Preliminary laboratory research on some geophysical properties of the shallow sedimentary calcareous rocks of the Yucatan Peninsula

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ABSTRACT

Preliminary laboratory research has been carried out on electrical resistance and seismic wave propagation (ultrasonic compression wave) of calcareous materials from the Carrillo Puerto formation of the Yucatan Peninsula. Simultaneously, values of moisture and density have been measured in small specimens of these materials. The main purpose of the study was to facilitate the interpretation of geophysical and geotechnical surface prospecting through determining physical and geophysical properties of these materials and the correlations amongst them. Furthermore, a reason of this study was to increase the daily practice reliability of geophysical exploration methods in sedimentary calcareous rocks from the Yucatan Peninsula region. The study was based on laboratory measurements of small cylindrical specimens of limestone, calcareous soil and red clay. The analysis of results indicated that there is a very small correlation between electrical resistivity and density; nevertheless, there is a better correlation between electrical resistivity and moisture content. These results also indicated that there is a good correlation between ultrasonic wave velocity and density, and that the correlation is increased when the analyzed data come from measurements on samples having uniform moisture or at least small variations of their moisture distribution. Finally, some recommendations are given to improve the interpretations of tomograms resulting from geophysical shallow explorations based on electrical resistivity and compressional wave velocity applied in calcareous formations.

Keywords: Electrical resistivity, Ultrasonic wave propagation, Calcareous rocks, Density and Moisture.

Ensayes de laboratorio preliminares de algunas propiedades geofísicas de las rocas sedimentarias calcáreas de la península de Yucatán

RESUMEN

Se realizaron ensayes preliminares de resistividad eléctrica y velocidad de onda sísmica (onda de compresión ultrasónica) de materiales calcáreos procedentes de la formación Carrillo Puerto, localizada en la Península de Yucatán. Simultáneamente se efectuaron mediciones de humedad y densidad en especímenes de dichos materiales. El objetivo principal de este estudio fue mejorar la interpretación de los resultados de la prospección superficial a través de la determinación de las propiedades físicas y geofísicas de estos materiales calcáreos y las correlaciones entre ellas para incrementar la confiabilidad de los métodos geofísicos de exploración en la península de Yucatán en su aplicación cotidiana. El estudio se efectuó con base en ensayes de laboratorio, utilizando pequeños especímenes cilíndricos tanto de la roca caliza como de los materiales térreos o calcáreos no consolidados. El análisis de los resultados permite concluir y confirmar que, en materiales calcáreos, que la correlación que existe entre la resistividad eléctrica y la densidad es muy pequeña. Sin embargo, entre la resistividad eléctrica y la humedad existe una mejor correlación. Entre la velocidad de onda de compresión y la densidad existe una correlación que es mayor cuando la información proviene de muestras con humedad uniforme o al menos con pequeñas variaciones en su distribución de humedad. Finalmente, se proporcionan algunas recomendaciones para mejorar la interpretación de la tomografía resultante de la aplicación de la resistividad eléctrica y velocidad de onda sísmica de compresión en la exploración geotécnica superficial de terrenos calcáreos.

Palabras clave: Resistividad eléctrica, velocidad de onda ultrasónica, rocas calcáreas, densidad y humedad.

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INTRODUCTION

Calcareous rocks occupy more than 15% of the total surface of our planet. Karsticity is the main characteristic of this type of rock. Globally, the evolution of karsticity has different stages. The original sedimentation environment of the calcareous rocks in the Yucatan Peninsula (tropical, epineritic, and with coral reefs), causes a highly heterogeneous distribution of the different types of carbonates. Heterogeneity affects mainly the horizontal distribution of the rocks and it is not uncommon to find a very hard rock formation beside one that is very soft and friable.

When the sedimentary calcareous rocks had their origin at the bottom of deep seas and oceans, the rock formations were much more uniform and horizontally homogeneous over distances of several kilometers. When dealing with constructions in general and with foundation engineering in particular, the mechanical properties of the rock formations, the distribution of the calcareous materials and the presence or absence of karsticity, must be known (Sánchez et al 1998). To achieve this information it is necessary to perform a costly and time consuming direct ground exploration which consists mainly of drilling boreholes with and without core recovery, trenches, open pits and adits; taking samples whenever it is necessary. In the last thirty years this direct exploration procedure has been commonly combined with geophysical prospecting. These two methods combined have not achieved reliable results when dealing with carbonate or calcareous formations.

Several geophysical exploration methods for geotechnical purposes have been frequently applied (Burger 1992, Robinson and Coruh 1989, and Beck 1999). These are mainly: seismic exploration, considering refraction and reflection; electrical resistivity; gravity acceleration and the magnetic method (Parasnis 1967).

The focus of this research project is only on the seismic and the electrical resistivity properties of the calcareous materials. This decision was taken after considering the characteristics of calcareous formations and laboratory and field equipment available. The research project was undertaken to determine the correlations amongst the seismic and the electrical resistivity, density and moisture content. Therefore, the geophysical properties were measured and analyzed in specimens under different conditions of density and moisture content.

METHODOLOGY
Sampling

Recovery of calcareous material was performed in two extraction pits (Copó and Dzityá), located on the northern outskirts of Merida, Mexico in the so called Carrillo Puerto formation, belonging to the Pliocene and Miocene epochs of the Tertiary period, that covers the Peninsula area in a thirty percent, approximately (Figure 1).

The studied materials represent the most common ones of the Carrillo Puerto formation, that are constituted by a combination of different kinds of limestone, together with abundant soft rocks or a very well compacted calcareous soil and organic dark red soil located at the surface.

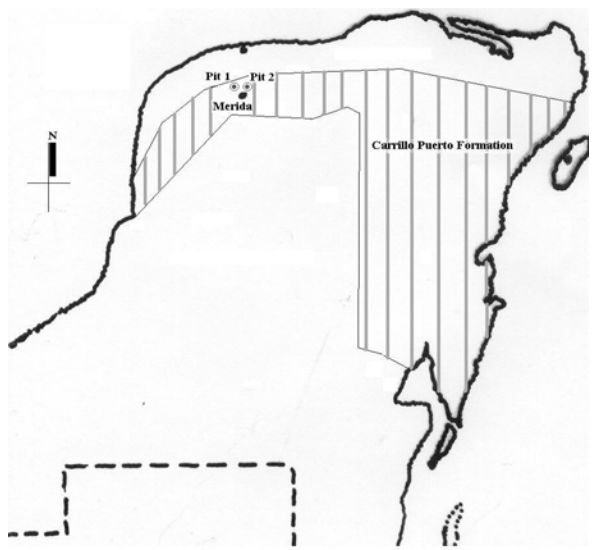

Figure 1. Pit locations on the Carrillo Puerto formation

Laboratory testing
Instruments for measuring geophysical parameters.

A Digital Multimeter DMM916 (manufactured by Tektroniks, Incorporated, Oregon) was applied to measure the electrical resistivity. This device has 0.5% accuracy in direct current (DC) measurements, and depends on securing a uniform and highly electric conductant contact between the specimen and the two electrodes (Figure 2).

Fig. 2. Digital Multimeter

The wave velocity was measured using a "V" Meter (manufactured by James Instruments Incorporated, Chicago, Illinois). This instrument is mainly used on rocks and concrete structures like columns and beams. Its accuracy of ± 2% to measure pulse velocity, allows detecting small variations on the conditions of the materials such as heterogeneity, presence of voids, cracks and other irregularities. The high accuracy of the V Meter requires securing specific and smooth contact between the specimen and both transducers (Figure 3).

Figure 3. V Meter device

Limestone rock. The superficial layer of limestone rock has a thickness that varies from one to two meters in the extraction pits. 169 blocks of around 50 kg were taken to the laboratory where cylindrical specimens were extracted by a sampler-boring machine. From two to six cylindrical specimens of 5.1 cm diameter and 10.2 cm length were taken from each block.

Non-consolidated calcareous soil. This material was collected from two extraction pits (Table 1). *In situ* measurements of moisture content and density were performed in each site of extraction. Each cylindrical specimen of 10.2 cm diameter and approximately 11.6 cm in length was obtained using a Proctor steel chamber mould in which the calcareous soil was compacted with the optimum moisture content under a pressure of 140 kg/cm^2. A total of 62 specimens were acquired. The optimum moisture content is obtained, for each specimen tested, performing the Proctor Standard Test. This test is applied to determine the optimum moisture for compaction of any soil or aggregate used in bases and sub bases of road construction (ASTM 1997).

Table 1. Densities and moisture content of the non-consolidated calcareous soil

Site No.	Extraction pit	Depth (cm)	Saturated state density (gr/cm^3)	Dry state density (gr/cm^3)	Moisture content (%)
1	1	18.5	1.647	1.464	12.5
2	1	17.5	1.785	1.662	7.4
3	1	18.0	1.678	1.485	13.0
4	1	18.0	1.709	1.456	17.3
5	2	16.0	1.962	1.683	16.7
6	2	17.0	2.000	1.669	19.9

Dark red organic clayey silt or silty clay. The specimens of this material were obtained through the same procedure used for the non-consolidated calcareous soil. A total of 16 specimens were acquired from one of the extraction pits.

Water. The electrical conductivity of the water used to moisturize the specimens varied from 1.200 to 1.500 μmhos/cm. The water came from the aquifer underneath the Engineering Faculty of the Autonomous University of Yucatan.

Specimens. A total of 247 cylindrical specimens were tested as follows: 169 limestone specimens of 5.1 cm diameter and 10.2 cm length; 62 non-consolidated calcareous soil specimens of 10.2 cm diameter and 11 cm length and 16 brown reddish silty clay specimens of 10.2 cm diameter and 11 cm length.

Sequence of testing. In order to cover the complete variation of properties in relation to moisture content, all specimens were sequentially tested considering them: saturated, with intermediate moisture content and dry.

The limestone specimens were immersed in clean water for 24 to 48 hours, defining the resultant water content as the **saturated** state, based in the fact that after 24 to 48 hours of water immersion the specimen stops increasing weight because of the absorbing water. Subsequently, after an approximately fifty percent loss of moisture content at room temperature, a second test was performed on the specimen, defining the **intermediate moisture state**. And finally, specimens were tested in **dry state** after a period of several hours in the oven at a constant temperature of 105° C.

The **saturated state** of the calcareous soil and the silty clay or clayey silt, was defined as the optimum moisture content obtained applying the Proctor Standard Test (ASTM 1997). That optimum moisture content so obtained is considered equivalent to the **saturated state**.

The soil specimens (calcareous soil and red clay) were tested first at the optimum moisture content immediately after being compacted and extracted from the Proctor mould. After preparing the limestone specimen using the same procedure, the second and third tests were performed.

RESULTS

The statistical central values of electrical resistivity and compression wave velocity were: sample mean and standard deviation. Table 2 presents these values from laboratory measurements on three types of materials from pit one for three different moisture content states. Table 3 presents results from two types of materials from pit 2 for the same three moisture content states.

Table 2. Saturated, intermediate and dry moisture states of materials from extraction pit 1

Material	sample	Electric resistivity (ohm-m)						Compression wave velocity (m/s)					
		Saturated		Intermediate		Dry		Saturated		Intermediate		Dry	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Limestone	66	2432	2435	4078	4336	0.96×10^6	1.2×10^6	4528	864	4458	761	4552	787
Calcareous soil	32	6167	4624	25.4×10^3	17.8×10^3	32.8×10^6	24.9×10^6	526	60	1129	125	1255	153
Reddish clay	16	968	353	23.1×10^3	12.1×10^3	6.04×10^6	4.34×10^6	505	35	974	132	1038	134

SD = Standard deviation

Table 3. Saturated, intermediate and dry moisture states of materials from extraction pit 2

Material	Sample	Electric resistivity (ohm-m)						Compression wave velocity (m/s)					
		Saturated		Intermediate		Dry		Saturated		Intermediate		Dry	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Limestone	103	3358	2850	6037	5827	2.14×10^6	1.31×10^6	4322	854	4310	874	4340	798
Calcareous soil	30	993	1268	7692	5101	834×10^3	736×10^3	593	62	1639	158	1894	114

SD = Standard deviation

From tables 2 and 3, values for corresponding coefficients of variation can easily be deducted. Large coefficients of variation of the electrical resistivity values (seven times larger than that of the compressional wave velocity) can be calculated on the three types of materials. These tables also show a large increment of the mean of the electrical resistivity values when the moisture content changes

from saturation, to an intermediate humidity and to a dry state. Mean compression wave velocity values, standard deviations and thus coefficients of variation are rather constant along the different moisture conditions.

Mean compression wave velocity

The mean compression wave velocity of limestone was in a range between 4,552 and 4,458 m/s in specimens from pit number 1; and between 4,340 and 4,310 m/s in specimens from pit number 2.

The mean compression wave velocity of calcareous soil increases when the moisture content decreases. The compression wave velocity values, from pit number 1, show an increment from 526 m/s, in saturated specimens, to 1,255 m/s, in dry specimens. Similarly, the compression wave velocity of calcareous soil from pit number 2 show an increment from 593 m/s, in saturated specimens, to 1, 894 m/s, in dry conditions.

The dark red organic clay showed a similar behaviour with velocities from 505 m/s, in saturated specimens, to 1, 067 m/s, in dry conditions.

Electrical resistivity

The electrical resistivity increases as the moisture content decreases, independently of the material type. The coefficients of variation are very large (from 0.41 to 1.51). These results show that the electrical resistivity applied in shallow geophysical exploration is not useful for detecting different types of materials.

Compression wave velocity

The analyses of results show that there is a good correlation between the compression wave velocity of the three materials tested and the other two parameters considered: density and moisture content.

Four model equations of correlation (linear, multiplicity, exponential and reciprocal), were preliminarily tested with data obtained from measurements on limestone specimens from pit number 1. From those four models, the linear is the better adjusted model to the preliminary the data, R^2 (coefficients of determination) values over 0.80. This comparison of the four coefficients of determination is presented in table 4.

Table 4. Coefficients of determination between the compression wave velocity of limestone rock and the other two considered parameters.

Parameters	Models	Coefficients of determination (R^2)
Density	Linear	0.8196
	Multiplicity	0.7735
	Exponential	0.8127
	Reciprocal	0.8025
Moisture content	Linear	0.9547
	Multiplicity	0.9247
	Exponential	0.9393
	Reciprocal	0.8310

Figures 4 and 5 present graphs of the plotted data, the linear correlation equations and coefficients of determination corresponding to the laboratory measurements of materials obtained from pit number 1. This information illustrates the correlation between each one of two physical characteristics (density and moisture content) and each one of the two geophysical parameters (electrical resistivity and wave velocity).

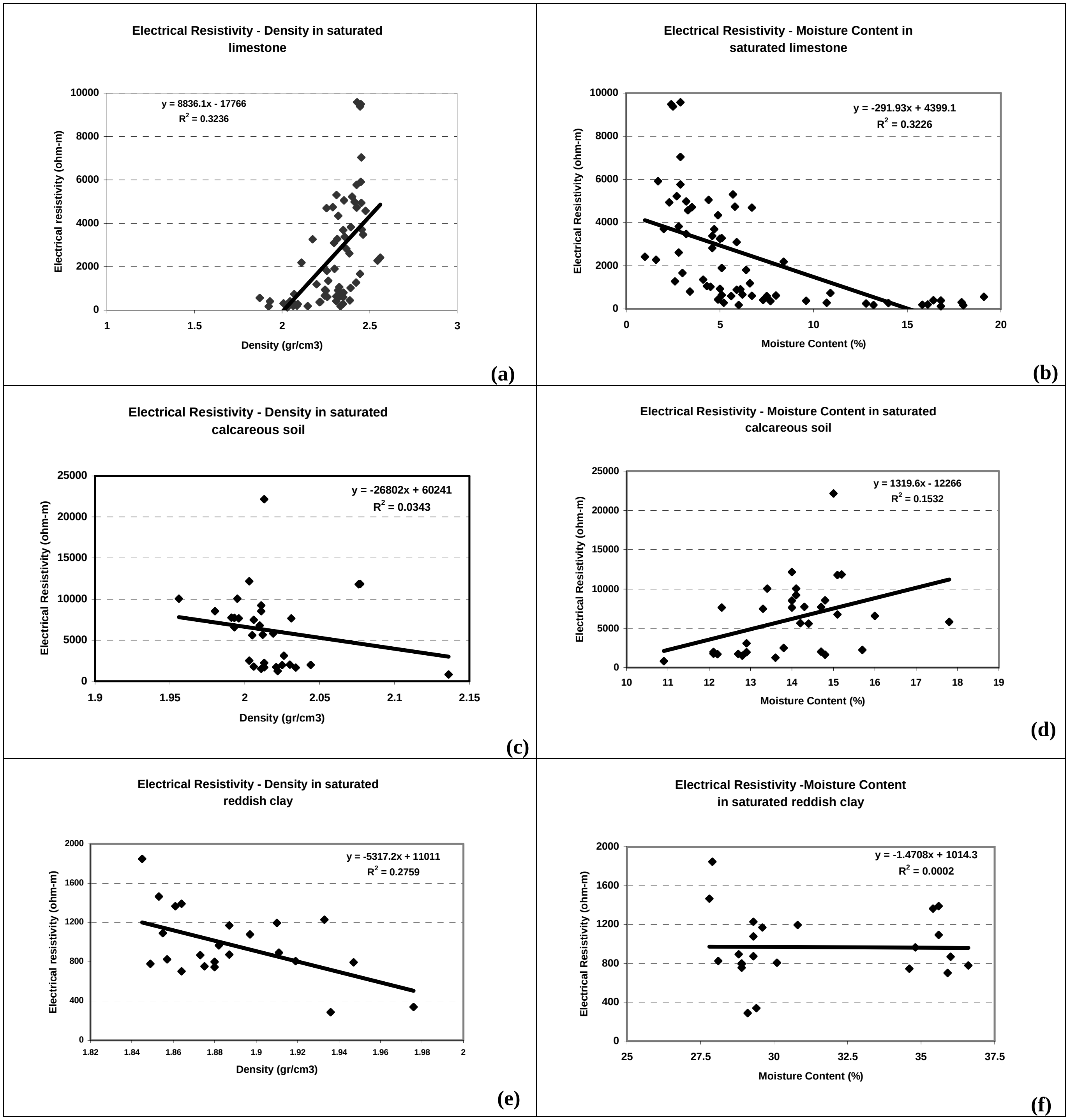

Figure 4. Correlations between Electrical resistivity and density (left) and between Electrical resistivity and moisture content (right) for limestone, calcareous soil and reddish clay.

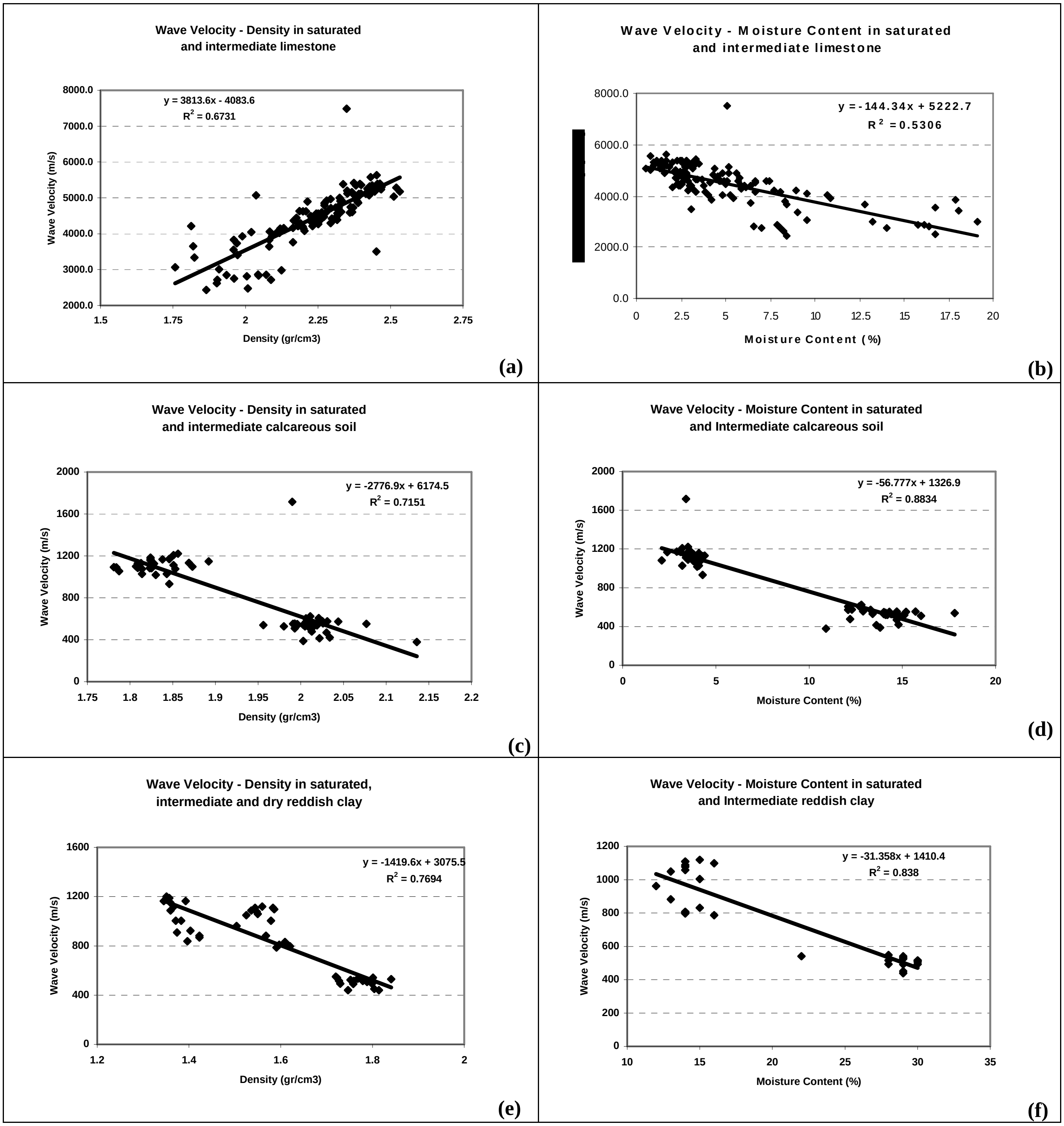

Figure 5. Correlations between Wave velocity and density (left) and between Wave velocity and moisture content (right) for limestone, calcareous soil and reddish clay.

DISCUSSION

Electrical resistivity. The information presented in the six graphs of figure 4, in which the coefficients of determination (R^2) are less than 0.4, illustrate that there is a very small correlation between electrical resistivity and density or electrical resistivity and moisture content in the saturated state.

Taking into consideration that limestone is a material with a very high electrical resistivity when dry; small porosity volume (from 1 to 22 percent), and that its conductivity increases in function of the amount of water that fills its voids, a high correlation between electrical resistivity and density and also between electrical resistivity and moisture content could be expected when saturated. In other words, in limestone specimens the highest densities correspond to the smallest porosities and smallest amount of water filling the voids when saturated.

Calcareous soil and reddish clay materials have very large porosity volumes (from 20 to 58 percent), that reduces the electrical resistivity of the material in intermediate moisture state. Therefore, there is a very low correlation between electrical resistivity and density in these materials.

Wave velocity. It is a known fact that if a stress is suddenly applied to an elastic medium the resultant strain propagates within the medium as an elastic wave. It is also known that there are several kinds of elastic waves: longitudinal or compressional (P waves), transversal or shear (S waves), and superficial waves of two types named Raleigh and Love waves (Parasnis 1967). In prospection or surface exploration methods only the P waves are of importance. The velocity of the waves (V) is always inversely proportional to the square root of the density, but directly proportional to the rigidity of the medium given by both the compressional modulus (k) and the shear modulus (s). The P wave velocity is given by:

$$V = [(k + 1.33\ s)/(\rho)]^{1/2} \qquad (1)$$

where ρ is the density of the medium

The correlation equations related with the measurements in **limestone** presented in figure 5, show that the velocity of the P wave is directly proportional to density. This result seems to be contradictory with equation 1, but can be explained by the fact that in limestone rock (cemented sedimentary rock integrated mainly by calcium carbonate molecules, $CaCO_3$) any increment of density, even small, means a closer contact between molecules, less empty voids, and therefore, more stiffness, and consequently, a greater compressional and shear modulus.

The information presented in the six graphs of Figure 5, in which the coefficients of determination (R^2) varies from 0.53 to 0.88, illustrate that there is an important correlation between wave velocity and density, and also between wave velocity and moisture content, in the saturated state alone, and the saturated and the intermediate moisture content taken together.
The graphs and correlation equations related with measurements in **calcareous soil** and **reddish clay** presented in figure 5, show that the velocity of the P wave is inversely proportional to density. The calcareous soil and red clay specimens were prepared at a similar degree of compaction, and so, the increment in density, in each specimen, was due only to the weight of water filling the porosity volume, further more, the filling water had also a softening effect, therefore, any increase of density causes a stiffness decrease, and consequently a reduction in the P wave velocity.

As a consequence of the behaviour of calcareous soil and red clay, the increase in moisture content (going from dry to intermediate and saturated) corresponds always to a decrement in the wave velocity in all the three materials tested (see the corresponding graphs of Figure 5).

The graphs of Figure 5 also show that the minimum values of the compression wave velocity of the limestone correspond to the highest moisture contents filling the specimens of smallest density. These minimum values of the compression wave velocity of the limestone specimens are always larger than the maximum values from the calcareous soil and reddish clay, maximum values that, in these non consolidated materials, correspond to the driest and most compacted specimens.

CONCLUSIONS AND RECOMMENDATIONS

1) The comparison of the results between limestone rock and calcareous soil specimens, show that despite the different specimen moisture content, the compressional wave velocity values of the limestone are notoriously larger than those of the calcareous soil specimens. The understanding of this behaviour facilitates the interpretation of wave velocity profiles obtained from seismic shallow exploration in the calcareous rocks and soils in the area of the Carrillo Puerto formation of the Yucatan peninsula.

2) Subsoil solution cavities above the ground water level could be detected through shallow exploration methods. This can be done based on compressional wave velocity, independently of the ground humidity and the assumption that the wave velocity

through the cavities is the one of the ordinary sound waves (about 330 m/s), which is several times smaller than those of the calcareous materials tested.

3) Subsoil solution cavities below the ground water level, and also above, except when the materials are completely dry, could be detected through shallow exploration methods based on electrical resistivity. This statement is valid below the ground water level, considering that the electrical resistivity of the ground water is several times smaller than those of the calcareous materials. It is also valid above the ground water level, except when the calcareous materials are completely dry, because the electrical resistivity of the air is several times bigger than those of the calcareous materials partially wet or saturated by capillarity.

4) The humidity status of a site, mostly when there is a uniform petrographic profile, can be determined applying the electrical resistivity exploration method.

5) To correlate the compression wave velocity with humidity and density requires the application of appropriate model equations. Computer programs for interpretation of tomography profiles, obtained from shallow seismic exploration, should take into account the linear model correlation equations.

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