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Testing of Saudi Sandstones for Potential Use in Hydraulic Fracturing of Hydrocarbon Reservoirs

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Abstract. This paper presents the results of testing four Saudi sandstone containing formations namely; Dammam, Al-Biyad and Al-Wassia, Al-Manjour, and Durma to be used as propping agents for hydraulic fracturing operations. A review of Saudi oil reservoirs showed that about 35% of these reservoirs have permeabilities lower than 0.05 darcy and may need hydraulic fracturing operations in the future to increase oil productivity.

The analysis showed that the Saudi sandstones are friable and composed mainly of quartz. The sands can produce four proppant mesh sizes: 30/50, 40/70, 60/120 and 70/140, which are common in hydraulic fracturing operations. The physical properties meet or exceed the recommended API values. The proppants produced from Dammam and Al-Manjour sands can be used in hydraulic fracturing with acid attack. The other proppants are to be used in hydraulic fracturing without acid attack. Also, the proppant mesh sizes are to be recommended for fracturing shallow and medium depth Saudi reservoirs, depth down to 8000 feet, and can be produced economically.

Introduction

Hydraulic fracturing plays a major role in enhancing petroleum reserves and daily production. The first fracturing treatment specially designed to stimulate well production was conducted in Hugoton gas field, July 1947, on Kelpper well 1 located in Grant County, Kansas, USA [1]. Since that time facurting has made a significant contribution in enhancing oil and gas production rates and recoverable reserves.

The goal of hydraulic fracturing treatment is to establish a flow channel that has, and will maintain throughout the life of a well, enough flow capacity to permit a desired rate of production. After a treatment is completed, the only material that remains in the fracture to maintain the flow capacity is the propping agent [2].

The function of the propping agent is to hold the fracture open after the fluid injection is stopped and fracturing fluid has been removed. One of the first proppants used in the early days of hydraulic fracturing was sand dredged from Arkansas river, USA [1]. Silica sand is currently the most common used proppant material in USA. The ready availability and low cost of high quality sand that can provide good fracture conductivity for a wide range of conditions make it attractive for use in fracture stimulation. The American Petroleum Institute (API) has established sand quality specifications for fracturing treatments. The specifications basically cover size distribution, sphericity and roundness, solubility in acids, silt and clay content, and crush resistance. The most famous proppant sand is Ottawa sand.

Another material commonly used as a propping agent is sintered bauxite (aluminum oxide). It is stronger than sand and is used in deep wells between 8000 to 10000 ft (2440 to 3050 m). Also, a variety materials – alumina cordierite, mullite, silicon carbide, and some ceramic oxides have been introduced as proppants.

The purpose of this paper is to highlight the possibility of hydraulic fracturing operations in Saudi Arabia and to test the potential use of some Saudi sands as propping agents for Saudi reservoirs. The test program follows the API recommendations, RP-56, and RP-60 [3;4], recommended for sands as propping agents for hydraulic fracturing operations.

Fracturing Activity in Saudi Arabia

According to the present statistics, Saudi Arabia prossesses about 25% of the world proven oil reserves. This reserve is distributed to about 200 reservoirs which are mostly located in the Eastern Province. These reservoirs contain rocks of different permeabilities ranging from 0.5 millidarcy to 6750 millidarcy [5]. About 35% of these reservoirs have an average permeability lower than 50 millidarcy (Fig. 1). These reservoirs can be classified as low permeability reservoirs and may need hydraulic fracturing in the future to increase their productivity. Moreover, publication [6] describes a hydraulic fracturing operation that has successfully been applied in Saudi Arabia.

According to reservoir depth, Fig. 2 gives the distribution of Saudi reservoirs against depth. This figure shows that these reservoirs can be classified as shallow, depth less than 6000 ft; medium, depth from 6000 to 9000 ft; and deep, depth more

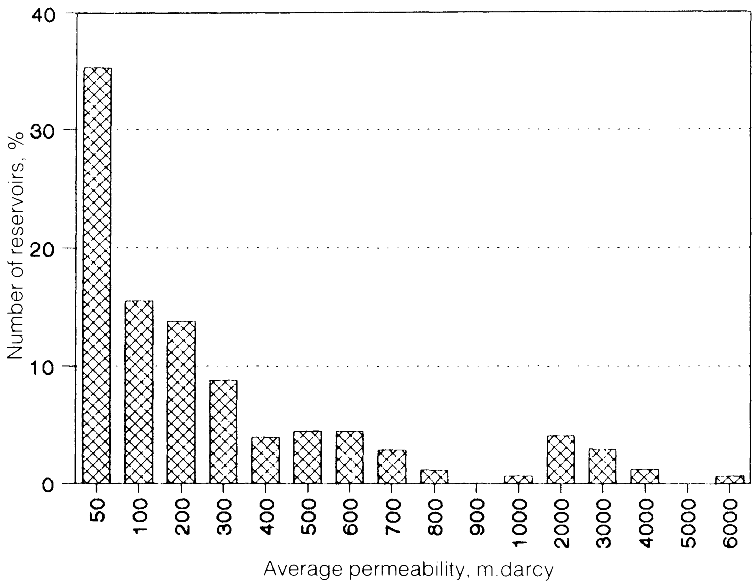


Fig. 1. Average permeability distribution of Saudi reservoirs

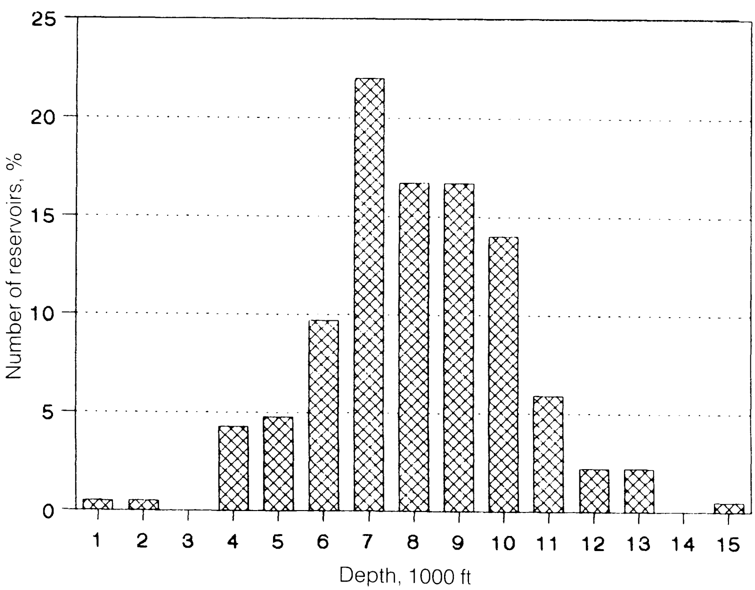


Fig. 2. Depth distribution of Saudi reservoirs

than 9000 ft. Actually, reservoir permeability is not function of depth. Low permeability reservoir can be shallow, medium deep, or deep. Figure 3 shows a semilogarithmic plot of reservoir permeability versus depth where low permeability reservoirs are marked at all depths. This means that the future fracturing operations are not required for deep reservoirs only, but also for shallow and medium deep reservoirs. Moreover, these operations will need a huge amount of propping agents which can be produced from local Saudi sands.

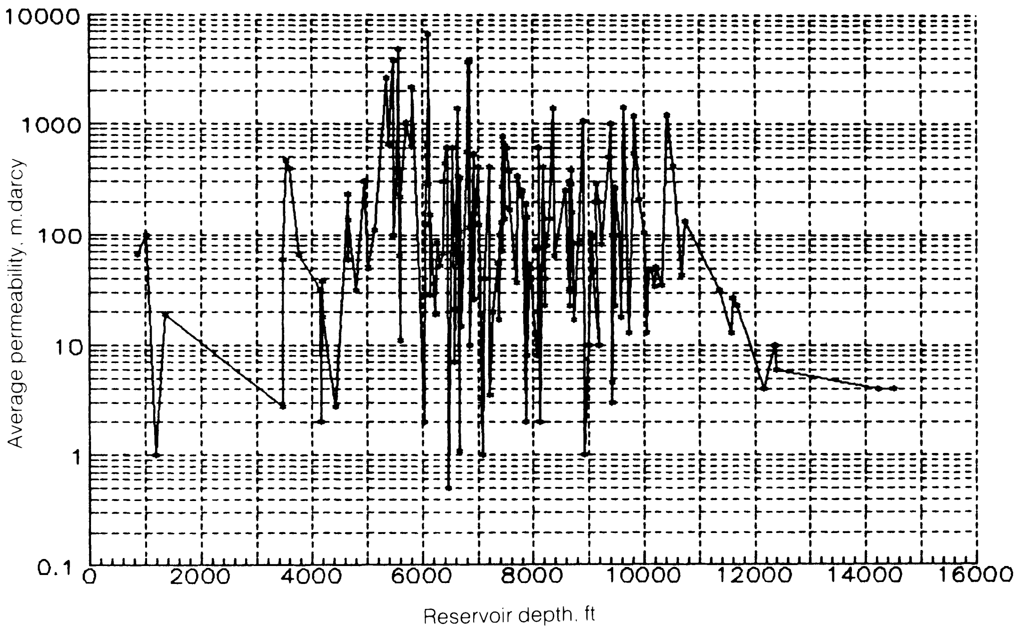


Fig. 3. Average permeability of Saudi reservoirs versus depth

Geological Background and Sand Outcrops

Geologically, the Arabian Peninsula is divided into two structural zones. The western zone, known as the Arabian Shield, consists of igneous and metamorphic rocks. The eastern zone, known as Arabian Shelf, consists of a sequence of continental and shallow water marine sediments ranging in age from Cambrian to Pliocene. Plaeozoic and lower Tertiary strata are exposed in the center of Saudi Arabia forming a great curved belt bordering the Shield [7].

The sands under investigation belong to major sandstone formations outcrop in the Eastern province as well as the Central (Riyadh) province. Figure 4 shows a schematic presentation of the outcrops of the major sandstone formations in Saudi Arabia which are Al-Neujeen, Dammam, Um Radoma, Al-Biyad and Al-Wassia, Al-Manjour, Durma, Tabuk, Al-Wajeed, and Al-Saak formations [8]. For this study, four sandstone formations are selected to perform the experimental program, namely: Dammam, Al-Biyad and Al-Wassia, Al-Manjour, and Durma sands.

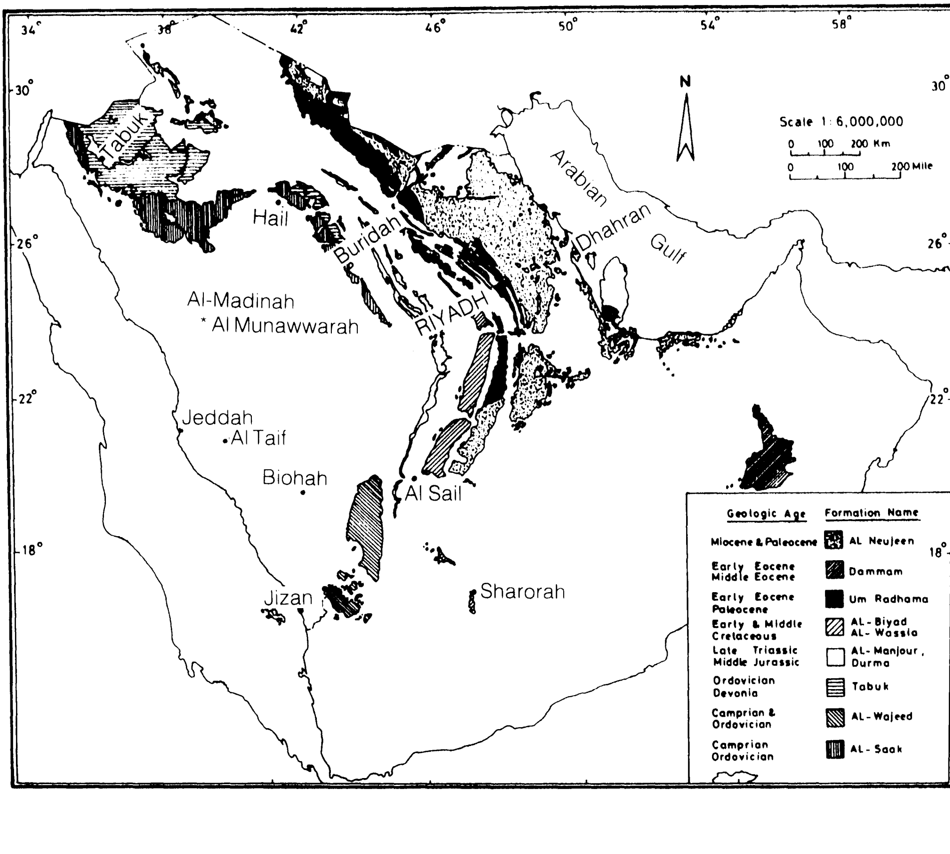


Fig. 4. Outcrops and extensions of major Saudi sandstone formations [8]

Dammam sandstone was deposited during Early and Middle Eocene age. It outcrops at the city of Dammam in the Eastern province and at Riyadh-Dammam road, 80-90 kilometer from Riyadh (longitude 26° 19′ North and latitude 50° 08′ East) where the sample was taken [8].

Al-Biyad and Al-Wassia sandstone outcrops are found in the Eastern part of Riyadh (longitude 47° North and latitude 20° East). This formation was deposited during the Early and Middle Cretaceous epoch [8]. The sample was brought from an excavation area at the Eastern of Riyadh (longitude 47° 10′ North and Latitude 22° 05′ East).

Al-Manjour sandstone outcrops as a narrow belt over an area 10 to 23 kilometer wide and 820 kilometer extension from latitude 21° 30′ to 28° 01′ North. This sand was deposited in the Late Triassic epoch [8]. The sample was brought from an excavation area in Muzahmyia city at longitude 24° 39′ North and latitude 23° 05′ East.

Durma sandstone outcrops at Durma and Quwaiyiyia cities on the old Riyadh-Al-Hijaz road in the middle of the Kingdom. This sandstone was deposited in the Middle Jurassic epoch [8]. This sandstone is basically composed of quartz stands. The sample was taken from an excavation area around Quwaiyiyia city located at longitude 24° 22′ North and latitude 45° 17′ East.

In this research work, these sands have been selected among the major sandstone formations shown in Fig. 4 to find out a suitable propping agent from Saudi sands. This selection is made because of their existence near oil fields in Saudi Arabia.

Experimental Work

According to API recommendations RP-56 and RP-60 [3;4], propping agent should fulfil certain physical properties so that it will be used for hydraulic fracturing operations. These properties contain grain size distribution (sorting), roundness, sphericity, density of propping agent, crushing resistance, acid solubility, and clay and silt content. To specify the sand for these properties, various analyses and tests have been performed.

The importance of grain size and grain size distribution goes back to the fact that sands which give large variety of meshes and uniform grain size distribution are suitable for yielding large number of proppant sizes. A granulometric analysis was made using shaker and ASTM sieves ranging from mesh number 20 to mesh number 230.

Roundness and sphericity are properties related to the shape of the grain itself. These have been determined using a microscope having a specified degree of magnification from 4 to 100 degrees. According to API recommendations, these properties were valuated by randomly selection of not less than 20 grains of proppants.

These grains were viewed through a 10 to 20 magnifying lens microscope. The shape of each grain was compared with Krumbein and Sloss chart, and the roundness and sphericity were evaluated [4]. The average roundness and sphericity of all the grains were determined and considered as the roundness and sphericity of the proppant. This property is a main factor in fracture permeability after propping precipitation as well as embedment of the proppant into the formation.

proppant density is another physical property extremely important for proppant transport and design of fracture operations. This property has been determined using pycnometer.

Crushing resistance can be considered as the most important property of the proppant. It is considered as the best starting point in proppant selection. If the proppant is not strong enough to withstand closure stress of the fracture, it will crush and the permeability will be drastically reduced. According to API recommendations, a specified proppant weight has been put in a cylindrical cell between two steel pistons and subjected to certain amount of load by press machine for two minutes. After that time, the load was removed and the percent of fines generated thereafter has been calculated. The load that had generated a specified percent of fines was considered as the crushing load [3].

Acid solubility is an important property when acid is used to dissolve formation matrix. The test was conducted by calculating the weight loss of dry proppant after aging in hydrochloric-hydrofloric acid (12% and 3% concentrations, respectively) for 30 minutes at 65°F. The test determines the resistance of proppant to acid attack.

Clay and silt contents have been evaluated by X-ray differactometer and turbidity test. The importance of these contents is to predict pore plugging through filtration during fracturing operations.

All these properties were tested using the standard devices following API recommendations.

Results and Discussion

The granulometric analysis showed that the samples of sandstone formations have grain size distributions ranging from mesh number 30 (600 micrometer diameter) to mesh number 200 (75 micrometer), Fig. 5. The largest amount of sand lies between mesh number 40 to 170. The amount of sand on pan is very small which means that the sand is very poor in silt and clay contents. According to API recom-

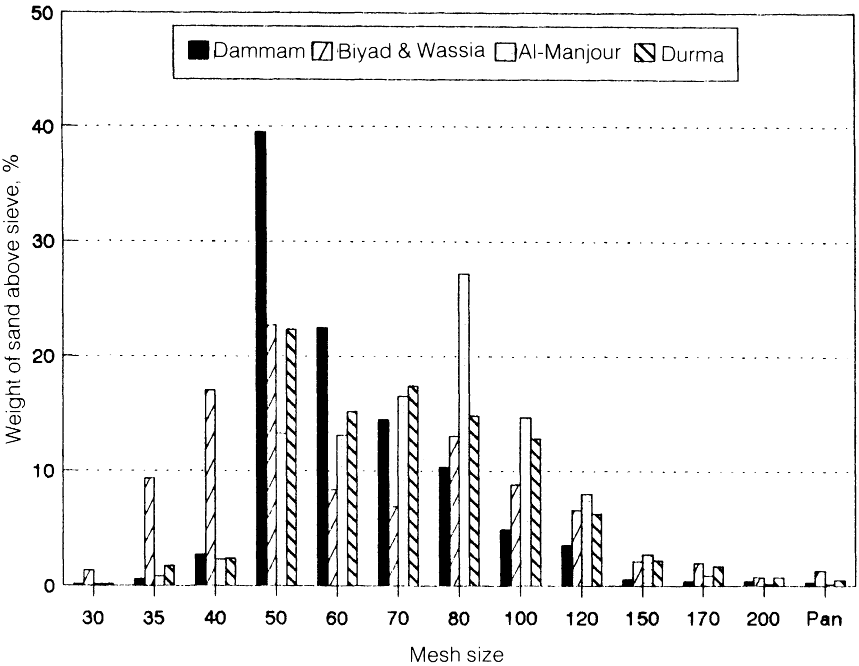


Fig. 5. Grain size distributions of Dammam, Al-Biyad and Al-Wassia, Al-Manjour, and Durma sands

mendations, each sand produced four mesh sizes of propping agents. These sizes are 30/50, 40/70, 60/120 and 70/140. Each size composed of a set of 6 meshes at specified amount of sand from each size (Tables 1 to 4). The Proppant mesh sizes are prepared and the physical properties of each one are tested separately. Tables 1 to 4, give a complete picture of the physical properties of prepared proppant mesh sizes for each sand.

The microscopic analysis of sphericity and roundness, Fig. 6, showed that the sphericity as well as the roundness of the proppant mesh sizes ranged between 0.6 and 0.8 which is equal or higher than the recommended API values. Sphericity and roundness actually affect the porosity and permeability of the fracture. However, grain roughness will decrease these properties as well as fracture width due to the embedment in the formation.

The proppant mesh size densities which are important for selecting fracturing fluid and fracturing equipment are also determined. The test showed that the bulk and grain densities are below the maximum specified values from API. This means

Table 1. Typical physical properties of Dammam sand proppant mesh sizes

API Property	Recommended limits	Mesh size 30/50	40/70	60/120	70/140
Particle diameter range, μm	Standard	600 to 300	425 to 212	250 to 125	212 to 106
Sieve analysis, wt% retained					
Top sieve	0.1 maximum	0.0 *	0.0 *	0.0 **	0.0 *
Between primary sieves	90.0 minimum	93.1	91.8	91.0	90.0
Second and sixth sieves		6.9	9.2	9.0	10.0
Pan	1.0 maximum	0.0	0.0	0.0	0.0
Total		**100.0**	**100.0**	**100.0**	**100.0**
Krumbein shape factor					
Roundness	0.6 minimum	0.7	0.8	0.8	0.8
Sphericity	0.6 minimum	0.8	0.8	0.8	0.8
12/3 HCl/HF Solubility	**3.0 maximum**	2.0	2.0	2.0	2.0
Crush resistance, % fines	variable with size	10.0	8.0	7.0	6.0
Crush resistance, psi		2250	4360	4850	5500
Particle density, lbm/gal	22.11 maximum	22.00	21.50	21.55	21.60
Bulk density, lbm/ft^3	105.0 maximum	102.30	96.72	98.56	99.20

* Comparable to Ottawa proppant sizes (1)

** Proposed from the laboratory

Table 2. Typical physical properties of Al-Biyad and Al-Wassia sand proppant mesh sizes

API Property	Recommended limits	Mesh size 30/50	40/70	60/120	70/140
Particle diameter range, μm	Standard	600 to 300	425 to 212	250 to 125	212 to 106
Sieve analysis, wt% retained		*	*	**	*
Top sieve	0.1 maximum	0.0	0.0	0.0	0.0
Between primary sieves	90.0 minimum	93.1	91.8	91.0	90.0
Second and sixth sieves		6.9	9.2	9.0	10.0
Pan	1.0 maximum	0.0	0.0	0.0	0.0
Total		**100.0**	**100.0**	**100.0**	**100.0**
Krumbein shape factor					
Roundness	0.6 minimum	0.7	0.8	0.6	0.8
Sphericity	0.6 minimum	0.8	0.8	0.7	0.7
12/3 HCl/HF Solubility	3.0 maximum	4.0	4.0	4.0	4.0
Crush resistance, % fines	variable with size	10.0	8.0	7.0	6.0
Crush resistance, psi		2250	4000	4250	4500
Particle density, lbm/gal	22.11 maximum	21.70	22.20	21.70	21.20
Bulk density, lbm/ft^3	105.0 maximum	101.70	99.80	99.20	95.50

* Comparable to Ottawa proppant sizes (1)

** Proposed from the laboratory

Table 3. Typical physical properties of Al-Manjour sand proppant mesh sizes

API Property	Recommended limits	Mesh size 30/50	Mesh size 40/70	Mesh size 60/120	Mesh size 70/140
Particle diameter range, μm	Standard	600 to 300	425 to 212	250 to 125	212 to 106
Sieve analysis, wt% retained					
Top sieve	0.1 maximum	0.0 *	0.0 *	0.0 **	0.0 *
Between primary sieves	90.0 minimum	93.1	91.8	91.0	90.0
Second and sixth sieves		6.9	9.2	9.0	10.0
Pan	**1.0 maximum**	0.0	0.0	0.0	0.0
Total		**100.0**	**100.0**	**100.0**	**100.0**
Krumbein shape factor					
Roundness	0.6 minimum	0.8	0.7	0.7	0.6
Sphericity	0.6 minimum	0.8	0.8	0.7	0.6
Crush resistance, % fines	variable with size	10.0	8.0	7.0	6.0
Crush resistance, psi		1740	2130	2320	3570
Particle density, lbm/gal	22.11 maximum	21.91	21.52	21.8	21.275
Bulk density, lbm/ft^3	105.0 maximum	95.35	96.22	94.85	95.85

* Comparable to Ottawa proppant sizes (1)

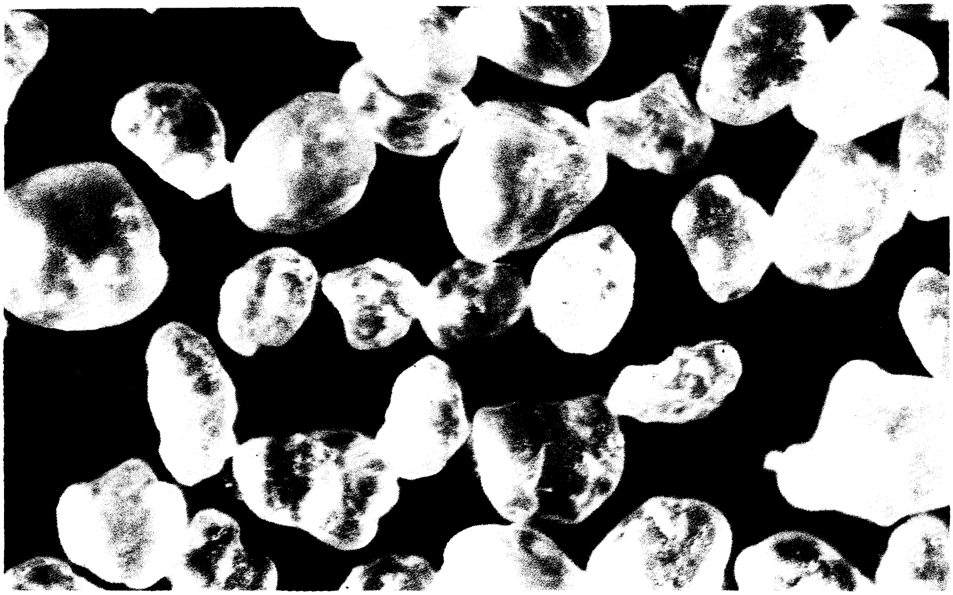
** Proposed from the laboratory

Table 4. Typical physical properties of Durma sand proppant mesh sizes

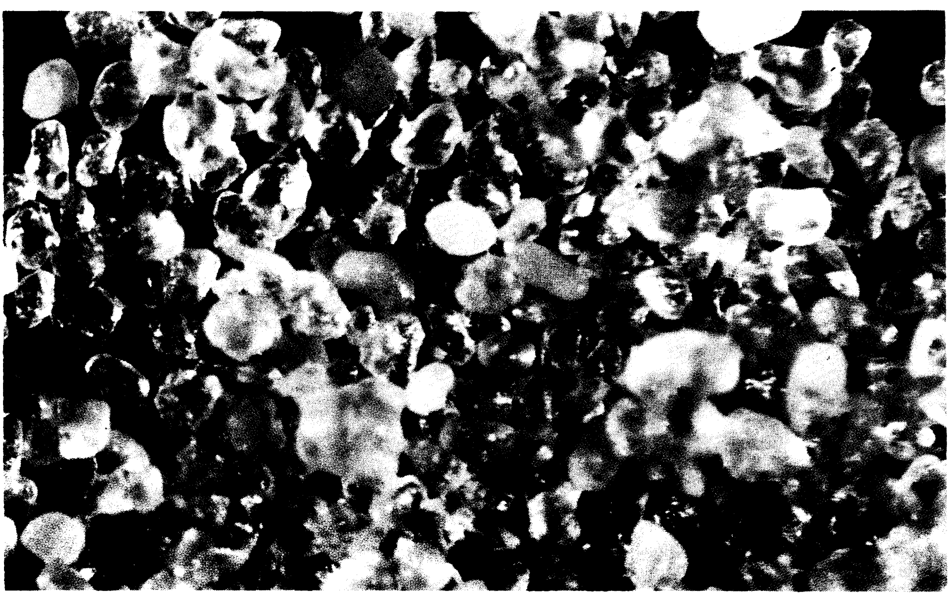
		Mesh size			
API Property	**Recommended limits**	**30/50**	**40/70**	**60/120**	**70/140**
Particle diameter range, µm	Standard	600 to 300	425 to 212	250 to 125	212 to 106
Sieve analysis, wt% retained					
Top sieve	0.1 maximum	0.0 *	0.0 *	0.0 **	0.0 *
Between primary sieves	90.0 minimum	93.1	91.8	91.0	90.0
Second and sixth sieves		6.9	9.2	9.0	10.0
Pan	1.0 maximum	0.0	0.0	0.0	0.0
Total		**100.0**	**100.0**	**100.0**	**100.0**
Krumbein shape factor					
Roundness	0.6 minimum	0.8	0.7	0.7	0.6
Sphericity	0.6 minimum	0.8	0.8	0.7	0.6
Crush resistance, % fines	variable with size	10.0	8.0	7.0	6.0
Crush resistance, psi		2080	1480	1870	3130
Particle density, lbm/gal	22.11 maximum	21.5	22.22	21.6	22.31
Bulk density, lbm/ft^3	105.0 maximum	95.22	94.85	95.41	94.72

* Comparable to Ottawa proppant sizes (1)

** Proposed from the laboratory



Dammam sand 30/50 proppant size, 10X



Dammam sand 70/140 propant size, 20X

Fig. 6. Photographs of two Dammam sand proppant sizes used in roundness and sphericity evaluation

that the proppant mesh sizes are suitable to be used with known fracturing fluids. Also, no settlement problems will be faced during fracturing operations.

The acid solubility tests showed that proppant mesh sizes prepared from Dammam and Al-Manjour sands are acid resistive. The resistivity is important in case of acid fracturing operations in which acid is mixed with proppant and pumped through the formation. The results concluded that proppant mesh sizes from Dammam and Al-Manjour sands are suitable for acid fracturing operations. The proppant mesh sizes from Al-Biyad and Al-Wassia, and Durma sands are suitable for hydraulic fracturing only. The solubility is actually due to the amphibole group in sand composition which is soluble in acid.

Regarding to the crushing resistance of proppant sizes, the tests were conducted at four stress levels, namely: 7500, 10000, 12500, and 15000 psi. The percent of fines after each test were determined and plotted versus the same stress level as in Fig. 7. At specified limit of fines ranged from 6% to 10% depending upon the proppant mesh size, the crushing resistance was evaluated from the plot. For example, the specified limit of fines for 30/50 proppant mesh size is 10%. Drawing a horizontal line

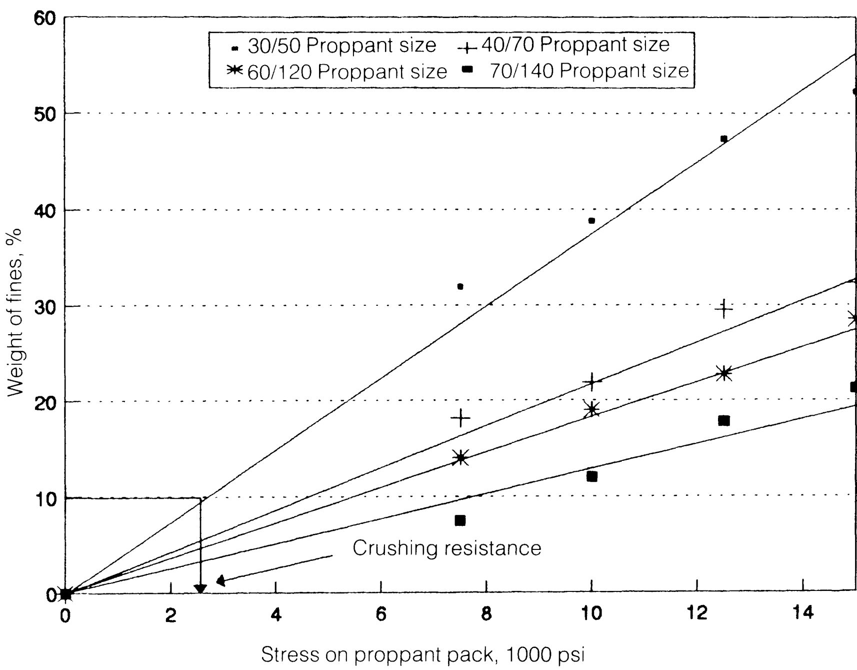


Fig. 7. Crushing resistance of Dammam proppant sizes

from this value to intersect the plot, see Fig. 7, will give the crushing resistance of the proppant mesh size. The results showed that the crushing resistance laid between 1500 psi to 5500 psi depending on the proppant mesh size and the type of sand as shown in Tables 1 to 4.

According to the theories of hydraulic fracturing, the fracture gradient of sedimentary basins is between 0.6 psi/ft and 0.8 psi/ft [1;6;9]. The lower value is normally applied for tectonically relaxed areas. This means that the fracture gradient in Saudi Arabia can be considered as 0.6 psi/ft. Applying this gradient and taking the measured crushing resistance of the proppant mesh sizes, it can be concluded that proppants from Saudi sands are suitable for hydraulic fracturing of reservoirs found at depths down to 8000 ft. These reservoirs can be classified as shallow and medium deep reservoirs.

To provide a complete picture of proppant mesh sizes, X-ray analyses are made to show the composition of these proppants, Fig. 8. The analysis showed that quartz is the main component of these sands. Amphibole and some heavy minerals are also detected. These can be considered as impurities and are responsible for acid solubility of proppant prepared from Al-Biyad and Al-Wassia, and Durma formations. However, these impurities are rare in proppant mesh sizes prepared from Dammam and Al-Manjour sands.

Conclusions

Based on the analysis and laboratory tests conducted on the four Saudi sandstone formations, the following conclusions are obtained:

1. The analyzed samples from four different Saudi sandstone formations produce four proppant mesh sizes which are 30/50, 40/70, 60/120 and 70/140. These sizes are very common in hydraulic fracturing operations.
2. The proppant mesh sizes produced from Dammam and Al-Manjour sands are suitable for hydraulic fracturing operations with acid attack, while the proppants from the other sands are to be recommended for hydraulic fracturing only.
3. The proppant can be used with common fracturing fluids without any serious problems.
4. The proppants are to be recommended for fracturing shallow and medium deep Saudi reservoirs with depth down to 8000 ft.
5. The sandstone are friable and outcrops in the Eastern and Central provinces of Saudi Arabia which means low preparation costs and high efficiency.

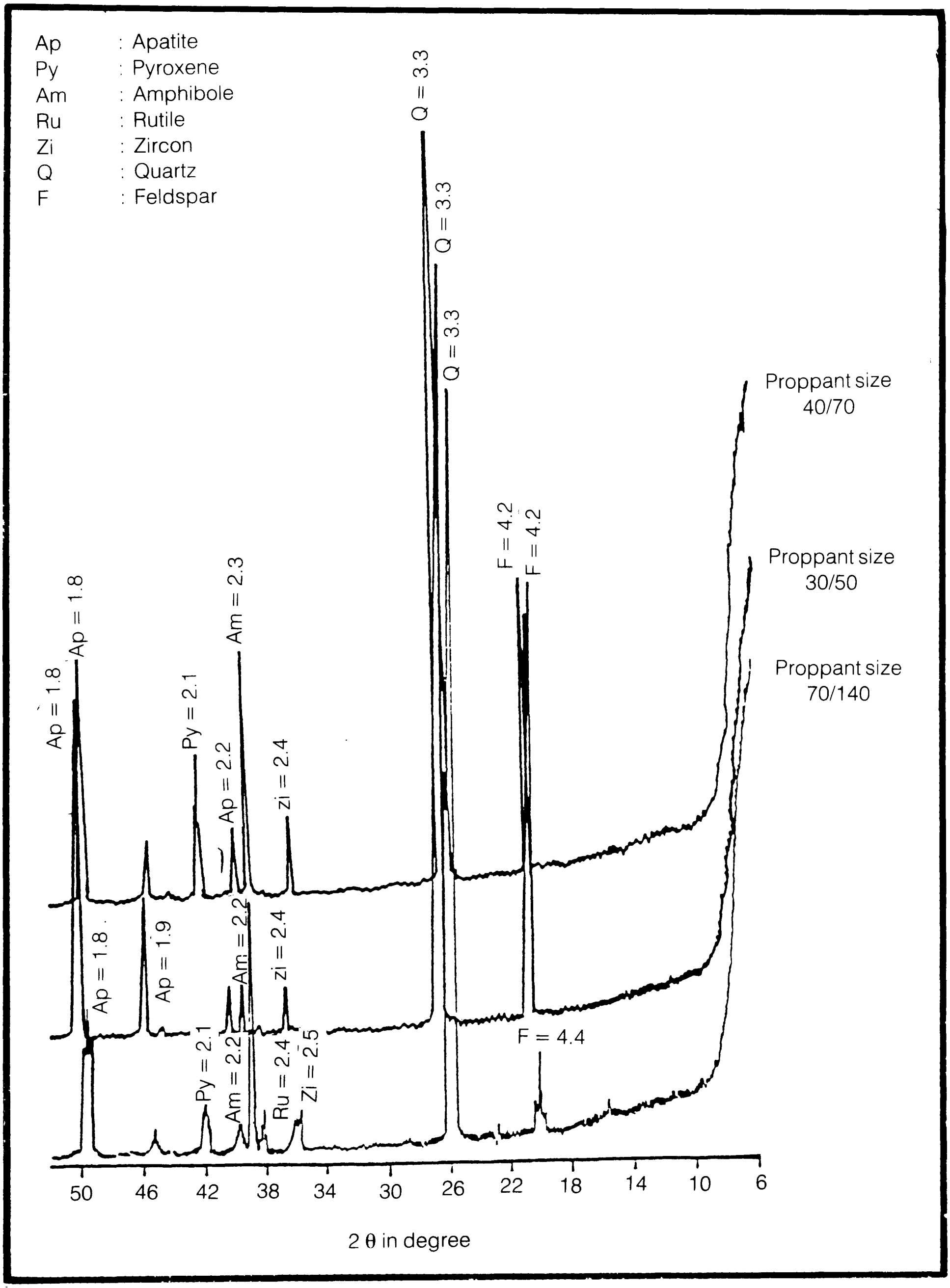


Fig. 8. X-ray differactometer pattern of Dammam sand proppant sizes

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اختبار صخور الرمال السعودية لاستخدامها في عمليات التشقيق الهيدروليكي لمكامن النفط

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الرياض ١١٤٢١، المملكة العربية السعودية

(استلم في ١١/٤/١٩٩٣م؛ قبل للنشر في ٣/٥/١٩٩٤م)

ملخص البحث. يقدم هذا البحث نتائج اختبارات أربع تكوينات من الصخور الرملية السعودية، وهي: الدمام، البياض والوسيع، المنجور، وضرما لاستخدامها كعوامل تدعيم في عمليّات التشقيق الهيدروليكي. وقد بيّنت الدراسات التي أجريت على مكامن النفط السعودية أن حوالي ٣٥٪ من هذه المكامن ذو نفاذيّة أقل من ٠,٠٥ (خمسة من المائة) من الدارسي (وحدة قياس النفاذيّة) مما يجعلها تحتاج إلى عمليات تشقيق هيدروليكي في المستقبل لزيادة إنتاجيّة النفط منها.

ولقد أثبتت نتائج التحاليل التي أجريت أنّ الصخر الرملي السعودي مفكك ويتكون أساسًا من معدن الكوارتز ويمكن إنتاج أربعة أحجام من عوامل التدعيم، وهي ٣٠/٥٠، ٤٠/٧٠، ٦٠/١٢٠ و ٧٠/١٤٠ والتي تعتبر شائعة الاستخدام في عمليّات التشقيق الهيدروليكي، كما أنّ الخواص الفيزيقيّة لهذه العوامل تقابل أو تزيد في قيمها عن القيم الموصى بها من قبل معهد البترول الأمريكي (API)، كما أنّه يمكن استخدام عوامل التدعيم المنتجة من رملي الدمام والمنجور في عمليّات التشقيق الهيدروليكي المعرض للأحماض بينما لا تتحمل الأنواع الأخرى التعرض للأحماض، ويوصى باستخدام عوامل التدعيم المذكورة في الآبار السطحيّة والمتوسطة العمق، (ذات أعماق تصل إلى ٨٠٠٠ قدم)، بالإضافة إلى إمكانيّة إنتاجها إقتصاديًا.