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EXPERIMENTAL AND MODELING OF FRIABLES AND STONE OIL RESERVOIRS CONSOLIDATION USING STEEL MAKING SLAG

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ABSTRACT

A mathematical model was developed simulating the process of sand production in under downhole stress state. The model was derived based on Mohr-Colomb failure criterion, Darcy equation for radial flow and reservoir stress state. In order to predict the on-set of sand production (critical drawdown) using the developed model, data obtained from the consolidation study in connection with the physical and mechanical properties of the consolidated samples as well as the stress state acting on the reservoir under investigation were used as an input in the model.

Results of this study showed that a mixture of Steel Making Slag, calcium chloride ($CaCl_2$), calcium hydroxide ($Ca(OH)_2$) and water was able to control sand production with a 22% maximum loss in productivity. The mathematical model predicts the maximum allowable drawdown and sand-free production rates of the consolidated friable sandsone samples under downhole in-situ stress state. Furtherore, the model can be applied as well to predict the critical drawdown and sand-free production rates for naturally cemented formations.

NOMENCLATURE

h	reservoir thickness, ft.
k	reservoir rock permeability, mD.
P_e	reservoir pressure gradient, psi/ft.
P_{wc}	critical wellbore pressure gradient, psi/ft.
q_c	critical production rate, bbl/day.
r_w, r_e	wellbroe and reservoir radii respectively, ft.
TVD	total vertical depth, ft.
α, β	well inclination and orientation angles respectively, degree.
θ	angular position around the borehole, degree.
μo	reservoir fluid viscosity, cp.
σ	normal stress at failure gradient, psi/ft.
σo	uniaxial compressive strength, psi.
σ_H, σ_h, σ_v	in-situ principal stresses gradient, psi/ft.
σx, σy, σzz	transformed in-situ stress gradients in cartesian form, psi/ft.
σ_r, σ_θ, σ_z	induced stresses gradients in polar form, psi/ft.
σ_1, σ_2, σ_3	principal stresses gradients acting on the borehole, psi/ft.
v	Poisson's ratio, fraction.
ϕ	rock angle of internal friction.
τ_f	shear stress gradient at failure, psi/ft.
τ_{Max}	calculated shear stress gradient from the in-situ stresses, psi/ft.
τ_o	apparent cohesion of the reservoir rock, psi.
τ_{xy}, τ_{xz}, τ_{yz}	induced shear stresses gradients acting on the borehole, psi/ft.
$\tau_{r\theta}$, τ_{rz}, $\tau_{\theta z}$	induced stresses gradients acting on the borehole, psi/ft.

1. INTRODUCTION

Sand production problems are encountered throughout the world and recently are detected in Saudi Arabian oil fields. Several techniques could be used to minimize sand production such as drawdown control, gravel packing, screen liners, resin consolidation, etc. The most advanced method for sand control among the previously mentioned techniques is the in-situ consolidation. Sand in-situ consolidation involves the process of injecting chemicals into the naturally unconsolidated formation which provide an in-situ grain-to-grain cementation without affecting formation permeability. Sand production problems are experienced in many oil and gas productive formations in Saudi Arabia [1-4]. They are most significant in unconsolidated sandstone reservoirs. Sand influx into the wellbore may lead to various problems such as erosion of valves and pipelines, plugging the production liner and sand accumulation in the separators. Cleaning and repair works related to sand production plus loss of revenue due to production rate restriction amounts to great costs incurred by the industry every year. Furthermore, undetected erosion of production equipment may pose a major safety hazard in case of high-pressure gas wells [5].

Sand production can be explained in several ways. The most convincing theory attributes sand production to cementing material failure due to the induced in-situ stresses generated due to the reservoir pore pressure drop. Furthermore, the individual sand grains are displaced and carried into the wellbore by means of the flowing hydrocarbon. The chemical incompatibility between the interstitial water and water contained in the aquifer are another strong causes of sand production. High water cut can actually dissolve a part of the cementing material between sand grains and leads to sand production problem [6].

Several methods were proposed and adopted for the control of sand production in the past [7-9]. These methods were intended either to prevent or reduce the flow of sand particles into the wellbore during the course of production. These methods include mechanical means such as sand screens, filters, perforated or slotted liners, gravel packing [7-11]; chemical agents such as plastic consolidations and a combination of mechanical and chemical usually referred to as resin-sand packed [12-24].

Low and high temperature oxidation of crude oil has been used to test its potential as sand consolidation technique. The crude oil reacts with oxygen through numerous and complex reaction processes. These reactions in turn depend upon the employed temperature. Low temperature oxidation is found below 500° C and is characterized by different products such as oxygenated hydrocarbons like aldehydes, alcohol, ketones, acids and hydro-peroxides with carbon oxides. Light oils were found to be more susceptible to low temperature oxidation than heavy oils, because low temperature affects the viscosity, density and hence alters the distillation characteristics of the oil [25-31].

For successful sand consolidation operation, there are two major factors: firstly, the binding film must adhere to the surface of sand grains and do not obstruct the flow of the fluid and secondly it must provides reasonable strength to resist the flow induced stresses.

Screening these proposed methods shows that these methods are either expensive or incapable to prevent the flow of sand particles into the wellbore. In this work Steel Making Slag (SMS) which is produced as a byproduct from the Saudi steel industry was tested for potential use as a cementing material for in-situ consolidation of friable sandstone reservoirs. In this process, the Steel Making Slag and chemical activators were mixed with the friable sand and the slurry was cured at 95° C for 24 hours. The uniaxial compressive strength and the absolute permeability of the consolidated sand have been evaluated after 24 hours curing period and after 30 days aging in water and kerosene to evaluate the deterioration trend of these consolidated samples due to water and oil production.

The current work presents the results of a new in-situ consolidation technique of friable sandstone oil reservoirs using a byproduct resulted from steel manufacturing (Steel Making Slag). The utilization of this byproduct can greatly protects the local environment from pollution problems resulted from dumping this material. To integrate laboratory consolidation tests into the real reservoir conditions, a mathematical model simulating sand production process is developed.

2. EXPERIMENTAL WORK AND RAW MATERIALS

Properties of The Used Friable Sand

Sand used in this study was brought from half-moon beach in the eastern province of Saudi Arabia. The sand was sieved using US-ASTM set of sieves. The grain size distribution of this sand is given in Fig. 1. Granulometric analysis showed that this sand is rich in size 50 mesh. This friable sand was packed in a Hoek cell and its absolute permeability was measured. The permeability of the used friable sand pack was 0.50 Darcy. It was used as a reference value in the physical and mathematical analysis performed in this study.

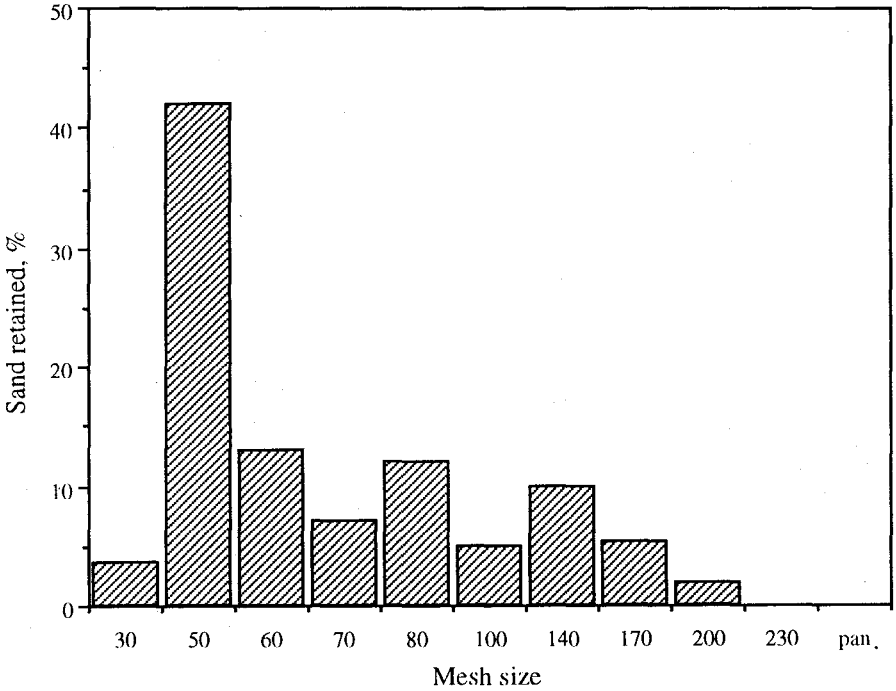

Fig. 1. Granulometric analysis of the friable sand used.

Composition of Steel Making Slag

Slag is a major byproduct in iron and steel-making industry. Slag produced is classified into two categories: Blast Furnace Slag and Steel Making Slag. Blast Furnace Slag is produced in the process of reducing iron ore to pig iron in a blast furnace, while the Steel Making Slag is a byproduct of steel making process. Blast Furnace Slag has been accepted for used by the construction industry [24]. It has also been introduced to the oil industry to consolidate drilling fluids [25-27]. There are three basic steel making processes in use today. They are open hearth (OH), basic oxygen (BO), and electric arc (EA). The chemical composition of the Steel Making Slag will vary depending upon the process used to produce steel [24]. Steel Making Slag has been investigated for use in asphalt pavement. The Steel Making Slag used in this investigation was obtained from Hadeed steel plant in Jubail industrial area in the eastern province of Saudi Arabia. This plant unitizes the direct reduction-electric arc furnace (DR-EAF) technology for steel making which generates slag at the rate of 250,000 metric tons per year. The chemical composition of the Steel Making Slag is given in Table 1 [24].

Table 1 Chemical composition of the used Steel Making Slag [28].

Component	Percent by weight
Iron (Fe) total	20.58
Lime (CaO)	31.42
Silica (SiO_2)	17.55
Alumna (Al_2O_3)	7.84
Magnesia (MgO)	12.78
Iron oxide (FeO)	19.12
Manganese oxide (MnO)	2.46
Others	3.54

Friable Sand Consolidation Technique

To prepare consolidated sand samples with slag, chemical activators (CaOH and $CaCO_3$) were mixed with water using a blender for 10 minutes. The Steel Making Slag was then added to the water-activator mixture at a low rate keeping the blender rotating for another 10 minutes. A pre-designed weight of sand were added to the slurry and the mixture was blended until a uniform slurry was obtained. The uniform slurry was poured into molded and shacked a magnetic shaker to remove any trapped gasses. The molds were covered with aluminum foil and cured at 95°C for 24 hours. After 24 hours curing time, samples were picked up from the molds and tested for absolute permeability and uniaxial compressive strength (see Table 2). Consolidated sand deterioration was evaluated by aging the consolidated samples in water and kerosene for 30 days to simulate water and oil flow effect (see Table 3).

Table 2 Composition and results of samples consolidated using Steel Making Slag.

Mixture components weight, g						Curing conditions		Measured properties	
Mix no.	H_2O	Slag	$Ca(OH)_2$	$CaCl_2$	Sand	Temp. ,°C	Time, hrs	Uniaxial compressive strength, MPa	Absolute permeability, Darcy
Mix 1	750	150	150	150	2250	95	24	Soft	NM
Mix 2	750	225	225	225	2250	95	24	0.069	NM
Mix 3	750	300	150	150	2250	95	24	0.138	0.35
Mix 4	750	300	225	225	2250	95	24	0.586	0.21
Mix 5	750	375	225	225	2250	95	24	1.069	0.14

Table 3 Permeability and compressive strength of consolidated sand using Steel Making Slag at various curing environments.

Mixture no.	24 hours curing at 90°C		Uniaxial compressive strength, MPa		Absolute permeability, Darcy	
	Uniaxial compressive strength, MPa	Absolute permeability, Darcy	30 days aging in fresh water at 21°C	30 days aging in Kerosene at 21°C	30 days aging in fresh water at 21°C	30 days aging in Kerosene at 21°C
Mix 1	Soft	NM	—	—	—	—
Mix 2	0.069	NM	—	—	0.39	—
Mix 3	0.138	0.35	1.379	2.414	0.36	0.39
Mix 4	0.586	0.21	10.689	12.276	0.23	0.24
Mix 5	1.069	0.14	14.483	17.241	0.18	0.203

Sand Production Prediction Modeling

One of the most famous and applied rock failure criterion is the Mohr-Coulomb failure criterion which is defined as follows [1, 4]:

$$\tau_f = \tau_o + \sigma \tan \phi \tag{1}$$

The in-situ principal stresses can be transformed parallel to the wellbore axis (for inclined or horizontal wells as shown in Fig. 2) using the following matrices [1, 4]:

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{zz} \end{bmatrix} = \begin{bmatrix} \mathrm{Cos}^2\beta\mathrm{Cos}^2\alpha & \mathrm{Sin}^2\beta\mathrm{Cos}^2\alpha & \mathrm{Sin}^2\alpha \\ \mathrm{Sin}^2\beta & \mathrm{Cos}^2\beta & 0 \\ \mathrm{Cos}^2\beta\mathrm{Sin}^2\alpha & \mathrm{Sin}^2\beta\mathrm{Sin}^2\alpha & \mathrm{Cos}^2\alpha \end{bmatrix} \begin{bmatrix} \sigma_H \\ \sigma_h \\ \sigma_v \end{bmatrix} \tag{2}$$

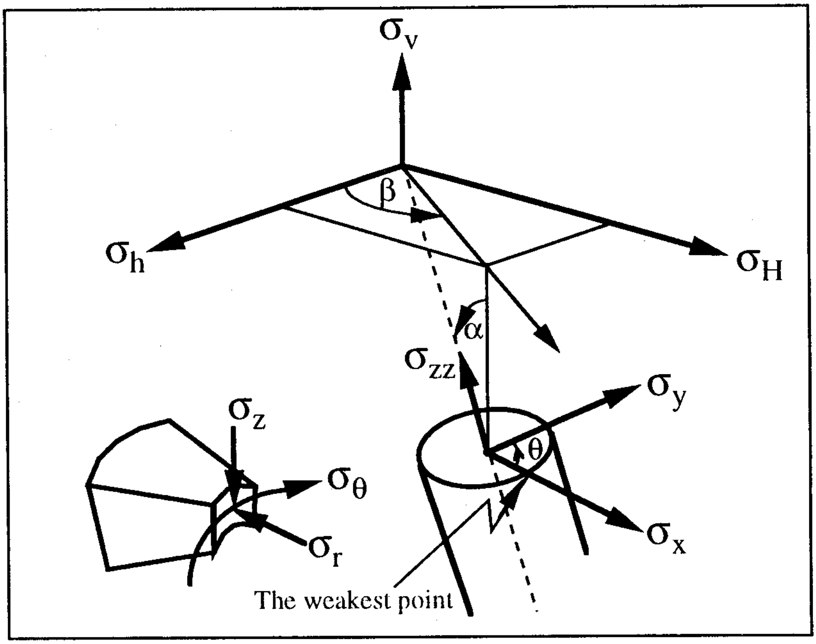

Fig. 2. Distribution of stresses acting on a deviated well.

$$\begin{bmatrix}\tau_{yz}\\ \tau_{xz}\\ \tau_{xy}\end{bmatrix}=\frac{1}{2}\begin{bmatrix}\mathrm{Sin}2\beta\mathrm{Sin}\alpha & -\mathrm{Sin}2\beta\mathrm{Sin}\alpha & 0\\ \mathrm{Sin}2\alpha\mathrm{Cos}\beta & \mathrm{Sin}^2\beta\mathrm{Sin}2\alpha & -\mathrm{Sin}2\alpha\\ \mathrm{Cos}^2\beta\mathrm{Sin}^2\alpha & -\mathrm{Sin}2\beta\mathrm{Cos}\alpha & 0\end{bmatrix}\begin{bmatrix}\sigma_H\\ \sigma_h\\ \sigma_v\end{bmatrix} \tag{3}$$

The in-situ principal stresses acting on the wall of a borehole or a perforation cavity can be computed as follows [1, 4]:

$$
\begin{aligned}
&\sigma_r = P_{wc} \\
&\sigma_\theta = \left(\sigma_x + \sigma_y - P_{wc}\right) - 2\left(\sigma_x - \sigma_y\right)\mathrm{Cos}2\theta - 4\tau_{xy}\mathrm{Sin}2\theta \\
&\sigma_z = \sigma_{zz} - 2\nu\left(\sigma_x - \sigma_y\right)\mathrm{Cos}2\theta - 4\nu\tau_{xy}\mathrm{Sin}2\theta \\
&\tau_{r\theta} = \tau_{rz} = 0 \\
&\tau_{\theta z} = 2\left[-\tau_{zx}\,\mathrm{Sin}\theta \;+\; \tau_{yz}\,\mathrm{Cos}\theta\right]
\end{aligned}
\qquad (4)
$$

The critical bottom hole pressure is calculated using Darcy equation for radial fluid flow [1]:

$$
q_c = \frac{7.082\,k\,h\left(P_e - P_{wc}\right)}{\mu_o \ln\left(\dfrac{r_e}{r_w}\right)} \qquad (5)
$$

Using the calculated bottom hole pressure from Eq. 5, then the induced principal stresses acting on the wall of a borehole or a perforation cavity can be computed [1]:

$$
\begin{aligned}
&\sigma_1 = \sigma_r = P_{wc} \\
&\sigma_2 = \frac{1}{2}\left(\sigma_\theta + \sigma_z\right) - \frac{1}{2}\sqrt{\left(\sigma_\theta - \sigma_z\right)^2 + 4\tau_{\theta z}} \\
&\sigma_3 = \frac{1}{2}\left(\sigma_\theta + \sigma_z\right) + \frac{1}{2}\sqrt{\left(\sigma_\theta - \sigma_z\right)^2 + 4\tau_{\theta z}}
\end{aligned}
\qquad (6)
$$

The maximum and minimum induced stresses acting on the wall of a borehole or perforation will be as follows [1]:

$$\bar{\sigma}_1 = \text{Maximum of } \left[\sigma_1, \sigma_2, \sigma_3\right] \tag{7}$$

$$\bar{\sigma}_3 = \text{Minimum of } \left[\sigma_1, \sigma_2, \sigma_3\right] \tag{8}$$

Finally the borehole or perforation stability can be predicted by comparing the computed and the experimentally measured shear stresses as follows:

$$\tau_f = \tau_o + \left[\frac{\bar{\sigma}_1 + \bar{\sigma}_3}{2}\right] \tan\phi \tag{9}$$

$$\tau_{Max} = \left[\frac{\bar{\sigma}_1 - \bar{\sigma}_3}{2}\right] \tag{10}$$

If $\tau_{Max} \geq \tau_f$ then unstable conditions will take place and sand will be produced. Therefore, data obtained from laboratory in connection with the known reservoir Stress State will be used to predict the critical drawdown required to avoid sand production problem in the studied oil field.

Results and Discussion

The uniaxial compressive strength, permeability and stability (stress resistance) under flow conditions (the major and important factors) were evaluated for the consolidated sand. The 30 days uniaxial compressive strength, Mohr-Coulomb failure criterion parameters and Poisson's ratio were listed in Table 4. Table 5 shows the maximum reduction in oil production rate due to consolidation process predicted using the mathematical model presented in this work as well as the physical and mechanical properties of the oil reservoir under consideration (see Table 6).

Table 4 Mechanical properties of the consolidated sand using Steel Making Slag.

Consolidated sand properties	30 days aging in fresh water at 21°C			30 days aging in Kerosene at 21°C		
	Mix 3	Mix 4	Mix 5	Mix 3	Mix 4	Mix 5
Uniaxial compressive strength, MPa	1.379	10.689	14.483	2.414	12.276	17.241
Apparent cohesion, MPa	0.344	2.732	3.878	0.602	3.210	4.721
Angle of internal friction, degree	37	36	34	37	36	34
Poisson's ratio	0.24	0.26	0.28	0.24	0.25	0.30

Table 5 Predicted sand-free production rates for the consolidated sand at various curing environments.

Water aging for 30 days			
		Maximum reduction on the production rate (Δq), bbl	
Mixture no.	**Critical drawdown, bbl/psi**	**Vertical well**	**Horizontal well**
Mix 3	**12.75**	**1256**	**2353**
Mix 4	**8.10**	**4050**	**6398**
Mix 5	**7.20**	**2844**	**6169**
Kerosene aging for 30 days			
		Maximum reduction on the production rate (Δq), bbl	
Mixture no.	**Critical drawdown, bbl/psi**	**Vertical well**	**Horizontal well**
Mix 3	**17.10**	**1128**	**1994**
Mix 4	**8.50**	**4561**	**6825**
Mix 5	**7.20**	**3936**	**7023**

Table 6 Properties of the studied oil reservoir.

Vertical principal in-situ stress gradient = 1 psi/ft
Maximum horizontal principal in-situ stress gradient = 0.85 psi/ft
Minimum horizontal principal in-situ stress gradient = 0.75 psi/ft
Orientation angle = Azimuth angle = 90°
Inclination angle = 0 to 90°
Connate water saturation = 0.15
Average reservoir temperature = 190 ° F
Average porosity = 21%
Average reservoir pressure gradient = 0.25 psi/ft
TVD = 7200 ft
Reservoir drainage radius = 912 ft
Well radius = 0.375 ft
Pay zone thickness = 46 ft
Oil viscosity = 1.18 cp
Average initial permeability = 500 mD
API gravity = 32 °

Compressive Strength, Poisson's Ratio and Failure Criteria

The mechanical properties of the consolidated sand using Steel Making Slag (SMS) were measured using a stiff compression machine equipped with a servo-control confining pressure system and data acquisition unit. The tabulated uniaxial compressive strength values are an average of three measurements using three different samples prepared at the same conditions. It is clear from Table 2, that the application of Steel Making Slag increased the uniaxial compressive strength of friable sand up to 0.586 MPa (85 psi) from an initial value of zero which is considered as an encouraging result. After aging the samples in water and kerosene for 30 days, a tremendous increase in the uniaxial compressive strength was recorded as shown in Table 3.

Absolute Permeability

Absolute permeability of the consolidated sand samples was measured using Ruska gas permeameter while the permeability of the friable sand was measured using a liquid permeameter. The initial permeability of the friable sand was 0.50 Darcy while the permeability of the consolidated sand ranged from 0.14 to 0.35 Darcy as shown Table 2.

A reduction of 30 to 70% in the absolute permeability of the consolidated sand was recorded. After aging the samples in water and kerosene for 30 days, a slight increase in the absolute permeability was recorded while a drastic increase in compressive strength was noticed indicating that the consolidated sand will sustain its strength and permeability under in-situ conditions providing sand-free production.

Prediction of Sand-free Production Limit

Sand is produced from friable sandstone formation when the drag forces caused by the flow of reservoir fluids exceeds the inherent strength bonding sand grains together. Thus, an external bonding material is required to resist drag forces caused by fluid flow as well as any induced stresses may be initiated due to excessive fluid drawdown. In this study, Steel Making Slag provides the cementing action for the reservoir under investigation. Physical and mechanical properties of the consolidated sand as well as the in-situ stress state acting on this reservoir (computed using Eqs. 2, 3 and 4) have been used as input parameters in the mathematical model presented herein. The critical darwdown as well as the critical production rates were predicted by substituting the critical wellbore pressure computed using Eq. 6 in Eq. 5 as shown in Table 5 and Figs 3 to 8 for mixtures 3, 4 and 5. For example critical drawdown of 17.10 bbl/psi and 12.75 bbl/psi were predicted for mixture 3 (aged in kerosene and water respectively). This means any additional increases in the drawdown will results in sand production. Using this critical drawdown the productivity of non-treated sand is calculated and plotted in the same graph for comparison as shown in Figs. 3 and 4. Drawdown and critical production rate values for mixtures 3, 4 and 5 aged in water or kerosene for 30 days are presented in Table 5 and plotted in Figs. 5 to 8. As seen in Figs. 3 to 8, a higher sand-free drawdown can be achieved from a horizontal well if compared with a vertical well. This difference in drawdown was attributed to the absolute difference in the induced in-situ shear stresses resulted from the difference between the vertical and the horizontal principal in-situ stresses acting in the area where the oil reservir lies. These differential stresses for the studied case can be evaluated as follows:

$$\text{Differential stress for a vertical well} = \left|\sigma_V - \frac{\sigma_h + \sigma_H}{2}\right| = 0.2\ \text{psi/ft} \tag{11}$$

$$\text{Differentàl stress for a horizontal well}//\sigma_h = \left|\sigma_h - \frac{\sigma_v + \sigma_H}{2}\right| = 0.175\,\text{psi}/\text{ft} \tag{12}$$

$$\text{Differentia stress for a horizontal well}//\sigma_H = \left|\sigma_H - \frac{\sigma_v + \sigma_h}{2}\right| = 0.025\,\text{psi}/\text{ft} \tag{13}$$

Thus drilling horizontal wellbores parallel to the maximum principal horizontal in-situ stress yields the maximum sand-free production rate when compared to the vertical or horizontal wellbores parallel to the minimum principal horizontal in-situ stress. Thus, it can be concluded that, sand production is minimized as the well inclination angle goes from zero (vertical well) to 90° (horizontal well). Therefore, Steel Making slurry can be used to consolidate friable sandstone reservoirs to prevent sand production.

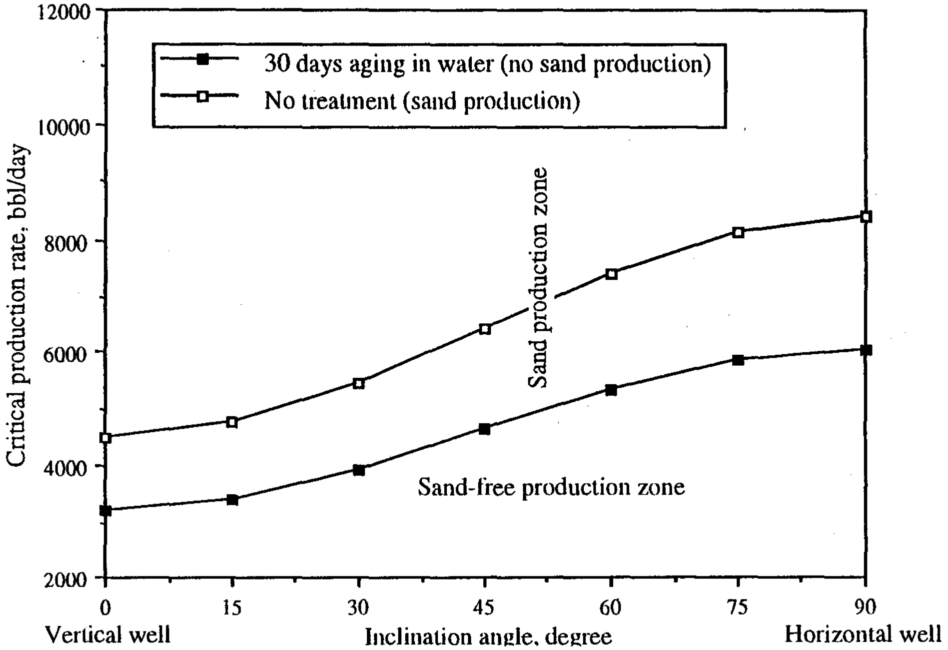

Fig. 3. Predicted sand – free production rate for mixture 3 at various well inclinations at a maximum drawdown of 12.75 bbl/psi.

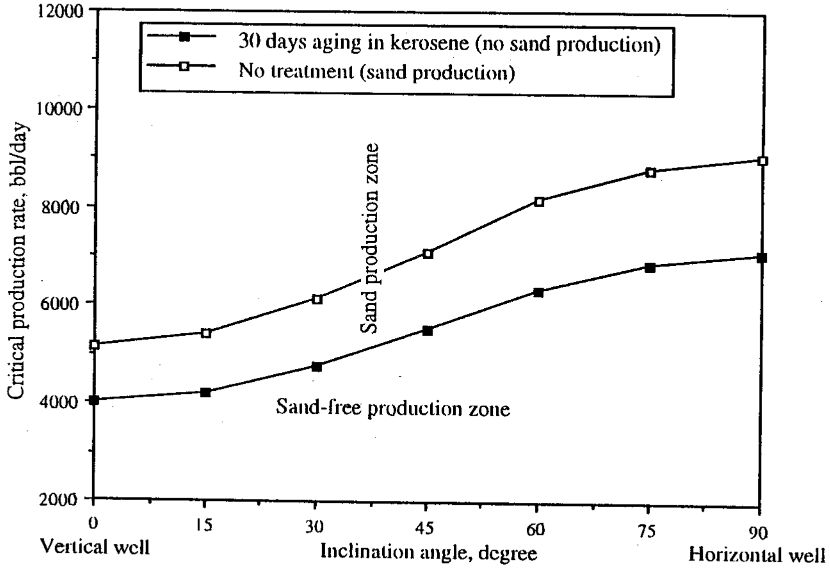

Fig. 4. Predicted sand – free production rate for mixture 3 at various well inclinations at a maximum drawdown of 17.1 bbl/psi.

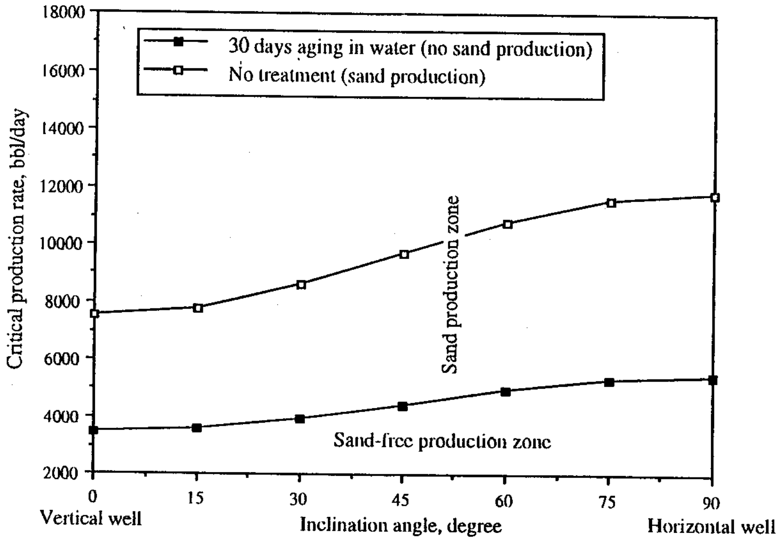

Fig. 5. Predicted sand – free production rate for mixture 4 at varous well inclinations at a maximum drawdown of 8.1 bbl/psi.

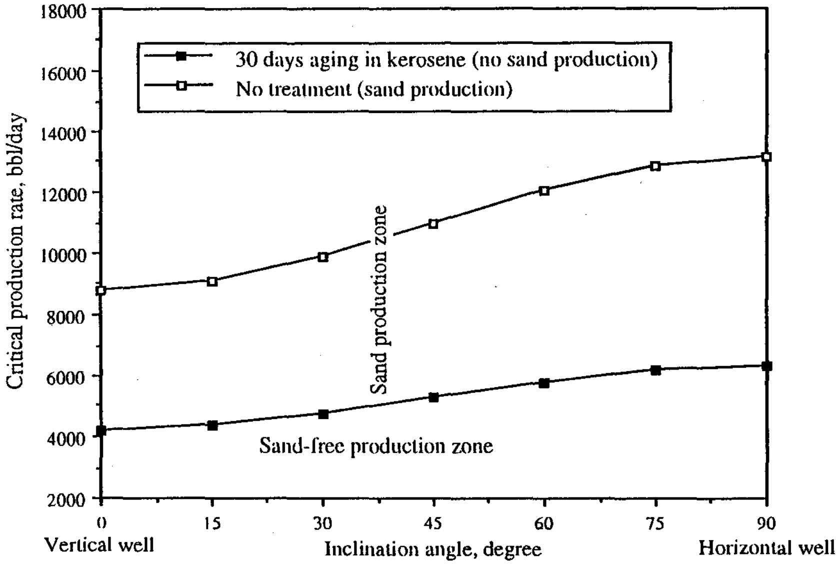

Fig. 6. Predicted sand – free production rate for mixture 4 at vrious well inclinations at a maximum drawdown of 8.5 bbl/psi.

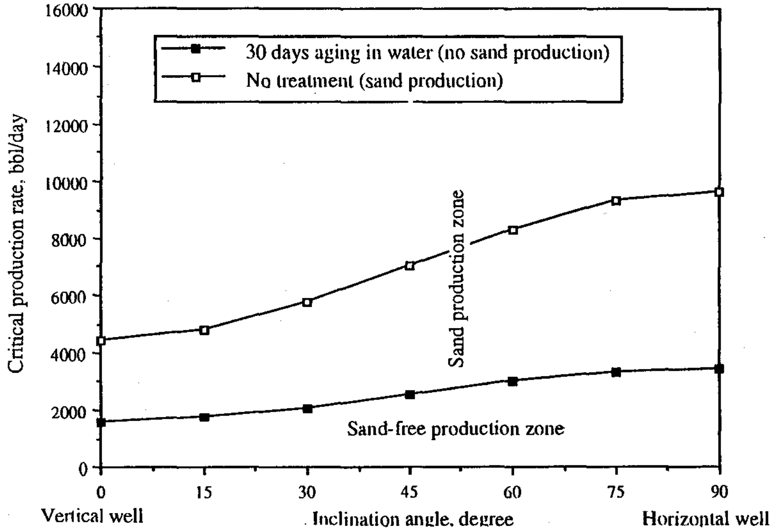

Fig. 7. Predicted sand – free production rate for mixture 5 at various well inclinations at a maximum drawdown of 6.4 bbl/psi.

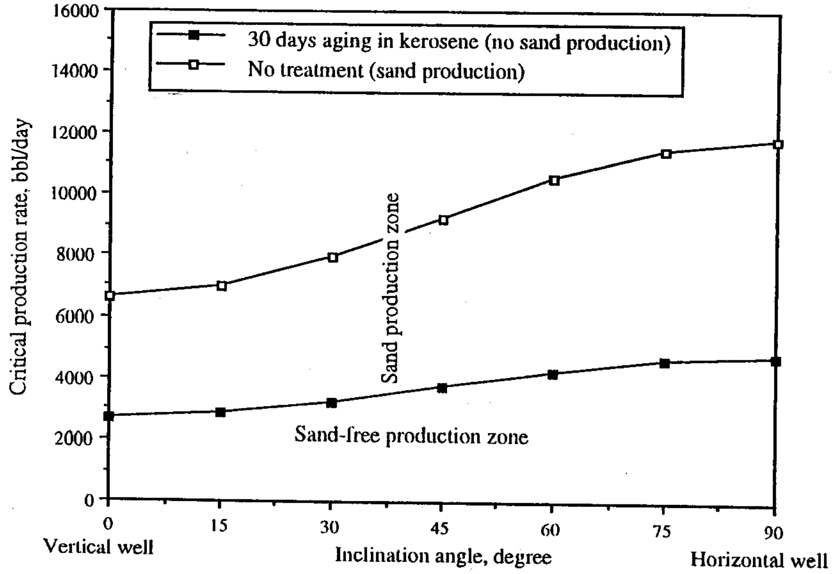

Fig. 8. Predicted sand – free production rate for mixture 5 at various well inclinations at a maximum drawdown of 7.2 bbl/psi.

CONCLUSIONS

Based on the experimental results obtained in this study and the mathematical model, the following conclusions have been reached:

1. Steel Making Slag (SMS) mixed with the appropriate chemical activators has consolidated the friable sand.

2. A mixture of 13.3% Steel Making Slag plus 6.7% Calcium Chloride ($CaCl_2$) and 6.7% Calcium Hydroxide ($Ca(OH)_2$) in addition to 33.3% fresh water by weight of the friable sand cured at 90°C for 24 hours and aged by immersion in kerosene for 30 days was able to control sand production with a 22% maximum loss in productivity.

3. Aging the consolidated samples by immersion in water or kerosene has greatly affected both the compressive strength and the absolute permeability.

4. Chemical activators that recommended for this process is Calcium Chloride $CaCl_2$ and Calcium Hydroxide $Ca(OH)_2$.

5. The mathematical model presented in this paper provides a powerful tool for the prediction of the critical drawdown as well as the critical production rates under simulated reservoir conditions.

6. Sand production minimizes as the well inclination angle goes from 0° (vertical well) to 90° (horizontal well).

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