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Potential Use of Blast Furnace Slag and Steel Making Slag for Consolidation of Friable Sandstone Reservoirs

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Abstract. Sand production problems are encountered throughout the world and recently detected in Saudi Arabian oil fields. Maximum reliability and productivity are particularly essential offshore and in remote locations. These objectives are difficult to attain where formation sands are unconsolidated or subjected to failure. Sand production mechanism is exceedingly complex, and it is influenced by every completion operation from first bit penetration to start of production or injection. Sand control by consolidation involves the process of injecting chemicals into the naturally unconsolidated formation to provide an in-situ grain-to-grain cementation. Techniques for accomplishing this successfully are perhaps the most sophisticated undertaken in completion work. Many methods have been suggested to consolidate the wall of the wellbore for few inches or feet deep around the borehole. These methods are either expensive or temporarily. The aim of this work is to find out a byproduct from the Saudi industry able to consolidate friable sand formations. Byproducts used in this work are Steel Making Slag (SMS) and Blast Furnace Slag (BFS) obtained from Hadid steel plant in Jubail. This slag is mixed with chemicals as activators and with sand and cured at 95° C for 24 hours. The compressive strength and the absolute permeability of the consolidated sand have been evaluated. Also, the effect of aging in kerosene as a representative to crude oil and water to show the effect of produced fluids on the consolidated sand has been investigated. The results show that the Steel Making Slag mixed with calcium chloride ($CaCl_2$) and calcium hydroxide ($Ca(OH)_2$) at 30% to 50% by weight of water is able to consolidate friable sand. The permeability of the consolidated sand lies between 70% to 28% of the absolute permeability of the friable sand, which is considered reasonable. Immersing samples in kerosene or water increases both compressive strength and permeability.

Introduction

Sand production problems are experienced in many oil and gas productive formations [1]. 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. Therefore, sand control has attracted much research effort for more than six decades [2].

Sand production is explained in several ways. The most convincing theory attributes sand production to friction and resultant pressure drop as well fluid passes through the small pores of the sand body. If the cementing materials are not strong enough and that the pressure drop is high, the individual sand grain is displaced and carried into the well pore. Another plausible explanation considers the fact that the formation compaction as the bore pressure decreases, and the variations of the load, tends to shift sand grains and shear present cementing material. Another strong explanation highlights the chemical difference between the water initially present when the sand grains were first deposited and that water contained in the aquifer. Water production can actually dissolve a part of the cementing material between sand grains.

Several methods were proposed and adopted for the control of sand productions in the past [3-5]. These control methods are intended either to prevent or reduce the flow of sand particles into the wellbore during the course of production. Three processes are employed predominately for the control of sand production in oil and gas wells. These methods include mechanical means such as sand screens, filters, perforated or slotted liners, gravel packing [3-7]; chemical agents such as plastic, phenolic, expoxy, furan, and enzymes consolidations or a combination usually introduced to the oil industry [8-22]. Certain completion and production practices are also used to reduce or totally prevent sand production. Each method has brought some useful achievements.

Low and high temperature oxidation of crude oil has been used to test its potential as sand consolidation material [23-25]. The crude oil reacts with oxygen through numerous and complex reactions. These reactions in turn depend upon the temperature. Low temperature oxidation is found below 500° C and is characterized by products such as oxygenated hydrocarbons like aldehydes, alcohol, ketones, acids and hydro-peroxides with carbon oxides [21]. Light oils were found to be more susceptible to low temperature oxidation than heavy oils, because low temperature increases the viscosity and density and hence alters the distillation characteristics of the oil. It also affects the quantity of the fuel available for combustion [24].

In sand consolidation, there are two major factors: The first concerns the replacement. The binding film must adhere to the surface of sand grains and do not obstruct the flow of the fluid. The second factor regards the strength. This is particularly useful in the design of consolidation method of steam displacement wells, where temperatures in the stimulation phase goes up 700°F.

A high temperature sand consolidation system that is stable to the wellbore temperatures of 700°F was developed [25]. The development resulted from two improvements in the technique. First a controlled amount of catalyst is adsorbed on the sand, so that consolidation takes place near the sand grains. This action is useful for obtaining higher permeability consolidation. The second improvement comes from the elimination of the adverse effects of water by driving the reaction to completion. The resin used, in achieving this accomplishment, is a very viscous derivative of furlfuryl alcohol, which requires a dilution to make it easy to inject. A hydrolyzable ester that reduces viscosity is employed for a dilution.

The screening of these proposed methods shows that they are either expensive or incapable to prevent the flow of sand particles into the wellbore. This work presents the results of testing a byproduct of steel industry that is defined as slag for potential use in friable sand consolidation. This byproduct is a waste and causes an environmental problem.

Composition of Steel Making Slag

Slag is a major byproduct in iron and stealmaking 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 use by construction industry [26]. It has also been introduced to the oil industry to consolidate drilling fluids around casing strings [27-29]. The Blast Furnace Slag used in this work is obtained from local Blast Furnace Factory in Jubail Industrial Area, Saudi Arabia. The chemical analysis of this slag is shown in Table 1. The slag is rich in iron, iron oxide and calcium oxide. It also has a medium amount of silica and magnesium oxides. Low amounts of aluminum and magnesium oxides are found in the slag.

Table 1. Chemical composition of Blast Furnace Slag

Component	Percent by weight
Iron (Fe) total free	31.76
Lime (CaO)	23.10
Silica (SiO_2)	12.17
Alumina (Al_2O_3)	5.17
Magnesia (MgO)	14.96
Iron oxide (FeO)	31.18
Manganese oxide (MnO)	2.5
Others	10.92

Steel Making Slag is a byproduct in the steel making process. There are three basic steel making processes in use today. The chemical composition of the steel making slag will vary depending upon the process used to produce steel [26]. Steel Making Slag has been investigated for use in asphalt pavement. It was found to have the quantities desirable in road surfacing materials, making an economical, stable, durable and skin resistance road surfacing [26].

The Steel Making Slag used in this investigation was obtained from Hadeed steel plant in Jubail, Saudi Arabia. The plant utilizes the direct reduction-electric arc furnace (DR-EAF) technology for steel making. According the data provided the plant generates slag at the rate of 250,000 metric tons per year. The chemical composition is given in Table 2. It shows that the slag is rich in both iron and iron oxide but lime has the maximum value in the composition [26].

Table 2. Chemical composition of Hadeed plant Steel Making Slag

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

Experimental Procedures

The sand used in this study was brought from Half Moon beach, Eastern Province, Saudi Arabia. The sand was sieved using ASTM set of sieves and shaker. The grain distribution of the sand is given in Fig. 1. The Figure shows that the sand is rich in size 50 mesh. The friable sand was packed in a Hoek Cell to measure its permeability. The absolute permeability of the friable sand pack is 0.5 Darcy. This value is used as a reference for the consolidated samples.

To prepare consolidated sand samples with slag, chemical activators ($Ca(OH)_2$ and $CaCO_3$) have been mixed with water using cement blender for 10 minutes. Slag has been added to the water and activator mix at a low rate during blender rotation to ensure complete mix with the water. After adding the amount of salg to the mix, blending process continued for another 10 minutes. Amount of sand was weighed and added to the slag mix and blended for another 10 minutes. Cement moulds were tighted, greased and prepared for making cubical samples. The slag mix was poured in the moulds. The moulds were tapped continuously using electric vibrator to allow any gasses in the mix to perculate and escape from the mixture. After ensuring complete gas percolation, the moulds were covered with aluminum foil, put into oven and cured for 24 hours. The oven temperature increased gradually to simulate wellborn temperature till 95°C and kept constant for the specified curing time.

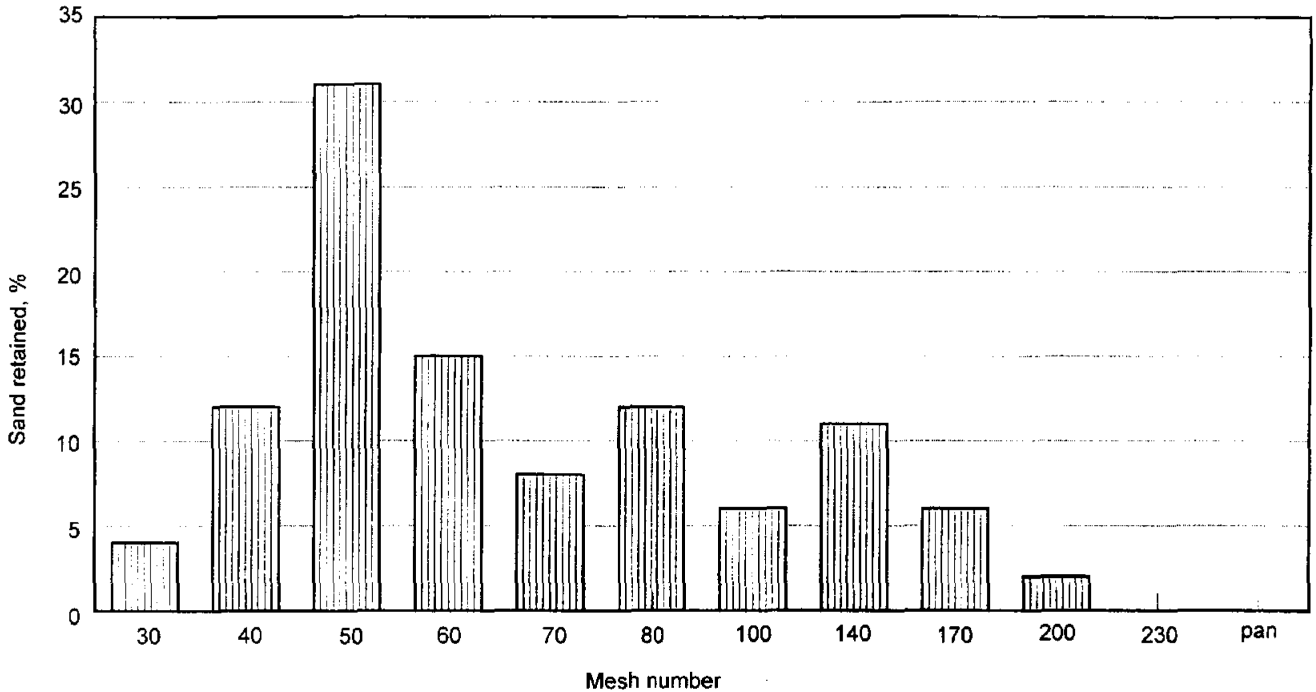

Fig. 1. Granulometric analysis of friable sand used.

After curing time, the samples are picked up, cooled and dismantled from the moulds. Some samples were used to evaluate the compressive strength using Versa Tester machine. Other samples were used to measure the rock permeability using Ruska gas permeameter. Finally, other samples were immersed in kerosene or water to measure their deterioration in water and oil. The samples immersed in kerosene and water were kept for 30 days under these fluids, and then they were dried and tested for compressive strength and permeability. The amount of activators as well as slag was changed to find out the optimum composition to be used for sand consolidation.

Results and Discussion

For any friable sand consolidation technique, compressive strength, rock permeability and rock stability under fluid flow are the major important factors. Therefore, the work is concentrated on these properties to evaluate the consolidation process using both Blast Furnace Slag and Steel Making Slag. The properties of the mixtures prepared are listed in Tables 3 and 4. The amount of slag is changed between 20% and 50% relative to the amount of water. The amount of calcium hydroxide and calcium chloride lies between 20% and 40% of the amount of water added. The amount of sand is kept constant at 2250 gm for all experiments. Three samples were used for each experiment and the average value is taken as a result of that experiment.

Table 3. Composition and results of samples consolidated using Blast Furnace Slag

	Composition					Curing Conditions		Results	
No	H_2O cc	Slag %	$Ca(OH)_2$ %	$CaCl_2$ %	Sand gm	Temp. °C	Time Hrs	Comp. Str. psi	Perm. Darcy
1	750	20	20	20	2250	95	24	Soft	NM
2	750	30	30	30	2250	95	24	102	0.2
3	750	40	30	30	2250	95	24	102	0.28
4	750	40	30	30	2250	95	24	84	0.18
5	750	50	30	30	2250	95	24	100	0.19

Table 4. Composition and results of samples consolidated using Steel Making Slag

	Composition					Curing Conditions		Results	
No	H_2O cc	Slag %	$Ca(OH)_2$ %	$CaCl_2$ %	Sand gm	Temp. °C	Time Hrs	Comp. Str. psi	Perm. Darcy
1	750	20	20	20	2250	95	24	Soft	NM
2	750	30	30	30	2250	95	24	10	NM
3	750	40	30	30	2250	95	24	20	0.35
4	750	40	30	30	2250	95	24	85	0.21
5	750	50	30	30	2250	95	24	155	0.14

Compressive Strength

The compressive strength of the friable sand consolidated using both Blast Furnace Slag (BFS) and Steel Making Slag (SMS) is measured by Versa Tester and plotted in

Fig. 2. The compressive strength is taken as the average of three samples prepared at the same conditions. It is measured after curing the samples at 95°C for 24 hours.

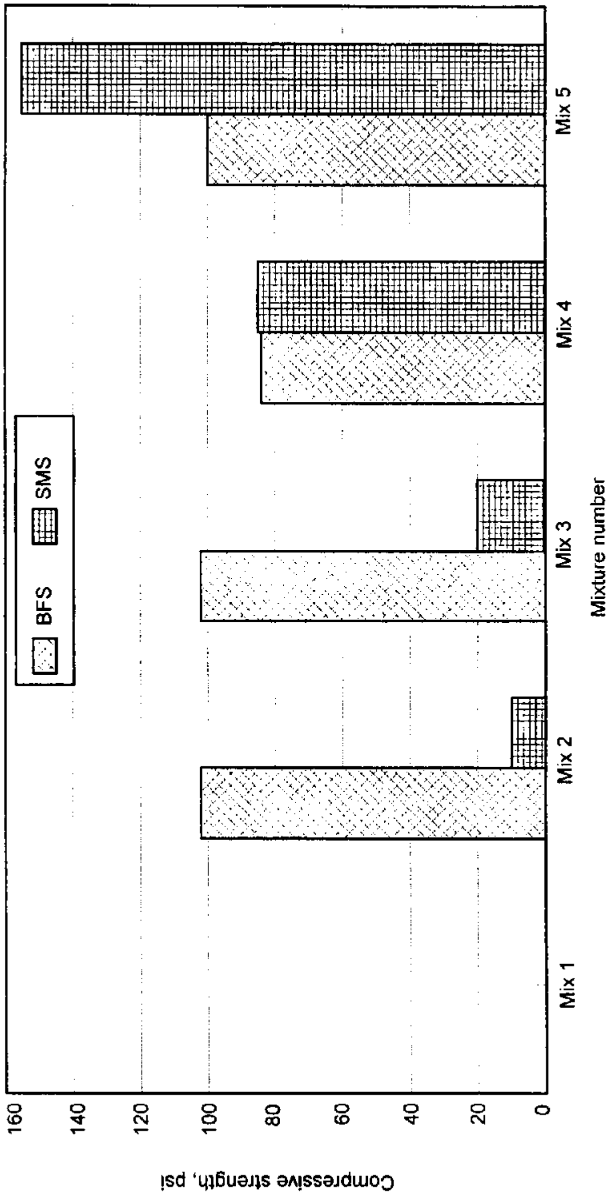

Fig. 2. Compressive strength of friable sand consolidated with BFS and SMS.

For BFS, the compressive strength of Mix 2 to Mix 5 lies between 102 and 83 psi. However, Mix 1 does not produce any compressive strength because the sample stayed soft without consolidation. The figure shows that there is no trend for compressive strength. Also, there is no recognizable increase or decrease in the compressive strength as the amount of slag or chemical activators is increased. This means that the process of depositing cementing material using BFS is limited to a certain value and is not affected by increasing the amount of slag or chemical activator.

For SMS, the compressive strength increases from 10 psi at 30% of slag and 30% of chemical activators to 158 psi at 50% of slag and 30% chemical activators. Mix 1 that contains 20% slag and 20% chemical activators does not produce any compressive strength. This means that the compressive strength of consolidated sand increases by increasing the amount of SMS. Also, Mix 4 and Mix 5 are suitable for friable sand consolidation because they have shown relatively higher compressive strength after 24 hours curing time.

Absolute Permeability

Absolute permeability of the consolidated samples is measured using Ruska gas permeameter and the liquid permeability is calculated by correcting Klinkenburg effect based on the measurements obtained. The results are given in Tables 3 and 4 and plotted in Fig. 3 for Mix 2 to Mix 5 for both BFS and SMS.

For BFS, the absolute permeability changes between 0.28 to 0.18 Darcy. It shows also no trend of absolute permeability change with changing mixture composition. Knowing that the absolute permeability of the friable sand is 0.5 Darcy, BFS reduced the absolute permeability between 44% and 64% of the original absolute permeability. This reduction can be considered very reasonable for the case of Blast Furnace Slag. But one cannot predict the absolute permeability of the process as other compositions because of the flocculation of the results and the absence of the trend in these mixtures.

For SMS, the absolute permeability lies between 0.375 and 0.14 Darcy. There is a reduction in the absolute permeability as the amount of slag and chemical activators increases. Relative to the absolute permeability of the friable sand the SMS reduced the absolute permeability of the consolidated sand in the range of 30% to 72% of the original absolute permeability. From these results, one can conclude that to avoid high reduction in absolute permeability, Mix 3 is the recommended mixture for the friable sand consolidation. In case of the need of high compressive strength Mix 3 and Mix 4 can be applied.

Aging in Water and Kerosene

Aging samples in water and kerosene as a representative of crude oil is used to evaluate the deterioration of the samples due to production of fluids that is normally water and oil. For this test, the samples are immersed in water and in kerosene for 30 days and tested for compressive strength and absolute permeability.

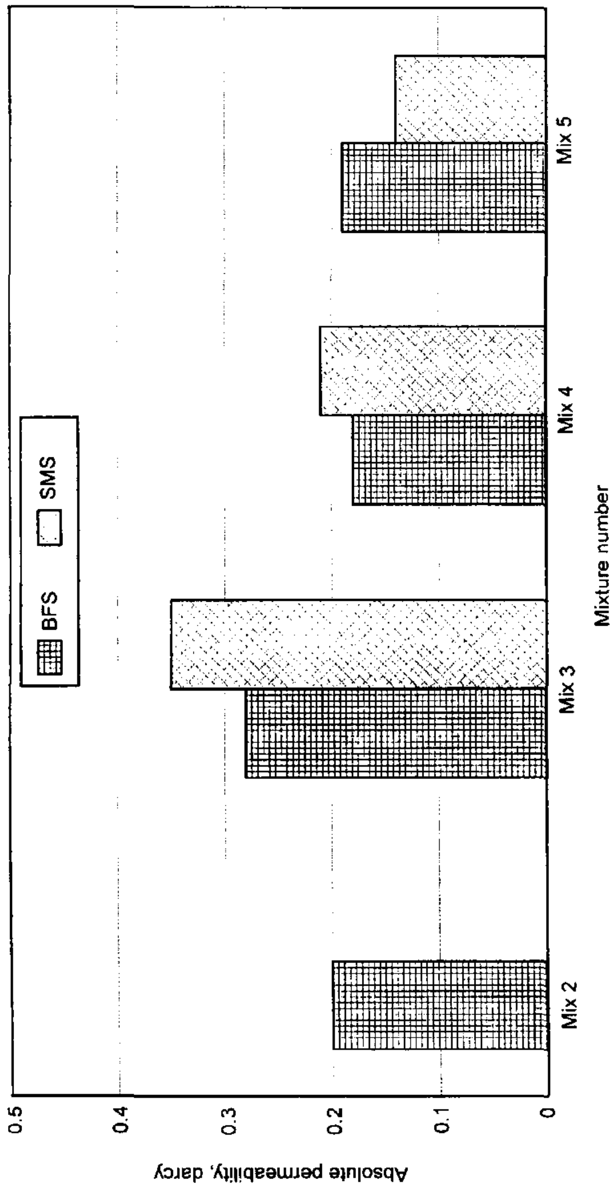

Fig. 3. Absolute permeability of friable sand consolidated with BFS and SMS.

For the BFS, the samples are deteriorated after 24 hours. This means that sand starts to be produced after BFS consolidation process just as the well is put on production. From this, it can be concluded that BFS is not suitable for friable sand consolidation.

For SMS, the compressive strength is plotted in Fig. 4. The figure shows that there is a remarkable increase in compressive strength due to aging in both water and kerosene. This increase is higher with kerosene than with water. This means that the flow of formation fluids through the consolidated sand increases the compressive strength and there will be no sand production when production resumed later on.

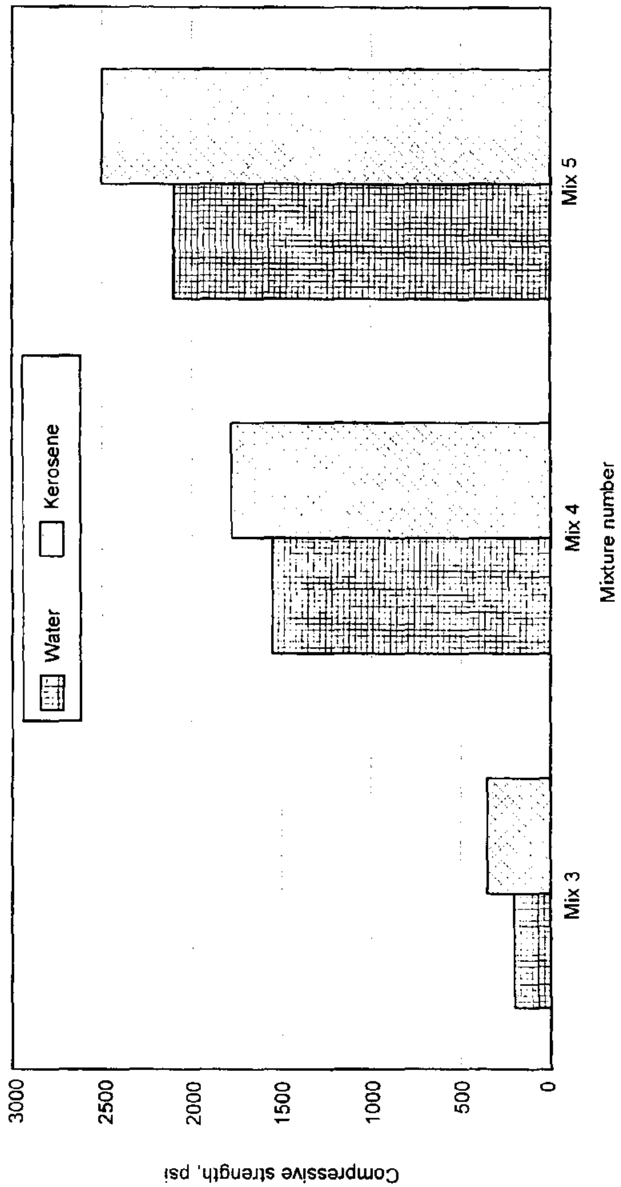

Fig. 4. Compressive strength of friable sand consolidated with SMS and aged in water and kerosene.

The absolute permeability of the aged samples is shown in Figure 5. The figure shows that the absolute permeability increases by aging in both water and kerosene. This can be attributed to the solution of some salt that was previously precipitated between the grains, in both water and kerosene, resulting in the absolute permeability increase. However, more research is needed to prove these phenomena.

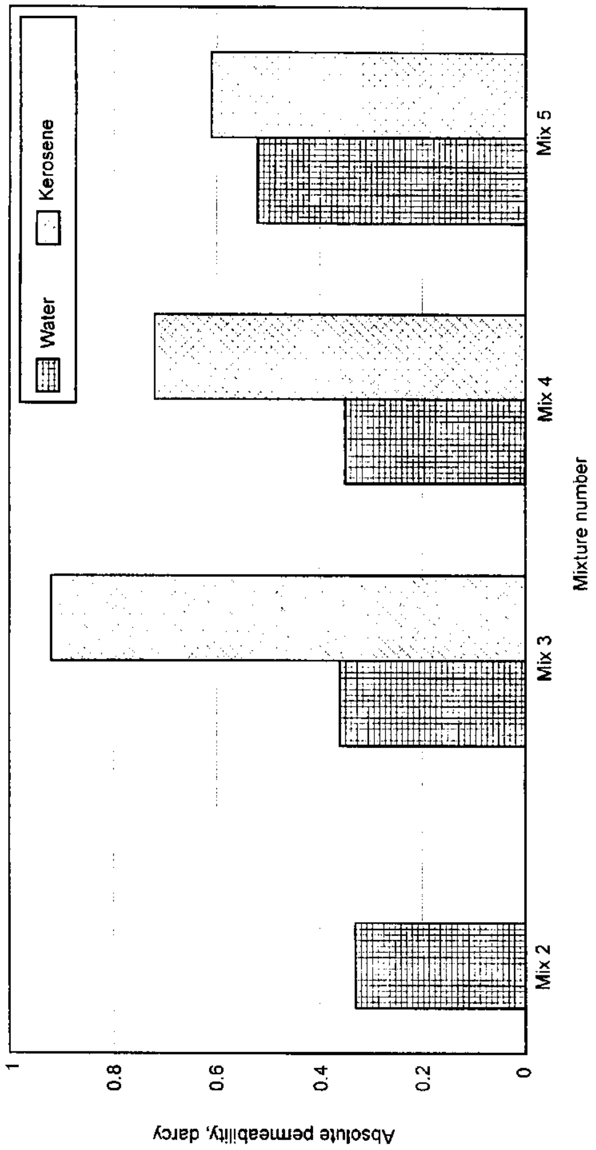

Fig. 5. Absolute permeability of friable sand consolidated with SMS and aged in water and kerosene.

Conclusions

Based on the experimental results obtained, the following conclusions have been reached:

1. Blast Furnace Slag (BFS) mixture activated with calcium chloride and calcium hydroxide consolidated friable sand at low temperatures, but the formed rock lost its compressive strength by immersing it in water and in kerosene.
2. Steel Making Slag (SMS) mixture with the same activators consolidated the friable sand at low temperature. Immersing the samples in water and in kerosene increased both compressive strength and permeability.
3. The best composition for consolidation process is by using 30% to 50% by weight of water slag and 30% to 40% by weight of water activators.
4. Chemical activators recommended for this process are calcium chloride and calcium hydroxide.
5. More research is recommended to simulate borehole sand consolidation process.

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إمكانية استخدام مخلفات صناعة الحديد لزيادة تلاحم مكامن الحجر الرملي الهش

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الرياض ١١٤٢١، المملكة العربية السعودية

(استلم في ١٩/١١/١٩٩٩،وقبل للنشر في ١٥/٠٥/٢٠٠٠م)

ملخص البحث. إن الرمل المصاحب للبترول المنتج ظاهرة شائعة في الكثير من الحقول البترولية المنتشرة في أنحاء العالم. وتم رصد هذه الظاهرة مؤخرا في الحقول البترولية السعودية. كذلك إن الإنتاجية القصوى تعتبر أمرا أساسيا خصوصا في المناطق البحرية والنائية. إن تحقيق هذه الأهداف يعتبر صعبا عندما يكون المتكون الرملي المنتج للنفط غير متماسك أو متعرض للتفتت. إن ميكانيكية إنتاج الرمل المصاحب للنفط عملية معقدة ، وتتأثر بكل عمليات إكمال الآبار ابتداء من اختراق لقمة الحفر للطبقة المنتجة وحتى بداية الإنتاج أو الضخ. إن التحكم بالرمل المتفتت بزيادة تماسكه صناعيا يتضمن عملية ضخ بعض الكيماويات خلال المكمن الرملي غير المتماسك لإحداث تلاحم بين حبيبات الرمل. إن التقنيات اللازمة لتحقيق هذا الهدف بنجاح ربما تعتبر الأكثر تقدما في مجال إكمال الآبار.

هنالك عدة طرق مقترحة لجعل جدار البئر متماسك لعمق عدة بوصات إلى قدم حول الحفرة. وهذه الطرق إما مكلفة أو مؤقتة. إن الهدف من هذه الدراسة هو إيجاد منتج صناعي محلي له القدرة على جعل طبقة الرمل الهشة متلاحمة. إن المنتج المستخدم في هذه الدراسة هو عبارة عن مخلفات صناعة الحديد حصل عليها من وحدة إنتاج الحديد في الجبيل (شركة حديد). تم خلط هذا المنتج ببعض المواد الكيميائية المنشطة ومن ثم خلطه بالرمل و بعد ذلك عُرّض المخلوط لحرارة تصل إلى ٩٥ درجة مئوية لمدة ٢٤ ساعة. وبعد ذلك تم قياس قوة التحمل للانضغاط و النفاذية لتلك العينات الرملية المتلاحمة. وكذلك تم استقصاء تأثير ترك العينات الرملية المتلاحمة في الكيروسين ، بديلا عن النفط الخام ، والماء لمدة طويلة من الزمن ، وذلك لقياس تأثير السوائل المنتجة على خواص الصخر المتماسك.

أظهرت النتائج أن مخلوط مخلفات الحديد مع كلوريد الكالسيوم وهايدروكسيد الكالسيوم بنسبة ٣٠ إلى ٥٠٪ من وزن الماء له القدرة على جعل الرمل الهش متماسكا. إن نفاذية الرمل المتلاحم بهذه المادة تتراوح بين ٧٠٪ إلى ٢٨٪ من النفاذية المطلقة للرمل الهش، دارسي، ويعتبر هذا الانخفاض مقبول بالنسبة إلى مخلوط مخلفات الحديد المضافة. كما وإن غمس العينات الرملية المتلاحمة في الكيروسين أو الماء قد زاد من النفاذية وقوة تحمل الإنضغاط لتلك العينات.