MECHANICAL AND PETROPHYSICAL ANALYSIS OF SYNTHETIC SANDSTONE FOR ENHANCED OIL RECOVERY APPLICATIONS

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ABSTRACT

The present work aims to develop a methodology for the preparation of synthetic sandstone to be used in enhanced oil recovery (EOR) studies. It also analyzes synthetic sandstone's properties. A 2³ factorial planning with central point in triplicate was performed, evaluating parameters such as concentration of ceramic clay, compaction pressure and sintering temperature through porosity, permeability, and uniaxial compression strength. The sandstone produced presented porosity and permeability similar to those found in natural rocks, which make them suitable for use in EOR research.

KEYWORDS

synthetic sandstone; porosity; permeability; uniaxial compression strength; enhanced oil recovery

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1. INTRODUCTION

Currently, Petroleum is the main source of energy on the planet (Tarifa et al., 2016). Due to the high demand for petroleum, many researchers try to find ways to increase its production. Recovery processes can be used to increase well production. Primary recovery depends only on reservoir pressure, while secondary recovery involves water and immiscible gas injection (Aguilar & Mansur, 2016). Since, during extraction, two thirds of oil remains inside the reservoir, even after both the primary and secondary recoveries (Lu et al., 2014; Yuan et al., 2015), the use of enhanced oil recovery (EOR) method becomes necessary to maximize production.

EOR studies in oil laboratories have been performed with several types of reservoir rocks, such as limestone and Botucatu and Berea sandstones (Cardoso & Balaban, 2015; Santos, 2015; Soares, 2012). However, samples from natural sources are difficult to obtain, and usually they are anisotropic (that is, they present different properties when analyzed from different directions), and may be expensive to acquire (Fattahpour et al., 2014; Marques et al., 2011). Therefore, the utilization of homogeneous analogous synthetic samples for experimental testing can be an advantage (Costa, 2016).

Ceramic clay is a naturally available material, presenting very fine grain size, which acquires some plasticity when moistened. It is made from

crystal particles from a restricted number of minerals known as clay minerals, which are composed of hydrous aluminium and iron silicates, and contain a certain amount of alkaline and alkaline earth elements. Even though the clay may be molded easily, prior to sintering, after this process it presents a tough, firm shape (Avelino, 2013). When mixed with sand, it allows the making of consolidated porous media.

In this context, the present work aims to obtain homogeneous synthetic sandstone from mixing sand and ceramic clay to be used potentially in EOR studies, to analyze its mechanical (uniaxial compression strength) and petrophysical (porosity and permeability) properties and, then, compare those to natural anisotropic sandstone samples used in EOR.

2. MATERIALS AND METHODS

2.1 Synthetic sandstone preparation

The synthetic sandstone samples were prepared using sand from the Redinha beach (Natal/RN, Brazil) and ceramic clay (Lagoa de Velhos/RN, Brazil). The present work evaluated the amount of ceramic clay, compaction pressure, and sintering. The methodology was carried out as follows.

- The impurities (roots) were removed from the ceramic clay. Following, the clay was set to dry

Figure 1. Cast used in sample compaction (mean scale in mm).

Table 1. Sandstone production experimental planning.

Process variable	Upper level (+1)	Central level (0)	Lower level (-1)
C ^a (% m/m)	40	30	20
P ^b (kgf/cm ²)	200	150	100
T ^c (°C)	950	900	850

C^a: Ceramic clay content; P^b: Compaction pressure; T^c: Sintering temperature.

for 24 hours at 110 °C in a lab oven. Then, the clay was ground in a ball mill for 1 hour, and sifted in a 200-mesh sieve. Contents used in the mixture were 20, 30, and 40 % in weight;

- b) The sand was sifted and the (-65+100) mesh fraction (mean diameter of 181.0 µm) was used because it presented a diameter similar to the Berea sandstone (170 µm) (Rutter & Glover, 2012);
- c) The ceramic clay and sand were mixed (60 grams total weight) and either 4.0 or 4.2 mL of water were added to the mixture (4.0 mL in the 20 and 30% ceramic clay concentration, and 4.2mL in the 40 % one) to mix the components and hydrate the ceramic clay. The homogenization lasted 10 minutes and the mixture was inserted in the cast (Figure 1) for compaction, at 100, 150, and 200 kgf/cm². After compaction, the samples were taken off the cast and dried for 24 h at 115 °C in a lab oven;
- d) Finally, the samples were sintered in a furnace at a 10 °C/min heating rate, at temperatures of 850, 900, and 950 °C for 3 hours.

A 2³ factorial planning with central point in triplicate (Table 1) was used to evaluate the effect of each factor over the variables in question. The

tests used the software *Statistica 8.0*. The variables adopted for analysis were porosity, permeability, and uniaxial compression strength.

2.2 Porosity (Φ)

The sandstone measurements were obtained using a caliper rule, and the porosities were acquired using a porosimeter as shown in Figure 2. The sandstone samples were accommodated inside the porosimeter in chamber (b), and the porous volume was obtained from the relationship between initial pressure from chamber (a) and the system total pressure from chambers (a) + (b). Thus, based on the relationships described above, the porosity was determined (Costa, 2016).

2.3 Permeability (k)

The permeabilities of the synthetic sandstone samples were acquired through an experiment using the fluid injection system presented in Figure 3. The pump flow rate was kept at approximately 3 mL/min. The values of plug dimensions, viscosity, injected fluid flow rate, and system pressure were applied to Darcy's Law (Equation 1) to obtain the sample's permeability.

Figure 2. Porosimeter: (a) cell 1, (b) cell 2, (c) steel bodies used as standard volume, (d) compressor, (e) manometer, and (f) pressure transducer.

Figure 3. Permeability experiment system: (a) mineral oil flask, (b) injection pump, (c) acrylic cell, (d) piston, (e) internal pressure manometer, (f) compressed air cylinder, (g) external pressure manometer, (h) holder, (i) synthetic sandstone, and (j) cylinder.

$$k = \frac{-q\mu L}{A\Delta P} \quad (4)$$

Where:

k = absolute permeability of porous medium (mD);

q = fluid flow rate through porous medium (cm³/s);

μ = fluid viscosity (cP);

L = porous medium length (cm);

A = transversal area open to flow (cm²);

ΔP = head loss (atm).

2.4 Uniaxial Compression Strength (UCS)

The samples were sanded until they reached 1.5 cm height and their uniaxial compression strengths were analyzed using the AG-I 100-kN universal mechanical testing machine. The testing occurred at room temperature (25 °C).

temperature, Φ^d is porosity, k^e is permeability and UCS^f is uniaxial compression strength.

The Pareto charts for porosity, permeability, and uniaxial compression strength were based on the results displayed in Table 2 (Figure 5). One can observe that concentration of ceramic clay is the most relevant parameter, followed by the compaction pressure. One can also note that the increase in ceramic clay content causes a decrease in porosity and permeability. The physical reason for that resides at the binder distribution (clay) between the grains. For lower ceramic clay contents, the clay is found in the grains' contact area, creating binder bonds that, when sintered, get harder and unite sand particles. As the amount of clay increases, the number of bonds and their extensions increase. At a certain moment, this increase promotes the involvement of particles and the filling of empty spaces, leading to the reduction of porosity and permeability (Holt et al., 2005).

3. RESULTS AND DISCUSSION

Figure 4 displays samples of sandstone sintered at different temperatures.

The synthetic sandstone plugs presented physical consistence. The experiment analyzes the samples' porosity, permeability, and uniaxial compression strength. The results are displayed in Table 2, where C^a is concentration of ceramic clay, P^b is compaction pressure, T^c is sintering

Figure 4. Sandstone samples sintered at (a) 850 °C, (b) 900 °C, and (c) 950 °C.

Table 2. Results from the 2^3 factorial planning with central point in triplicate.

Number	C ^a	P ^b	T ^c	Φ^d (%)	k ^e (mD)	UCS ^f (MPa)
1	-	-	-	61.2996	21.9548	2.3391
2	+	-	-	54.8204	3.8952	26.4793
3	-	+	-	59.6067	13.1160	4.5558
4	+	+	-	50.9985	2.6718	39.2123
5	-	-	+	61.9282	25.1389	1.5780
6	+	-	+	54.6267	5.5531	22.2442
7	-	+	+	59.6216	14.0688	2.7423
8	+	+	+	51.2338	3.8726	31.7800
9	0	0	0	56.7968	9.6678	12.0961
10	0	0	0	56.7026	8.9974	15.2574
11	0	0	0	56.7968	9.7939	11.2369

The increase in pressure during sample preparation also leads to a decrease in porosity and permeability. This phenomenon happens due to the greater compaction of particles at higher pressures (Costa, 2016).

Increases in temperature increase permeability and, in general, also affect porosity. This is due to the greater volumetric dilatation of the beach sand,

rich in silicon, at higher temperatures. The silicon sand expands when exposed to temperatures around 500 °C (Soares, 2000), and that dilatation leads to the formation of additional empty and permeable spaces inside the synthetic sandstone.

Since the UCS presents an opposite behavior from the porosity (Fattahpour et al., 2014), an increase in evaluated variables is observed as the

Figure 5. Pareto Diagrams for (a) porosity, (b) permeability, (c) uniaxial compression strength, with a 95 % confidence level.

Figure 6. Real and predicted values for (a) porosity, (b) permeability, and (c) uniaxial compression strength.

ceramic clay content and compaction pressure increase and sintering temperature decreases.

Through coefficient regression, linear models for porosity (Equation 2), permeability (Equation 3), and uniaxial compression strength (Equation 4) were obtained. The significant effects from each equation appear below in bold.

$$\Phi = \mathbf{56.767} - \mathbf{3.847 C} - \mathbf{1.402 P} + \mathbf{0.086 T} - \mathbf{0.402 CP} - 0.075 CT - 0.023 PT \quad (2)$$

$$k = \mathbf{10.794} - \mathbf{7.286 C} - \mathbf{2.852 P} + \mathbf{0.874 T} + \mathbf{2.126 CP} - 0.160 CT - 0.336 PT \quad (3)$$

$$UCS = \mathbf{15.411} + \mathbf{13.562 C} + 3.206 T - 1.780 T^2 + 2.361 CP - 1.137 CT - 0.531 PT \quad (4)$$

Figure 6 presents the experimental data and the linear models for each variable.

The proximity between real data and linear fitting reveals that Equations 2, 3, and 4 are capable of modeling the experimental data properly.

To validate the empirical models, analysis of variance (ANOVA) and F-tests were conducted. The results can be seen in Tables 3, 4, and 5.

The values of the quadratic sums and degrees of freedom were obtained using the *Statistica 8.0* software, and the quadratic means were acquired by dividing the former and the latter. The F_1 parameters were obtained through the ratio between the regression and residue quadratic

Table 3. ANOVA for porosity ($R^2 = 0.9986$).

Source of variation	Quadratic sum	Degrees of freedom	Mean square	$F_{\text{calculated}}$	F_{table}
Regression	135.4726	4	33.8682	$F_1 = 1061.6975$	$F_1 = 4.53$
Residual	0.1914	6	0.0319		
Lack of Fit	0.1855	4	0.0464	$F_2 = 15.7203$	$F_2 = 19.25$
Pure Error	0.0059	2	0.0030		
Total	135.6640	10			

Table 4. ANOVA for permeability ($R^2 = 0.9835$).

Source of variation	Quadratic sum	Degrees of freedom	Mean square	F _{calculated}	F _{table}
Regression	531.9697	4	132.9920	F ₁ = 89.4849	F ₁ = 4.53
Residual	8.9172	6	1.4862		
Lack of Fit	8.5506	4	2.1377	F ₂ = 11.6620	F ₂ = 19.25
Pure Error	0.3666	2	0.1833		
Total	540.8869	10			

Table 5. ANOVA for UCS ($R^2 = 0.8798$).

Source of variation	Quadratic sum	Degrees of freedom	Mean square	F _{calculated}	F _{table}
Regression	1471.4950	1	1471.4950	F ₁ = 65.8584	F ₁ = 5.12
Residual	201.0900	9	22.3433		
Lack of Fit	192.1250	7	27.4464	F ₂ = 6.1230	F ₂ = 19.35
Pure Error	8.9650	2	4.4825		
Total	1672.5850	10			

Table 6. Porosities and permeabilities of natural rocks.

Rock	Reference	Φ / %	k / mD
Açu Sandstone	Curbelo (2006)	24.00 to 29.78	1.21 to 8.36
Limestone	Soares (2012)	48.99 to 74.28	-
Botucatu Sandstone	Souza (2013)	28.81 to 44.05	-
Berea Sandstone	Rosenbrand et al. (2014)	18	9.8 to 13.7
Botucatu Sandstone	Firmino (2016)	37.19 to 54.96	-
Botucatu Sandstone	This work	44.51 to 57.84	24.76 to 28.09
Berea Sandstone	This work	20.41	2.43
Synthetic Sandstone	This work	50.998 to 61.928	2.672 to 25.139

means; the F_2 parameters, through the ratio between lack of adjustment and pure error quadratic means. This was done to make the comparison of tabulated values possible.

According to the results presented in Tables 3, 4, and 5; one can state that the models are significant, since the calculated F_1 was higher than the reference F_1 , and predictive, since the calculated F_2 was smaller than the reference F_2 . Thus, the models may be used to predict results inside the chosen factors domain (Barros Neto et al., 2001). The determination coefficient (R^2) was applied to assess the adjustment of the models to the experimental data. The correlation between values calculated using the models and the experimental ones improves as R^2 reaches 1. This indicates that the models well represent the results obtained experimentally (Carvalho et al. 2016). Thus, the best determination coefficient was

achieved with the porosity analysis, followed by the permeability. The determination coefficient found for uniaxial compression strength was the lowest one, probably due to the error displayed in Figure 6c, where two points presenting values between 11 and 13 distance themselves from the main diagonal; while most data points are exactly on the diagonal or very close to it, indicating that the results from this parameter are also reproducible.

The response surfaces are displayed in Figure 7. They show the linear behavior between the evaluated variables and the concentration of ceramic clay and compaction pressure. It is also noticeable that lower values of these two properties lead to higher values of porosity and permeability, and to lower uniaxial compression strength values.

Figure 7. Response surfaces at $T = 900\text{ }^{\circ}\text{C}$ for (a) porosity, (b) permeability, and (c) uniaxial compression strength.

Since the petrophysical properties porosity and permeability are important to reservoir rocks, the values found for the synthetic sandstone can be compared to the natural rocks' ones, most commonly used in studies involving enhanced oil recovery, as shown in Table 6.

One can observe that porosity and permeability ranges for the synthetic sandstone are similar to the ones found in natural rocks used in EOR studies, which supports the utilization of synthetic sandstone samples in these studies.

4. CONCLUSION

The goal of the present work was to develop a methodology to prepare homogeneous synthetic sandstone plugs by mixing sand and clay to be used in enhanced oil recovery research projects. It also sought to evaluate synthetic sand plugs' properties and compare those to anisotropic natural sandstone samples used in EOR. Based on the results achieved, one can obtain the following conclusions:

- It is possible to obtain synthetic sandstone by mixing and sintering beach sand and ceramic clay;
- Increases in compaction pressure and ceramic clay content along with decreases in temperature lead to lower porosities and permeability, and higher uniaxial compression strength of synthetic sandstones;
- Based on statistical analysis, the concentration of ceramic clay was the most relevant parameter;
- The acquired models were adequate to describe the data;
- Linear behaviors were obtained between evaluated variables, ceramic clay content, and compaction pressure;
- Finally, porosity and permeability ranges found for the synthetic sandstone samples are similar to the ones from natural rocks, supporting the utilization of those samples in enhanced oil recovery research projects.

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