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RESEARCH ARTICLE-CIVIL ENGINEERING

Evaluation of Natural Building Stones' Characterizations Using Ultrasonic Testing Technique

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Abstract

Natural building stones are widely used in the construction field in the Middle East and Mediterranean areas. Stones are chosen for their durability, attractiveness, and low cost compared to other construction materials. Building stones come with different natural origins and vary in their mechanical and thermal characterizations. Compressive strength, water absorption, and thermal conductivity of the external walls are significant characteristics in evaluating the structure's durability and sustainability. External walls that are made of natural stones with high thermal conductivity lead to extensive use of energy and raise ongoing costs for cooling and heating. In addition, low compressive strength and high-water absorption adversely affect the long-term durability of natural building stones. This paper aims to establish in-situ evaluation models of compressive strength, thermal conductivity, and water absorption of natural building stones using the non-destructive Ultrasonic Pulse Velocity (UPV) testing technique. Laboratory experimental tests were conducted for ninety-nine specimens of eleven types of natural building stones with dimensions of $50 \times 50 \times 50$ mm. Based on the obtained results, UPV values depend on the mechanical properties of building stones. Ultrasonic pulse velocities of the building stones are directly proportional to their compressive strength and thermal conductivity with a satisfactory correlated relationship. However, UPV values are inversely proportional to water absorption with a non-sufficient correlated relationship. The results emphasize that there are slight differences in the obtained values of compressive strength of natural building stones that are loaded parallel or perpendicular to the natural rift. The study found that Ultrasonic Pulse Velocity testing technique is an easy-to-use, economical, and non-destructive method for a preliminary prediction of the mechanical and physical properties of natural building stones. Compressive strength, water thermal conductivity, and water absorption estimation models are proposed for field evaluation of building stones based on the Ultrasonic Pulse velocities.

Keywords Building stones · Ultrasonic pulse velocity · Compressive strength · Water absorption · Thermal conductivity · Mechanical properties

1 Introduction

Energy consumption in residential and industrial structures is dramatically growing in developing countries [1]. Worldwide, the residential building sector consumes 23 and 30% of the global energy and electricity, respectively [2]. This raises numerous environmental challenges that impact structures' sustainability [3–5]. Therefore, energy-efficient construction materials need to be developed and utilized in the building industry.

In the Middle East and Mediterranean areas, natural building stones are one of the most used construction materials that meet the continuous development and growth in the real estate field [6, 7]. Natural stones show a good mechanical behavior that makes them durable and preferable as a construction material. Moreover, stones are chosen for their durability, attractiveness, and economy as they are made from rocks into various dimensions and surface textures [8]. Stones' properties depend on the mineralogical composition of the original rocks. Rocks are generally divided into three major groups according to their historical formation process.

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These groups are Igneous rocks, which have hardened from molten materials called magma; Sedimentary rocks, those made of fragments derived from pre-existing rocks; and Metamorphic rocks, which have been derived from either igneous or sedimentary rocks under extreme conditions that caused changes in their mineralogical composition, texture, and internal structure [9]. Stones are categorized into building stones, ornamental stones, and dimension stones. Limestones and Sandstones are extensively used as dimension stones for cladding in the Middle East and Mediterranean areas. They are sedimentary rocks with great variation in their properties and appearance.

Mechanical properties of building stones are affected by different physical characterizations, such as porosity, grain size, and mineralogy [7]. Compressive strength is an important property that measures stone's quality. The strength of natural building stones depends on their mode of formation; composition; texture and structure; moisture content and extent of suffered weathering [10]. Igneous rocks have very high compressive strengths compared to sedimentary and metamorphic rocks. This attributed to the fact that igneous rocks were crystallized, compacted, and interlocked in texture and uniform possesses. However, compressive strengths of sedimentary and metamorphic rocks are affected by the abundance of planes of weakness such as bedding planes and foliation [11]. The compressive strength of building stones is inversely proportional to the porosity and grain size [12]. Moreover, the quartz content of building stones influences the compressive and tensile strengths. It was found that building stones with high quartz content have greater strength [7].

The porosity of natural building stones depends on the size, shape, and degree of packing of the crystals or grains in a rock. Porosity is the ratio between the total volume of the pores and the total volume of the rock sample itself. The low porosity of stones is caused by interlocking crystals, angular grains of different sizes, and uniformly distributed cementing material in the original rock. On the other hand, high porosity can be maintained by rocks composed of spherical or rounded grains or if the cementing material is unevenly distributed. It was found that water absorption and porosity of rocks are directly related [6, 13]. Limestones and sandstones may show some varieties in absorption values as high as 10%. The presence of water within the pores not only decreases the strength of natural stones but also makes them vulnerable to disintegration due to the frost action in cold humid climates [13].

During the last decades, several researchers studied natural building stones and evaluated their mechanical and physical properties. The mechanical characteristics of limestones were studied by Mawloud et al. [6]. They examined different mechanical properties of natural building stones such as stress–strain behavior, modulus of rupture, modulus of elasticity, Poisson ratio, and compressive strength. The study proposed a formula to estimate the modulus of elasticity of limestones based on their compressive strength. Other experimental studies were conducted to investigate the ability to measure the thermal conductivity of natural stones by mean of the P-wave velocity [7, 13], and infrared thermography [14–16]. A good correlation was found between the thermal conductivity and P-wave velocity of natural stones.

The thermal conductivity of natural building stones depends on several factors: chemical composition; moisture content; density; and isotropy and homogeneity of the original rock [13]. Thermal conductivity of rocks varies from 1.163 to 8.6 W/mK [17, 18]. Clauser and Huenges [19] studied different factors that influence the thermal conductivity of natural building stones. They established diagrams of different types of rocks with factors that impact their thermal conductivity. Thermal insulation of external walls depends on the thermal conductivity of the used building stone [20]. Building stones with high thermal conductivity lead to extensive use of heating and cooling that raises facilities' energy consumption and running costs. Therefore, it is essential to evaluate natural building stones before being used in constructing the external walls. Ultrasonic pulse velocity is a non-destructive, economic, and easy-use technique that is commonly used in different engineering fields. It can be utilized in estimating the strength and elastic modulus of structural elements made of concrete or timber [21–23]. Such testing technique can be employed also for in-situ and laboratory characterization of physical and mechanical properties of natural building stones.

Regional building codes and guidelines in the Middle East and Mediterranean areas do not provide enough information about the mechanical properties and thermal conductivity of natural building stones. Moreover, there are no reliable and practical in-situ techniques to evaluate natural building stone characterizations before being used in construction. Traditional evaluation methods that utilize laboratory testing are costly and time-consuming. Such tests are always influenced by different factors, which may result in significant interpretation errors. As a result, the research in this field has been very active and led to the development of a wide variety of destructive and non-destructive testing methods. Natural building stones of a low thermal conductivity enhance the insulation of buildings and gives an energy-efficient solution. Accordingly, this paper aims to investigate the mechanical properties and thermal conductivity of natural building stones and establish in-situ evaluation models using the non-destructive ultrasonic testing technique.

2 Experimental Program

2.1 Material

Eleven types of natural building stones were selected from different locations in Jordan and Palestine, Fig. 1. Ninety-nine specimens of natural building stones were prepared according to the ASTM code with dimensions of 50 × 50 × 50 mm. The number of specimens had to be large enough to obtain reliable results and overcome the effect of the scatter in the obtained results on the mean values of the natural building stones' characterizations [24]. The labeling system of the tested specimens contains two letters and two numbers. Letters refer to the stone type: "RH" for Ruwaished Hard, "RS" for Ruwaished Soft, "MA" for Ma'an, "HA" for Hay'an, "TA" for Tafooh, "BA" for Ba'aer, "HL" for Hallabat, "BS" for Basalt, "TR" for Travertine, "OR" for Oriental, "SA" for Sahrawi, and "CR" for Concrete. Numbers indicate the specimen's number of each type of stones, Fig. 2.

The selection of stone samples was based on mineralogical and structural characteristics. Along with the origin source of the natural building stones, the stones' composition and chemical properties have a significant effect on their mechanical and physical properties. The most common minerals in the composition of building stones are quartz, feldspar, mica, calcite, dolomite, kaolin, pyroxene, amphibole, and serpentine [25]. Magnesium, also called Dolomite, improves the strength of Limestone. On the other hand, Feldspar causes weakness when it is found in large quantities, because CO2 dissolves Potassium, Sodium, and even Calcium and leaves pure white clay behind. The presence of Mica, even less than 2–3%, makes the stone undesirable for building purposes. Moreover, stones with silicates as cementing materials are resistant to weathering [26].

Fig. 1 Map showing locations of the obtained samples

2.2 Instrumentations and Testing Procedures

Nine specimens of each type of stone were tested according to ASTM codes to determine: water absorption [27], thermal conductivity [28], and P-Wave velocity [29]. Later, all specimens were oven-dried and tested under compression monotonic loading, using a universal testing machine with 250 kN axial force capacity, to determine the compressive strength [24]. The machine was operated under load control with a loading rate of 1 kN/sec until failure as shown in Fig. 3. The compressive strength was calculated by means of the applied load at failure divided by the cross-sectional area of the specimen.

The main goal of using Ultrasonic Pulse testing as a non-destructive technique is to find the correlation of the ultrasonic pulse velocity with respect to water absorption, compressive strength, and thermal conductivity. This implies

Fig. 2 Specimens of natural building stones

Fig. 3 Compressive strength test using the universal testing machine

Fig. 4 Testing P-wave velocity using Proceq Pundit Lab + UPV Instrument

that measurements of these mechanical properties and the ultrasonic pulse should be made on the same specimens. Thus, before conducting the compressive strength tests, the ultrasonic pulse velocity test was conducted using the Proceq Pundit Lab + UPV Instrument, Fig. 4. Specimens were exposed to a laboratory condition at 25 °C and their faces were covered with gel to provide high conductivity. The ultrasonic pulse velocity was calculated by dividing the specimen length by the measured transit time. Later, mean values of the ultrasonic pulse velocity were obtained by the average of three measurements of the transit time recorded during the test of each specimen.

The thermal conductivity was calculated based on the analysis of the temperature response of each type of natural building stone to heat flow impulses, using the ISOMET 2104 instrument. This testing is based on the transient heat-pad technique. The heat pulse is generated for a time interval and the temperature response is influenced by the measured infinite medium that is analyzed using a temperature sensor connected to the heater. The testing was conducted four times for each sample at room temperatures of 25 °C.

3 Results and Discussion

The mean value and standard deviation of water absorption, compressive strength, thermal conductivity, and P-wave velocity were computed for each set of the natural building stones, Table 1. The obtained results show a random variation in stones' characterizations with respect to the P-wave velocity as shown in Figs. 5, 6, 7. This can be attributed to the direction of the stones' rift and grain size as stated by [6, 12, 19]. A strong relationship between the measured mechanical and physical properties was found in the natural building stones. Ultrasonic pulse velocities are proportionated inversely with the water absorption and directly with the compressive strength and thermal conductivity. This is valid for all types of the tested natural building stones and concrete.

The linear variation of compressive strength, thermal conductivity, and water absorption with respect to the ultrasonic velocity of natural building stones was apparent. Further, it can be seen that the thermal conductivity of natural

Table 1 Summary of the obtained results of the experimental tests

Stone type	Water absorption (%)	Compressive strength (MPa)	Thermal conductivity (W/mK)	P-Wave velocity (m/s)
Ruwaished Hard	1.5 (±0.15)	85 (±13.4)	2.62 (±0.20)	6118 (±448)
Ruwaished Soft	4.3 (±0.11)	30 (±4.5)	0.52 (±0.08)	3735 (±350)
Ma'an	0.9 (±0.20)	85 (±4.7)	2.71 (±0.10)	6070 (±256)
Hay'an	1.9 (±0.19)	47 (±5.0)	0.86 (±0.16)	4272 (±167)
Tafooh	1.7 (±0.11)	67 (±15.6)	2.13 (±0.13)	5050 (±401)
Ba'aer	2.5 (±0.25)	96 (±6.5)	2.71 (±0.11)	5302 (±354)
Hallabat	2.4 (±0.29)	42 (±2.1)	0.92 (±0.23)	4296 (±108)
Basalt	0.5 (±0.06)	178 (±8.8)	5.48 (±0.12)	8849 (±84)
Travertine	1.8 (±0.26)	54 (±10.7)	1.64 (±0.20)	5392 (±342)
Oriental	2.7 (±0.11)	38 (±6.7)	0.67 (±0.04)	4120 (±291)
Sahrawi	2.0 (±0.20)	43 (±4.8)	0.77 (±0.20)	4341 (±641)
Concrete	3.5 (±0.05)	30 (±3.3)	0.85 (±0.05)	4010 (±176)

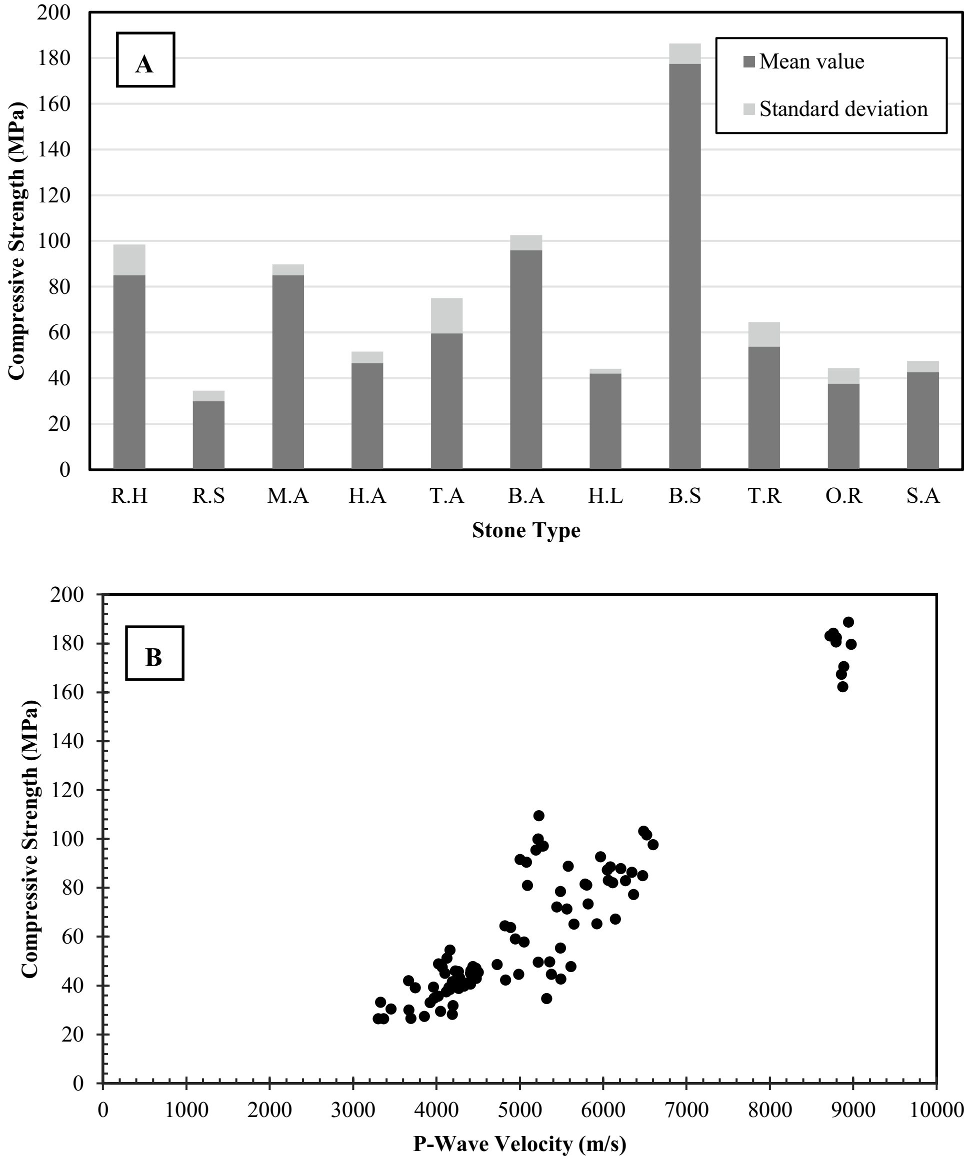

Fig. 5 **a** Variation in compressive strength for each type of the natural building stones. **b** Variation in compressive strength versus P-wave velocity of the natural building stones

building stones is directly proportional with respect to the compressive strength. Natural building stones made of igneous rocks such as Basalt have higher compressive strength and thermal conductivity compared to those made of sedimentary rocks. Basalt stone has the lowest water absorption and the highest thermal conductivity, compressive strength, and P-wave velocity among the other tested natural building stones. However, Ruwaished Soft has the highest water absorption and the lowest thermal conductivity, compressive strength, and P-wave velocity. Nevertheless, it was found that building stones have similar physical and mechanical behavior to concrete.

The original mineralogical composition of the natural building stones affects their mechanical and physical properties. Porosity and thermal conductivity play a major role in the sustainable characterization of natural building stones. For instance, the presence of pores in building stones decreases their strength and thermal conductivity. Rigid matrixes in building stones are created due to bonding portions of the solid material and shape in different forms of small voids and hollow spaces. This system is referred to as cellular insulation [30]. Evacuation of the air in the void space will reduce the effective thermal conductivity of the natural building stones. On the other hand, the presence of voids in the pores will increase the effective thermal conductivity. Therefore, the internal structure of a natural stone having open and closed pores in its texture affects its heat transfer. Porosity can be considered as a determinative parameter of compressive strength and thermal conductivity of natural building stones. The P-wave velocity of natural building stones is dependent also on

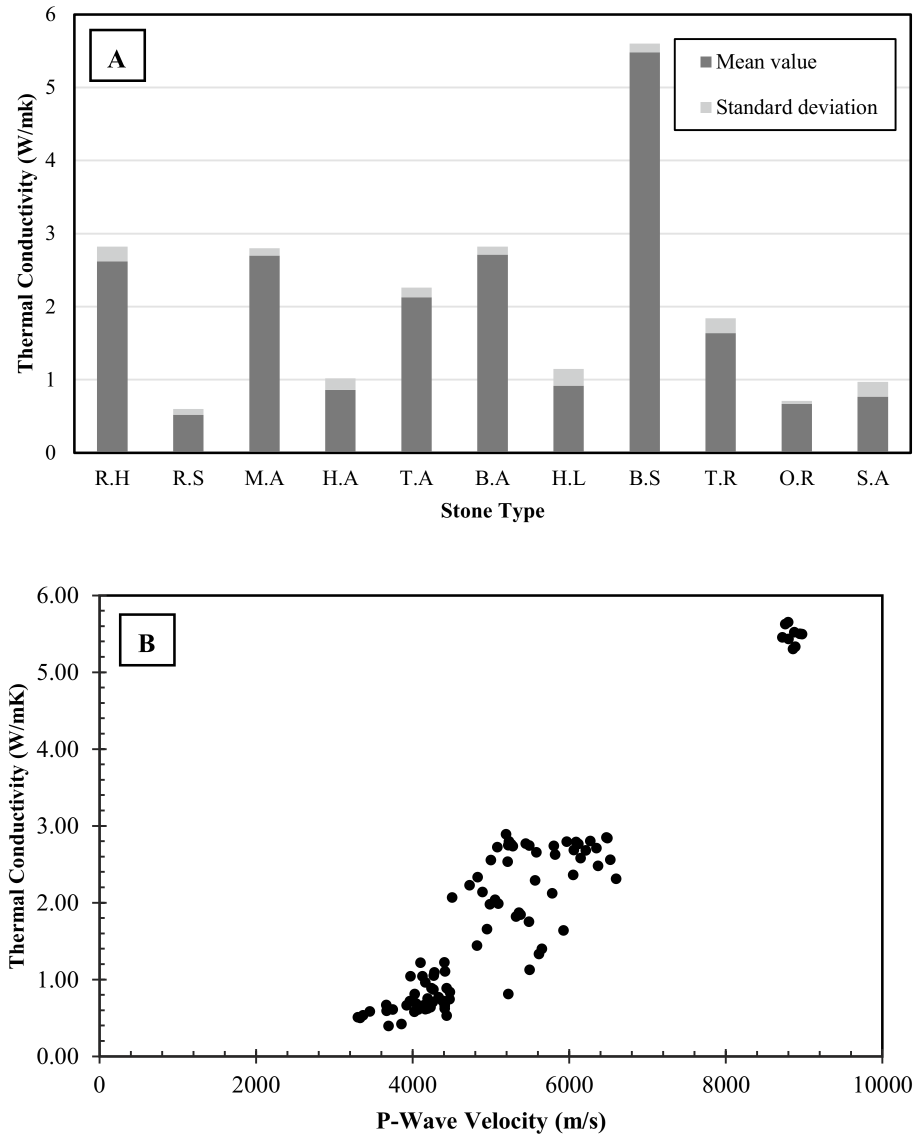

Fig. 6 **a** Variation in thermal conductivity for each type of the natural building stones. **b** Variation in thermal conductivity versus P-wave velocity of the natural building stones

their porosity. Therefore, natural building stones can be evaluated and characterized by the P-wave velocity.

Based on the obtained results as shown in Table 1 and Figs. 5, 6, 7, there is a statistical correlation that allows us to estimate the mechanical properties of building stones based on the ultrasonic pulse velocity. The mechanical properties of natural building stones can be estimated with respect to the ultrasonic pulse velocity by a nonlinear power regression model, which is based on the following equation:

$$M = Av^{B} \quad (1)$$

where (A) and (B) are fitting constants; (M) is the mechanical property; and (v) is the P-wave velocity. The regression line is determined to make the sum of the squares of the vertical distances of the data points from the line as small as possible. The regression analysis was performed to indicate the level of confidence and the acceptability of the obtained water absorption, compressive strength, and thermal conductivity based on the measured P-wave velocity of the tested specimens. The estimation models establish a relationship between P-wave velocity to compressive strength, thermal conductivity, and water absorption, as shown in Figs. 8, 9, 10.

P-wave velocity is directly proportional to compressive strength and thermal conductivity. The evaluation model of the compressive strength of natural building stones based on the P-wave velocity is given following with a correlation factor of 0.94:

$$f = 1.37 \times 10^{-6}(v)^{2.063} \quad (2)$$

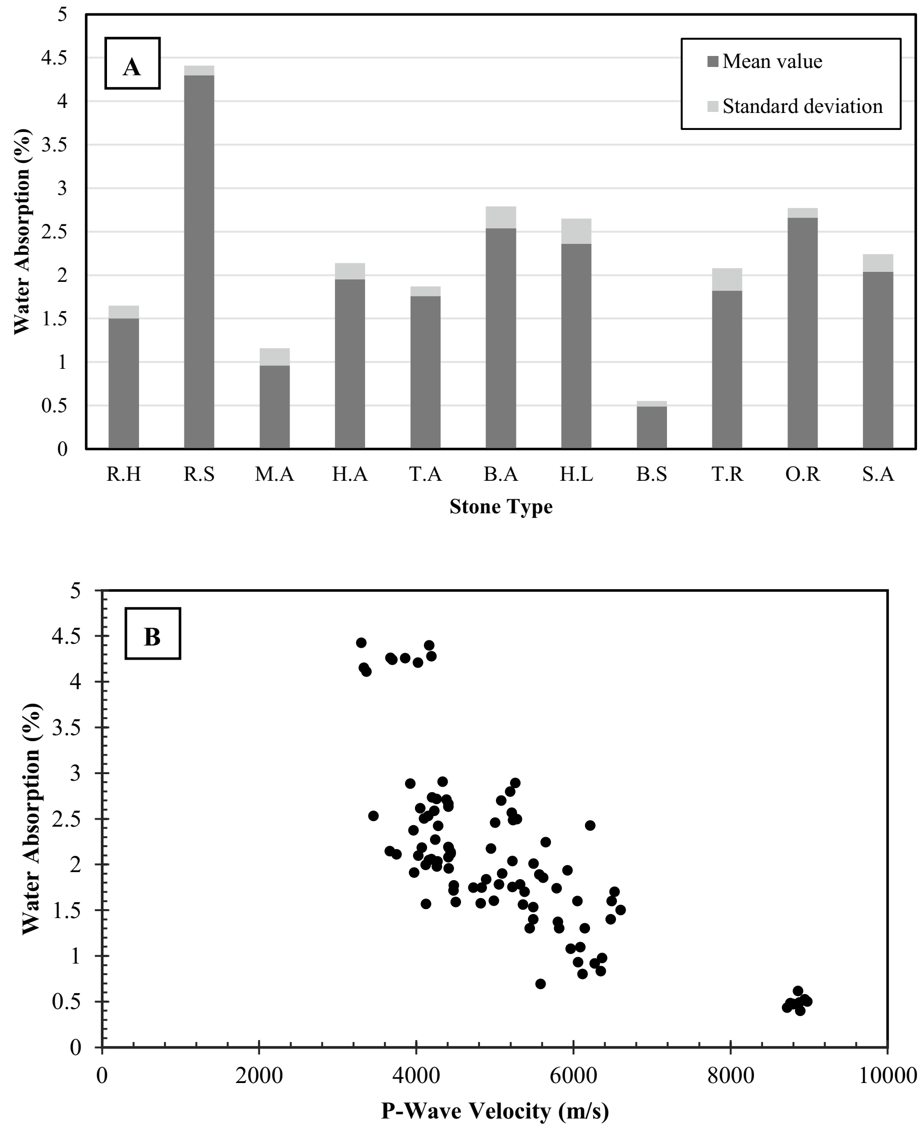

Fig. 7 **a** Variation in water absorption for each type of the natural building stones. **b** Variation in water absorption versus P-wave velocity of the natural building stones

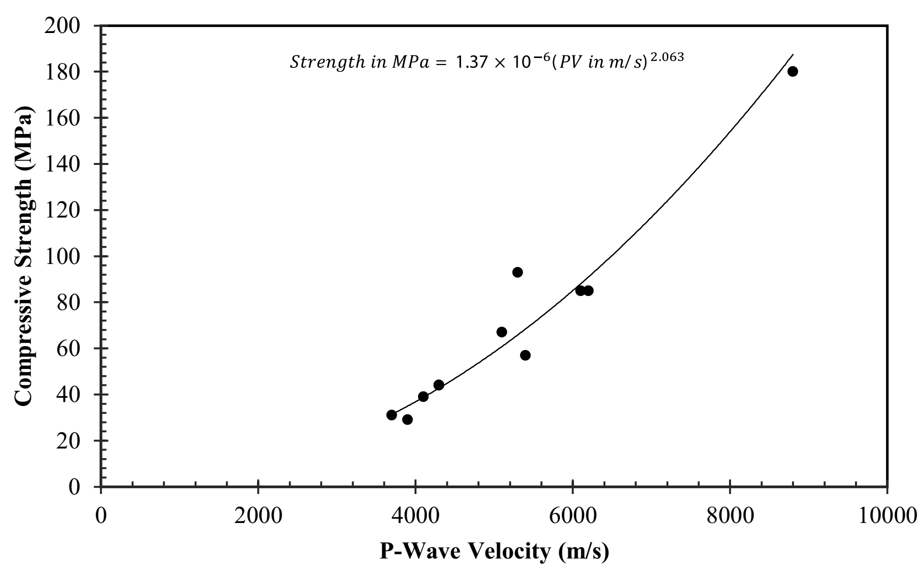

Fig. 8 Compressive strength versus P-wave velocity of the natural building stones

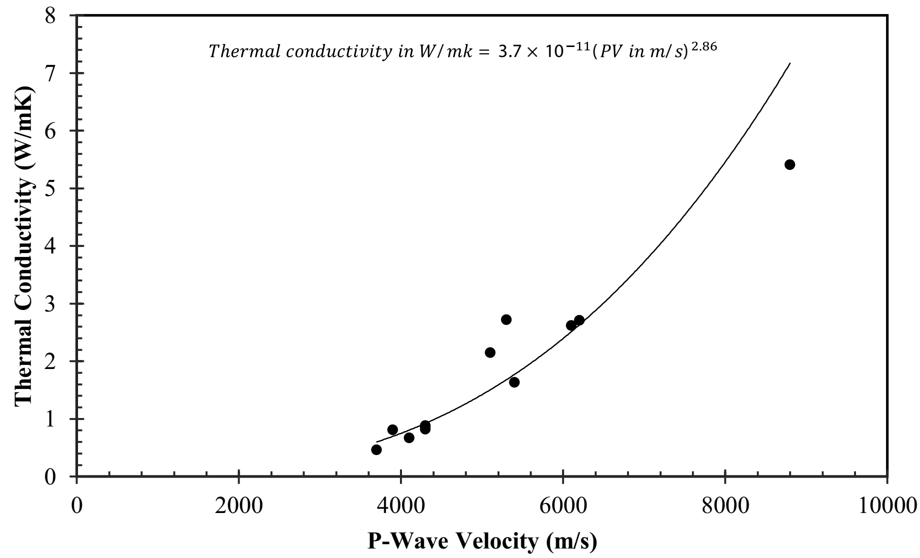

Fig. 9 Thermal conductivity versus P-wave velocity of the natural building stones

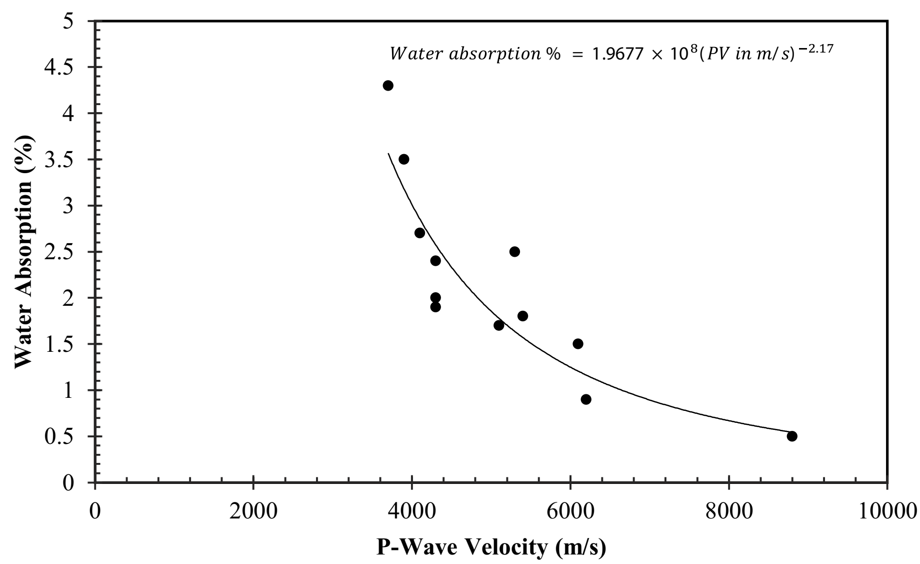

Fig. 10 Water absorption versus P-wave velocity of the natural building stones

where (*f*) is the compressive strength in (MPa), and (v) is the P-wave velocity in (m/sec). The evaluation model of the thermal conductivity of natural building stones based on the P-wave velocity is given following with a correlation factor of 0.91:

$$\lambda = 3.7 \times 10^{-11}(v)^{2.86} \quad (3)$$

where (λ) is the thermal conductivity in (W/mK), and (v) is the P-wave velocity in (m/sec). The evaluation model of water absorption of natural building stones based on the P-wave velocity is given following with a correlation factor of 0.86:

$$W = 1.9677 \times 10^{8}(v)^{-2.17} \quad (4)$$

where (W) is the water absorption in (%), and (v) is the P-wave velocity in (m/sec). The applicability of the proposed models in evaluating natural building stones has been investigated with respect to different experimental data that were selected from the literature [7, 13, 31]. Compressive strength, thermal conductivity, and water absorption of natural building stones have been calculated by substituting the experimental values of ultrasonic velocity in the proposed models. Comparison of the experimental and analytical values are presented in Fig. 11, where the computed values are plotted against their corresponding experimentally obtained values.

It was observed that the proposed evaluation model of the compressive strength has an average absolute error of 14%. On the other hand, the proposed evaluation model of

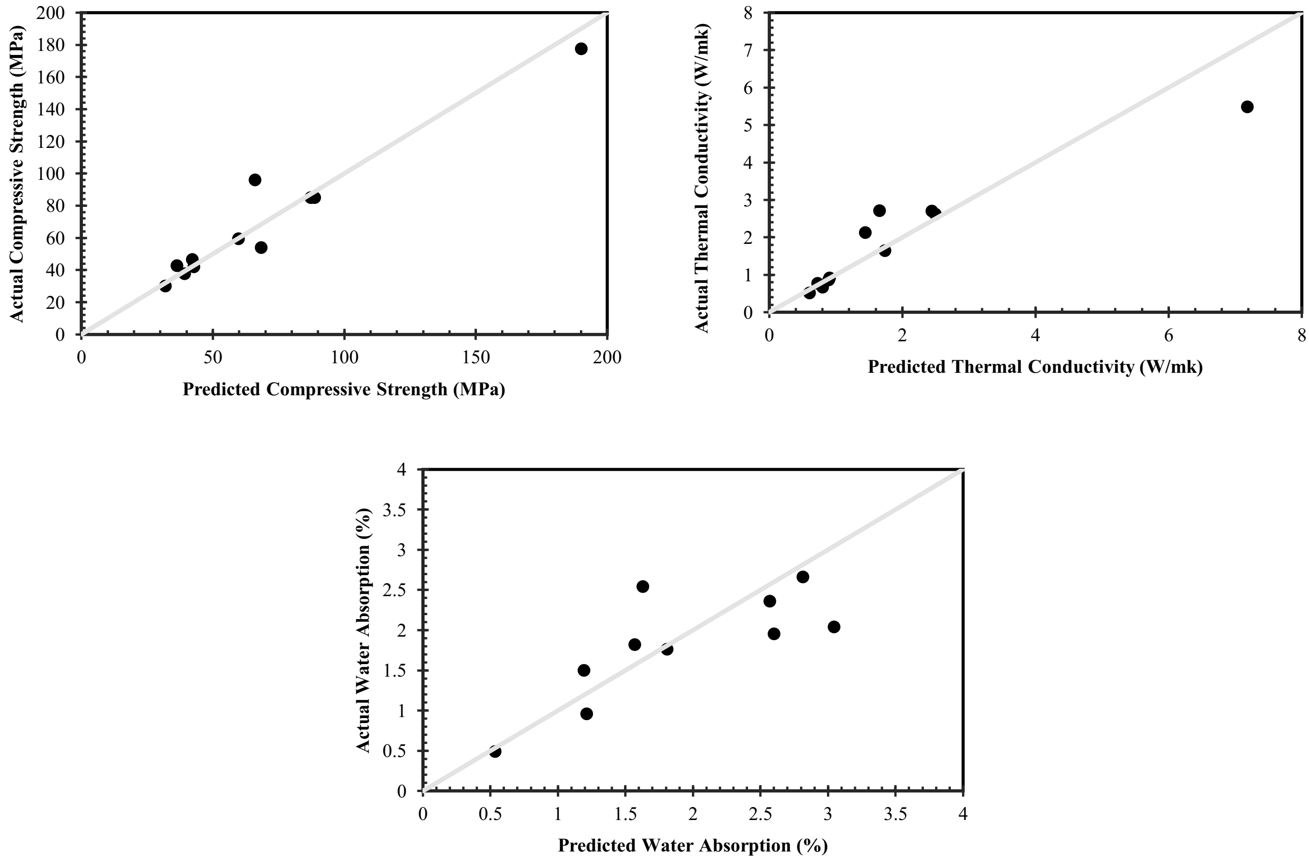

Fig. 11 Comparison between actual and predicted characterizations of natural building stones based on the proposed models

thermal conductivity has an average absolute error of 9%. The absolute error percentage was obtained by dividing the difference between the theoretical and experimental values by the calculated theoretical value. There is an inconsistency between the analytical and the experimental values of water absorption of natural building stones. Nevertheless, the proposed models are still applicable for evaluating natural building stones.

4 Conclusions

This paper presents an experimental study that aims to establish in-situ evaluation models of mechanical properties and thermal conductivity of natural building stones using the non-destructive ultrasonic testing technique. As a result of the study, the following conclusions can be drawn:

- Ultrasonic pulse velocity is a non-destructive, easy, and confidential method that allows an in-situ estimation of compressive strength, thermal efficiency, and water absorption of the building stones.
- Ultrasonic pulse velocity of building stones depends on their mechanical properties. Ultrasonic pulse velocity is proportionated inversely to water absorption and directly to the compressive strength and thermal conductivity.
- Natural building stones made of igneous rocks, such as Basalt, have higher compressive strength and thermal conductivity than those made of sedimentary rocks. Ruwaished Soft stone has the lowest thermal conductivity among the tested building stones.
- The direction of stones' rift affects their mechanical properties. The results emphasize that there are slight differences in the compressive strength of natural building stones when loaded parallel or perpendicular to the rift.
- Based on the P-wave velocity, prediction models were established of compressive strength, thermal conductivity, and water absorption of the building stones. Strong statistical correlations were found between the P-wave velocity and the mechanical properties of the natural building stones. The established models can be used for an in-situ evaluation of the natural building stones with sufficient accuracy.

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