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Ultrasonic velocity as a tool for mechanical and physical parameters prediction within carbonate rocks

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Abstract. Physical and mechanical properties of rocks are of interest in many fields, including materials science, petrophysics, geophysics and geotechnical engineering. Uniaxial compressive strength UCS is one of the key mechanical properties, while density and porosity are important physical parameters for the characterization of rocks. The economic interest of carbonate rocks is very important in chemical or biological procedures and in the field of construction. Carbonate rocks exploitation depends on their quality and their physical, chemical and geotechnical characteristics. A fast, economic and reliable technique would be an evolutionary advance in the exploration of carbonate rocks. This paper discusses the ability of ultrasonic wave velocity to evaluate some mechanical and physical parameters within carbonate rocks (collected from different regions within Tunisia). The ultrasonic technique was used to establish empirical correlations allowing the estimation of UCS values, the density and the porosity of carbonate rocks. The results illustrated the behavior of ultrasonic pulse velocity as a function of the applied stress. The main output of the work is the confirmation that ultrasonic velocity can be effectively used as a simple and economical non-destructive method for a preliminary prediction of mechanical behavior and physical properties of rocks.

Keywords: ultrasonic velocity; non-destructive testing; carbonate rocks; compressive strength; UCS; porosity; density

1. Introduction

Rocks show a variety of physical and mechanical properties that may affect their use as a construction material (Irfan 1996). For instance, many disasters were associated with the misunderstanding of the mechanical properties of rocks. Rock physical properties include density and porosity. Mechanical properties mainly include rock strength. Tensile strength and compressive strength are the widely used rock strength parameters (Peng and Zhang 2007).

The uniaxial compressive strength (UCS) is one of the most important mechanical parameters

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in rocks. However, it is not always possible to conduct uniaxial compressive strength test as it is expensive, time consuming and destructive. Consequently, the ability to estimate this parameter accurately is very necessary (Lai *et al*. 2016). That's why researchers have been developing improved, fast and reliable techniques to measure rock characteristics indirectly. An example of such techniques is the ultrasonic testing which appears to be a promising technique for experimental investigation in the laboratory (Lai *et al*. 2016). Acoustic radiations are frequently used to evaluate and predict geo-materials resistance (Vergara *et al*. 2001, Lotfi *et al*. 2010 and Kurtulus *et al*. 2012). In fact, Ultrasonic wave propagation depends on the physical and mechanical parameters of a geo-material (Maev 2008). It was shown that the sound velocity of a rock is closely related to its dynamic properties (Yasar and Erdogan 2004). For that reasons, many researchers used ultrasonic techniques, such as ultrasonic pulse velocity and ultrasonic tomography, to characterize different materials such as rocks and concrete, and claimed that these techniques are among the best ways to investigate the elastic properties of such materials (Hall and Popovics 2016, Maev 2008, Lotfi *et al*. 2010, Vasconcelos *et al*. 2008, Shariati *et al*. 2011). Ultrasonic techniques are non-destructive and easy to apply, both for site and laboratory conditions in rock engineering researches. Ultrasonic velocity was used to characterize the compressive strength, density and porosity of concrete and rocks.

Therefore, the ultrasonic velocity test has been pointed out by several authors as useful and reliable nondestructive tool of assessing the mechanical properties of various materials. Over the years, different correlations between mechanical and physical parameters of geo materials with ultrasonic velocities were set (Lai *et al*. 2016, Kurtulus *et al*. 2012, Yasar and Erdogan 2004, Del Rıo *et al*. 2004, Vasconcelos *et al*. 2008, Shariati *et al*. 2011 and Chen *et al*. 2015).

Kurtulus *et al*. 2012 determined the mechanical properties of serpentinized ultrabasic rocks through ultrasonic velocity measurements. Yasar and Erdogan (2004) correlated sound velocity with density, compressive strength and Young's modulus in carbonate rocks. Within concrete samples, Del Rıo *et al*. (2004) reported the correlation between compressive strength and ultrasonic velocity. UCS and other physical properties of basalt samples were determined by ultrasonic p-wave velocity (Chen *et al*. 2015). More recently, Ongpeng *et al* studied the behavior of the compressive stress using ultrasonic test in concrete (Ongpeng *et al*. 2017).

Carbonate rocks are present in many geological formations of the Mediterranean region yielding a variety of carbonate rocks. Tunisia is actually among the countries that produces carbonate ornamental stones commonly used as building stone, and thus constituting an important industry nowadays (Calvo and Regueiro 2010). Thus, the central issue of the present paper was to evaluate the suitability of the ultrasonic method for describing the mechanical and physical properties of carbonate rocks. Correlations between ultrasonic velocity and the mechanical and physical properties of carbonate rocks were discussed.

2. Experimental procedure

2.1 Carbonate rock material and sample preparation

15 samples were collected from 8 localities (see Fig. 1), and shaped to form a cube of dimensions 10×10×10 cm (Fig. 2). Localities were chosen to contribute with different degrees of strength in order to cover a wide range of compressive strength values. Table 1 summarizes the mains properties of the 15 samples collected for this study.

2.2 Ultrasonic testing

The velocities of longitudinal waves were determined using the pulse transmission method, which consists of coupling two piezoelectric sensors on the opposite faces of the sample (see Fig. 3). 'Time-of-flight' of the ultrasonic waves was calculated with a commercially available meter (Matest Company). A visco-elastic gel was applied on flat surface of the sample to act as a coupling medium and to enhance the transmission of ultrasonic waves.

The sample was positioned between the transmitter and the receiver and the faces of the transducers were firmly pressed against the surfaces of the rock cubes until a stable transit time is

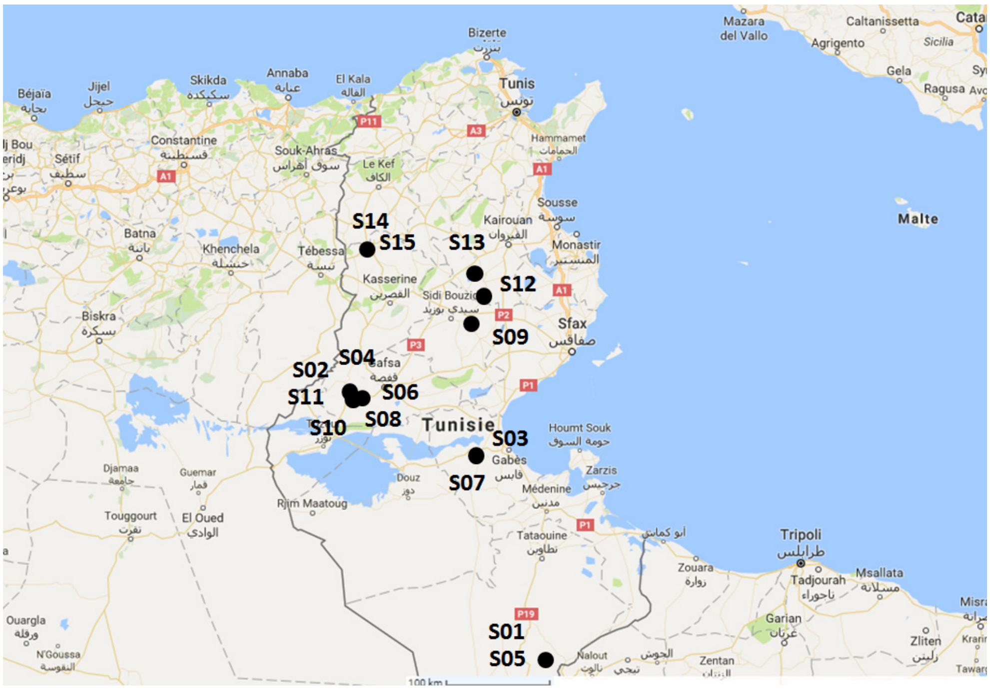


Fig. 1 Localities of carbonate rock samples (Scale 1/10000000)

Fig. 2 Picture of carbonate rocks samples

Table 1 Rock samples description

Sample	Location	Geologic age	Ultrasonic velocity (m/s)	Effective porosity (%)	Density (g/cm^3)	Compressive strength (MPa)
1	DJ MATOUS sahara	Turonian	4221,31148	11,7435681	2,07063819	18,1277
2	KEF EDDOUR METLAOUI	Paleocene	2814,20765	17,8464825	2,09902643	16,8723
3	DJ AZIZA HAMMA	Cenomanian	5396,8254	1,93530846	2,60247608	45,6404
4	KEF EDDOUR METLAOUI	Paleocene	2263,73626	19,2026496	2,1278826	17,022
5	MATOUS sahara	Turonian	4227,64228	12,69063	2,05864208	20,0287
6	KEF EDDOUR METLAOUI	Paleocene	3316,99346	18,9837473	2,12805578	15,6958
7	DJ AZIZA HAMMA	Cenomanian	4951,45631	3,00112429	2,64797084	41,1304
8	KEF EDDOUR METLAOUI	Paleocene	3468,01347	17,7199382	2,11745374	16,1119
9	DJ MATLEG SIDI BOUZID	Cenomanian-Turonian	4858,49057	10,4101975	2,40560453	37,0198
10	KEF EDDOUR METLAOUI	Paleocene	3312,10191	19,3463494	2,11325083	15,4161
11	KEF EDDOUR METLAOUI	Paleocene	3211,00917	19,1088779	2,09757157	21,901
12	KABBARA	Maastrichtian-Paleocene	4724,77064	6,84662853	2,49525241	66,3695
13	Essoualem	Lutetian-Ypresian	3845,88951	6,31828716	2,35919509	33,3246
14	THALA	Campanian-Maastrichtian	4871,794871	5,78787879	2,63333333	50,3621
15	THALA	Campanian-Maastrichtian	5636,363636	3,95	3,03875	50,274

displayed. The velocities are calculated from the measured travel times and the distance between transmitter and receiver. Thus, the ultrasonic pulse velocities (m/s) were calculated as follows: $V = L/T$ where:

V = pulse velocity (m/s),

L = length of the straight-wave-path through the specimen which corresponds to the distance between transducer faces, (i.e., 100 mm in this study).

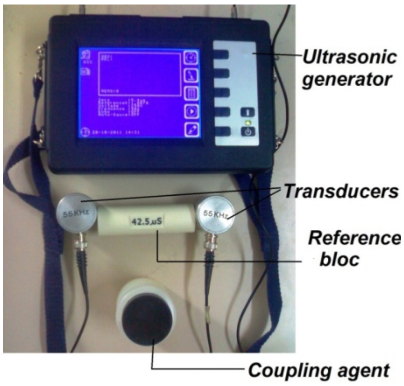


Fig. 3 Ultrasonic device

Fig. 4 Uni-axial compression apparatus

T = transit time (s).
The transducers were placed perpendicularly to the load axis.

2.3 Uniaxial compressive assay

Specimens are loaded continuously to failure at a constant stress rate of 0.020 (MPa/second) using the testing machine; Matest equipment Cyber-plus evolution (Italy) (see Fig. 4). Travel time of the ultrasonic pulse was recorded at 5 kN intervals of the incremental uniaxial loading in order to capture all important trends of the velocity development under continuous increasing stress.

2.4 Uni-axial compressive strength measures

The uni-axial compressive strength UCS (stress at failure) of a specimen during the test was calculated by dividing the total maximum load (compressive stress) by the loaded surface area.

2.5 Porosity and density measures

Effective porosity was calculated using saturated samples. Effective porosity represents the ratio of the interconnected pore space to the total volume of the rock (Peng and Zhang 2007). It is represented by the volume of the water that fills the accessible pores. Porosity was then determined by measuring the difference between the weight at saturated conditions and the weight before saturation (Lafhaj and Goueygou 2009). Rock density is a measure of mass of the rock contained in a given unit volume (density = mass/volume). It is usually expressed in g/cm^3 (Peng and Zhang 2007). Therefore, density measures were based on weight and volume measures.

3. Results and discussion

Ultrasonic velocity is a non-destructive technique used in the estimation of the strength of geo-materials. The procedure implies the definition of a calibration curve that is applied to materials of identical composition, which are tested under similar conditions. The assessment of the rock properties by means of simple non-destructive techniques, revealed the dependence of the mechanical properties, namely the compressive strength, the density and porosity on ultrasonic velocity.

For this purpose, results of measurements of the ultrasonic velocities through carbonate rocks was carried out on specimens collected from distinct regions of the south and the middle of Tunisia, known to carry a large variety of such rocks. The economic interest of carbonate rocks is very important for many fields. Carbonate stones are commonly used as building stone constituting an important industry in Tunisia and over the world.

In carbonate rocks exploitation, strength density and porosity are important parameters to consider. In marble rocks for example: strength, porosity and color are the main factors for exploration. A fast and economic in situ technique that enables to estimate such parameters within carbonate rocks is required regarding the complexity of laboratory techniques.

The present section aims to present and discuss correlations that enable the estimation of carbonate rocks properties from ultrasonic velocities.

3.1 Correlation between uni-axial compressive strength and ultrasonic velocities

The relationship between the velocity of the longitudinal ultrasonic waves and the uniaxial compressive strength are displayed in Fig. 5.

Because rocks vary so widely, the compressive strength is a useful and widely quoted rock index property. Uniaxial compressive strength UCS is one of the key properties for the characterization of either rock or other materials. It is widely used for the engineering classification of rocks determined in a laboratory test.

In fact, ultrasound is practically among the best of non-destructive techniques for the assessment of resistance characterized by compressive strength. In our study, compressive strength values of carbonates rocks ranges from 15 to 50 MPa. According to literature, compressive strength could range from 3 to 120 Mpa (Yasar and Erdogan 2004, Madhubabu *et al*. 2016).

As shown in the Fig. 5, the initial ultrasonic velocities and the corresponding UCS values, within carbonate rocks, has a linear correlation (Ultrasonic velocity V = 47,36 UCS + 2605).

In fact, discontinuities are barriers to wave propagation. They diminish the intensity of the transmitted wave and decrease its velocity. A higher propagation velocity means a more compacted medium and, therefore, more resistant. That's why it is expected that the initial velocity (measured at rest) increases for samples with a higher strength. Overall, higher velocities go with higher UCS, as Lafhaj *et al*. (2006) explained.

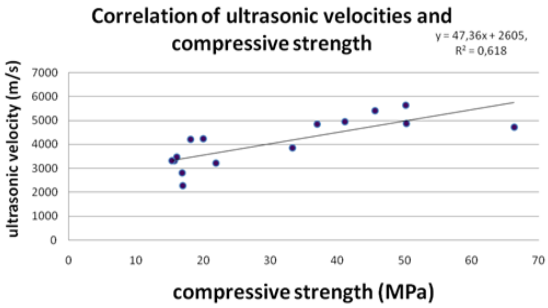


Fig. 5 Correlation between ultrasonic velocities and compressive strength within carbonate rocks

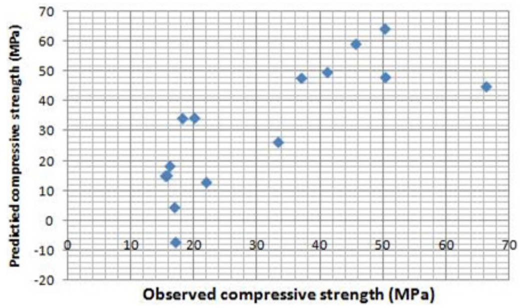


Fig. 6 Observed UCS versus predicted UCS

Within concrete, Shariati *et al*. (2011) reported a linear relationship between UCS and ultrasonic velocity. Yasar and Erdogan (2004) reported a similar relationship within carbonate rocks. Chen *et al*. (2015) established a linear correlation between UCS and ultrasonic velocities within basalt. A recent Malaysian study established empirical correlations (exponential correlations) to estimate the value of UCS from ultrasonic velocity travel time for granite and schist (Lai *et al*. 2016).

In order to verify our equations, we compared the observed UCS from lab measurements with the predict value using the empirical equation. Here as shown in the Fig. 6, the observed compressive strength versus predicted data plots almost follow a diagonal line.

As mentioned above, the uniaxial compressive strength is one of the most common mechanical parameters required to characterize the compressive strength of rocks. It is determined by applying an increasing compressive stress to the sample until it fails. Measurements of UCS are expensive, time consuming and destructive and thus, not applicable *in situ*. Therefore, a simple and practical application is needed for the estimation of UCS, such as ultrasonic testing, throughout the established calibration curve.

3.2 Correlation between effective porosity and ultrasonic velocity for carbonate rock samples

Effective porosity is considered to reflect the total interconnected pore space of a specimen. Porosity is a control factor of rock strength. It is a key parameter that controls the deformation and failure modes of carbonate rocks (Nicolas *et al*. 2016). In addition, porosity is the main controlling factor in determining the sonic velocity in rocks (Eberli *et al*. 2003).

In our study, the initial ultrasonic velocities (measured at rest) were plotted against porosity. In fact, ultrasonic velocities decrease as porosity increases, as expected, because the voids in the material constitute probably a sort of barrier to the waves (Lafhaj and Goueygou 2009, Hernández *et al*. 2002). Thus, a linear relation was established between ultrasonic velocity and effective porosity following the equation $V = -13411$ P + 5638) where P is Porosity (Fig. 7). Similarly, Kurtulus *et al*. (2012) correlated ultrasonic velocity with effective porosity in serpentinized rocks. Within granite, Vasconcelos *et al*. (2008) and Chen *et al*. (2015) reported an exponential correlation. Eberli *et al*. (2003) established the correlation velocity versus porosity within carbonates; the latter followed an exponential curve. According to him and similarly to our results, he explained this trend by the fact that velocity is strongly dependent on the rock-porosity.

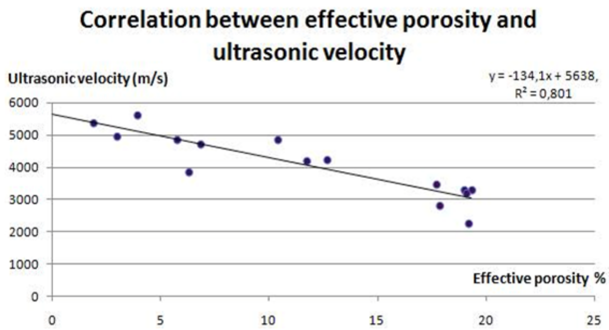


Fig. 7 Correlation between ultrasonic velocities and effective porosity within carbonate rocks

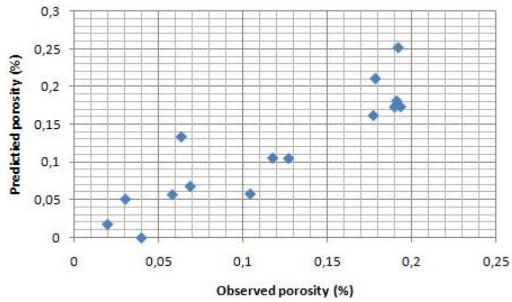


Fig. 8 Observed porosity versus predicted porosity

Therefore, a plot of porosity versus velocity displays a clear inverse trend; an increase in porosity produces a decrease in velocity. Actually, the processes that affect the durability of such a material are mostly related to its porous structure (Vergara *et al*. 2001). Consequently, it is important to produce accurate porosity estimates from ultrasonic pulse velocity measurements. Further work is needed to predict total porosity.

Once again, and in order to verify our equations, we compared the observed values with the predicted values. It was shown that the mentioned are well correlation using the established equation (see Fig. 8).

3.3 Correlation between density and ultrasonic velocity for carbonate rock samples

To evaluate these results, a linear regression is performed as presented in the Fig. 9. (V = 2467 D – 1551) where D is density. The propagation velocity increases linearly with the density. In accordance with what we previously discussed, a relatively denser material is actually less porous and thus presents a higher velocity. The study conducted by Vasconcelos *et al*. (2008) established a similar linear relationship between the density of granite and ultrasonic velocity. Yasar and Erdogan (2004) reported such a relationship between the density of carbonate rocks (dolomite, marble) and ultrasonic velocity measured by transmission mode. More recently, Chen *et al*. (2015) concluded that density and ultrasonic velocities follows a linear relationship within basalt samples.

The observed density values and the predicted ones are plotted on Fig. 10.

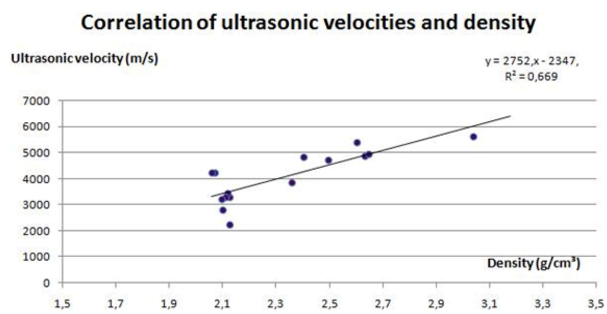


Fig. 9 Correlation between density and ultrasonic velocity for carbonate rocks samples

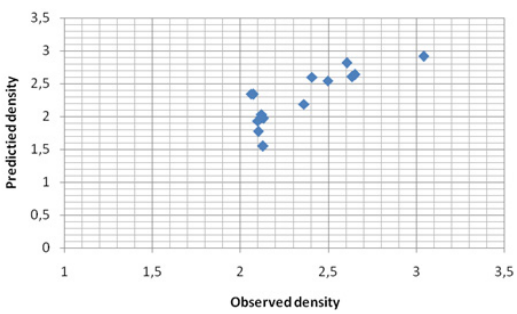


Fig. 10 Observed density versus predicted density

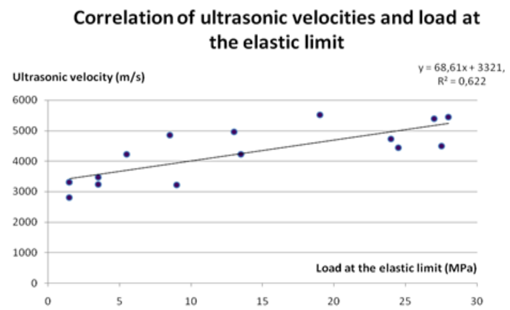


Fig. 11 Correlation between ultrasonic velocities and load at the elastic limit

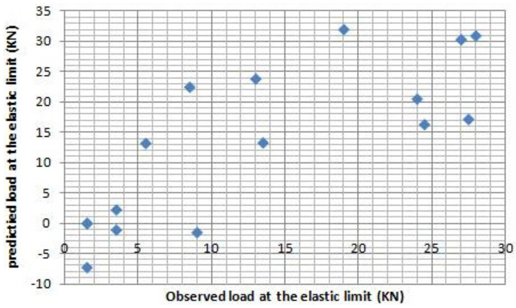


Fig. 12 Observed load at the elastic limit versus predicted load

3.4 Correlation between load at the elastic limit and ultrasonic velocities for carbonate rock samples

The load at the elastic limit is the load (MPa) measured at the elastic limit, which induces the irreversible deformation phase. For our knowledge, there is no single expression in the literature relating load at the elastic limit to ultrasonic velocity. In fact, it's expected that for higher velocities (more resistant samples), the material can hold higher charges at the elastic limit. With such formulation, the load that stimulates irreversible plastic deformation can subsequently be estimated from ultrasonic velocity measurements. Such predictions can be useful to detect the amount of charges that causes irreversible damage on the material.

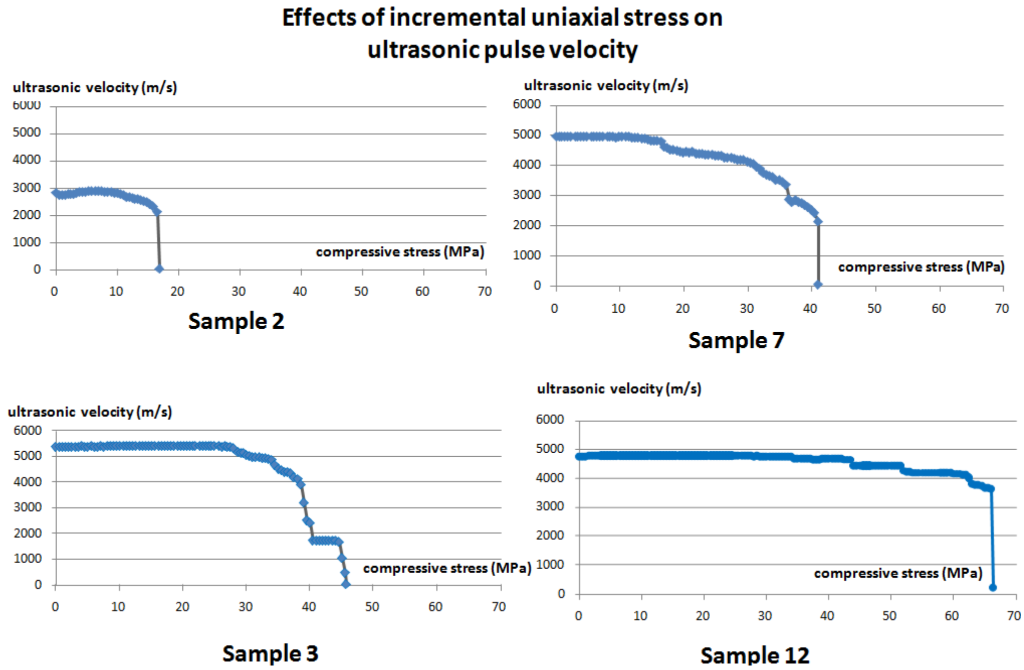
A linear relationship between initial velocities and the load applied at the elastic limit for carbonate rocks have been established (see Fig. 11) (V = 68,61 L + 3321 where L is the load at the elastic limit). Fig. 12 confirms the correlation established through the empirical equation.

Overall, the significant statistical correlations that were established between the ultrasonic velocity and the mechanical properties, namely the uni-axial compressive strength, the porosity and the density, indicate that these parameters can be reasonably estimated by means of this nondestructive method. Ultrasonic measurements could be made *in situ* on a sample shaped with a portable device, to generate two parallel surfaces.

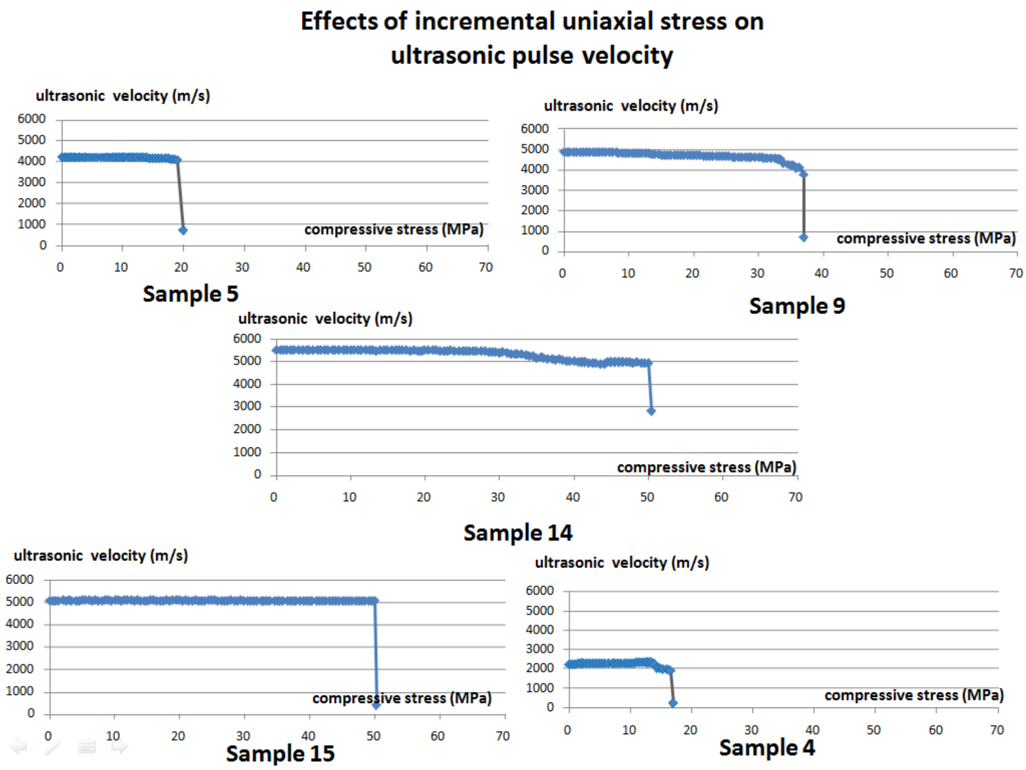
3.4 Effects of incremental uniaxial stress on ultrasonic pulse velocity within carbonate rocks

Usually, when a rock is subjected to increasing stress, it passes through 3 successive stages of deformation, the elastic deformation (wherein the strain is reversible), the ductile deformation (when the strain is irreversible) and the fracture (failure of the sample). The Fig. 13(a) where ultrasonic velocities were plotted against uni-axial compression illustrates this behavior. Three phases were observed, a practically constant region (elastic deformation), velocity decrease (ductile deformation) and failure of the sample.

In fact, rocks, which are inhomogeneous materials, exhibit different responses to stresses. They may deform like a brittle material, meaning that they fracture and fault. Brittle materials have a small or large region of elastic behavior but only a small region or negligible ductile behavior before they fracture. For ductile materials, stress induced behavior is characterized by a small region of elastic behavior and a large region of ductile behavior before they fracture.

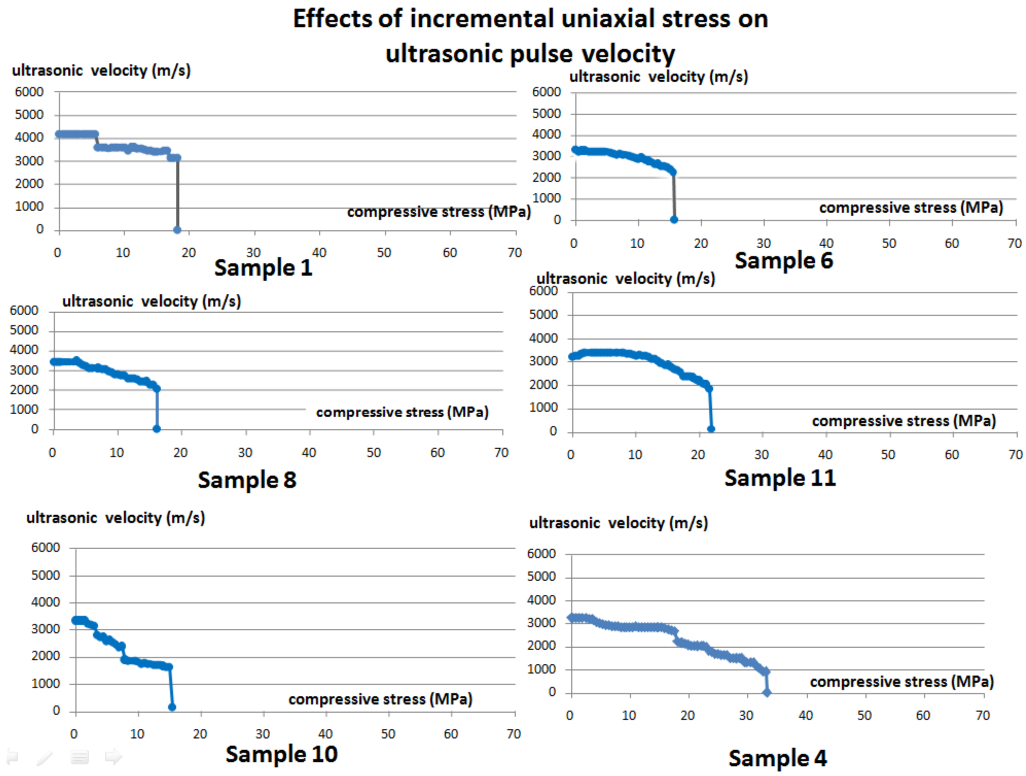


(a)



(b)

Fig. 13 Effects of incremental uniaxial stress on ultrasonic velocity city



(c)

Fig. 13 Continued

Considering the behavior of the carbonate rocks under stress, the curves established in our study enables to classify the samples according to their deformation type.

In fact, samples number 4, 5, 9, 14 and 15, the area where velocity does not vary significantly, was directly followed by the failure of the sample (see Fig. 13(b)). That means that the latter showed a large elastic range and lacked the ductile deformation. Such a behavior is observed within brittle material (a material is brittle if, when subjected to stress, it breaks without significant deformation). In this case, the velocity is not influenced until the sample breaks (sudden drop in velocity). It is therefore a non-ductile brittle material. Such a behavior is a result of the greater resistance oh this type of rock.

Samples number 1, 6, 8, 10, 11 and 13 are characterized by a large plastic range where the micro-cracking is important and causes velocity drop (see Fig. 13(c)). Such rocks behave as a ductile material. The deformation occurred when the strain is irreversible and the material is able to change its shape permanently without fracturing.

With similar findings, Popovics and Popovics (1991) explained the region where velocity remains constant by the fact that the pulse velocity is, to a large extent, non-responsive to existing initial load stresses. They suggested that ultrasonic behavior is independent of the stress applied to a large extend (until 70% of the total load applied).

Popovics *et al*. (1990) reported a similar trend in mortar and concrete but in that case, loading was stopped each time velocity measures were taken. Popovics explained the reasons for this unexpected pattern. According to him, the expectation was that a gradual decrease in pulse velocity would be observed with the increasing load (Popovics and Popovics 1991 and Popovics *et al*. 1990). He reported that this behavior may be explained by the fact that small loads do not produce sizable microcracking yet but they do consolidate the specimen (crack closure) which can produce slight velocity increase (this increase highlights the closure of pre-existing cracks).

Nicolas *et al*. (2016 explained a similar behavior of a carbonate rock wherein general trend included crack closure, elastic region, dilatancy and pore collapse. In our study, it would be the case for some porous rocks samples (where porosity exceeds 15%). Within samples number 2, 4 and 11 where calculated porosity is relatively high (superior to 15%), velocities increased slightly with stress at low values corresponding to the crack closure region. Differently, samples 6, 8 and 10 where porosity is also relatively high (> 15%), the specimen was not compacted because, due to the ductile behavior, elastic range were limited and the pores were not compacted but connected. Thus the ductile range occurs rapidly and velocities decreases.

The stage where there is no variation of velocities logically corresponds to the elastic region (stable cracking phase). Then, as microcracking becomes extensive, the velocity drops. Here, the most intense velocity variation (decreased velocity) occurs during the dilatancy step and pore collapse when cracks are created and/or opened (when plastic deformation begins). This interpretation conforms to previous results established by Couvreur *et al*. (2001) and Eberli *et al*. (2003) within carbonates.

Generally, the stress-strain diagram reveals the mechanical properties discussed above. It allows dividing materials into two broad categories; the ductile and the brittle materials. In order to avoid strain measures in stress-strain analysis, the procedure could be replaced by the assessment of the behavior of ultrasonic velocity during the compression test. It is therefore evident that the velocity of the ultrasonic wave is a function of the applied stress on the material. This effect has been used in this study to characterize the behavior of carbonate rocks under stress.

4. Conclusions

The major output of the work is the confirmation that ultrasonic velocity can be used as a simple and economical method for the prediction of mechanical and physical properties, namely the strength, of carbonate rocks. The correlational relationship between ultrasonic velocity, density, porosity and UCS within carbonate rocks was determined. Such correlations may provide a good estimation in related or similar geological setting regions for density, porosity, and uniaxial compressive strength. It was also used to follow the behaviors and to estimate the type of deformation of the rock material under uni-axial stress. This work could avoid time-consuming and tedious lab test methods. Ultrasonic velocity testing is a simple, nondestructive and fast method as velocities can be measured easily both in laboratory and *in situ*. Thus, this technique is expected to be useful as a practical approach for characterization of physical and mechanical properties of rock material and to predict the behavior of rock material under applied forces. Such technique is of much interest due to the usual difficulties in removing specimens for mechanical characterization.

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References

Calvo, J.P. and Regueiro, M. (2010), "Carbonate rocks in the Mediterranean region–from classical to innovative uses of building stone", *Geol. Soc. London Spec. Publ.*, **331**(1), 27-35.

Chen, X., Schmitt, D.R., Kessler, J.A., Evans, J. and Kofman, R. (2015), "Empirical relations between ultrasonic P-wave velocity, porosity and Uniaxial Compressive Strength", *CSEG Rec.*, **40**(5), 24-29.

Couvreur, J.F., Vervoort, A., King, M.S., Lousberg, E. and Thimus, J.F. (2001), "Successive cracking steps of a limestone highlighted by ultrasonic wave propagation", *Geophys. Prpspect.*, **49**(1), 71-78.

Del Rıo, L.M., Jimenez, A., Lopez, F., Rosa, F.J., Rufo, M.M. and Paniagua, J.M. (2004), "Characterization and hardening of concrete with ultrasonic testing", *Ultrasonics*, **42**(1), 527-530.

Eberli, G.P., Baechle, G.T., Anselmetti, F.S. and Incze, M.L. (2003), "Factors controlling elastic properties in carbonate sediments and rocks", *Leading Edge*, **22**(7), 654-660.

Hall, K.S. and Popovics, J.S. (2016), "Air-coupled Ultrasonic tomography of solids: 1 Fundamental development", *Smart. Struct. Syst., Int. J.*, **17**(1), 17-29.

Hernández, M.G., Anaya, J.J., Izquierdo, M.A.G. and Ullate, L.G. (2002), "Application of micromechanics to the characterization of mortar by ultrasound", *Ultrasonics*, **40**(1), 217-221.

Irfan, T.Y. (1996), "Mineralogy, fabric properties and classification of weathered granites in Hong Kong", *Q. J. Eng. Geol. Hydrogeol*, **29**(1), 5-35.

Kurtulus, C., Bozkurt, A. and Endes, H. (2012), "Physical and mechanical properties of serpentinized ultrabasic rocks in NW Turkey", *Pure Appl. Geophys.*, **169**(7), 1205-1215.

Lafhaj, Z. and Goueygou, M. (2009), "Experimental study on sound and damaged mortar: Variation of ultrasonic parameters with porosity", *Constr. Build Mater.*, **23**(2), 953-958.

Lafhaj, Z., Goueygou, M., Djerbi, A. and Kaczmarek, M. (2006), "Correlation between porosity, permeability and ultrasonic parameters of mortar with variable water/cement ratio and water content", *Cem. Concr. Res*, **36**(4), 625-633.

Lai, G.T., Rafek, A.G., Serasa, A.S., Hussin, A. and Ern, L.K. (2016), "Use of ultrasonic velocity travel time to estimate uniaxial compressive strength of granite and schist in Malaysia", *Ssains Malays.*, **45**(2), 185-193.

Lotfi, H., Faiz, B., Moudden, A., Izbaim, D., Menou, A. and Maze, G. (2010), "Characterization of mortars with ultrasonic transducer", *MJ Condensed Matter*, **12**(2), 131-133.

Madhubabu, N., Singh, P.K., Kainthola, A., Mahanta, B., Tripathy, A. and Singh, T.N. (2016), "Prediction of compressive strength and elastic modulus of carbonate rocks", *Measurement*, **88**, 202-213.

Maev, R.G. (2008), *Acoustic Microscopy: Fundamentals and Applications*, John Wiley & Sons, Betz-Druck GmbH, Weinheim, Germany.

Nicolas, A., Fortin, J., Regnet, J.B., Dimanov, A. and Guéguen, Y. (2016), "Brittle and semi-brittle behaviours of a carbonate rock: influence of water and temperature", *Geophys. J. Int.*, **206**(3), 438-456.

Ongpeng, J., Soberano, M., Oreta, A. and Hirose, S. (2017), "Artificial neural network model using Ultrasonic test results to predict compressive stress in concrete", *Comput. Concrete, Int. J.*, **19**(1), 59-68.

Peng, S. and Zhang, J. (2007), *Engineering Geology for Underground Rocks*, Springer Science & Business Media, Deblik, Berlin, Germany.

Popovics, S. and Popovics, J.S. (1991), "Effect of stresses on the ultrasonic pulse velocity in concrete", *Mat. Struct.*, **24**(1), 15-23.

Popovics, S., Rose, J.L. and Popovics, J.S. (1990), "The behaviour of ultrasonic pulses in concrete", *Cem. Concr. Res.*, **20**(2), 259-270.

Shariati, M., Ramli-Sulong, N.H., KH, M.M.A., Shafigh, P. and Sinaei, H. (2011), "Assessing the strength of reinforced concrete structures through ultrasonic pulse velocity and Schmidt rebound hammer tests", *Sci. Res. Essays*, **6**(1), 213-220.

Vasconcelos, G., Lourenço, P.B., Alves, C.A.S. and Pamplona, J. (2008), "Ultrasonic evaluation of the

physical and mechanical properties of granites", *Ultrasonics*, **48**(5), 453-466.
Vergara, L., Miralles, R., Gosálbez, J., Juanes, F.J., Ullate, L.G., Anaya, J.J., Hernández, M.G. and Izquierdo, M.A.G. (2001), "NDE ultrasonic methods to characterise the porosity of mortar", *NDT&E INT*, **34**(8), 557-562.
Yasar, E. and Erdogan, Y. (2004), "Correlating sound velocity with the density, compressive strength and Young's modulus of carbonate rocks", *Int*. *J*. *Rock Mech*. *Min*. *Sci*, **41**(5), 871-875.

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