Measurement 88 (2016) 202–213

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Prediction of compressive strength and elastic modulus of carbonate rocks

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ARTICLE INFO

Article history:
Received 8 June 2015
Received in revised form 18 March 2016
Accepted 24 March 2016
Available online 1 April 2016

Keywords:
Young's modulus
Porosity
Ultrasonic velocity
Carbonate rocks
Artificial Neural Network

ABSTRACT

Uniaxial Compressive Strength (UCS) and Modulus of elasticity (E) of carbonate rocks are very critical properties in petroleum, mining and civil industries. UCS is the measure of the strength of the rock and E depicts the stiffness, together they control the deformational behavior. But the heterogeneity introduced as a result of fractures, dissolution and dependency on pH and temperature makes them a difficult material to study. Complex diagenesis and resulting pore system makes the job even more daunting. So, an attempt is made to predict these properties using simple index parameters such as Porosity, Density, P-wave velocity, Poisson's ratio and Point load index. Multiple Linear Regression Analysis (MVRA) and Artificial Neural Networking (ANN) have been used for predicting the two properties and the accuracy is tested by root mean square error. The results show that ANN has a better predictive efficiency than MVRA and they can be applied for predicting UCS and Young's modulus of carbonate rocks with reasonable confidence.

1. Introduction

Carbonate rocks are formed in a variety of geological settings and are one of the best reservoir rocks for oil exploration [60]. It is assumed that the proportion of crude oil confined in carbonate rocks is around 50–60% with an estimated production lifetime of more than 50 years [11]. Carbonate rocks are very low strength and are highly susceptible to weathering due to chemically unstable mineralogical and textural combination, and their high reactivity with pH and temperature [41]. As important it is to determine the geomechanical properties with high accuracy, difficulty in sample preparation adhering certain standards along with several inherent heterogeneities makes it a formidable task for rock engineers. In rock engineering, both uniaxial compressive strength (UCS) and the Modulus of elasticity (E) are widely used parameters as they are important for intact rock classification and rock failure criteria [16]. These parameters have great importance in rock physics applications, viz., onshore and offshore geomechanical engineering, tunneling, dam design, rock drilling and blasting, rock excavation and even for slope stability.

There are two methods for assessing the properties of rocks. First is the direct method where tests are conducted on a crafted specimen in the laboratory, the other, known as the indirect method, uses the previously derived empirical equations from the literature [8]. The test procedure for measuring UCS and E have been standardized by both the American Society for Testing and Materials (ASTM) and the International Society for Rock Mechanics (ISRM). Sound rock specimens are required for direct determination of UCS and Young's modulus of rocks in

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http://dx.doi.org/10.1016/j.measurement.2016.03.050
0263-2241/

the laboratories. However, high quality core samples in sufficient quantities are not possible to obtain from weak, highly fractured, weathered carbonate rocks. Moreover, the test procedures are expensive because of the requirement to precisely, carefully prepare the specimens to ensure that the ends are smooth and perfectly parallel and several other details as per standards. In addition, careful execution of these tests are difficult, time consuming and requires expensive equipment [20,8,34]. Point load test is an alternative method to determine UCS as it gives reliable values at a lower cost and with ease [50]. In order to overcome these difficulties, indirect methods employing simple index parameters like the density, porosity, P-wave velocity, Point load index, Schmidt hammer were used [29,14,13,47]. These simple index tests require a relatively small number of samples, are quick, less expensive and easy to execute.

In recent years, statistical methods used in rock engineering, such as simple and multiple regression techniques have been used for establishing predictive models. In addition to these conventional methods, new techniques like Artificial Neural Networks (ANN), fuzzy interference systems, genetic programming and regression trees have also been tested to estimate the required properties [39,22,40,55,31,8,64,51,62]

ANN methods have become popular since the year 1990. It is a form of analysis which is based on the understanding of the brain and human nervous system [23]. Major advantage of ANN is its efficient handling of highly non-linear relationships among data, even when the exact nature of such relationship is not fully unknown [19]. Therefore, neural networks are best suited for UCS and Young's modulus predictions of carbonate rocks due of the complex nature of inter-relationships among the various quality parameters, composition and processing conditions [16]. The performance of the ANN methods was also compared with other statistical methods in the present study (e.g., Regression analysis). Previous studies have shown that ANN predictive models have better efficiency than the conventional statistical methods [46,56,8,16,62,34].

The objective of this study is to predict UCS and Young's modulus of carbonate rocks using the data gathered from previous studies (163 sample data) and the data set of carbonate rocks which have been collected from the Miocene section of the Kutch basin, Gujarat, India.

2. Study area

The investigated area lies in the Kutch district of Gujarat and is the westernmost part of India. It is a part of Kutch basin which is a peri-cratonic rift basin and has preserved a complete sequence from *Triassic* to *Recent* [9]. The area composed of *Cenozoic* sequences, especially the Miocene sediments, lies in Naliya, Kutch District, Gujarat. The *Lower Miocene* rocks are exposed in Khari river section (Fig. 1). A graphical log was also prepared showing the lithounits, lithology, sedimentary textures, structures and different lithofacies from the field data (Fig. 1). The first step towards preparation of graphic log was identification of different sedimentary units which was almost done in the field itself. In the present work, individual beds in the sequence are given a standard color, the thickness of individual beds, the texture, the sedimentary structures (if any), and fossil contents are marked. As can be seen from the log, clay minerals are ubiquitous throughout the sequence, even the carbonate samples collected from *Miocene Formation* for laboratory tests contains a maximum clay content ranging up to 20%. The limestone samples are enriched with fossils like *Turritella*, *Bivalves* (*Oysters and Pecten*), etc. (Fig. 2) and also the presence of cross lamination in the limestones were observed in the field (Fig. 3).

3. Methodology: laboratory tests

3.1. Petrography

Thin section of two areas (S14 and S18) are presented in this study as the prime focus was to predict strength parameters of carbonate rocks. No correlation was made between textural changes and geomechanical properties, although we don't neglect the possibility. The sections clearly show the presence of fossils of different assemblage along with micrite (brown) and sparite (off white) matrix (Fig. 4). In case of S14, fossils are cemented together with sparry calcite whereas mixed skeletal remains are surrounded by micritic matrix in S18. Signatures of re-precipitation of micrites on fossils can also be seen. Presence of micrite indicates deposition under calm water condition whereas, presence of sparry calcite in pore spaces suggests deposition under agitated water condition [10].

3.2. Ultrasonic velocity

Ultrasonic techniques for measuring P and S-wave velocities are non-destructive and easy to execute, both in the laboratories and field. Nowadays, pulse generation method is used for the determination of parameters using Pundit testing machine (Fig. 5) which consists of a pulse transmission generator, transducers and electronic tester for measurements of time [55,63]. A coupling gel is applied on the faces to avoid any air gap between the sample and transducers. A number of factors have been known to influence the seismic velocity of rocks which include water, clay, grain size, density, texture, porosity anisotropy and others [30]. Considering the fact that the data obtained by other researchers used in this study is to the standard along with the data obtained in this study, P-wave can be considered as a reliable parameter to relate with other geomechanical properties [43].

3.3. Strength test

A number of block samples of carbonate rocks were collected from the *Miocene* section of the Kutch basin. In addition, 163 sample data of carbonates were taken from previous research work around the world. Each data set includes Porosity ($\varnothing$), Density (ρ), P-wave velocity (V_p), Poisson's ratio (μ) Point load index (I_s), uniaxial