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Wellbore Fractures Sealing: Innovative Experimental Setup and Superb Seal Material

Musaed N. J. AlAwad, King Saud University, College of Engineering, Petroleum and natural Gas Engineering Department, Riyadh, Saudi Arabia; K. A. Fattah, King Saud University, College of Engineering, Petroleum and natural Gas Engineering Department, Riyadh, Saudi Arabia and Cairo University, Faculty of Engineering, Petroleum Engineering Department, Cairo, Egypt; Ahmed A. AlGobany, King Saud University, College of Engineering, Petroleum and natural Gas Engineering Department, Riyadh, Saudi Arabia.

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Abstract

Drilling the wellbore is the first and the most expensive step in the oil and gas industry. Expenses for drilling represent 25% of the total oilfield exploitation cost. Drilling fluids represent 15 to 18% of the total cost of petroleum well drilling operations. The main drilling fluids problem is the loss into formations with severe drilling induced fractures or natural fractures and vugs. Prevention or mitigation of severe lost circulation is a main challenge while drilling in these formations where conventional lost circulation materials (LCM) will not cure these losses. Therefore, specialized treatment using fracture seal materials (FSM) is required when drilling through these troublesome formations.

In this study, a superior FSM made from crushed date palm seeds was tested at laboratory for its ability to seal artificially fractured cores under High Temperature High Pressure (HT-HP) conditions. For this purpose, the conventional 500 ml HT-HP API filter press was modified to accommodate an artificially fractured core plug of length and diameter equal to 38.1 mm (1.5 inch) instead of the ceramic disc or filter paper. To study the effect of fracture width on seal efficiency, three different fracture sizes (width) were used in this study (3.0 mm, 4.0 mm and 5.0 mm).

Using the HT-HP filter press modified in this study, spud mud with mixtures of crushed date palm seeds of different grain sizes proved its ability to completely seal the artificially made fracture in the test core samples at overbalance pressures up to 1000 psi and temperatures up to 90^{o}C. In addition to its superior ability to seal fractured formations, the date palm seeds material is cheap, locally available in commercial quantities, environmentally friendly material, and easy to crush into various required grain sizes.

Introduction

Routine drilling fluids filtration measurements are performed on a filter paper using either the API filter press (100 psi and 25 ^{o}C) or the HT-HP filter press (175 ml or 500 ml). Alternatively, HT-HP filtration can be performed on a ceramic disc as shown in Fig. 1. Filter papers or ceramic discs are used to simulated rock matrix in non-fractured and non-vuggy formations. Several attempts have been performed to investigate the effect of various fluid loss control materials (LCM) on sealing formations with high permeability and/or very micro induced or natural fractures.

Fig. 1- Standard HT/HP API filter press (500 ml).

Mark W. Sanders et. al., 2008, and Oscar Contreras et. al., 2014 experimentally studied the mechanisms of lost circulation materials (LCM) seal of induced fractures in thick-wall cylindrical cores. Arunesh Kumar et. al., 2011, developed a tapered slot to physically resembling a wedge shaped fracture for testing various types of LCM. Matthew L. Miller et. al., 2013, developed a low-volume, laboratory-scale apparatus with multiple configurations to better model lost circulation conditions encountered while drilling through vuggy and severely fractured zones. The apparatus has a high working pressure and high pressure differentials can be used to test plugs formed by lost circulation materials. Hong (Max) Wang et. al., 2007, used boundary element analysis (BES) to theoretically investigate the process of cracks sealing to strengthen the wellbore. They concluded that perfect sealing of cracks enhances wellbore stability. Kuhan Chellappah et. al., 2015, a real attempt was done to simulate fractured formation by replacing the ceramic disc in the HT-HP filter press by slotted stainless steel. In a recent study, Amanullah, 2016 used crushed date palm seeds as a lost circulation material (LCM) for sealing fractured formations. In his study, he used 2mm slotted stainless steel discs fitted into 250 mm HT-HP filtration cell to test the possibility of fracture seal by a drilling fluid containing the crushed date palm seeds. The result was a perfect fracture seal indicating the possibility of utilizing this LCM in drilling oil and gas wells. In their first attempt to utilize date palm seeds as a fracture seal materials, AlAwad et al, 2017 developed new laboratory techniques that proved the success of the tested material and the new experimental procedure.

The previously mentioned studies to simulate fractures sealing process with LCM have several limitations such as:

1. Large scale core samples needed to simulate wellbore using thick-wall cylinders.
2. Neglecting filtration loss from the rock matrix inside and outside the fractures when using stainless steel slotted discs.
3. Real fracture shape is not perfectly simulated when stainless steel slotted discs are used.
4. The outlet valve in the HP-HT was not modified perfectly to allow LCM large particles to flow out of the test cell in case if no fracture seal was established.

The objectives of this study are of three folds:

1. Modifying the conventional API HT-HP filtration cell to accommodate fractured core plugs of 38.1 mm (1.5 inch) diameter and 38.1 mm thickness instead of filter paper or ceramic disc.
2. Appropriately simulating severely fractured or vuggy formations using natural core plug with manmade fracture.
3. Testing a new environmentally friendly and superior fracture seal material made from crushed date palm seeds.

Experimental Work

Experimental Set-Up

In this study the conventional 500 ml HT-HP filter press (Fig. 1) was modified to accommodate fractured rock plug by the developing of a special core holder made from durable rubber to replace the ceramic disk normally used in this apparatus as shown in Fig. 2.

Fig. 2- The developed core holder and the testing core plugs with fracture.

The core holder was modified to perfectly accommodate 38.1 mm (1.5 inch) core plug with 38.1 mm (1.5 inch) thickness. The developed core holder proved its integrity under temperatures up to 90^{o}C and pressure up to 1000 psi. To verify there is no leakage from the developed core holder, stainless steel cylindrical plug of 38.1 mm diameter and 38.1 mm thickness was fitted into the holder and placed inside the HT-HP filter press and a real test at 90^{o}C and 1000 psi was performed with perfect seal result (i.e. zero filtration). To allow the tested fracture seal materials flow freely outside the HT-HP cell without restrictions (other than the facture itself) in the case of none fracture seal existence, the outlet end cap was modified by removing the fine stainless steel screen and enlarging the outlet hole. The one mm flow channel (hole) in the outlet end cap seal was enlarged to 10 mm to prevent trapping of FSM material that may indicate a false fracture seal interpretation as shown in Fig. 3.

Fig. 3- HT-HP filtration cell end cap before and after modification.

Testing Materials

Drilling Fluids

Water based mud (spud mud) formulated from fresh water plus 7% by weight bentonite was used as a base mud for all experiments in this study. The basic properties of the base mud are shown in Table 1.

Table 1- Properties of the base mud used in this study.

Properties	Measured Values
Density, ppg	8.7
pH	7.2
Apparent viscosity, cp	5.0
Yield point, lb/100 ft^2	7.8
10 sec gel strength, lb/100 ft^2	6.4
10 min gel strength, lb/100 ft^2	10.7

Date Palm Seeds

According to Feedipedia, 2016, date palm seeds are the by-product of date stoning, either for the production of pitted dates or for the manufacture of date paste (see Fig. 4). The date seed is a hard coated seed, usually oblong, ventrally grooved, with a small embryo. Date seed weigh 0.5 g to 4.0 g and represent 6 to 20% of the fruit weight depending on maturity, variety and grade.

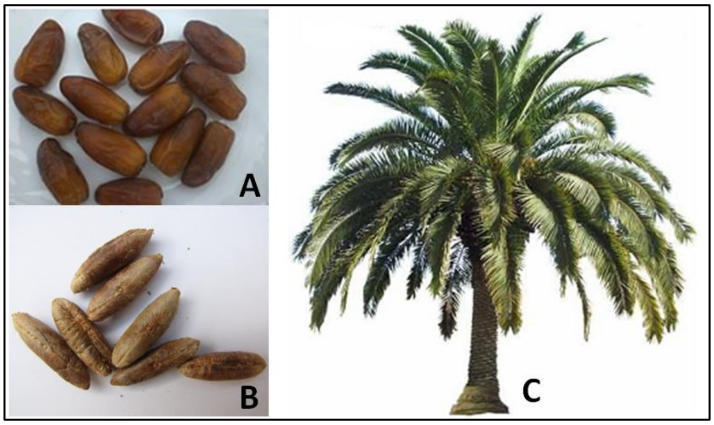

Fig. 4- Dates fruit (A), date palm seeds (B), and date palm tree (C).

Date palm seeds are traditionally used for animal feed. They can also be used as a source of oil (which has antioxidant properties valuable in cosmetics), as a coffee substitute, as a raw material for activated carbon or as an adsorbent for dye-containing waters as shown in Table 2. Dates by-products are usually fed to animals during winter, though they can be used at any time of the year.

Table 2- Approximate composition of date palm seeds.

Moisture	5-10%
Protein	5-7%
Oil	7-10%
Fibers	10-20%
Carbohydrates	55-65%
Ash	1-2%

In this study, date Palm seeds obtained from a local food factory were cleaned and dried in at room temperature for one week. The dried date palm seed are crushed using a heavy duty crushing machine.

Crushed date palm seeds sieving produced four groups based on grain size distribution, fine, medium, coarse-1 and coarse-2 as shown in Figs. 4 and 5.

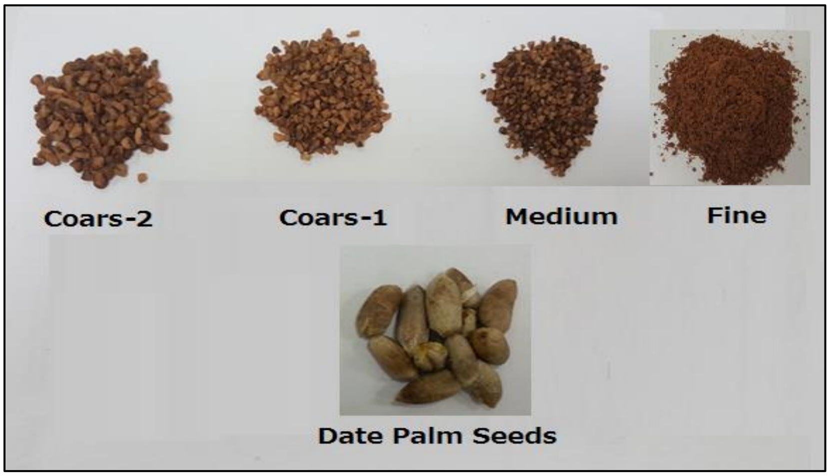

Fig 4- Grain sizes of the crushed date palm seeds.

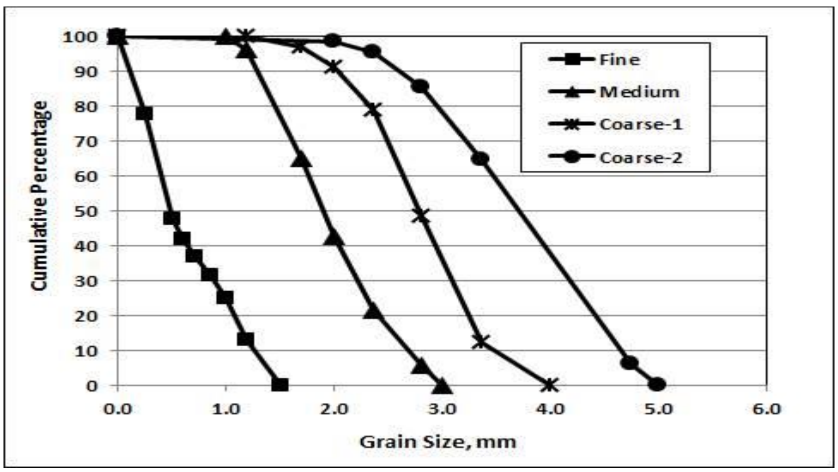

Fig 5- Grain size distribution of the tested crushed date palm seeds.

The granulometric analysis of the crushed date palm seeds (fine, medium coarse-1 and coarse-2) are taken as the bases for selecting the geometry of the manmade fracture in the test core plugs used in this study. The FSM size was selected to either freely passed through the fracture or perform a seal by bridging in the fracture inlet.

Core Samples

Core plugs of 38.1 mm diameter and 38.1 mm thickness were cored from an artificial sandstone blocks. The properties of the utilized sandstone are shown in Table 3.

Table 3- Properties of the used sandstone.

Properties	Measured Values
Rock Type	Artificial white sandstone
Porosity	30%
Permeability	266 md
Unconfined Compressive Strength	14 MPa
Tensile Strength	2.7 MPa
Plug Diameter	38.1 mm (1.5 inch)
Plug Length	38.1 mm (1.5 inch)
Fracture Top (width)	3.0, 4.0 and 5.0 mm
Fracture Bottom	1.0 mm
Fracture Length	38.1 mm (1.5 inch)

After coring and trimming to the required dimensions, a single fracture was performed in each core. Three fracture sizes were prepared with an opening (top) size of 3.0, 4.0 and 5.0 mm until half way of the core length, then a tip (bottom) size of 1.0 mm along the remaining thickness up to the bottom of the core. The fracture dimensions was selected based on the FSM grain size distribution shown in Fig. 4 so that the coarse FSM materials can enter the fracture and accumulate in the middle resulting in a potential fracture seal as shown in Fig. 6. Both fine FSM and bentonite in the base mud contribute to the developed seal as well in the fractured and non-fractured parts of the core plug.

Fig. 6- Demonstration of the date palm seeds trapping in the induced facture.

Testing Procedure

The experimental work for the verification of the potential fractures seal ability of crushed date palm seed was designed to investigate the effect of the following factors for potential fracture sealing:

1. Fine size of the crushed date palm seeds in base mud.
2. Coarse size of the crushed date palm seeds in base mud.
3. Mixture of sizes (fine + coarse) of the crushed date palm seeds (FSM) in base mud.
4. Temperature.
5. Pressure difference (ΔP).

The experimental design (mud composition and FSM type and concentration, temperature, pressure difference, and achievement made) used for the verification of the potential use of crushed date palm seeds to seal fractured formations while drilling is summarized in Table 4.

Each experiment was repeated three times to validate the obtained results. Testing mud prepared by mixing 7% by weight bentonite and the required FSM in fresh water. The test core plug is perfectly fit into the rubber sleeve using a temperature resistant adhesive tap as shown in Fig. 6. Then, the mixed mud was poured into the 500 ml HT-HP filter press cell. After that, the sleeve was placed over the O-ring and the cell cover was firmly tight with the six screws. At this stage the cell with its contents (drilling fluid and the fractured core plug) was placed up-side-down in the heating well until reaching the required temperature.

The filtration test was then started by opening the nitrogen cylinder valve to apply the required pressure difference on the top of the mud. Then, the bottom valve was slowly opened and removed. The mud spurt as well as filtrate volumes were recorded with time. At the end of the test, the cell was left to cool to laboratory temperature, then the cell pressure was released and the core plug was extracted for inspection.

Table 4- Experimental work results.

Fracture Type	Exp. #	Fracture Size, mm		FSM Additives, wt. %				Test Base Mud	Applied Temperature °C	Applied Pressure, psi		Achievement at the end of the experiment
		Top (Width) (Inlet)	Bottom (End) (Outlet)	Fine	Medium	Coarse				Initial	Final	
						1	2					
	1			-	-	-	-					Complete Loss
	2			5.0	-	-	-					Complete Loss
	3			-	5.0	-	-					Complete Loss
	4			2.0	2.0	-	-					Partial Loss
	5			2.5	2.5	-	-		25	200	200	Partial Loss
I	6	3.0		3.5	3.5	-	-					Complete Seal
	7			4.25	4.25	-	-	Fresh Water + 7% Bentonite + FSM				Partial Seal
	8			5.0	5.0	-	-					Partial Seal
	9		1.0	6.5	6.5	-	-					Partial Seal
	10			3.5	3.5	-	-		90	200	200	Copmlete Seal
	11			3.5	3.5	-	-		90	200	1000	Complete Seal
	12			3.5	3.5	-	-					Complete Seal after 8 sec
II	13	4.0		3.5	-	3.5						Complete Seal
	14			3.5	-	-	3.5		25	200	200	Complete Seal after 9 sec
	15			3.5	3.5	-	-					Complete Seal after 4 sec
III	16	5.0		3.5	-	3.5						Complete Seal after 6 sec
	17			3.5	-	-	3.5					Complete Seal

Results and Discussion

In experiment 1, the base mud (fresh water + 7% bentonite by weight) without additives was tested for its potential ability for fracture sealing at pressure difference of 200 psi and 25°C. The result was a complete loss of the mud within one minute. The inspection of the core plug after the test (Fig. 7A) showed that a mud cake has formed and sealed only the core matrix while the fracture was remained open. This result indicated the need for the FSM to seal the fracture.

In experiments 2 and 3, 5% Fine and 5% medium crushed date palm seeds are added to the based mud respectively. Base mud with 5% fine crushed date palm seeds failed to seal the facture and a complete loss of the mud within one minute was the result (Fig. 7B). Similar result was occurred when a base mud with 5% medium crushed date palm seeds was used (Fig. 7C). Therefore, it was decided to test a mixture of equal amounts of fine and coarse crushed date palm seeds for potential fracture sealing as shown in Table 4.

In experiments 4 through 9, mixtures of fine and medium crushed date palm seeds of 4%, 5%, 7%, 8.5%, 10%, and 13% by weight of fresh water were tested (Fig. 7D through 7I). The 10 minutes filtrate volumes for these experiments are plotted in Fig. 8.

As shown in Fig. 8, the optimum crushed date palm seeds mixture was 7% (3.5% fine + 3.5% medium) which gave 2.5 cc filtrate within 10 minutes with a perfect seal of the fracture as shown in Fig. 7F. It must be noticed that all the previously mentioned experiments was performed at a pressure difference of 200 psi and a temperature of 25°C.

The optimum mud composition (fresh water + 7% bentonite + 3.5% fine crushed date palm seeds + 3.5% medium crushed date palm seeds in weight bases) was used to test the effect of higher pressure and temperature on the ability of the optimum mud composition to seal the test core plug fracture (width = 3mm).

In experiment 10, the relationship between the temperature (25°C, 65°C, and 90°C) and the 10 minutes filtrate volume at 200 psi pressure difference was tested. The 10 minutes filtrate volumes of these experiments are plotted in Fig. 9.

It can be noticed from Fig. 9 that the filtrate volume increases as the temperature increases. The change of temperature from 25°C to 90°C increases the volume of the mud filtrate from 2.5 cc to 18 cc indicating 3.6% total loss from the whole tested mud sample. This result indicated that this utilized FSM mixture is working well under temperatures up to 90^{o}C or more (Fig. 7J).

In experiment 11, the relationship between the pressure difference (200 psi, 400 psi, and 600 psi) and the 10 minutes filtrate volume at 90^{o}C were studied. It can be noticed from Fig. 10 that the filtrate volume increases as the pressure difference increases (Fig. 7K) however, a complete seal was achieved.

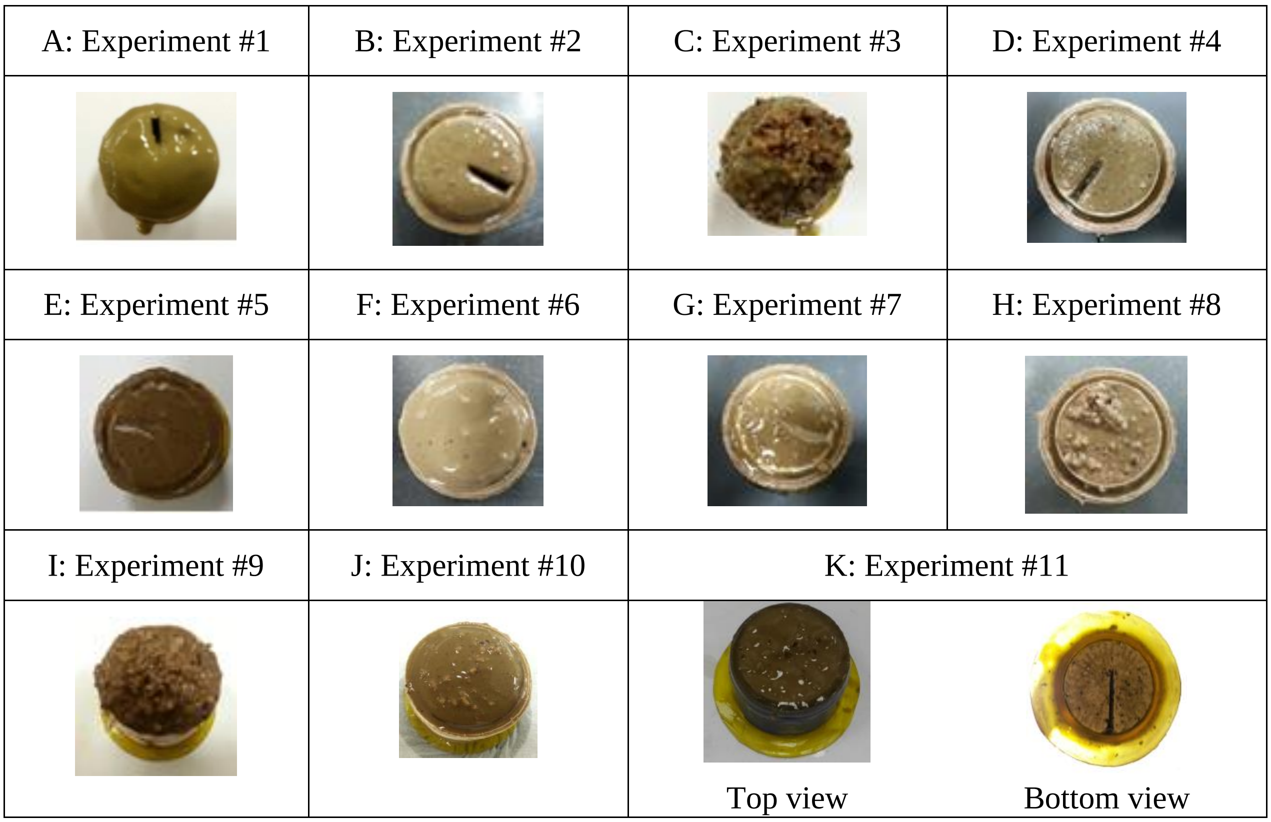

Fig. 7- The fractured sandstone core plugs at the end of experiments.

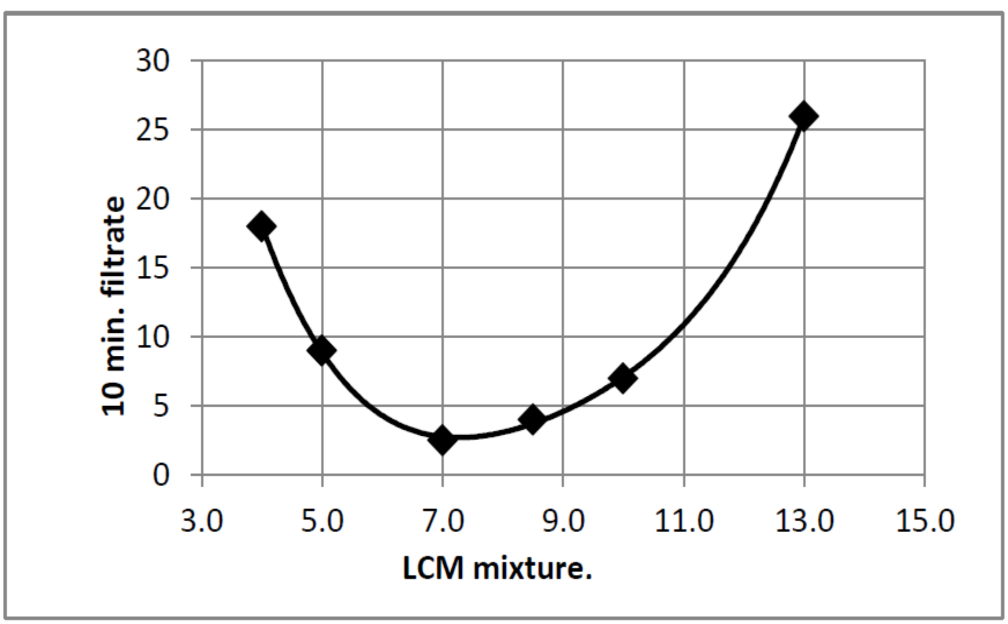

Fig. 8- Relationship between FSM weight percent and 10 min filtrate volume @ 200 psi & 25^{o}C.

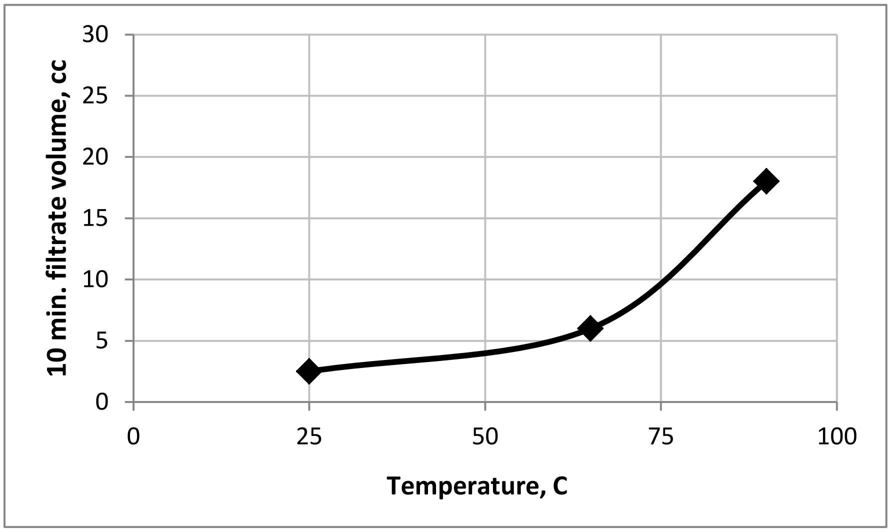

Fig. 9- Relationship between temperature and 10 min filtrate volume @ 200 psi.

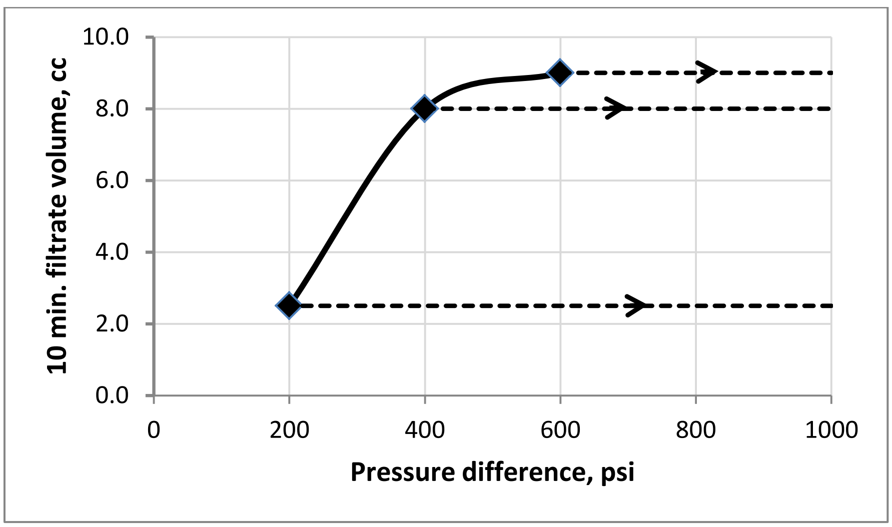

Fig. 10- Relationship between pressure difference and spurt volume at 90^{o}C.

The change of pressure difference from 200 psi to 600 psi increases the volume of the mud filtrate from 2.5 cc to 9 cc indicating 1.3% total loss from the whole tested mud sample. Furthermore, the pressure difference was increased gradually to 1000 psi in each experiment where no more filtrate loss was noticed indicating the excellent integrity of the performed fracture seal (Fig. 7K).

To investigate the effect of fracture inlet size, new cores with fracture width of 4.0 and 5.0 mm were prepared. It was found that as the fracture size increases a coarser FSM is required to perform good seal. For cores with fracture width equal to 4.0 mm, a mixture of 3.5% fine FSM plus 3.5% coarse-1 FSM performed complete seal (experiments 12 through 14). For cores with fracture width equal to 5.0 mm, a mixture of 3.5% fine FSM plus 3.5% coarse-2 FSM performed complete seal (experiments 15 through 17). The results are reported in Table 4.

From the previous discussed experiments, it is clear that there is a linear relationship between the fracture size (width) and the FSM required for perfect seal as shown in Fig. 11. Additionally, Fig. 11 shows the borderline between fractures, vugs or pores that require LCM treatment from those require require FSM to mitigate or completely stop filtration or mud loss.

From Fig. 11, it is clear that for fromations with fractures, vugs or pores less than 1.4 mm require LCM rather than FSM. As seen in Table 4 and Fig. 12, the FSM provided complete seal for the fracture type I can also seal larger fractures (Types II and III) after some time using larger quantities of the FSM.

Therefore, to perform a good fracture seal with minimum (optimum) amount of FSM, the size of the utilized FSM must be proportional to the size of the fractures.

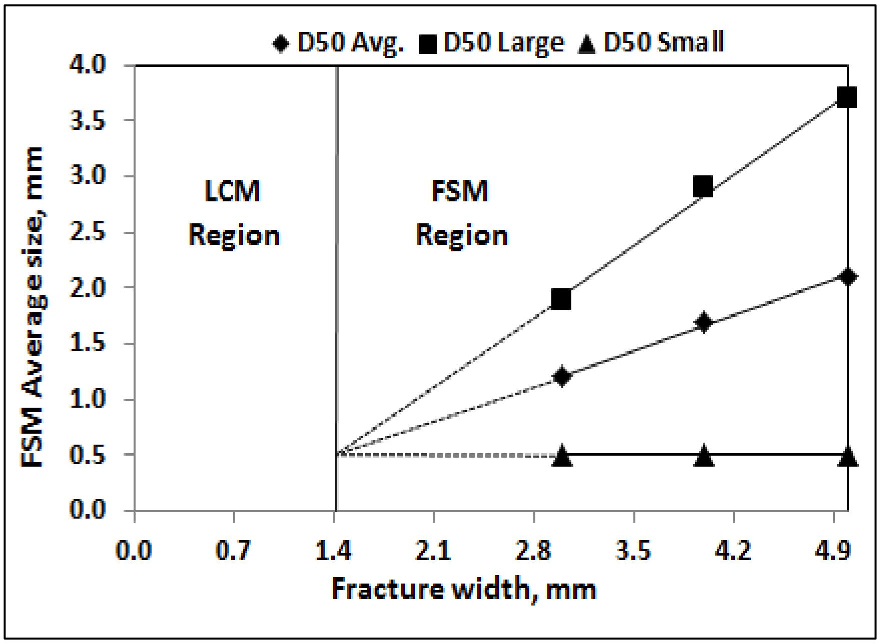

Fig. 11- Relationship between fracture size and FSM size.

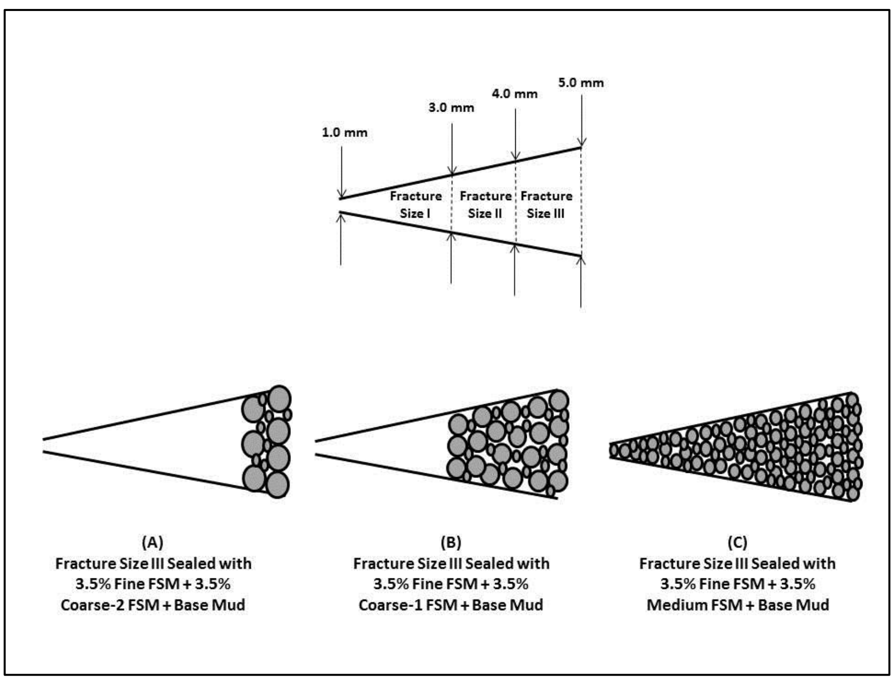

Fig. 12- Effect of optimum FSM size on quantity required for complete seal.

Conclusions

Based on the analysis performed in this study, the following conclusions can be made:

1. The conventional HT-HP 500 ml filter press has been modified to accommodate real core sample of 38.1 mm (1.5 inch) diameter and 38.1 mm (1.5 inch) length with manmade fracture instead of filter paper or ceramic disc.
2. The experimental setup and procedure developed in this study represents a realistic method to test fracture seal material under simulated high temperature and high pressure conditions.
3. Crushed date palm seeds proved its superior ability to seal fractured core plugs at temperatures and pressures up to 90^{o}C and 1000 psi respectively.
4. For economic considerations, the selection of crushed date palm seeds size required for perfect seal is dependent on the fracture size. Fromations with openings (fractures, vugs or pores) less than 1.4 mm require LCM rather than FSM to control mud filtration.

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