

# Correlation of Ultrasonic Pulse Velocity with Porosity and Compressive Strength of Mortar with Limestone for Building Quality Assessment

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## Correlation of Ultrasonic Pulse Velocity with Porosity and Compressive Strength of Mortar with Limestone for Building Quality Assessment

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### ABSTRACT

Mortar is used for bonding bricks, filling gaps in masonry, and as a plaster for strengthening and smoothing wall surfaces in finishing works. Poor quality of mortar can cause cracks in the walls which are identified after the building is completed. Assessment of a building is essential to determine its quality. Non-destructive testing is widely chosen because it will not directly affect the physical building condition. However, there still needs to achieve a good fit equation that can be used to estimate mortar quality using non-destructive testing. This research aimed to propose a formula to predict the mortar quality using an ultrasonic pulse velocity (UPV) test with porosity and compressive strength in the mortar with limestone. Variations in adding the lime powder to the mortar mix are 20%, 30%, 40%, and 55%. It was divided into M, S, N, and O types. The mortar cubes were prepared based on ASTM C-141 and ASTM C-270. The specimens were then evaluated with UPV, porosity, and compressive strength test using three samples for each test. Equations for the relationship between UPV and porosity and compressive strength can be derived from these tests. The results showed that the value of the ultrasonic pulse speed is directly proportional to the compressive strength of the mortar, which fits the equation  $y = 0.0542e^{0.0015x}$ , and is inversely proportional to the porosity, showing the equation  $y = 108.57e^{-6E-04x}$ . The results of this study can be used to assess the quality of new construction works and existing buildings.

### 1. Introduction

Mortar is a type of building material that is very common in Indonesia. Mortar is mainly used as a binding agent for brick walls and plaster. In mortar work, the bricklayers still poorly understood the quality control and efficiency of materials in the mixture process. This condition leads to cracks in the walls that are often identified after the construction work is completed. In addition, it also wastes the material in the process. This condition cannot be

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ignored because it will affect the building's strength, performance, and aesthetics [1]–[6]. Previous researchers also strive to obtain mortar and concrete mixtures that are more environmentally friendly but still possess good physical and mechanical characteristics so that they can increase construction cost efficiency and facilitate the implementation of construction work [7]–[11].

Based on field observations, it can be identified that from the experience of building construction work in general, in the implementation of wall work, lime is commonly used as an admixture in mortar or plaster production, which aims to simplify the work and reduce the use of cement. The addition of this material can change the quality of the resulting mortar. Mortar quality is generally measured based on compressive strength and porosity. According to ASTM C 1329 and ASTM C 270-10 [12], [13], mortar can be divided into four groups based on its compressive strength and application. The mortar types are categorized as M, S, N, and O. Several previous studies indicate that adding too much limestone powder into the mortar mixture will decrease the compressive strength of the mortar and increase porosity. The compressive strength of Portland-limestone cement pastes decreased in all ages with an increasing amount of limestone due to the dilution effect [14]–[16].

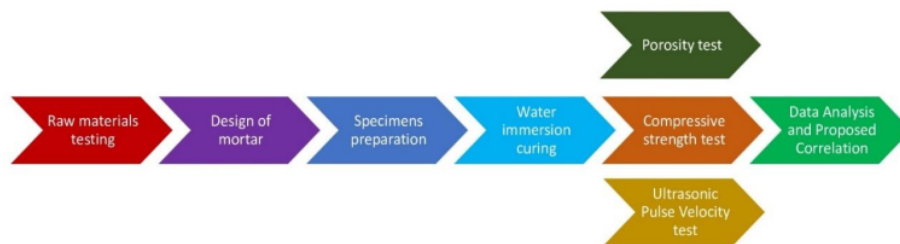
This condition will potentially cause a decrease in the structural performance and reduced durability and furthermore leads to a shortening of the service life of the building. The deterioration of mortar quality is often found in existing buildings. This condition can occur due to aging buildings, improper mix composition, or swelling and shrinkage due to temperature changes. Therefore, many existing buildings, whether designated as heritage or public buildings, need to be evaluated to ensure their safety and feasibility. Destructive testing on existing buildings is not simple, potentially increasing the damage and usually high cost, so commonly avoided in practice.

Ultrasonic Pulse Velocity (UPV) testing is one of the non-destructive methods which, in its implementation, will not destroy the physical object of the test and is easily implemented in its application. UPV can indicate the homogeneity, density, and compressive strength of mortar and concrete. It can be understood well because the denser the test object, the higher the ultrasonic wave propagation speed. Therefore, the UPV test is suitable for evaluating existing buildings [17]–[25]. However, at present, no standard correlation equation can be used to estimate the quality of mortar in various quality ranges by means of non-destructive test (NDT) techniques.

This research is aimed to obtain and propose a correlation formula to predict the mortar quality using an ultrasonic pulse velocity (UPV) test with porosity and compressive strength in the mortar with limestone. The research was conducted based on ASTM C-1329 and ASTM C-270. Various mortar compositions are prepared to meet types S, M, N, and O, with variations in the addition of limestone. The specimens were then tested for UPV, porosity, and compressive strength. The data was then used to obtain an equation for the relationship between UPV, porosity, and compressive strength. The results of this study can be used to assess the quality of new or existing buildings.

## 2. Research Method

This research was conducted using an experimental method, starting with raw material testing, mix design calculations, mixing, tap water immersion for the curing process, compressive strength testing, and UPV test at 3, 7, 14, 21, and 28 days and porosity test at 28 days. The test results were then analyzed by quantitative descriptive statistics to obtain correlations between test variables and to develop equations that could be used to predict mortar quality based on the results of the UPV test. The complete stages of the research procedure can be seen in the following Figure.



Source : *Research Flow Analysis* (2022).

**Figure 1.** Experimental Works Procedure

### 2.1 Materials

The main materials used in this study consist of Portland composite cement, limestone powder that passed the #200 sieve, and local natural sand with a fineness modulus of 1.78, a specific gravity of 2.45, and a loose density of 1.60. Each type of mortar was then prepared based on the volume ratio for the mix proportion. The mortar types were categorized as M, S, N, and O. Type M mortar was prepared in a ratio of 1 cement: 0.25 limestone powder: 2.5 sand, type S was 1: 0.5: 2.5 sand, type N was 1: 0.75: 2.5 sand, and Type O with a volume ratio of 1 cement: 1.25 limestone powder: 2.5 sand.

Cement, sand, limestone powder, and water, which have been weighed, are mixed in a mortar mixer bowl and then put into a 50 mm three-gang mortar cube mold. The mortar is then compacted by hand compaction in a standard specified manner. After that, the molds were placed in the cabin at a temperature of  $27^{\circ} \pm 2^{\circ} \text{C}$  for 24 hours; then, the specimen was removed from the molds and submerged in clean water for curing.



a. Portland Cement

b. Limestone Powder

c. Sand

Source : Research Documentation (2022).

**Figure 2.** Materials for the Experimental Works: Cement, Limestone Powder, and Sand

## 2.2 Experimental Works

The porosity can be defined as the ratio of pore volume to the total volume of mortar. The porosity of mortar will affect its durability and compressive strength. The smaller porosity value leads to higher durability and compressive strength of the mortar. The porosity test was conducted after 28 days old. The porosity test procedure started after mixing and specimen casting; the mortar was removed from the mold after one day and put in for water immersion curing. The mortar dried in the oven at  $105^{\circ} \text{C}$  for 24 hours, as shown in Figure 3.



Source : Research Documentation (2022).

**Figure 3.** Mortar Cubes in the Drying Oven

The formula for the mortar porosity determination can be expressed in the following equation:



$$P = \frac{A-B}{B} \times 100\%$$

where:

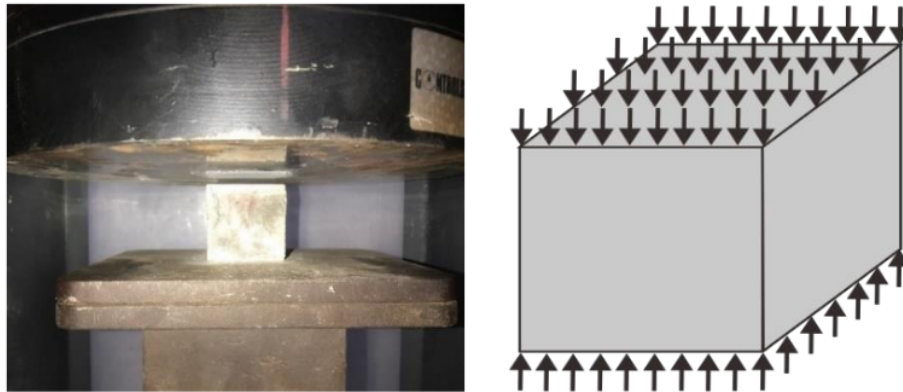
A = mortar weight (gr)

B = mortar weight after dried in the oven (gr)

The porosity test aimed to measure the pore structures of mortar which are significantly influenced by the type of binder, and the degree of hydration will fundamentally control its durability and strength. Porosity testing was conducted on three specimens from each variant. Therefore, the porosity test was done on 15 mortar cube specimens with a dimension of 50x50x50 mm.

The compressive Strength Test is a test that aims to find the axial capacity of the mortar specimen caused by compressive force. Based on ASTM C 109, the compressive strength of mortar is measured by the axial compression load that causes the mortar specimens to collapse by a compressive force in a compression testing machine [26]. Therefore, the compressive strength of mortar is the maximum force per unit area operating on a cube-shaped test object.

The compressive strength and ultrasonic wave propagation speed were measured on three mortar cubes for each variant (S, M, N, and O) carried out 3, 7, 14, 21, and 28 days after casting. Thus, it was conducted on 60 cubes with a dimension of 50x50x50 mm. The compressive strength test was conducted using a well-calibrated compression testing machine, as shown in Figure 4.



Source : Research Documentation (2022).

**Figure 4.** Compressive Strength Test

The formula for calculating the compressive strength of mortar is applied according to the centric compression loading test, as shown in the following equation.

$$\sigma_m = \frac{P_{20}}{A}$$

where:

$\sigma_m$  = compressive strength (MPa)

$P_{max}$  = compression load (N)

$A$  = cross-sectional area (mm<sup>2</sup>)

UPV test works based on measuring the travel time of ultrasonic waves that propagate in the mortar test object. Ultrasonic waves are transmitted from the transmitter transducer, which is placed on the surface of the mortar to propagate through the mortar material to the receiver transducer. The wave's travel time is measured by the Read-Out unit of the Portable Unit Non-Destructive Indicator Tester (PUNDIT) in m/second.

UPV tests were carried out on various concrete quality and age ranges to obtain sufficient data to find a correlation between pulse velocity and compressive strength. The two transducers can be placed directly with the distance between the two transducers, as shown in Figure 5.



a. Transducer and Receiver



b. Display Unit

Source : Research Documentation (2022).

### Figure 5. Ultrasonic Pulse Velocity (UPV) Test

The ultrasonic wave velocity in the concrete material can then be calculated as the thickness of the concrete divided by the travel time. Therefore the pulse velocity can be calculated as follows.

$$V = \frac{L}{T}$$

where:

$V$  = velocity (m/s)

$L$  = distance (m)

$T$  = time (second)

### 3. Results and Discussions

#### 3.1 Compressive Strength and Porosity Test Results

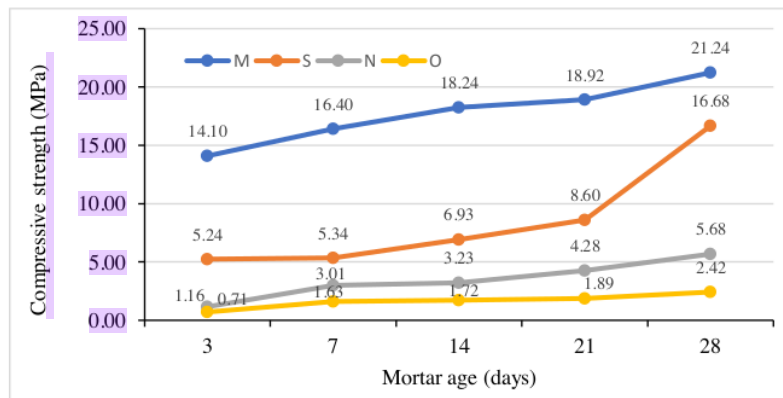
In this study, the compressive strength was tested at 3, 7, 14, 21, and 28 days after casting with three mortar cubes for each test, using a compression testing machine whose output was in the maximum compressive strength data value. The following Table shows the average of the compressive strength and porosity of the mortar cubes sample for each type:

**Table 1.** Compressive strength and Porosity of the Mortar Cubes

Type	Average Compressive Strength (MPa)					Porosity (%)
	3 days	7 days	14 days	21 days	28 days	
M	14,1	16,4	18,24	18,92	21,24	13,85
S	5,24	5,34	6,93	8,60	16,68	13,98
N	1,16	3,01	3,23	4,28	5,68	23,93
O	0,71	1,63	1,72	1,89	2,42	25,67

Source : Author's Analysis (2022).

The test results are then presented in graphical form to provide a clearer picture of the trend and relationship between age and the development of compressive strength and the relationship between porosity and the mortar's compressive strength. The tendencies and correlations between variables can be explained in more detail based on these graphs, and then propose a correlation formula between porosity and compressive strength.



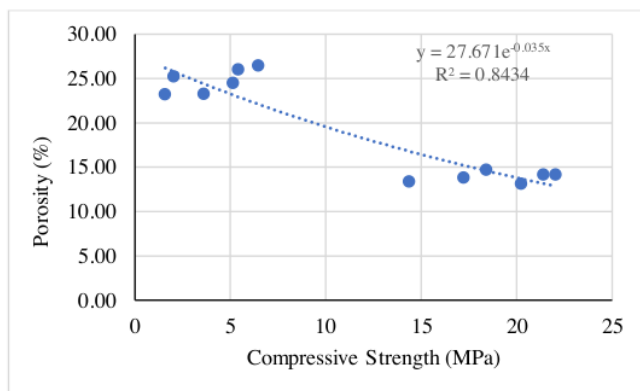
Source : Author's Analysis (2022).

**Figure 6.** Correlation between Mortar Ages and Compressive Strength

**Table 1.** and **Figure 6.** show that the compressive strength will increase as the mortar ages. It can be explained well because cement paste takes up to 28 days to complete the reaction. The results also showed that the more lime content in the mortar mixture, the lower the compressive strength of the concrete. This condition is achieved because the lime powder cannot react to donate the solid mass of the mortar. The more limestone powder content, the



more grains the cement paste must bind. It has a direct impact on reducing the compressive strength of concrete.



Source : Author's Analysis (2022).

**Figure 7.** Correlation between Mortar Compressive Strength and Porosity

**Table 1.** and **Figure 7.** show that the higher the compressive strength of the mortar, the lower its porosity will be. Tests result also showed that the higher the lime content in the mortar mixture, the lower the compressive strength of the concrete and the higher the porosity of the mortar. It can be understood clearly because the higher the compressive strength indicates the denser the mass of the test object, so the results of the mortar porosity test are consequently decreasing [27].

### 3.2 Ultrasonic Pulse Velocity Test Results

The wave propagation speed in UPV tests performed on each variant at 3, 7, 14, 21, and 28 days are presented in **Table 2.** below.

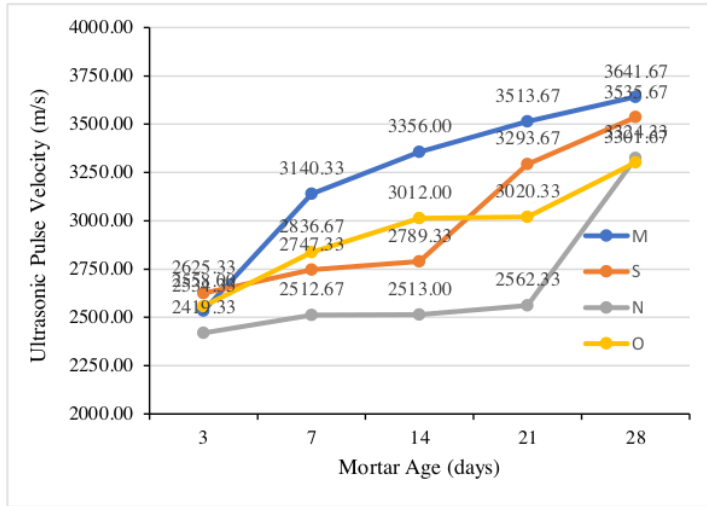
**Table 2.** Ultrasonic Pulse Velocity of the Mortar Cubes

Type	Average Ultrasonic Pulse Velocity (m/s)				
	3 days	7 days	14 days	21 days	28 days
M	2534,33	3140,33	3356,00	3513,67	3641,67
S	2625,33	2747,33	2789,33	3293,67	3535,67
N	2419,33	2512,67	2513,00	2562,33	3324,33
O	2558,00	2836,67	3012,00	3020,33	3301,67

Source : Author's Analysis (2022).

**Table 2.** and **Figure 8.** show that as the mortar ages, the ultrasonic wave propagation speed will increase, as measured in the test. It can be understood because the higher the mortar age, the more perfect the cement hydration process occurs so that the test object becomes

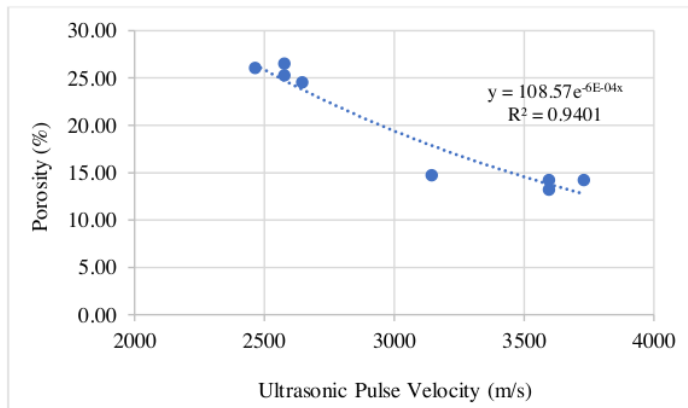
denser. As the density of the test object increases, the ultrasonic wave propagation media gets tighter, and the measured wave speed increases.



Source : Author's Analysis (2022).

**Figure 8.** Correlation between Mortar Ages and Ultrasonic Pulse Velocity

**Figure 9.** shows that the ultrasonic wave propagation speed is inversely proportional to the measured mortar porosity for each variant in the test. The higher the porosity of the mortar indicates the more voids in the specimen. This condition causes the ultrasonic wave propagation to be not well connected, so the ultrasonic wave propagation speed is reduced.

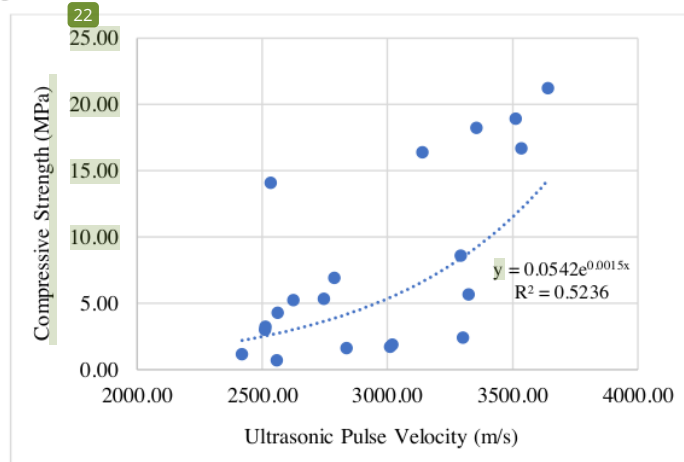


Source : Author's Analysis (2022).

**Figure 9.** Correlation between Ultrasonic Pulse Velocity and Mortar Porosity

**Figure 10.** shows that the ultrasonic wave propagation speed is directly proportional to the concrete compressive strength measured in each variant in the test. The higher the compressive strength of the mortar indicates the fewer voids in the specimen. This condition

causes the ultrasonic wave propagation to be better connected so that the ultrasonic wave propagation speed increases [22].



Source : Author's Analysis (2022).

**Figure 10.** Correlation between Ultrasonic Pulse Velocity and Compressive Strength

The test results above indicate that testing with the non-destructive test method can provide good enough results to predict the porosity and compressive strength of mortar. The ultrasonic wave propagation speed is inversely proportional to the porosity of the mortar, which satisfies the equation  $y = 108.57e^{-6E-04x}$ . On the other hand, the pulse velocity is directly proportional to the compressive strength of the mortar, and the correlation can be expressed in the equation  $y = 0.0542e^{0.0015x}$ .

These equations can be applied in evaluating existing heritage or other public buildings. In this building evaluation work, a non-destructive test can be carried out using the ultrasonic pulse velocity test method, especially the direct method measurement. It can then be used to estimate the compressive strength and porosity of the mortar for quality control in new construction works, analyze the building's adequacy and safety, and predict the remaining service life without using the destructive test technique that is relatively risky and costly.

#### 4. Conclusion

Based on the test results, testing with the direct ultrasonic pulse velocity test method can provide a good prediction for the porosity and compressive strength of mortar. The compressive strength of the mortar can be predicted by the ultrasonic pulse velocity method, where the value of the ultrasonic pulse velocity is directly proportional to the compressive strength, which shows the equation  $y = 0.0542e^{0.0015x}$ . The higher the compressive strength of

the mortar, the greater the pulse velocity. On the other hand, the value of the ultrasonic wave velocity is inversely proportional to the porosity, which shows the equation  $y = 108.57e^{-6E-04x}$ . The higher the porosity of the mortar, the smaller the pulse velocity. The results of this study can be used to assess the quality of new or existing buildings.

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