PROCEEDINGS of the
23rd International Congress on Acoustics

9 to 13 September 2019 in Aachen, Germany

The effect of water saturation on the P-wave velocity of sedimentary rocks

Sair KAHRAMAN[1]

Hacettepe University, Turkey

ABSTRACT

Since ultrasonic methods are non-destructive and easy to apply, they have been widely used in various fields such as mining and civil engineering applications. The water content of rock strongly influences seismic waves. Rock engineers sometimes need to estimate the wet-rock P-wave velocity from the dry-rock P-wave velocity. In this study, in order to investigate the predictability of wet-rock P-wave velocity from the dry-rock P-wave velocity, P-wave velocity measurements were performed on the thirty-six core specimens pertaining to six different sedimentary rocks. The evaluation of the results showed that P-wave velocity increment due to saturation was about 30 %. The wet-rock P-wave velocity values were also correlated to the dry-rock P-wave velocity values. A very strong linear correlation was found between the two parameters. Concluding remark is that the wet-rock P-wave velocity values of sedimentary rocks can be predicted from the developed empirical equation.

Keywords: P-wave velocity, Sedimentary rocks, Water saturation

1. INTRODUCTION

Seismic methods are non-destructive and easy to apply. Therefore, they are increasingly being used in various fields such as mining, geotechnical, civil, and underground engineering applications or laboratory investigations.

There are a number of factors that influence the sound velocity of rocks. The important factors are rock type, texture, density, grain size and shape, porosity, anisotropy, water content, stress and temperature. In addition to these factors, rock mass properties also influence the sound velocity. Weathering and alteration zones, bedding planes and joint properties (roughness, filling material, water, dip and strike etc.) have important influence on the sound velocity.

Early theories were proposed by Gassmann (1) and Wood (2) on the effects of saturation on the seismic velocities. The variation of velocity in sandstone as a function of water content was studied by Wyllie et al. (3). They observed a marked decrease in the P-wave velocity as the saturation was reduced from 100 % to approximately 70 %. Between 70 % and 10 % the P-wave velocity was nearly constant and below 10 % P-wave velocity usually increased to dry P-wave velocity. Wyllie et al. (4) clearly showed that the velocity of fluid-saturated rocks was dependent on the ratio between the velocity of rock and the velocity of pore fluid. The influence of saturation on pulse velocity in St. Cloud granodiorite was examined by Thill and Bur (5). They observed that a remarkable velocity changes could occur even in compact rock having only a minute amount of porosity. Nur and Simmons (6) measured the compressional wave velocity in a sample of Chelmsford granite, initially saturated with water but allowed to dry in the atmosphere over a period of four days. They indicated that a rapid change of velocity occurred in the first a few hours even though the porosity of the sample was only about 1%.

The study carried out by Ramana and Venkatanarayana (7) on Kolar rocks indicated that in general both weight and velocity increased with increasing the time of saturation. Beyond 48 hours the saturation curves tended to be steady. Gregory (8) studied the influence of saturation by water, oil, gas, and mixtures of these fluids on the densities, velocities, reflection coefficients, and elastic moduli of consolidated sedimentary rocks in the laboratory by ultrasonic wave propagation methods. He found that fluid saturation effects on compressional wave velocity were much larger in low-porosity than in high-porosity rocks. Lama and Vutukuri (9) and Bourbié et al. (10) reported that the wetting of rocks

[1] sairkahraman@yahoo.com

usually leads to a rise in the P-wave velocities. However, since the P-wave velocity in water is less than the P-wave velocity in mineral skeleton, generally the wave velocity in more porous rocks completely saturated with water is less than in slightly porous rocks.

Guéguen and Palciauskas (11) state that elastic wave velocities in rocks are closely related to microstructural changes such as pore structure and connectivity. A theoretical model was suggested by David and Zimmerman (12) for predicting the wet P- and S-wave velocities as function of the dry ones, based on thin, closable cracks having a distribution of aspect ratios, and stiff, nearly spherical pores that do not close under pressure. Pimienta et al. (13) showed that elastic velocities in Fontainebleau samples appeared to depend on the moisture content, while such relation were not observed for limestones. Furthermore, the decrease in the velocities for quartz-pure sandstone increases with porosity. These measurements thus confirm that weakening from moisture does not originate from the presence of clay minerals, but from the rock microstructure.

Kahraman (14) carried out dry- and wet-rock P-wave velocities on the different rocks types and found a strong linear correlation between the dry- and wet-rock P-wave velocities. Recently, Kahraman et al. (15) investigated the correlations between the dry- and wet-rock P-wave velocities for pyroclastic rocks. They derived estimation equations between the two parameters for the samples having porosity values of less than 20 % and greater than 20 %, respectively.

In this study, the influence of water saturation was investigated on the P-wave velocity of sedimentary rocks such as limestone, travertine, and sandstone, and a prediction equation was developed for the dry-rock P-wave velocity from the wet-rock P-wave velocity.

2. SAMPLING

The block samples of rocks were collected from the stone processing plants in Kayseri and Konya areas of Turkey for the laboratory testing. In order to provide the test specimens free from fractures, partings or alteration zones, block samples were inspected for macroscopic defects. A total of 6 different rock types were sampled, 4 of which were limestone, 1 of which were travertine, and 1 of which was sandstone. The locations and the types of the rocks sampled are given in Table 1. Thirty-six core specimens in NX size were prepared from the block samples.

Table 1 – The rock types and the locations of the tested rocks.

Rock code	Location	Rock type
1	Yahyali/Kayseri	Dolomitic Limestone
2	Bunyan/Kayseri	Limestone (Bunyan rosa)
3	Bunyan/Kayseri	Limestone (Bunyan beige)
4	Bogazliyan/Yozgat	Limestone (Bogazliyan beige)
5	Bogazliyan/Yozgat	Travertine
6	Niğde	Sandstone

3. LABORATORY STUDIES

The samples having a diameter of 54.7 mm and a length of 110 mm were used in the P-wave velocity measurements. The end surfaces of the core samples were polished sufficiently smooth to provide good coupling. In the tests, the PUNDIT 6 instrument and two transducers (a transmitter and a receiver) with the frequency of 1 MHz were used. A good acoustic coupling between the transducer face and the rock surface is necessary for the accuracy of transit time measurement. Stiffer grease was used as a coupling agent in this study. The transducers were pressed to either end of the sample and the pulse transit time was recorded (Figure 1).

The sound velocity tests were first carried out on the samples oven-dried at a temperature of 105ºC for a week. Then, the samples were saturated with tap water for a week and the tests were repeated. The P-wave velocity values were calculated by dividing the length of core to the pulse transit time. The average P-wave velocity values are given in Table 2 for each rock type.

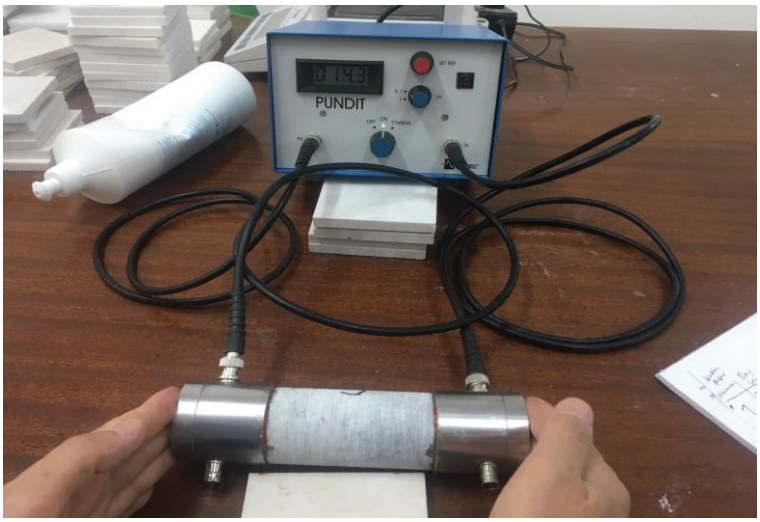

Figure 1 – P-wave velocity measurement.

Table 2 – The average P-wave velocity values for each rock type

Rock code	Number of the specimen	Dry rock P-wave velocity (km/s)	Wet rock P-wave velocity (km/s)	Increment in the P-wave velocity (%)
1	7	5.01	6.50	29.8
2	7	4.67	6.30	34.9
3	8	4.51	5.86	30.0
4	7	4.98	6.52	31.0
5	4	4.19	5.61	33.9
6	3	3.90	4.99	28.0

4. EVALUATION OF THE RESULTS

The dry rock P-wave velocity values range from 3.90 km/s to 5.01 km/s as shown in Table 2. Correspondingly, the wet rock P-wave velocity values vary from 4.99 km/s to 6.52 km/s. Table 2 also presents the increments in the P-wave velocity values due to the water saturation. It can be said that the average increment in the P-wave velocity due to the saturation is about 30 %.

The dry- and wet-rock P-wave velocity values were evaluated using the method of least squares regression. As shown in Figure 2, there is a very strong linear correlation (r = 0.96) between the two parameters. The equation of the line is:

$$V_{P(wet)} = 1.31V_{P(dry)} \tag{1}$$

where, where $V_{P(wet)}$ is the wet-rock P-wave velocity (km/s), and $V_{P(dry)}$ is the dry-rock P-wave velocity (km/s).

Kahraman (14) derived the following equation between the dry- and wet-rock P-wave velocity for sedimentary rocks:

$$V_{P(wet)} = 1.19V_{P(dry)} + 0.67 \tag{2}$$

In order to see if there is a difference or similarity between the derived equation and Kahraman's equation Figure 3 was plotted. The lines of the two equations are quite similar at high P-wave velocity values. However, there is a significant difference between the two lines at low velocity values. The reason for the differences between the two equation is probably due to the fact that the differences of the tested rock types and the number or the tested specimens. Thirty-six specimens were tested in this study while Kahraman (14) tested fifteen specimens. It can be said that the derived relation is more reliable than Kahraman's equation since it has a very high correlation coefficient and far more data points.

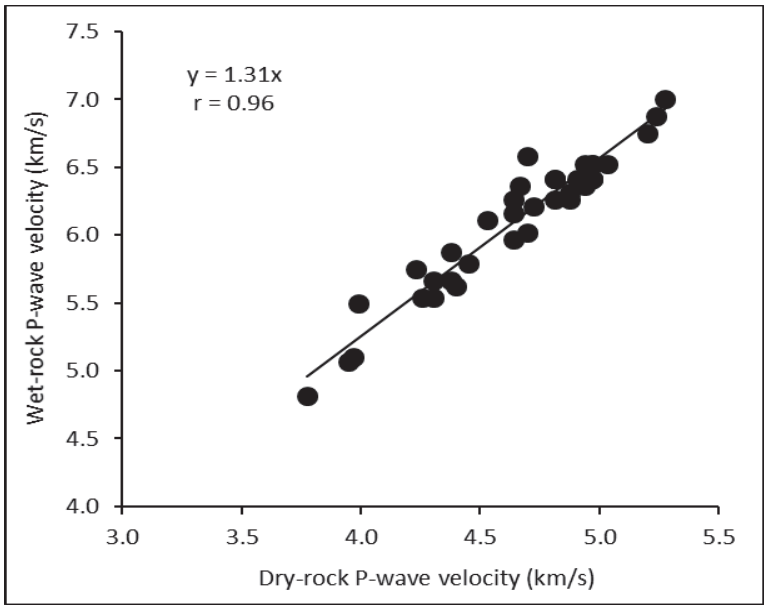

Figure 2 – The correlation between the dry- and wet-rock P-wave velocity values.

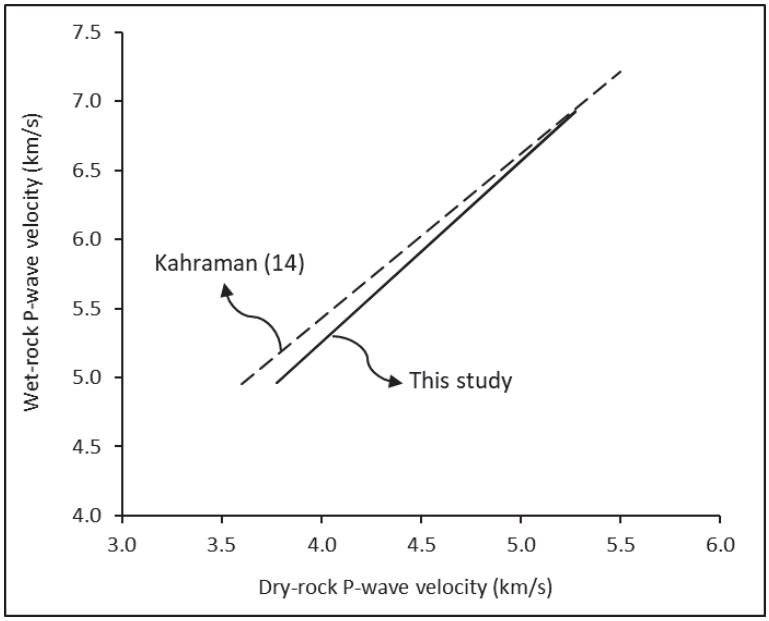

Figure 3 – The comparison between the derived relation and the previous relation.

5. CONCLUSIONS

The influence of water saturation on the P-wave velocity of sedimentary rocks was investigated. The relation between the dry-rock and wet-rock P-wave velocities was also studied. The results indicated that P-wave velocity increment due to saturation was about 30 %. A very strong linear correlation was also found between the dry-rock and wet-rock P-wave velocities.

It can be concluded that the wet-rock P-wave velocity values of sedimentary rocks can be estimated using the developed empirical equation. Further research is required to check the validity of the derived equation for the other sedimentary rocks such as marl, shale, siltstone etc.

REFERENCES

1. Gassmann F. Über die Elastizität poröser Medien. Zürich, Switzerland: Inst. für Geophysik an der ETH; 1951.
2. Wood AB. A textbook of sound. London, UK: G. Bell and Sons Ltd.; 1941.

3. Wyllie MRJ, Gregory AR, Gardner LW. 1956. Elastic wave velocities in heterogeneous and porous media. Geophysics 21: 41-70.
4. Wyllie MRJ, Gregory AR, Gardner GHF. An experimental investigation of factors affecting elastic wave velocities in porous media. Geophysics 1958;23: 459-493.
5. Thill RE, Bur TR. An automated ultrasonic pulse measurement system. Geophysics 1969;34: 101-105.
6. Nur A, Simmons G. The effect of saturation on velocity in low porosity rocks. Earth and Planetary Science Letters 1969;7: 183-193.
7. Ramana YV, Venkatanarayana B. Laboratory studies on Kolar rocks. Int. J. Rock Mech. Min. Sci. 1973;10: 465-489.
8. Gregory AR. Fluid saturation effects on dynamic elastic properties of sedimentary rocks. Geophysics 1976;41: 895-721.
9. Lama RD, Vutukuri VS. Handbook on mechanical properties of rocks, Vol. 2. Clausthal, Germany: Trans Tech Publications; 1978.
10. Bourbié T, Coussy O, Zinszner B. Acoustics of porous media. Paris, France: Editions Technip; 1987.
11. Guéguen Y, Palciauskas V. Introduction to the Physics of Rocks. New Jersey, USA: Princeton University Press; 1994.
12. David EC, Zimmerman RW. Pore structure model for elastic wave velocities in fluid-saturated sandstones. J. Geophys. Res. 2012;117, B07210, doi:10.1029/ 2012JB009195.
13. Pimienta L, Fortin J, Guéguen Y. Investigation of elastic weakening in limestone and sandstone samples from moisture adsorption. Geophysical Journal International 2014;199(1): 335-347.
14. Kahraman S. The correlations between the saturated and dry P-wave velocity of rocks. Ultrasonics 2007;46: 341-348.
15. Kahraman S, Fener M, Kilic CO. Estimating the wet-rock P-wave velocity from the dry-rock P-wave velocity for pyroclastic rocks. Pure Appl. Geophys. 2017;174: 2621–2629.