MECHANICAL PROPERTIES EVALUATION OF BLUE MOSQUE MINARET STONES: AN EXPERIMENTAL CAMPAIGN

G. Uncu[1] , S. Dede[2] , E. Çaktı[3]

[1] Phd Candidate, Earthquake Engineering Department, Kandilli Observatory and Earthquake Research Institute,
Boğaziçi University, İstanbul
[2] Research Student, EPICentre, University College London, London, U.K.
[3] Prof. Dr, Earthquake Engineering Department, Kandilli Observatory and Earthquake Research Institute,
Boğaziçi University, İstanbul
Email: gulen.uncu@boun.edu.tr, sahin.dede.21@ucl.ac.uk, eser.cakti@boun.edu.tr

Abstract: Engineering modeling and analysis of historical structures include various uncertainties and related difficulties. The most important difficulty is to obtain consistent data of structural materials without damaging historical texture as much as possible. The aim of this study is to determine the average compressive strength of the minarets of the Blue Mosque by means of ultrasonic testing. In the scope of the study, cube samples were collected from the unusable stones that were remained from restoration works carried out in the mosque. Compressive strength tests were performed following ultrasonic tests and a highly correlated relation was obtained. This relation was used in a detailed ultrasonic test study carried out in the minarets of the Blue Mosque and afterward, the mean compressive strength distributions for each minaret were estimated. It is thought that the results of the compressive strength test applied for the first time on the Blue Mosque stones as well as the detailed results for each minaret will make a significant contribution to the literature for future restoration studies and analyzes.

Keywords: Blue Mosque, compressive strength, non-destructive techniques, cultural heritage, masonry structure

1 Introduction

Historical monuments are one of the most important components of cultural heritage. Their preservation is of global concern and therefore great effort is put for this objective around the globe. However, preservation of historical structures, especially the ones in the seismically active regions, is a very challenging task to accomplish. In this concept, İstanbul and its vicinity stand as a significant example. This area, which also includes the Blue Mosque, is also home to many monuments that are on the UNESCO world heritage list (1) and is near to a fault line that is expected to produce a large earthquake in the next 30 years (2).

Besides their cultural and historical value, engineering modelling and analysis of historical structures is also an important topic as this process include various uncertainties and related difficulties. The most important difficulty is to obtain consistent data of structural materials without damaging historical texture as much as possible. Therefore, common tendency is to minimize the destructive test applications to preserve integrity of the cultural heritage (3, 4, 5). At this step, complementary use of non-destructive tests (NDT) become important to determine the material properties to be used in analytical models (6,7,8). In addition, historical structures can experience significant variabilities in material properties due to aging and atmospheric conditions (9). By means of NDT, great amount of information can be collected. This makes it possible to detect anomalies and variances in the material properties in a comprehensive way along the structure (10).

In this study, the minarets of the Blue Mosque, which is among the UNESCO world heritage list with its 400-year history, have been examined (1). To achieve this, the stones that were left out of use during the restoration process of the historical building were cut into cubic samples. Ultrasound pulse velocity (UPV) tests, Schmitt hammer tests, and compressive strength tests were carried out on these samples in a laboratory environment. The relationships established based on the laboratory results have been applied to the extensive NDT field measurements carried out on 5 minarets of the Blue Mosque to estimate the compressive strengths. This study will make an important contribution to the literature because of examining the monument in detail and the difficulty of taking samples from historical buildings. In addition, the results of the study are not only important for the Blue Mosque. The stones used in the Blue Mosque were also used extensively to construct and restore many historical heritages in and around İstanbul, such as the Mihrimah Sultan Mosque in İstanbul and Süleymaniye Mosque in Edirne, Turkey (11, 12, 13). For this reason, the results obtained apply to many important historical structures.

2 Overview of the Minarets

Blue Mosque was constructed in between 1609-1616, with its 6 minarets. Landscape of the Blue Mosque and the settlement of its minarets is illustrated in Figure 1. The two of those five minarets (M1 and M4) have a height of 57 meters with two balconies, whereas the other three ones (M2, M5, M6) are 66-meter-tall with 3 balconies. The minarets are stone masonry constructions.

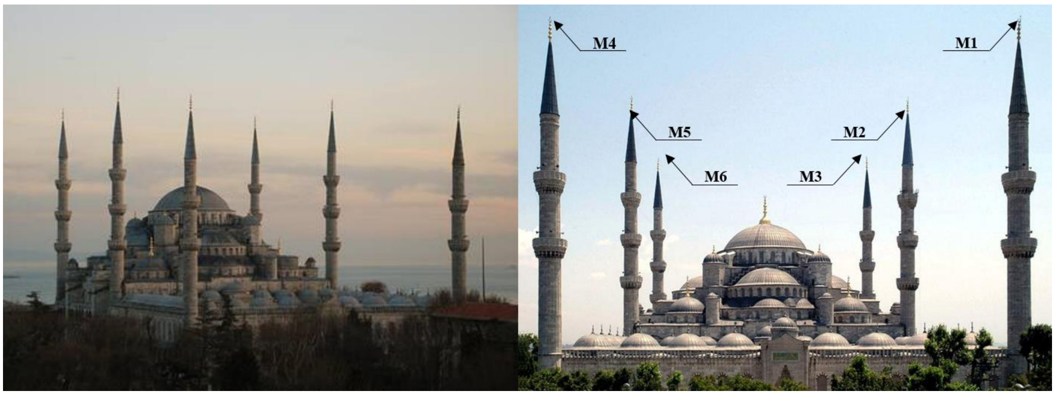

Figure 1. *Blue Mosque and the settlement of its minarets*

3 MEASUREMENTS AND TESTS

The laboratory experiments are worked on the stones of the minaret which is under restoration whereas the site investigation is carried on the other five minarets of the mosque. While this study is being carried, the honeycomb part of the minaret M3 was removed due to the restoration work. The UPV, the Schmitt hammer and the compressive strength tests are carried on the stones removed from the honeycomb and will not be reused after the restoration. Besides, ultrasound testing is done on the other five minarets on the site. Details are presented in the following subsections.

Ultrasound Pulse Velocity Test: Field and Laboratory

Ultrasound pulse velocity (UPV) test is a non-destructive method that uses high frequency sound wave to determine the material properties (14). It is based on evaluation of the P wave and S wave velocities which are transmitted and reflected through the material. The equipment utilized for the application is Proceq Pundit Lab Plus. It consists of two probes that transmit and receive the sound waves and a device that displays the obtained values. In this study, two probes are used: 250 kHz probe and 54 kHz probe. The 54 kHz probe only generates P waves, whereas the 250 kHz can generate both P and S waves (14). As can be seen in Figure 2, there are three types of measurement techniques: direct, semi-direct and indirect. The most reliable one is the direct measurement technique; however, it is only applicable when the material thickness is appropriate to transfer the waves through the probes which are across each other (14).

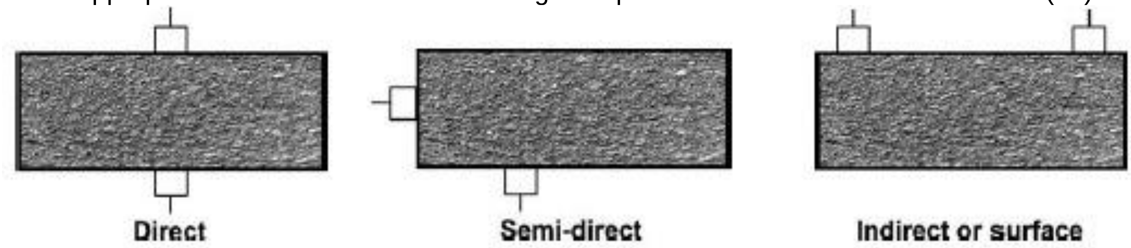

Figure 2. *The three types of measurement regarding the arrangement of the probes (Pundit Lab Operating Instructions)*

Field measurements are conducted in the five minarets of the Blue Mosque: M1, M2, M4, M5, and M6. Figure 3 shows inside the minarets where circular-shaped core and the stairs arise. Direct and semi-direct measurements are applied within each two-meter height along the minarets. Direct measurements are taken from the circular-shaped core of the stone stairs. Whereas semi-direct measurements are taken from the edges of the stone stairs. Prior to each test, a special liquid solution is applied to the surface to increase the performance of the transducers (14). An instance from in-situ application is given in Figure 4.

Figure 3*. Inside the minarets*

Figure 4. In-situ application of UPV testing

The field studies are followed by the laboratory tests. Figure 5. The debris removed from the minaret M3 and the created cubic specimens shows the debris removed from the minaret M3 and the created cubic samples. Debris is cut into the appropriate shape for the laboratory test procedure. The 7x7x7 cm and 5x5x5 cm cubic pieces, which are called “the large samples” and “the small samples” in this paper, are obtained.

Figure 5. The debris removed from the minaret M3 and the created cubic specimens

In the laboratory, UPV tests are applied on all samples with direct measurement technique from each opposite face which can be seen in Figure 6. Initially, large samples are tested. Five measurements are done for each three pairs of the non-reciprocal surfaces to evaluate the P and S wave velocities, not only the numerical values but also the wave forms. The 54 kHz probes are used for the P waves and the 250 kHz ones for the S waves. When it is completed, P wave velocity values are found to be reliable. However, the 250 kHz probes generate the P and S waves together, therefore the numerical wave velocity value shown on the screen is not respectable and the wave forms are required to be inspected. Nevertheless, it should be a detailed observation since the P and S waves are not clearly detectable due to the limited dimension of the specimens.

Figure 6. UPV application on the cubic samples

Schmitt Hammer Test and Compression Test

Following the UPV test, the Schmitt hammer test is carried and then the density of each cubic piece is determined. The main aim in the Schmitt hammer test is to find out a reliable relationship between surface hardness and the compressive strength (15). The Schmitt Hammer test is applied on each three non-reciprocal surfaces. The small samples are cracked during the Schmitt Hammer test, due to their dimensions, hence it is decided not to apply the test on them (Figure 7).

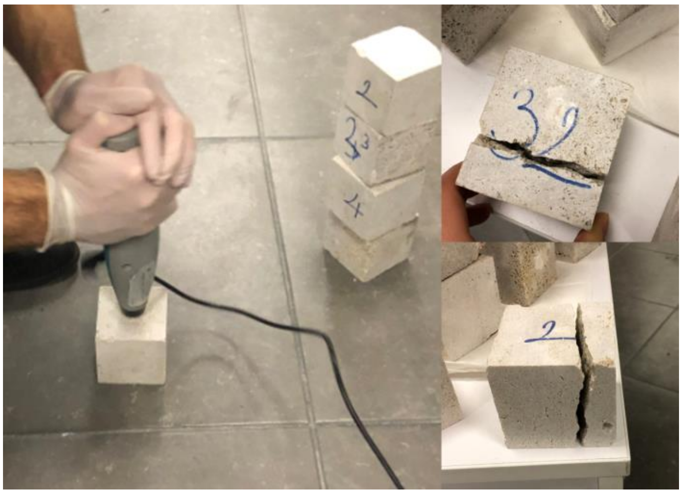

Figure 7. *Schmitt hammer test application and cracked samples*

Following the Schmitt hammer test, compression test is applied on the samples except the cracked ones. The Schmitt hammer test result of the large samples is not concluded in reliable correlation with the compression test. During the experiments, deterioration on the surface of several samples is observed, which might affect the Schmitt hammer readings considerably. Therefore, the Schmitt Hammer test results are not regarded in the scope of this research. Additionally, it is recognized on the cracked specimens that despite their soft surfaces they have quite stiff cores inside. This fact is considered as one of the reasons for not yielding reliable correlation between Schmitt Hammer test and compressive strength test results. The remarkable stiffness diversity between the inner core and the surface can be interpreted as the effect of the atmospheric conditions on the stones.

4 THE ANALYSIS

The analysis is launched after collecting the data from the previously mentioned tests. There are several ultrasound test measurements that resulted in remarkably different outcomes for each direction of the same sample. Regarding stress distribution within the samples under compression test, it is thought that the compressive strength result is affected by the other two axes which the force is not applied. Based on these, three different methods are asserted to inspect the correlation between the P wave velocity and the compressive strength value.

The S wave velocities are determined by observing the wave forms, then the regression analysis is carried to evaluate the correlation of the data. First, the correlation between the P wave velocity and the compressive strength is inspected. Concerning the readings on different surfaces of the samples, the correlations between the following three measurements are regarded respectively: the compressive strength and P wave velocity related to the compressed surface; the mean value of the P wave velocity related to each surface and the compressive strength; the minimum P wave velocity obtained from each surface and the compressive strength. As can be seen in Figure 8 and Figure 9, the correlations are found to be 66%, 77% and 79% respectively.

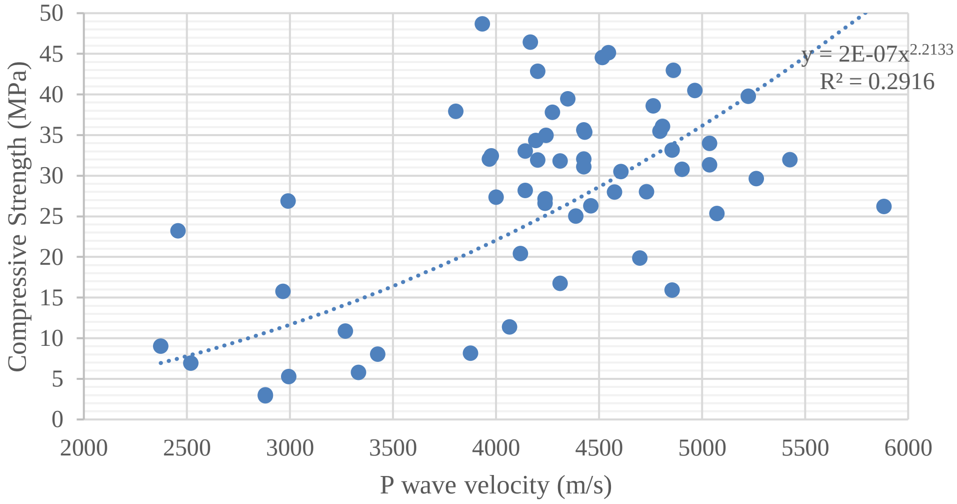

Figure 8. *The correlation between the compressive strength and P wave velocity related to the compressed surface.*

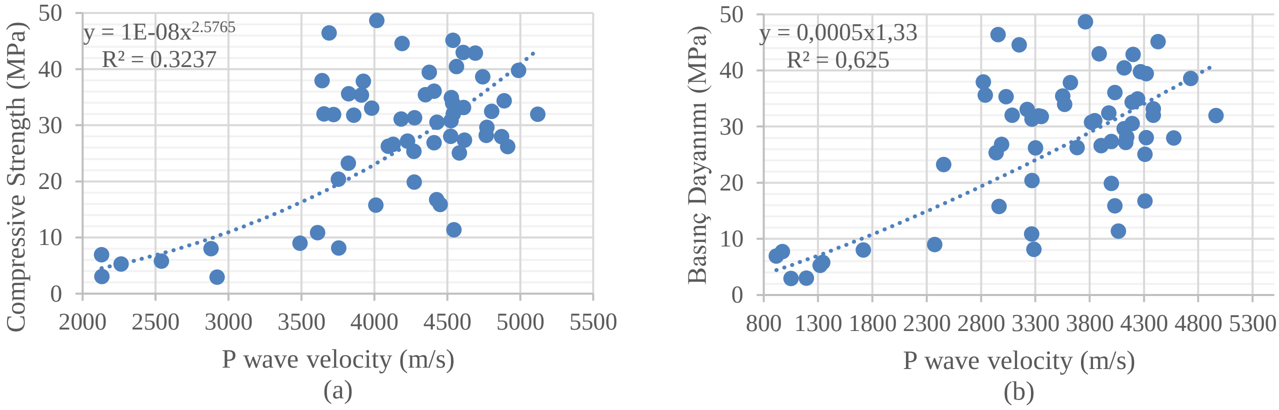

Figure 9*. The correlation between the compressive strength and (a) The mean value of the P wave velocity related to each surface (b) the minimum P wave velocity obtained from each surface*

Then, the correlation between the minimum P wave velocity obtained from each surface and the compressive strength is observed for the samples having 40MPa and below compressive strength. As Figure 10(a) points out, the correlation increases up to 81% in that case. Consequently, the same analysis is carried for the samples with a compressive strength of 35 MPa and below; 30 MPa and below. The correlations are found to be 81% and 85% respectively (Figure 10(b) and Figure 10(c)). It is clear that the correlation is the same for the samples with a compressive strength of 40 MPa and below and 35 MPa and below; whereas it increases for the ones with 30 MPa and below. However, there are 55 samples with 40 MPa and below compressive strength out of 61 total samples, whereas only 32 of them have 30 MPa and below compressive strength. It implies that, when only the samples with 30 MPa and below compressive strength are considered, almost the half of the specimens are disregarded.

Figure 10(d) represents that when the samples with a compressive strength of 25 MPa and below are considered, the correlation decreases to 77% and there are only 18 samples tested.

Respecting the previously mentioned results, when the correlation and the number of the tested samples are regarded, the correlation between the compressive strength and the P wave velocity for the specimens with a compressive strength of 40 MPa and below is found to be more reliable among the carried regression analyses.

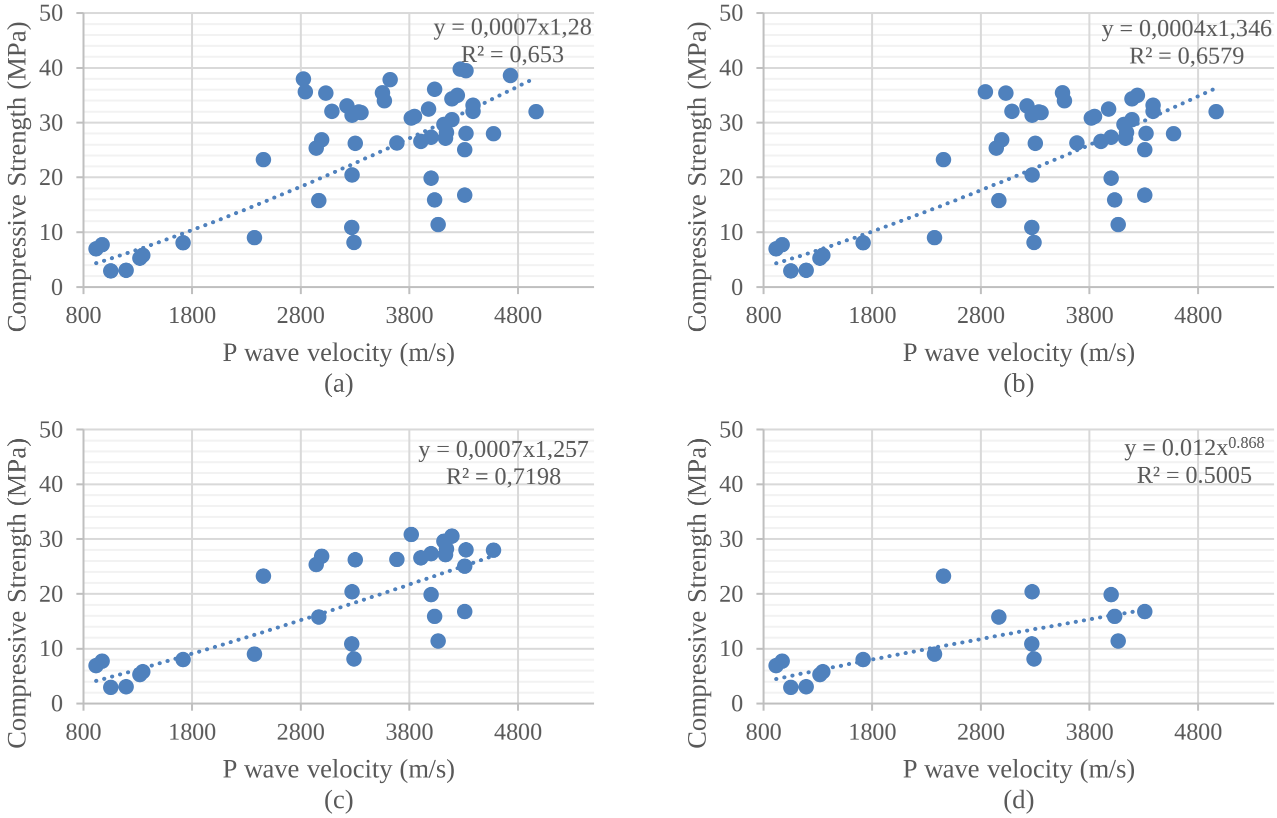

Figure 10. *Figure 8. Correlation between the minimum P wave velocity from each surface and the compressive strength for the samples having 40 MPa and below (a), 35 MPa and below (b), 30 MPa and below (c), 25 MPa and below (d)*

Furthermore, the correlation between the P and S wave velocities is examined. As explained earlier, the S waves requires a detailed eye observation on the waveforms. The observation declines that detecting the S wave velocity on a large cubic is easier and more reliable than that on a small one; since the wave path is longer. Therefore, the correlation between P and S waves is examined regarding the results obtained from the large samples. When the P wave velocity is considered, the mean value of the three surface readings is taken and as can be seen in Figure 11(a), it is found to be 86% correlated to the S wave velocity.

Furthermore, the correlation between the density and the P wave velocity is examined. The minimum value of the P wave velocity readings from the three surfaces is regarded. First, the analysis is carried concerning the results taken from the samples with a compressive strength of 40 MPa and below; however, it is revealed that the correlation and its equation does not change significantly when all the samples are considered. Therefore, the equation found when all samples are analysed is respected (Figure 11(b)).

The other five minarets M1, M2, M4, M5, M6 are observed by ultrasound testing equipment on site and the results are assessed regarding the laboratory test results mentioned above. The 54 kHz and 250 kHz probes are used for the site survey. Besides, the circular column at the core of the minarets where the stairs are rising, is measured by direct method using 54 kHz probes.

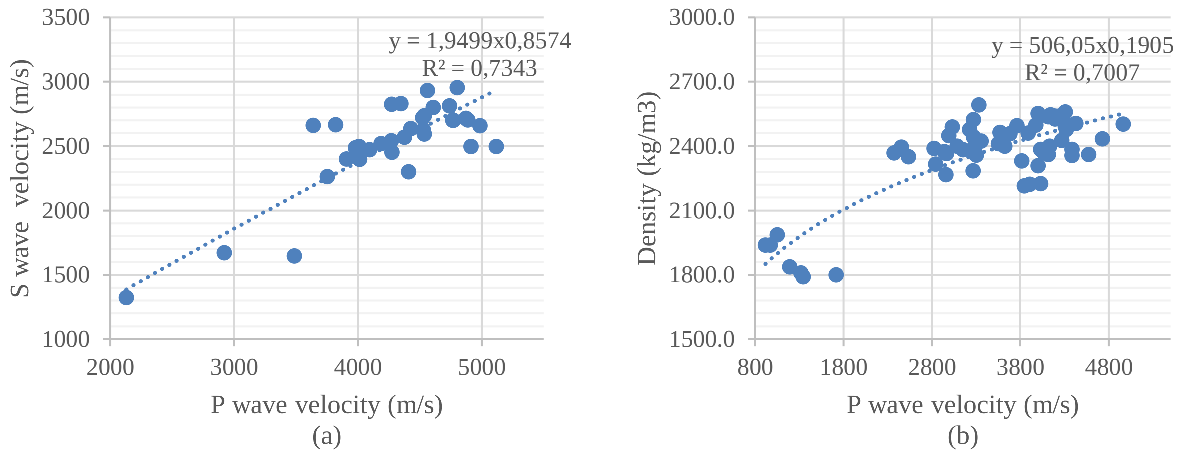

Figure 11. *The correlation between (a) Vs and Vp (b) Density and Vp regarding three surfaces of the samples*

5 RESULTS

First, the equations obtained from the laboratory tests are applied on the site survey results. The regression equation of the P wave velocity and compression strength correlation is adopted on the P wave velocity reading taken from the minarets on site to reveal the compressive strength of the material. The mean compressive strength values of each stone in a minaret is evaluated as following: 28 MPa for M1, 10 MPa for M2, 31 MPa for M4, 10 MPa for M5, 10 MPa for M6. Besides, the samples tested in the laboratory result in 28 MPa of mean compressive strength. The compressive strength of different parts of each minaret is indicated in Figure 12, by a colour scale.

6 DISCUSSIONS

This study is the most extensive field study conducted on the stones of the minarets on Blue Mosque. Therefore, it provides notable contribution to the literature when the future work not only for Blue Mosque but also a complete cultural heritage dating back to that era is considered.

The samples tested in the laboratory, result in 28 MPa of a mean compressive strength and the compressive strength of the other five minarets on the site is estimated part by part for each one on the basis of laboratory results. It is found to have a correlation of 81% between P wave velocity and the compressive strength of the stones. Besides, it is assumed that the compressive strength of the stones is affected by their nonhomogeneous structure.

The mean compressive strength of the minarets M1 and M4 are found to be higher than the minarets M2, M5 and M6. Moreover, it is known that M1 and M4 minarets underwent a restoration in the recent past, unlike the other three minarets. Additionally, Erdoğan et al. (2019) applied compressive strength test on the stones of these two minarets prior to the renewal. They estimated the mean compressive strength of each minaret as 16 Mpa, which seems similar to the results obtained in this study for the non-renovated three minarets. Furthermore, within the scope of the restoration work on M1 and M4, the damaged stones were replaced with the mussel stone (kufeki stone) which is a specific kind of limestone, typical in İstanbul vicinity and was also used in the original construction back in 1616. The research focusing on the mechanical properties of the mussel stone (17, 18) reveal that its compressive strength corresponds to the ones estimated for M1 and M4 minarets in this study. Hence, the previous works support the findings of the method developed in this paper.

When the unreliable Schmitt Hammer test results are considered, several stones with tough inner cores despite of their soft surfaces are blamed. Additionally, the Schmitt Hammer test is observed to damage the samples.

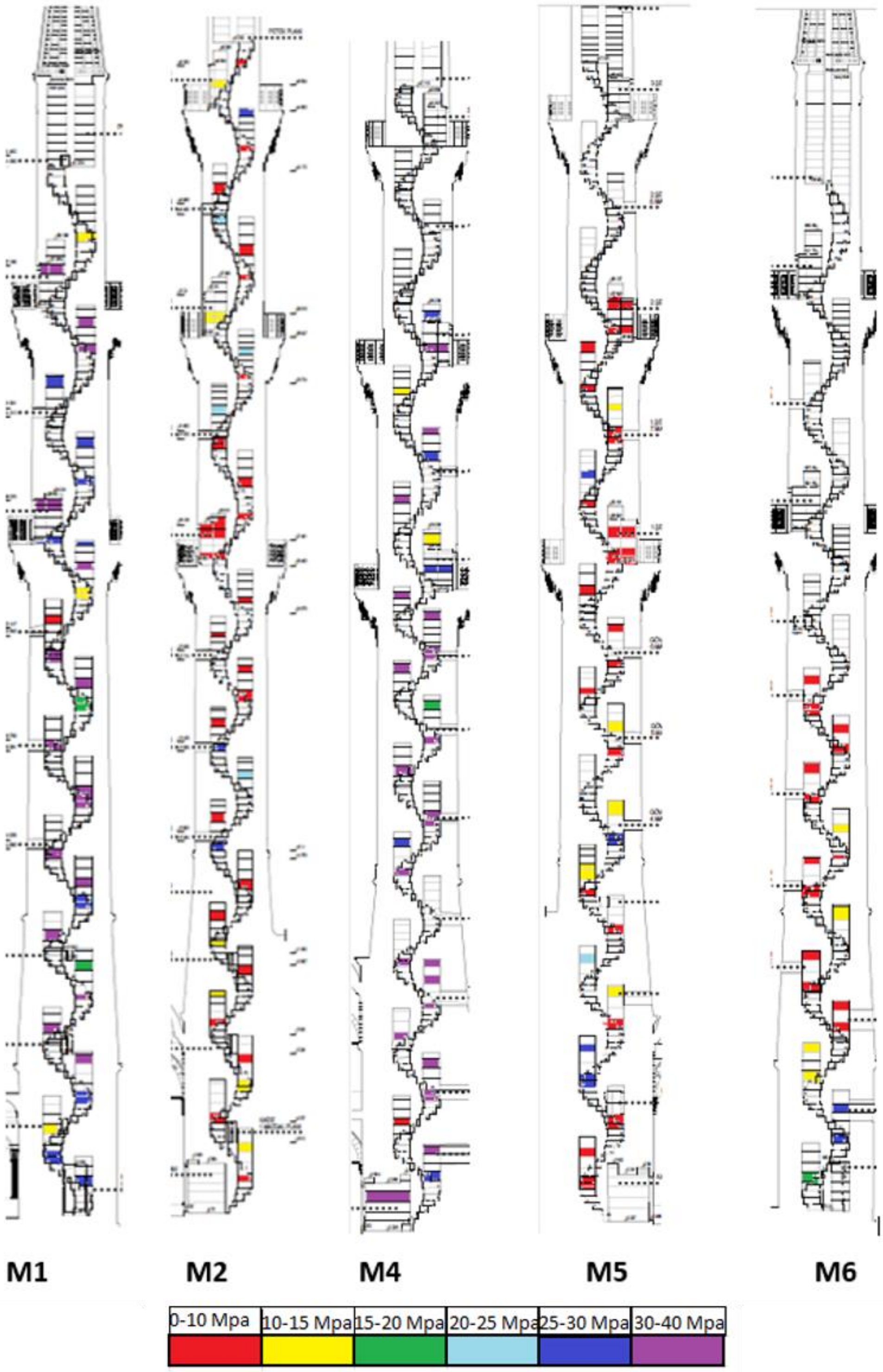

Figure 12. *The compressive strength of different parts of each minaret shown by a colour scale.*

The samples tested in the laboratory reveal that the P wave velocity obtained from different directions of the same cubic varies significantly and the compressive strength result is highly affected by this diversity. The most reasonable outcome is obtained when the correlation between the minimum of the P wave velocity readings taken from 3 different surfaces of the sample and the compressive strength. However, it must be regarded that, the five minarets on site are not appropriate for taking the readings from all directions of the material.

When the P wave velocity that appears on the screen during the reading and the S wave velocity that obtained by an eye observation on the wave form are compared, the former one is found to be more respectable. Therefore, especially for the site surveys, the limitations of reading the S wave velocity should be concerned. This study offers the idea to determine the material property using the P wave velocity, neglecting the S wave velocity.

When the larger samples are considered higher level of correlation is found between the P and S wave velocities and the correlation between the P wave velocity and the density. This relationship may lead to the evaluation of S wave velocity and the density; therefore, the shear and the elasticity modulus, employing the measured P wave velocity. This concept is left for a further study.

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