

Determination of Petrophysical and Mechanical Property Interrelationships for Simulated Sandstone Rocks

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Abstract

In the evaluation of a petroleum reserve, it is necessary to determine accurately certain petrophysical properties such as porosity and permeability of the reservoir rocks. These properties are affected by the relevant mechanical properties. Such mechanical properties affect also the drilling programs and the development plans for a reservoir. It is more convenient to use homogenous rock samples with nearly constant initial permeability, obtaining such cores is very difficult.

In this paper a simulated natural and homogeneous compacted sandstone rock with known mechanical and petrophysical properties was used. The mechanical properties include grain size, cementing material concentration, and compaction (confining) pressure. The effect of these properties on the petrophysical properties of rock such as permeability and porosity were also known.

For the same simulated natural sandstone rocks, sound wave velocity was measured using an ultra sound tool. Good relationships have been developed between sound wave velocity and other rock properties; porosity, permeability, cementing condition at different confining pressures.

The sandstone cores have been grouped according to grain size into five groups ranged between 45 and 300 μm mixed with different concentrations of cementing material. The mixture was compacted at three different compaction pressure ranges from 11000 to 23000 psi. These varying lithification factors gave these sandstone rocks a wide range of petrophysical and mechanical properties. The results of this study are presented as graphs of simulated lithification factors, porosity, and permeability versus sound wave velocity.

1. Introduction

The first essential element of a petroleum reservoir is a reservoir rock. It is very important to determine and understand the petrophysical properties and mechanical properties of reservoir rocks. There is a conjugate relationship between the mechanical and petrophysical properties of a rock. Rock texture plays a very important part in sedimentary rocks, because petrophysical properties of a rock, hence porosity and permeability, depend essentially on texture. Rock texture covers the geometrical aspects of the constituents of rocks: grain or crystals; size, shape, appearance, sorting and induced diagenetic changes caused by cementation and compaction.

Porosity and permeability are highly affected by the pore pattern. The pore pattern results from the complex interplay of the various factors. The pattern is comprised of the pore size, the pore shape, the nature of the connections between pores, the character of the pore wall, and the distribution and number of larger pores and their relations to one another. The pore pattern of clastic reservoir rocks depends on: 1) grains – size, shape, sorting, chemical

composition, mineral composition; 2) matrix – amounts of each mineral, mineral distribution and composition; 3) cement – character, composition, amount, distribution with respect to grains and matrix.¹⁻³

Cementation, compaction, recrystallization, replacement, authigenesis and differential solution exercise a considerable diagenetic effects on rock properties and more specifically porosity and permeability. The majority of diagenetic processes, apart from cementation and compaction involves an increase in porosity. Precipitation of cement, recrystallization and compaction will usually result in a substantial reduction of permeability along with a loss of porosity.⁴⁻⁶

In effect, porosity and permeability of a reservoir rock are subject to many variations: primary and secondary. Primary variations are those associated with depositional conditions such as grain size, pore pattern and primary cementation. While secondary variations are those happened to rock since it was deposited. This is due to certain diagenetic factors such as recementation and compaction. This paper uses the results of mechanical and petrophysical property testing in a previous paper (Ref. 7) including porosity and permeability as rock petrophysical properties and grain size, cementation and compaction pressure as rock mechanical properties. In this present study, by using the same core samples used in the previous study, certain correlations have been developed between sound wave velocity and the measured porosity and permeability at different cement concentrations, pore size distributions and compaction pressures.

2. Sample Preparation

The simulated sandstone samples were prepared using red to brown colored uniformly sorted sand with grains size in the range of 75 to 500 μm (from Kharje area, Saudi Arabia). After sieving, sand has been classified into five grain size groups (mean grain size range from 90 to 275 μm). Sodium silicate solution with specific gravity of 1.4 was used as cementing material with different concentrations by weight at 4, 6 and 8%.⁸ The solidification of the compacted sand-cement mixture was done at 300°C. Figure 1 shows the compaction cell used to compact the cement-sand mixture. The compaction pressures were varied between 11000 and 23000 psi. Rock permeability and porosity results were available for these core samples.

Sound wave velocity was measured for the same core samples using the Portable Ultrasonic Non-Destructive Digital Indicating Tester (PUNDIT-6).⁹ This tool generates low frequency ultrasonic pulses and measures the time taken for them to pass from one transducer to the other through the core sample between them, see Fig. 1. Sound wave velocity was calculated by dividing the sample length over the travel time as a direct wave. Empirical correlations were developed between sound wave velocity and sandstone core samples porosity and permeability at different compaction pressures with different cement concentrations.

3. Preview of the Effect of Different Factors on Rock Porosity and Permeability

This section presents an analysis of the mechanical testing results of a previous paper. This is to have a comprehensive picture of mechanical, petrophysical and acoustic properties of the studied sand core samples. The details of core samples preparation and mechanical properties testing can be found in Ref. 7.

3.1 Effect of Grain Properties on Reservoir Characteristics

Porosity and permeability are the main petrophysical characteristics of a reservoir. The primary porosity and permeability of clastic rocks depend on grain properties such as size, sorting, shape, roundness and grain arrangement.

Porosity is theoretically independent of grain size. This ideal situation, which corresponds to a maximum sorting, rarely occurs in nature. On the subject of contemporary sands, porosity decreases slightly when grain size increases. Figure 2 shows laboratory measured porosity values for the simulated sand samples. There is a slight decrease in porosity with the increase of grain size either with different cement percentage at constant compaction or at different compaction with the same cement percentage. This porosity decrease is probably due to a number of factors, which have only an indirect connection to grain size. Finer sands have a tendency to be more angular and are likely to be organized according to a less dense arrangement. Thus, they present a higher porosity than sands with coarser grains.

Contrarily to porosity, sandstone permeability increases with the increase of grain size. Figure 3 shows a significant increase in sand permeability with the increase of grain size both with different cement ratio at different compaction pressure and with the same cement ratio at different compaction pressures. This is easily explainable because the size of the pores and the throats, which connect the pores, are controlled by grain size: the larger the grains, the larger the pores and the section of the throats will be. Therefore, capillary attraction will be weaker and permeability will be higher.

3.2 Effect of the Degree of Cementation

Cementation is one of the most diagnostic phenomena. It is the deposition of minerals within the pore space. The minerals may be derived from the sediment itself by leaching or redeposition, or may also be derived from salts dissolved in interstitial or circulating water. Precipitation of cement will result in a substantial loss in porosity; Fig. 2a illustrates how cementation affects porosity. Also the degree of porosity loss due to cementation increases with the increase of compaction pressure.

Cementation after deposition either by chemical interaction between unstable grains and formation water or by circulation in the pore spaces of solutions under hydrodynamic forces causes a considerable reduction in permeability, along with the loss of porosity. Figure 3a shows a significant permeability reduction over all grain sizes of the tested sand samples. This rate of permeability reduction are not so much affected by the increase of compaction pressure.

3.3 Effect of Compaction

Compaction pressure causes sediment compaction, i.e. reduction in volume due to compression, the first stage of which is marked by a reduction in pore volume. In addition of compaction, there are other factors leading to a porosity reduction with depth, such as the temperature gradient increase and the passage of time, which also encourage other diagenetic phenomena. Figure 2b shows the porosity reduction due to compaction of sand grains with different cement percentages. It is observed that the effect of compaction decreases at large grain sizes. The amount of compaction depends not only on grain size and shape but also on the initial porosity and rate of sedimentation and passage of time.

Compaction creates a certain mechanical arrangement of grains and a new pore system pattern. This reduces the throats between pores, consequently causing a permeability reduction. Figure 3b illustrates a considerable permeability reduction with compaction pressure. A larger permeability reduction with compaction was observed at large grain sizes

than at small grain sizes. This reduction may be attributed to the effect of grain size on permeability.

4. Relation Between Acoustic and Petrophysical Properties

Porosity and permeability are the main petrophysical properties of a reservoir rock and have a vital impact on the evaluation processes at all stages. The acoustic property of a rock is the product of its seismic wave and density. It is an inherent property and depends on the elastic properties of the rock and rock density. In this section, we will examine the relationship between seismic wave velocity and porosity and permeability using the same sand core samples that was produced under different compaction pressure and with different cement percentages.

4.1 Seismic Wave Velocity and Porosity

Seismic wave velocity was measured in the laboratory, using the PUNDIT apparatus.⁹ This tool measures travel time of a seismic wave through the sample. This travel time depends on rock sample properties, which are: solid part (grains, matrix and cement), porosity and fluid filling the pores. In order to derive porosity from travel time or velocity, we need to know travel time in fluid and in the solid part. Many researchers have worked on this relation between seismic wave velocity and porosity, such as the relation developed by Wyllie *et al.*,¹⁰ which is valid for water saturated sandstone at depths greater than a few thousand feet:

$$1/V = \phi/V_f + (1-\phi) / V_m \quad (1)$$

Eq. 1 is referred to as the time average equation and it is a basic equation used in sonic logging in the form of $\Delta t = \phi\Delta t_f + (1-\phi) \Delta t_m$. In order to calculate porosity from travel time we need to know fluid travel time and matrix travel time.

Measured seismic wave velocities was plotted versus measured porosity for sand samples with different cement concentrations of 4%, 6% and 8% and different compaction pressures from 11000 to 23000 psi.

Figure 4 shows the behaviour of seismic wave velocity versus porosity with three cement percentages at two compaction pressures. It is obvious that with the decrease of cement percentage in these sand samples there is a reduction in seismic wave velocity for the same porosity. Also a decrease relation between seismic wave velocity and porosity at a given cement concentration and under definite compaction pressure.

For cores compacted at 11300 psi, the following relations between seismic wave velocity in m/sec and porosity in fraction have been found:

$$V = 4567.6 - 2604.5 \phi \quad \text{at 8\% cement} \quad (2)$$

$$V = 7679.7 - 15066 \phi \quad \text{at 6\% cement} \quad (3)$$

$$V = 8467.8 - 20511 \phi \quad \text{at 4\% cement} \quad (4)$$

For compaction at 22600 psi, the following relations between seismic wave velocity in m/sec and porosity in fraction have been found:

$$V = 6438.1 - 10506 \phi \quad \text{at 8\% cement} \quad (5)$$

$$V = 6517.9 - 12180 \phi \quad \text{at 6\% cement} \quad (6)$$

$$V = 7567.3 - 19919 \phi \quad \text{at 4\% cement} \quad (7)$$

Eqs. 2-7 can help in determining porosity from measured seismic wave velocity for rock samples with different cement concentrations.

4.2 Compaction Pressure Influence

Seismic wave velocity generally increases with increasing compaction. This increase is due to the relation between applied stress and rock elastic properties and density. The relation between seismic wave velocity and porosity at different compaction pressures has been tested. Figure 4 shows that seismic wave velocity is inversely proportional to porosity. With the increase of compaction, it is observed that porosity decreases and velocity increases regardless of cement percentages.

Certain relations between seismic wave velocity and compaction pressure were developed, see Fig. 5:

$$V = 1365.2 + 0.046 P \quad \text{at 4\% cement} \quad (8)$$

$$V = 2807.4 + 0.0481 P \quad \text{at 6\% cement} \quad (9)$$

$$V = 3355.3 + 0.0353 P \quad \text{at 8\% cement} \quad (10)$$

Eqs. 8-10 control the relation between compaction and wave velocity for different cement concentrations; so, they can be used to predict wave velocity at a given compaction or confining pressure.

4.3 Mean Pore Size Influence

Pore pattern of clastic rocks affects not only porosity and permeability of rock and fluid distribution in pore spaces but also most of the measured physical properties such as seismic wave velocity and electrical resistivity. Pore pattern is comprised of pore size, pore shape, and character of pore wall, and connection between pores and distribution of larger pores and their relation to each other. Pore size has a pronounced effect on seismic wave velocity. Test analysis has shown that seismic wave velocity decreases with larger pore size. Figure 6 illustrates this behaviour at two compaction pressures. A certain relation has been produced between seismic wave velocities and mean pore size:

$$V = 10014 - 211.9 D \quad \text{at 17000 psi} \quad (11)$$

$$V = 8057.7 - 207.42 D \quad \text{at 22600 psi} \quad (12)$$

Eqs. 11 and 12 show the velocity reduction with the increase of pore size, which reflects a porosity increase and the effect of the fluid filling pores on the velocity measurements.

4.4 Seismic Wave Velocity and Permeability

Greater porosity usually corresponds to greater permeability, but this is not always the case. Pore size, shape and continuity, as well as the amount of porosity, influence formation permeability. The conditions that affect permeability differ considerably from those that affect porosity. Temperature, hydraulic gradient and grain shape and packing have a bearing on the permeability of a potential reservoir rock. Compaction and cementation obviously reduce permeability based on primary porosity, whereas solution channels, fracturing joint planes and bedding planes increase permeability. The permeability of a reservoir rock is commonly determined in the laboratory by testing cores in a permeameter. Permeability can be derived from resistivity gradients, formation tester (FT) data, Nuclear magnetic resonance (NMR) and ϕ - S_{wi} charts. In this section, seismic wave velocity through core samples can be used to derive permeability. A decreasing function was observed between seismic wave velocity and permeability for the tested core samples at different cement concentrations, see Figure 7. Certain relations have been developed relating core permeability to seismic wave velocity in the cores.

$$V = 2760.4 - 284.34 K \quad \text{at 4\% cement} \quad (13)$$

$$V = 3892.3 - 198.01 K \quad \text{at 6\% cement} \quad (14)$$

$$V = 4076 - 186.22 K \quad \text{at 8\% cement} \quad (15)$$

Using Eqs 13-15, core sample permeability can be derived for a given sand core sample with a given cement concentration.

Conclusions

As the compaction pressure increases, the effect of grain size on porosity is reduced. Also, the compaction pressure factor can effect permeability more than the cementing material concentration factor could. For a small grain size, the effect of the grain size on the permeability was the main factor at all conditions, even at high compaction pressure.

The developed relations show that seismic wave velocity decreases with porosity and mean pore size, whereas it increases with cementation and compaction pressure.

A relationship has been developed between sand permeability and seismic wave velocity at different compaction pressures. This relation can help in determining rock permeability from measured physical property in addition to published techniques such as resistivity, NMR and $S_{wi}-\phi$.

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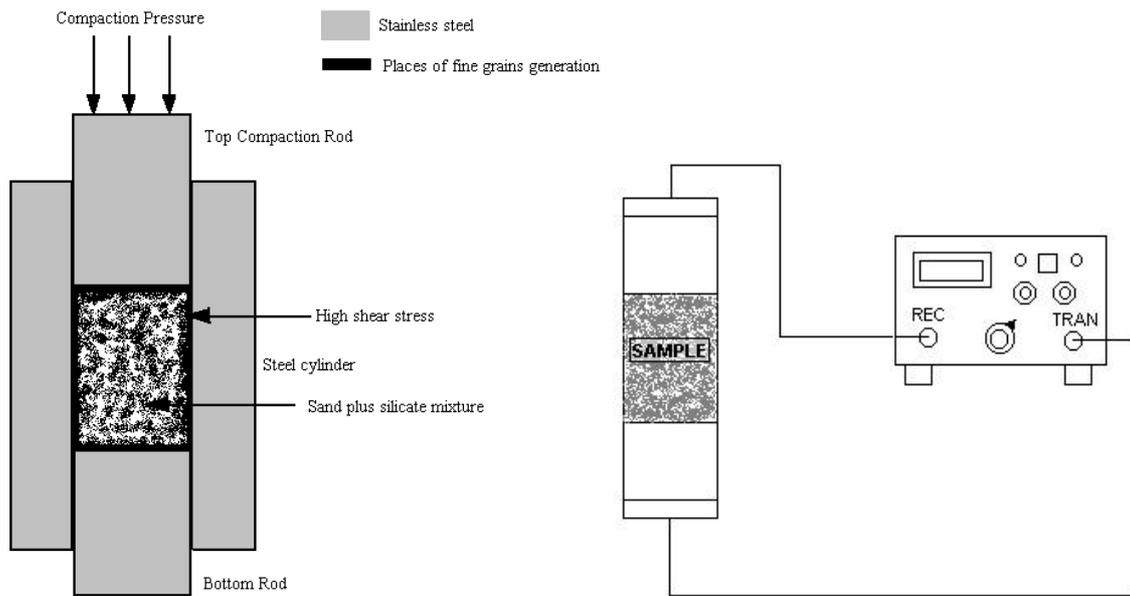


Figure 1: Compaction Cell (left) and PUNDIT connected to the rock sample (right).

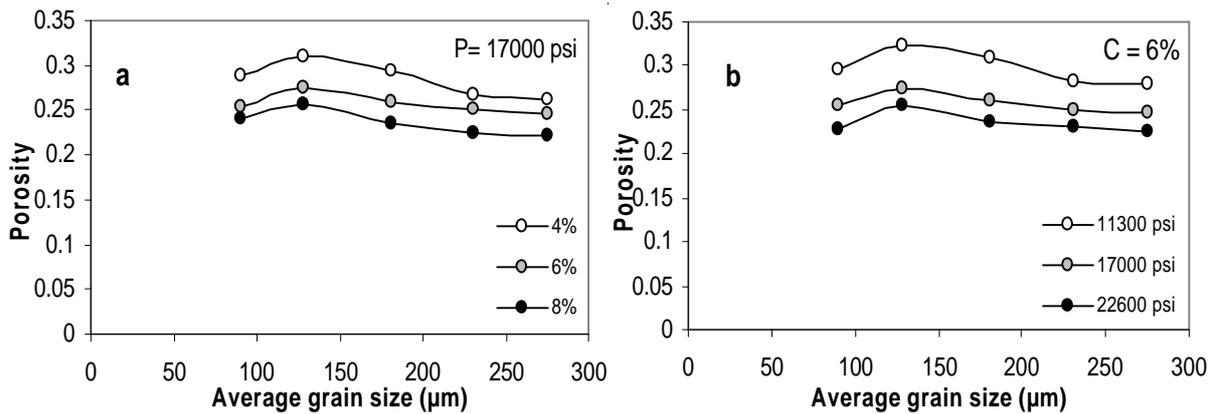


Figure 2: Effect of grain size on rock porosity (Ref. 7).

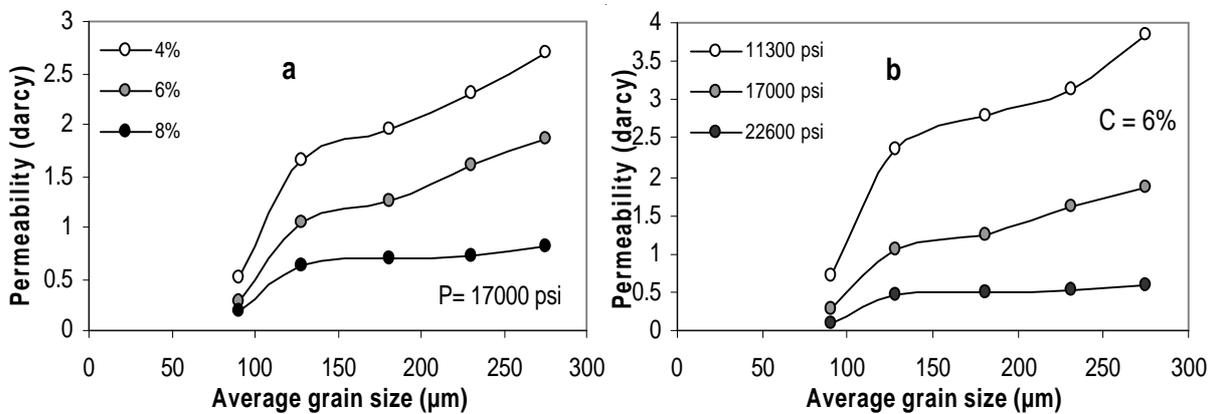


Figure 3: Effect of grain size on rock permeability (Ref. 7).

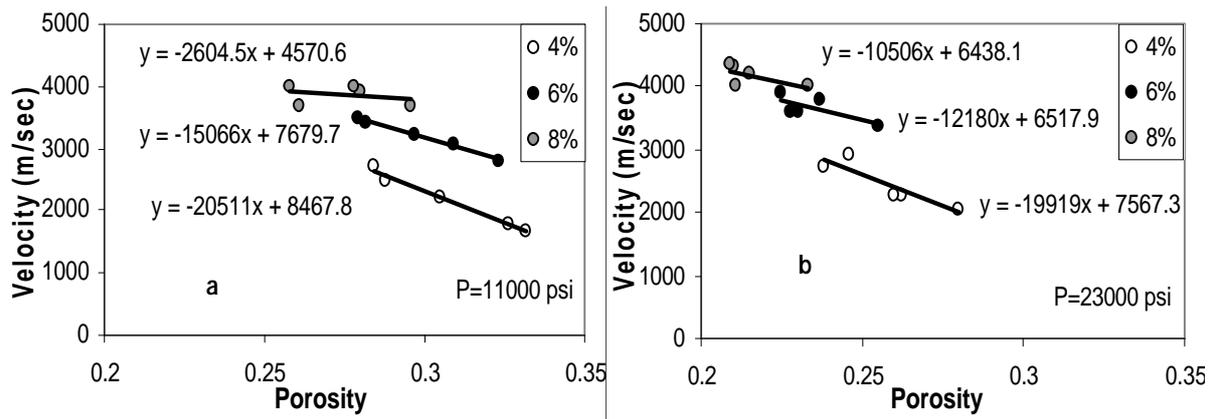


Figure 4: Rock porosity versus sonic velocity at varying cementation and compaction.

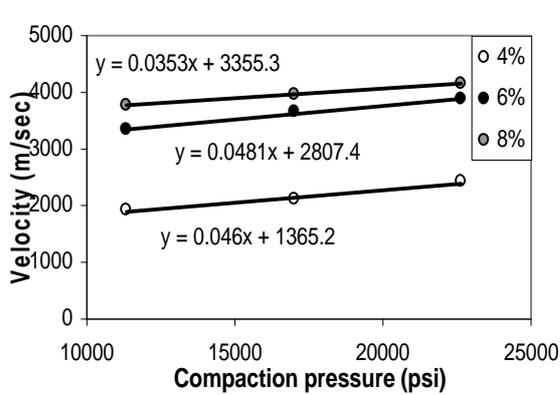


Figure 5: Compaction pressure versus sonic velocity at varying cementation.

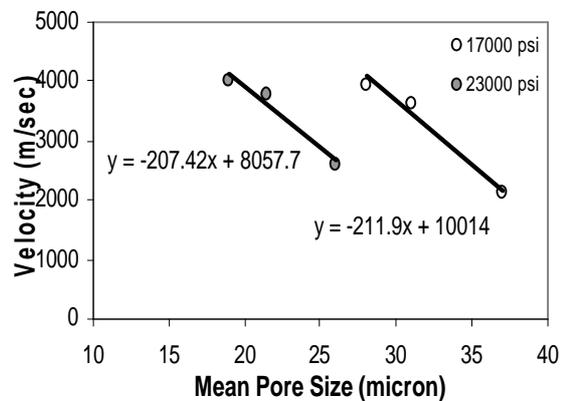


Figure 6: Mean pore size versus sonic velocity at varying compaction pressure.

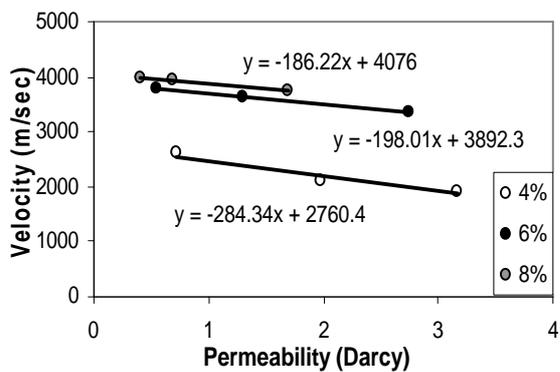


Figure 7: Rock permeability versus sonic velocity at varying cementation ratios.