.6 | 72-108 | 0.67-1.90 |
| Fully weathered | 0-0.4 | 0-72 | 1.90-100 |

According to the longitudinal wave velocity of fresh limestone and Eq. (2), the longitudinal wave velocity and the range of water absorption rate corresponding to different degrees of weathering limestone can be obtained, as shown in Table 2.

**Table 2.** Evaluation method of weathering degree based on longitudinal wave velocity of limestone.

| Weathering grade | Ratio of rock longitudinal wave velocity to fresh rock wave velocity | Corresponding wave speed range (m/s) | Corresponding limestone water absorption range (%) |
|---|---|---|---|
| Unweathered | 0.9-1 | 4050-4500 | 0-0.11 |
| Breeze-up | 0.8-0.9 | 3600-4050 | 0.11-0.17 |
| Moderately weathered | 0.6-0.8 | 2700-3600 | 0.17-0.55 |
| Strong weathering | 0.4-0.6 | 1800-2700 | 0.55-2.65 |
| Fully weathered | 0-0.4 | 0-1800 | 2.65-100 |

#### 4.3.3 Evaluation method of weathering grade of limestone artifacts surface layer based on water absorption characteristics

Combining the above two evaluation methods, it is found that the results obtained by the two evaluation methods are close in the four grades of unweathered, slightly weathered, moderately weathered, and strongly weathered, and the lower limit of the range of water absorption obtained by the longitudinal wave velocity-absorption rate evaluation method is much higher than that of the surface strength-absorption rate evaluation method in the case of total weathering. Considering that there are existing norms for relying on wave velocity to determine the weathering grade of rocks, the final evaluation method will be more inclined to the longitudinal wave velocity-absorption evaluation method, as shown in Table 3.

**Table 3.** Evaluation method of weathering degree based on water absorption rate of limestone surface layer.

| Weathering grade | Limestone surface water absorption range (%) |
|---|---|
| Unweathered | 0-0.12 |
| Breeze-up | 0.12-0.2 |
| Moderately weathered | 0.2-0.61 |
| Strong weathering | 0.61-2.4 |
| Fully weathered | 2.4-100 |

### 4.4 Validation of weathering grade evaluation system

The test object of Eq. (2) is the limestone in the area around the seated statue of Luohan in Feilai Peak (Fig. 11(a), next to the seated statue of Luohan). The test area of Eq. (1) is different from Eq. (2) because of the unevenness of some test areas, which is located at the back of the Huangji tombstone as well as the side (Fig. 11(b), back of Huangji tombstone). The test data of the area of the testimony of Eqs. (1) and (2) are shown in Table 4 and Table 5.

According to the field test data, it was found that the error between the limestone surface strength obtained from Eq. (1) and the strength obtained from the actual test was about 8.9%. The actual tested value is compared with the converted value by Eq. (1), although there is a small error, but the method is feasible.


(a) Type 2 (b) Type 1

**Fig. 11.** Corroboration testing points

**Table 4.** Eq. (1) corroborates the test results of the testing area.

| Points | Converted compressive strength (MPa) | Field test water absorption rate (%) | Eq. (1) obtained compressive strength (MPa) | Error (%) | Average error (%) |
|---|---|---|---|---|---|
| 1 | 91.8 | 0.73 | 104.8 | 12.44 | 8.44 |
| 2 | 132.6 | 0.26 | 140.4 | 5.53 | |
| 3 | 94.8 | 1.37 | 83.2 | 14.00 | |
| 4 | 88 | 1.72 | 75.3 | 16.83 | |
| 5 | 160 | 0.15 | 159.3 | 0.41 | |
| 6 | 123.6 | 0.55 | 114.6 | 7.86 | |
| 7 | 89.9 | 1.23 | 86.9 | 3.49 | |
| 8 | 113.7 | 0.81 | 101.3 | 12.29 | |
| 9 | 86.4 | 0.93 | 96.5 | 10.47 | |
| 10 | 93 | 1.06 | 92.0 | 1.09 | |

**Table 5.** Eq. (2) corroborates the test results of the testing area.

| Points | Field detection wave speed (m/s) | Field test water absorption rate (%) | Eq. (2) the resulting longitudinal wave speed (m/s) | Weathering degree by weathering evaluation system | Degree of weathering judged according to the Code |
|---|---|---|---|---|---|
| 1 | 2689 | 1.01 | 2233.2 | Strong weathering | Strong weathering |
| 2 | 2869 | 0.26 | 3061.4 | Moderately weathered | Moderately weathered |
| 3 | 2941 | 0.37 | 2820.3 | Moderately weathered | Moderately weathered |
| 4 | 2297 | 1.33 | 2094.8 | Strong weathering | Strong weathering |
| 5 | 3571 | 0.15 | 3720.1 | Breeze-up | Moderately weathered |
| 6 | 1915 | 1.56 | 2018.6 | Strong weathering | Strong weathering |
| 7 | 2339 | 1.47 | 2046.7 | Strong weathering | Strong weathering |
| 8 | 1754 | 3.89 | 1632.4 | Fully weathered | Fully weathered |
| 9 | 2701 | 0.43 | 2723.5 | Moderately weathered | Moderately weathered |
| 10 | 2903 | 0.52 | 2605.8 | Moderately weathered | Moderately weathered |

According to the field test data, it is found that the error between the longitudinal wave velocity of limestone obtained from Eq. (2) and the longitudinal wave velocity obtained from the actual test is 7.7%. The degree of limestone weathering judged by the weathering grade evaluation system is basically correct. It has been proved that the evaluation system of the weathering level of limestone artifacts based on the water absorption characteristics of limestone and the numerical fitting model are reliable.

## 5. Conclusions

Surface strength and wave velocity are the main indicators to evaluate the degree of rock weathering at present, but trying to accurately detect the strength and wave velocity will cause minor damage and contamination to the body of the artifacts. To realize the non-destructive detection of cultural relics, the relationships among limestone surface water absorption, the ultrasonic longitudinal wave velocity, and surface strength of limestone artifacts from Feilai Peak and Yue Temple were studied, and the main conclusions are as follows.

(1) The surface intensity and longitudinal wave velocity of limestone have obvious negative correlation with the water absorption rate. By Levenber-Marquardt iterative algorithm, after several iterations, a nonlinear fitting function that can express the relationship among surface intensity, water absorption rate, longitudinal wave velocity, and water absorption rate more accurately was obtained.

(2) The weathering grade evaluation method based on water absorption rate of rocks was derived from the field test data, and the rocks were classified into five grades: unweathered, slightly weathered, moderately weathered, strongly weathered, and fully weathered. The corresponding water absorption rates range from 0-0.12%, 0.12-0.20%, 0.20-0.61%, 0.61-2.40% and >2.40%, respectively.

(3) The weathering grade evaluation method established for limestone artifacts was found that the longitudinal wave velocity and surface intensity obtained were only slightly inaccurate compared with the actual values after practical verification, and the results obtained were more accurate and the evaluation method was feasible.

The currently established method for evaluating the weathering grade of limestone artifacts is only applicable to environments with temperatures between 20 °C and 30 °C and humidity between 50% and 60%, and is suitable for testing in spring as well as autumn. It is the the next research to investigate the relationships among the surface strength, longitudinal wave velocity, and water absorption rate of limestone under different temperature and humidity environments.

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