DEVELOPED CORRELATIONS BETWEEN PETROPHYSICAL, ACOUSTIC, PHYSICAL PROPERTIES FOR SYNTHETIC SANDSTONE

E.S. Al-Homadhi and G.M. Hamada, College of Engineering,
King Saud University, Saudi Arabia

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 physical properties. Such physical 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 physical and petrophysical properties were used. The physical 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 grain size to 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 physical properties. The results of this study were presented as graphs of simulated lithification factors, porosity, and permeability versus sound wave velocity.

INTRODUCTION

The first essenial element of a petroleum reservoir is a reservoir rock. It is very impotant to well determine and understand the petrophysical properties and physical properties of reservoir rocks. There is a conjugate relationship between the physical 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 diagentic 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, minerals distribution and composition; 3) cement- charater, composition, amount, distribution with respect to grains and matrix[1-3].

Cementation, compaction, recrystallization, replacement, authigensis and differential solution exercise a considerable diagentic effects on rock properties and more specifically porosity and permeability. The majority of diagenetic proceses, 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 subjected 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 diagentic fators such as recementation and compaction. This paper uses the results of physical and petrophysical properties testing in a previous paper including porosity and permeability as rock petrophysical properties and grain size, cementation and compation pressure as rock physical 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 cementing, pore size distribution and compation pressures.

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 grains 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%[9]. The solidification of the compacted sand-cement mixture was done at 300^{o}c. Figure 1a shows the compation 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 Portable Ultrasonic Non-Destructive Digital Indicating Tester (PUNDIT-6)[7]. This tool generates ultrasonic pulses and measures the time taken for them to pass from one transducer to the other through the core sample between them, Fig.1b. Sound wave velocity was calculated by dividing the sample length over the travel time as a direct wave. Imperical correlations were developed between sound wave velocity and sandstone core samples porosity and permeability at different compaction pressures with different cement concentrations.

PREVIEW OF THE EFFECT OF DIFFERENT FACTORS ON ROCK POROSITY AND PERMEABILITY

This section presents an analysis of the physical testing results of a previous paper. This is to have a comprehensive picture of physical, petrophysical and acoustic properties of the studied sand core samples. The details of core samples preparation and physical properties testing can be found in Ref (8).

Effect of Grain Properties on Reservoir Characteristics

Porosity and permeability are the main petrophysical charaterstics of a reservoir. The primary porosity and permeability of clastic rocks depend on grain properties such as size, sorting, shape, roundness and grains 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 contemorary sands, porosity decreases slightly when grain size increases. Figure 2a-b shows laboratory measured porosity values for the simulated sand samples. There is 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 3a-b shows a significant increase in sand permeability with the increase of grain size either with different cement ratio at different compaction pressure or with the same cement ratio at different compaction pressure. This is easly explainable because the size of the pores and the thoates, which connect the pores to one, another 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.

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 ciriculating water. Precipitation of cement will result in a substabtial loss in porosity (Fig. 2a) illustrates how cementation affects porosity at different compaction. Also the degree of porosity loss due to cementation increases with the increase of compaction pressure.

Developed 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. It is worthy to state that theses cementation concentrations are uniformly distributed on grain surface. Figure 3a shows a significant permeability reduction all over grains size of the tested sand samples. This rate of permeability reduction was not affected by the increase of compaction pressure as shown on the figure.

Effect of Compaction

Compaction pressure causes a reduction in volume due to compression, the first stage of which is marked by a reduction in pore volume. In addition to compaction there are another factors which cause porosity reduction with depth these are the temperature 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 grains size. The amout of compaction depends not only on grains size and shape but also on the initial porosity and rate of sedimenation and passage of time.

Compaction creates certain mechanical arrangement of grains and new pore system pattern. This will reduces the throats between pores, consequently causing a permeability reduction. Figure 3b illustrates a considerable permeability reduction with compaction pressure. More permeability reduction with compaction was oserved at lage grains size than at small grains size. We believe that this reduction might be attributed to the effect of grains size on permeability.

RELATION BETWEEN ACOUSTIC PROPERTIES 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. An acoustic property of a rock is the product of its wave velocity 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 ultrasonic wave velocity and porosity and permeability using the same sand core samples that was produced under different compaction pressure and with different cement percentages.

Ultrasonic Wave Velocity and Porosity

Ultrasonic wave velocity was measured in the laboratory-using PUNDIT under confining stress. This tool measures travel time of ultrasonic wave through the sample. Porosity was measured for the samples in the laboratory using gas-porosimeter. 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. There are many characters worked on this relation between ultrasonic wave velocity and porosity such as that relation developed by Wyllie et al 1958 which is valid for water saturated sandstone at depth greater than a few thousand feet:

$$1/V = \phi/V_f + 1\text{-}\phi \ / \ V_m \qquad (1)$$

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

Measured ultrasonic wave velocity was ploted versus measured porosity for sands samples with different cement concentrations 4%, 6% and 8% and different compaction pressures 11000 to 2300 psi.

Figure 4 shows the behviour of ultrasonic wave velocity with 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 ultrasonic wave velocity for the same porosity. Also a decrease relation between ultrasonic wave velocity and porosity at given cement concentration and under definite compaction pressure.

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

$$V = 4567.6 - 2604.5\ \phi \quad \text{at 8\% cement} \qquad (2)$$
$$V = 7679.7 - 15066\ \phi \quad \text{at 6\% cement} \qquad (3)$$
$$V = 8467.8 - 20511\ \phi \quad \text{at 4\% cement} \qquad (4)$$

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

$$V = 6438.1 - 10506\ \phi \quad \text{at 8\% cement} \qquad (5)$$
$$V = 6517.9 - 12180\ \phi \quad \text{at 6\% cement} \qquad (6)$$
$$V = 7567.3 - 19919\ \phi \quad \text{at 4\% cement} \qquad (7)$$

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

Compaction Pressure Influence

Ultrasonic wave velocity generally increases with the increasing of compaction. This incease is due the relation between applied stress and rock elastic properties and density. The relation between sismic wave velocity and porosity at different compaction pressures has been tested. Figure 5 shows siesmic wave velocity is inversly proportional to porosity. With the increase of compaction, it is observed that porosity decreases and velocity increases regardless of cement percentages.

Certain relations between ultrasonic wave velocity and compaction pressure were developed

For 4% cement $V = 1365.2 + 0.046\ P$ (8)
For 6% cement $V = 2807.4 + 0.0481\ P$ (9)
and for 8% cement $V = 3355.3 + 0.0353\ P$ (10)

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

Mean Pore Size Influence

Pore patterns 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 ultrasonic wave velocity and electrical resistivity. Pore pattern is comprised of pore size, pore shape, and charater of pore wall, and connection between pores and distribution of larger pores sand their relations to one another. Pore size has a pronounced effect on ultrasonic wave velocity. Tests analysis has shown that ultrasonic wave velocity decreases with lareger pore size. Figure 6 illustrates this behaviour at two compaction pressures. Certain relation has been produced between ultrasonic wave velocities and means pore size.

$V = 10014 - 211.9\ D$ at 17000 psi (11)
and $V = 8057.7 - 207.42\ D$ at 22600 psi (12)

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

Ultrasonic Wave Velocity and Permeability

Greater porosity usually coresponds 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 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. In this study permeability was measured using liquid permeameter and the measured values were used in developing the correlations. Permeability can be derived from resistivity gradients, formation tester (FT) data, Nuclear magnetic resonance (NMR) ?ϕ-S_{wi} charts. In this section, ultrasonic wave velocity on core samples can be used to derive permeability. A decreasing function was observed between ultrasonic wave velocity and permeability for the tested core samples at different cement concentrations, Figure 7. Certain relations have been developed relating core permeability to ultrasonic wave velocity in the cores.

$$V = 2760.4 - 284.34\ K \qquad \text{at 4\% cement} \qquad (13)$$
$$V = 3892.3 - 198.01\ K \qquad \text{at 6\% cement} \qquad (14)$$
$$V = 4076 - 186.22\ K \qquad \text{at 8\% cement} \qquad (15)$$

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

CONCLUSIONS

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

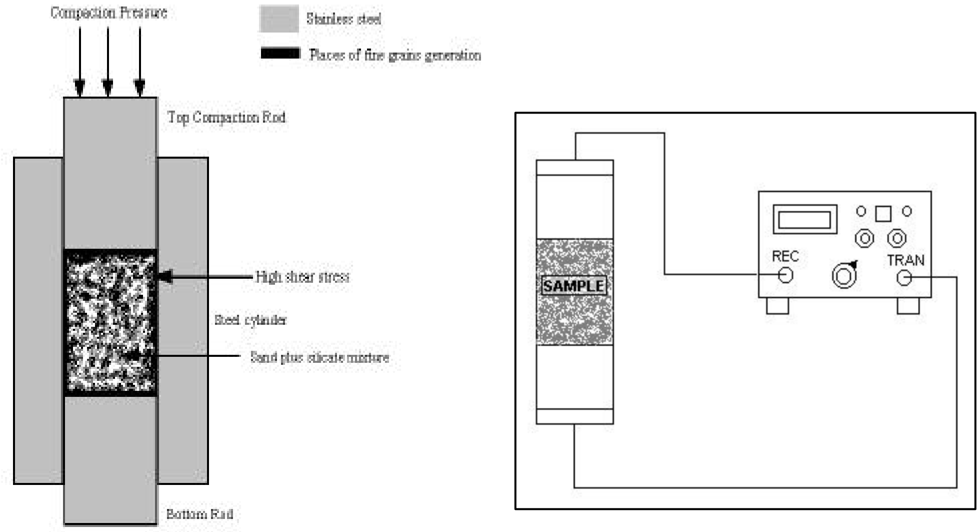
Developed relations have shown that ultrasonic wave velocity increases with the decrease of porosity, cementation, mean pore sizes and compaction pressure.

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

REFERENCES

1. Dodge, C.F., Holler, D.P. and Meyer, R.L.” Reservoir heterogeneities of some cretaceous sandstone”, *Bull. Amer. Assoc. Petroleum Geology*, Vol. **55**, p. 1814-1828, 1971.
2. Neasham, J.W.” The morphology of dispersed clays in sandstone reservoirs and its effect on sandstone shaliness, pore space and fluid flow characteristics”, SPE paper 6858 Presented at 52nd SPE meeting, Houston, 1977.
3. Serra, O.” Advanced interpretation of wireline logs” Schlumberger, 1986.
4. Allen, D.R. and Chilingarian, G.V.” Mechanics of sand compaction” Edited by Chilingarian, G.V. and Wolf, K.H., *Development in Sedimentology*, 18A, Elsevier, Amestrdam, 1975.
5. Maxwell, J.C.” Influence of depth , temperature and geologic age on porosity of quartzose sandstone”, *Bull. Amer. Asocc. Petroleum Geology*, 48, p. 698-709, 1964.
6. Rogers, W.F. and Head, W.B.” Relations between porosity and, median grain size, and sorting coefficients of synthetic sands” *J. sediment. Petrol*, Vol. 31, p. 467-470, 1961.
7. Farnel, CNS. ” Pundit-6 operation manual” CNS FARNEL, a division of Fullton Group Limited, UK, 1998.
8. Al-Homadhi, E.S. “Artificial sandstone cores production with a wide range of petrophysical properties” *J. King Saud University*, Eng. Sci. Vol.13 , p.45-61 , 2001.

9. Adwan Chemical Industries Co. Ltd, Industrial City, Riyadh, Kingdom of Saudi Arabia, 1999.



(a) (b)

Figure 1. a) Compaction Cell b) PUNDIT connected to the rock sample.

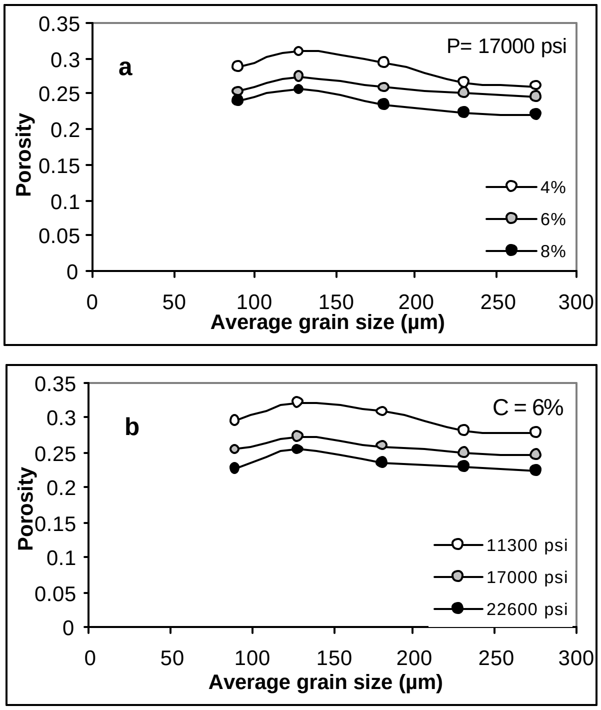


Figure 2a-b. Effect of grain size on rock porosity (Ref. 8).

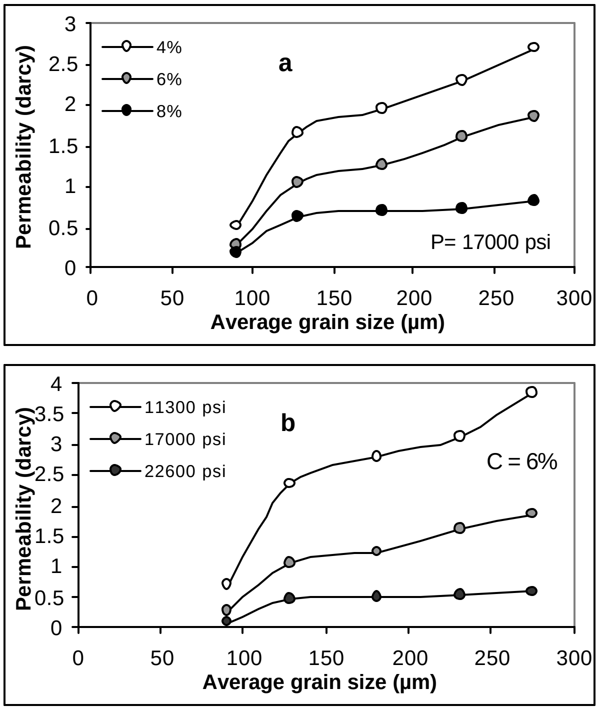


Figure 3a-b. Effect of grain size on rock permeability (Ref. 8).

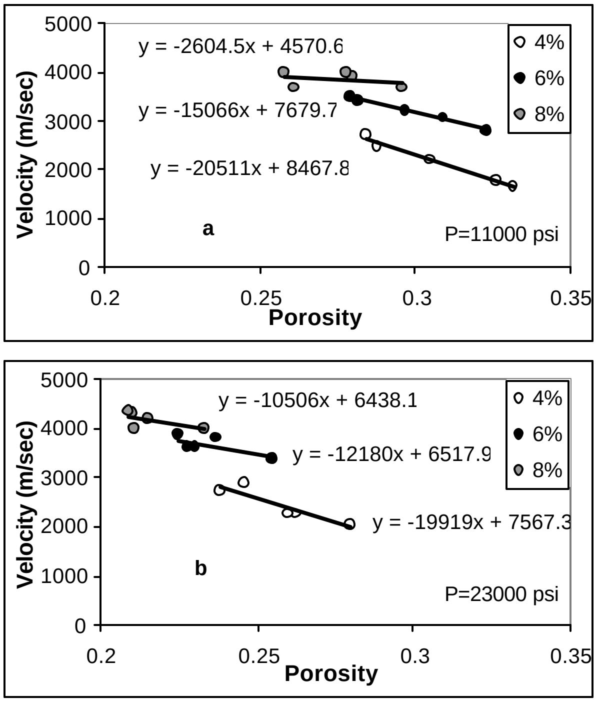


Figure 4a-b. Rock porosity versus sonic velocity at varying cementation and compaction.

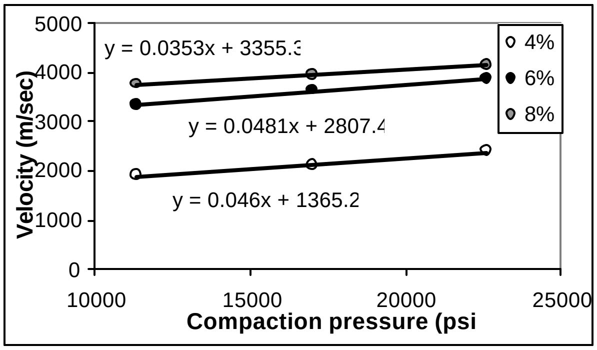


Figure 5. Compaction pressure versus sonic velocity at varying cementation.

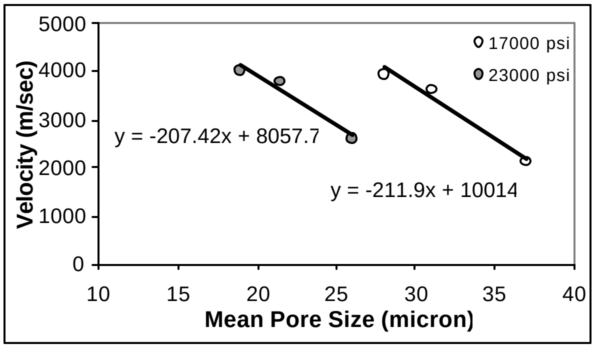


Figure 6: Mean pore size versus sonic velocity at varying compaction pressure.

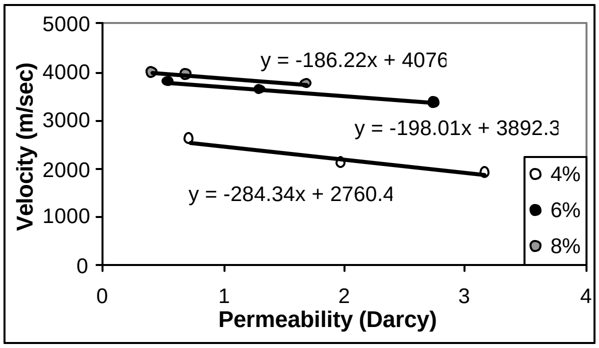


Figure 7: Rock permeability versus sonic velocity at varying cementation ratios.