AN EXPERIMENTAL STUDY OF PERMEABILITY REDUCTION DUE TO INVASION OF OIL DROPLETS AND SOLID PARTICLES IN POROUS MEDIA DURING OILY-WATER INJECTION

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ABSTRACT

Re-injection of producedwater is of increasing importance as water cuts continue to increase worldwide. It provides an environmentally acceptable solution to the disposal of produced water, and contributes to pressure maintenance when injection takes place in the reservoir itself. Injection can take place under matrix injection or fracturing conditions. In both cases, the performance of the injection well and the distribution of the injected water are strongly influencedby the build-up of formation impairment around the wellbore or the fracture face. Solid particles and small oil droplets dispersed in the injection water are deposited in the formation by a process of filtration, and therefore will cause this impairment. This paper presents results from an experimental study on formation damage associated with simulated produced oily water injection. Core flooding experiments were carried out with simulated produced oily water containing 200 to 1200 ppm crude oil and 600-1500 ppm solids (10 µmmean diameter) dispersed in brine. The formation damage along the length of a core was investigated and a number of parameters contributing to permeability decline were evaluated. The results indicate that produced oily water containing oil droplets and solid particles can contribute to the permeability decline observed in the cores. The most severe decline occurred in the low flow rate of oily water injection and permeability declines are decreased by increasing injection flow rate . Oildroplets with a dimension significantly less than the pore throat diameter also led to permeability decline. The permeability alteration resulting from a combination of both oil droplets and solid particles is more severe than obtained from the systems individually.

KEYWORDS: waterinjection, formation damage, permeability decline, produced water re-injection (PWRI), oily water injection.

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ISBN ۹۷۸-۶۰۰-۶۷۲۰-۰۰-۵

1-INTRODUCTION

Production of hydrocarbons is usually accomplished by the production of aquifer water. This produced water consists of formation water and/or water that has previously been injected into the formation. As more oil is produced, the amount of producedwater increases. Consequently, this requires water management. One technique is reinjectionfor disposal, pressure maintenance, or enhanced oil recovery. The amount of producedwater from the fields in the Norwegian part of the North Sea is steadily increasing as new fields come on stream and the water cut increases on older fields. Currently, the yearly discharge is approximately 30 Mm^3, and is expected to increase to around 90 Mm^3 by the year 2000.Typical discharge volumes are from 500 m^3/day to 25,000 m^3/day from one platform. An important and difficult task in the reinjectionprocess is the ability to predict the impact of water quality on well injectivity. This is mainly due to the poor knowledge of the deposition mechanism in the formation of suspended solids and oil droplets in the produced water. A successful injection project can be executed if two key questions are answered: is the water going where it is supposed to; and can the desired injection rate be met? There are several factors that can influence produced water reinjection(PWRI) performance. There has been much published data on the aspect of formation damage resulting from producing oily water injection. Tang (l982) studied filtered and unfiltered produced water containing crude oil and solids. He indicated that the injection of producedwater containing 600 ppm of oil and 14.2 ppm of solids can cause permeability reduction; the worst damage is caused by the invasion of oil rather than by the deposition of solids on the core face. He also commented that the oil content of the produced water has to be decreased to 20 ppm in order to prevent severe formation damage. His (1990) investigated the quality of producedwater of the Prudhoe Bay Field, Alaska and identified that solid particles and oil droplets entrained in waterfloodwater can block reservoir pore throats and cause rapid injectivity decline. He indicated that solids are the prime cause of permeability damage. Simpson et al (1991) reported results froma North Sea waterfloodingproject.The injectivitiesof particular wells may be higher than that predicted by laboratory core flood experiments, even when the quality of the injected water was below specification. The explanation given for this was that cold injection water cools the formation and this leads to rock fracture and water bypass. The paper also indicated, in terms of oil field experience that formation damage was caused by solids rather than oil droplets plugging the pore throats. McAuliffe (1973) studied the mechanism of emulsion flowing through a porous medium. His investigation was based on the concept that an emulsion, flowing in a porous medium, would enter the more permeable portions and restrict flow, thereby causing fluid to flow into less permeable zones and increase the sweep efficiency. McAuliffe believed that an emulsion with a greater proportion of larger droplets in relation to the pore-throat constrictions would be more effective in blocking pores than an emulsion with smaller droplets. Sooand Radke(1984, 1988) obtained results which indicated that oil droplets cannot contribute· to a catastrophic damage even though they may invade the porous medium to a considerable depth.Most studies indicate that water quality is a very important parameter for reservoir impairment processes, such as finemigration of the same formation during the injection operation (Civan1989, 1991, Ohen 1991, 1993, 1996), clay swelling (Barkman 1975), and biological effects. Recentresearchers have shown that completion fluids fines, an order of magnitude smaller than a given poresize, can also cause considerable damage (Gruesbeck 1982, Wojtanawicz 1987, Bennion 1994, 1995). In addition, largerquantities of suspended oil may impair injectivity by reducing the permeability of the formation towater, especially in injection zones that initially have less than the mobile oil saturation. Oil tends to foul deep-bed filtration and enormous effort is made to remove the majority of the oil content before reinjectionoperations. Produced water containing oil in the produced water in the range of 500mg/l to 5,000mg/l or higher must be treated before reinjectionof water for two reasons. First of all, the oil in the injection water may cause damage to the formation. Hence, the oil content of the injection fluid must be reduced to a suitable level for use. Secondary, the oil that is recovered from the produced water is routed to the oil sales meter to generate cash for the operation (Thro1994, Van der Zande 2000, Janssen 2000). Although the presence of oily-water by itself is relatively unlikely to cause any significant damage, when combined with suspended solids, it becomes extremely significant (Zhang 1993). The presence of solids even at very low concentration leads to low permeability and early filter cake buildup. The addition of oily-water causes solids particles to coalesce, acting as an emulsifying agent. More oil content in combination with solids leads to increased damage. Longeron(1955) concluded that an increase in oil viscosity tends to reduce spurt volume and cumulative filtration volume, thus decreasing the extent of damage. Well productivity can be seriously reduced by large solid and oil content during reinjection. If not adequately controlled, losses may push hydrocarbons away from the welland solids may plug the pores, increasing the time necessary for testing the well and distorting the evaluation of its productivity/injectivity potential (Xiao 1999).Mohammad A.J. Ali (2005) concluded that Permeability impairment due to oily-water alone at residual oil formation is insignificant, and the size of oil droplets does not play a big role in injecivtivitydecline Finally, recent studies by Vaz Jr. (2006a,b), suggest that in the presence of residual oil, injection of produced water containing suspended solid catianin fact increase the differential pressure and mobilize some of the residual oil. Mohammed A. Ba-Taweel et al (2006) based on Experimental results concluded that introducing different ratios of produced water (5, 10, 15 and 100 vol.%) to the seawater resulted in permeability loss of core samples and The damage was found to be proportional to the concentration of produced Water and so More reduction in permeability was found in low permeability core samples.

2-Experimental Setup :

Sample Conditions

In all flooding experiments, 18 sandstone cores with 10 cm length and of diameter 3.7 cm with average porosity of 17% and of initial permeability varied from 0.2 to 0.5 mdwere used. No oil was present in these cores. All the coreswere cleaned using distiller water in Soxhlet extractor and dried in an Oven at 110 °C for several hours before use. The density of Alumina is 3950 kg/m3, average grain diameter is 10 µm . Mineral oil with viscosity of 35 cpand density 0.82 gr/cc was used for tests. Four oily-water samples were prepared at200,400, 600 and 800 ppm in 500 mililitersof 2%NaCL brine(0.1, 0.2, 0.3 and 0.4 grams, respectively). Another three samples of oily-water containing Alumina at 400 ppm of emulsion mixed with 600, 1000, and 1500ppm of Alumina, in 500 mililitersof 2%NaCl were also prepared.

CorefloodPreparation

A stainless steel core holder designed for consolidated core samples, 20 cm length and 6 cm diameter, was used. The holder could withstand pressures up to 5500 psiaat 200ºC. A rubber sleeved core holder, subjected to an external confining pressure, into which a sandstone core is placed. The core sample is housed inside rubber sleeve. An end plug made of stainless steel is inserted into the end of the sleeve and is pressed against the core sample by a retaining screw. End plugs have circular grooves to ensure fluid injection into and production from the entire cross-section of the core. The outlet plug has one production port at the center. All data, such as confining pressure, differential pressures, temperature, time and The flow-rate were recorded and were used to calculated formation damage.

Emulsion Preparation

In order to simulate produced water re-injection, i.e. Oily water containing suspended solid particles, we need to prepare a stabilized oil-in-water emulsion. Oil in water emulsion droplet diameters is usually in the 0.05–100 µm range.Simulated produced oily water was prepared with crude oil (having a density of 0.82 g/cm3 and a viscosity of 35 cpat 25 ºC) dispersed by Triton X-100 surfactantsin 2% NaCI brine. The crude oil was mixed with the Triton X-100 surfactant, and added into the brine. The concentration of surfactantsin the dispersion was very low and no alteration of the absorbed chemistry was anticipated during the course of the experiments since the surfactantswere not present in the continuous phase of the dispersion. A very stable oil-in-water dispersion having an ideal oil droplet size distribution can be obtained by continuously stirring with a mixer at the prescribed.Based on Zhang et al (1993) by 1250 RPM for 30 minutes to produce 5 µm oil droplets at a concentration of 300 ppm. Therefore all different concentration emulsions prepared at 1250 RPM for 30 minutes mixing. Alumina particles, prepared by

Merck Company, of 600-1500 ppm concentration (10 µm mean diameter) were also employed in the core flooding experiments. Brine is prepared by adding 2% NaCl to de-ionized water (20 grams of NaCl in 1000 ml of water). It is kept heated with a magnetic stirrer and vacuumed for at least 2 hours, or until vacuuming is completed. Before the start of any test, brine is cooled down to room temperature. The brine is filtered using 0.45 µm filter paper to remove any non-dissolved salts. Suspension of Alumina particles in the water is achieved by a continuous high shear stress mixer. The mixer must be kept at an adequate RPM so that the particles are homogeneously dispersed yet no air bubbles are introduced into the water. Sometimes, if the RPM is too high, air bubbles are formed. It is very important to avoid air bubbles as they cause a major error in permeability measurement. Oil-in-water emulsion stability is harder to achieve than a purely solid suspension. In the case of oil–in-water emulsion, emulsifiers are usually used for stability. In our experiments, the emulsion was stabilized by continuous mixing. The same mixer was used for oil as for the solid suspension but with a higher RPM to achieve homogenous oily-water. The size of the oil droplets and the quality of the emulsion is controlled by varying the rate of mixing and choosing the appropriate perforated ring used in the mixer. Perforated rings with a small mesh opening generate small oil droplets. Stable emulsions of oily watercontaining suspended solids are easier to prepare than suspensions of either solids or oil drops alone, depending on the wettabilitypreference of the suspended solid particles. The preparation of solid-oil in water can be achieved in this way: Oil droplets dispersed in water first, then solid particles are added gradually. In both procedures, the mixture is kept under continuous mixing throughout the test. A high shear stress mixer was used to mix 3000 ml of brine water with 200, 400, 600 and 800 ppm of mineral oil, (Sample- A with 200 ppm, Sample-B at 400 ppm, Sample-C at 600 ppm, and Sample-Dat 800 ppm). The oily-water emulsion is kept mixing for 30 minutes before injecting to the core sample. The mixer must never be switched off before the experiment to prevent oil coalescence, and to insure constant emulsion properties. Once the emulsion property (size and concentration) is constant, then it is injected to the core sample. However, before introducing the emulsion to the core sample, brine water is injected at a constant flow - rate to measure the baseline pressure of the cores. The data are recorded stable differential pressure across the core during constant flow flooding experiments. Oily water with suspended solid particles were prepared at different concentrations. A 400 ppm concentration of emulsion mixed with, 600, 1000, and 1500 ppm solids, Sample-E at 600 ppm oil and 600 ppm solid, Sample-F at 600 ppm and 1000 ppm solid, and Sample-G at 600 ppm oil and 1500 ppm solid) . The emulsion is kept mixing for 30 minutes before injection into the core sample. After stabilization of the emulsion then it is injected into the core.

EXPERIMENTAL TECHNIQUE

Core flooding experiments were carried out in aCore flooding rig. The core plug was mounted in a core holder. Input fluid injection flow rates were arranged at the pump apparatus. The stabilize pressure data were finally recorded at endof each core flood test as inlet pressure is stable and ouletpressure . After displacement with 2% NaCI brine, a baseline of initial permeability of the core plug was established. Subsequently, the dispersions were injected through the core plug, the pressure drops measured and the permeability calculated. The flow rates used in the core flooding experiment were 0.05,0.1, 0.15, .02, 0.5 and 1 cc/ min, water injection schemes and which maintained a laminar flow in the core plug. All experiments were run until around 20-25 pore volumes had been injected.

3-RESULTS AND DISCUSSION

Syntheticproduced oily water has been made as a stable dispersion of alumina particles and oil droplets in a brine solution. This has been injected into sandstone cores and the decrease in permeability has been determined along all the seven cores. Table 1 summarizes the results of the experiments.

Linear Darcy equation (Eq-1)was used to calculate the initial permeability and the final permeability to gain decline of permeability:

$$Q = \frac{KA\Delta P}{\mu L} \text{(Eq-1)}$$

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permeabilitydecline due to the invasion of oil droplets and solid particles

Core No.	Oil Conc. (ppm)	Solid Conc. (ppm)	Init. Perm. (mD)	Dam. Perm. (mD)	Perm. Ratio	Dam. Perc. %
1	200	N/A	0.46	0.43	0.95	5.3
2	600	N/A	0.34	0.31	0.93	7.1
3	800	N/A	0.24	0.02	0.1	90.0
4	1200	N/A	0.31	0.02	0.08	92.3
5	600	600	0.29	0.24	0.83	16.7
6	600	1000	0.41	0.19	0.47	52.9
7	600	1500	0.44	0.10	0.22	77.8

As shown in figure 1 and 2 , oil droplet and solid particles caused permeability decline that the extent of the damage depends on the presence, concentrations of oil and solids. The damage produced individually by these components differs from the damage Caused by the presence of them both. Effects of concentration of oil droplets on permeability decline seen at high concentration and have not smooth tredline but as in figure 2 shown at a constant oil concentration with solid particle in fluid injection, permeability decline was decreased by increasing solid particle concentration at smooth tredline.

3.1-Permeability Decline

Initial experiments were conducted with water containing oil but no solids. Subsequently alumina particles were added into the simulated produced water to investigate the permeability change resulting from both solid particles and oil droplets. The permeability for a core plug is calculated from the pressure difference across with the cross-sectional area, flow rate and fluid viscosity. Figures 1 show permeability decline for Four experiments that caused by oil droplets:

That has 200 ppm- 800 ppm oil concentration without solids. And so Figures 2 show permeability decline for Three experiments by that caused oil droplets and solid particles that has 400 ppm oil concentration with 600-1500 ppm solid From these figures, it was observed that even at low oil concentrations, the permeability decline of the cores was evident. Inthis study, the overall permeability of the core plugs decreased to a value in the range of 5-92% of the initial permeability. Which was principally affected by the concentration of oil and solids, their sizes and size distribution, as well as flow rate.

3.2-Effect of Oil and Solid Concentration

It was found in this study that the effect of concentrations of oil droplets on permeability damage was not the same as that of solid particles. Droplet deformation is another important characteristic which differs from solid particle movement through a porous medium. The shear rate of fluid (including the droplet) in a porous medium, as the droplet moves through the pore space, may cause the droplets to deform thereby invading to a greater depth than solid particles. It was observed that permeability decline was not directly linked with oil concentration. In the core flooding tests within the range of 200 ppm to 800 ppm oil concentrations and with similar droplet sizes, the dispersions with greater mean oil droplet diameter caused greater damage . The addition of fine alumina particles to the simulated produced oily water generated a different trend of permeability decline. It was found by Becher et al(1961) that basic sulphates of iron, copper, nickel, zinc, and aluminium in a moist condition act as efficient dispersing agents for the formation of petroleum oil-in-water emulsions. The significance is that water, oil and solid dispersions maybe stable and difficult to treat, therefore significant formation damage would be expected when such a dispersion is injected into a core. The core flooding experimental results demonstrated that after the alumina particles ,produced oily water at concentration of 400 ppm, the pressure drop overall of a core plug increased, compared with the results of dispersions containing only oil. The initial permeability decline rates increased as the solid particle concentrations increased. The concentration of solids greater than 800 ppm in the water containing relatively high concentrations of oil contributed significantly to permeability decline. In these experiments in which the injected water contained both oil droplets and solid particles, the level of permeability decline was evidently different from the experiments on oil droplets alone. Figure 2 shows the effect of concentrations of both oil droplets and solid particles on permeability decline. Between oil concentrations of 600 and 800 ppm, there is a change in the slope of the permeability versus solids concentration. A possible damage mechanism may involve capture or bridging of the solid particles in pore restrictions. Ifthere were only oil droplets dispersed in the produced water, it would be difficult to plug the pore throats of a similar or greater diameter. But when solid particles mechanically plug or bridge the pore throats, they may provide a suitable configuration for oil droplets to further plug the pore throats. Consequently, a significant permeability decline may be contributed by both oil droplets and solid particles.

3.3- Effect of Flow Rate

The effects of flow rate of injected produced oily water on the permeability decline can be considered by different approaches for oil droplets and both oil droplets and solid particles. For oil droplets, it was believed that

1) When a droplet lodges in a small pore, it may be squeezed through the pore restrictions due to a high flow rate inducing a local high pressure;

2) It may be broken up or compacted with retained droplets to form a large droplet, which in turn affects the droplet capture rate and the state of the retained droplets (Soo and Radke, 1988). From core flooding data in this work, itwas observed that in the case of low concentration of oil droplets, higher flow rates correspond to relatively low levels of permeability decline than lower flow rates. (Figures 3-9) From these figures, it was observed that the permeability decline of core samples depends on injection flow rate, that concluded permeability decline is decreased by increasing flow rate.

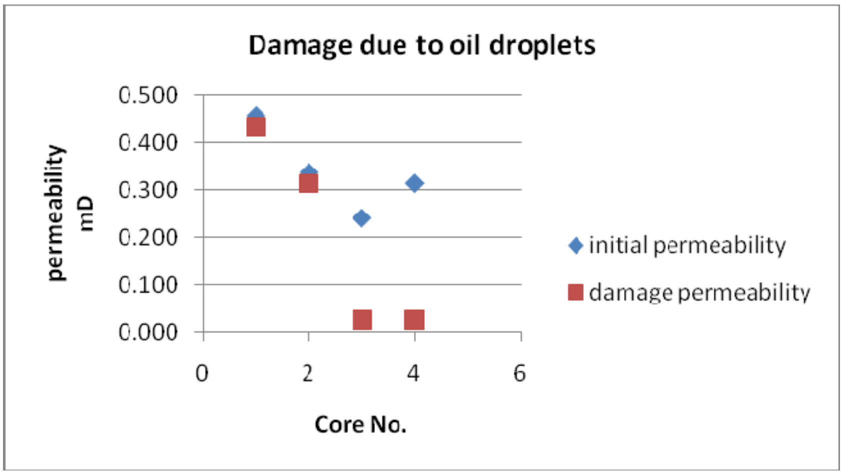

Figure 1

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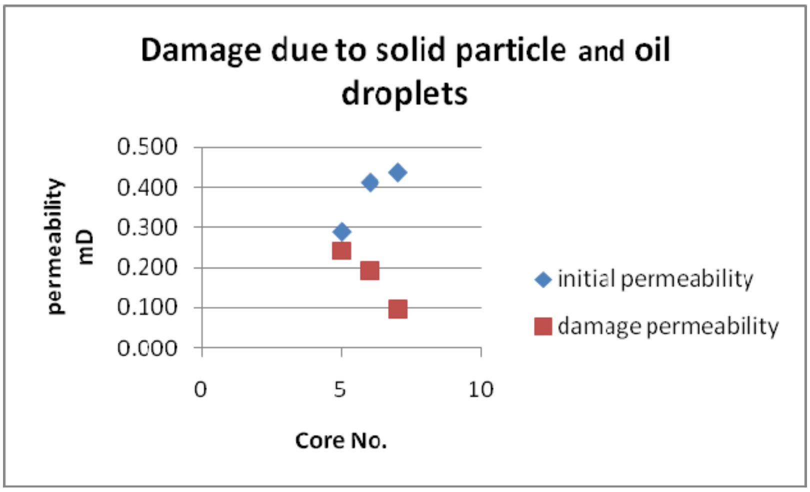

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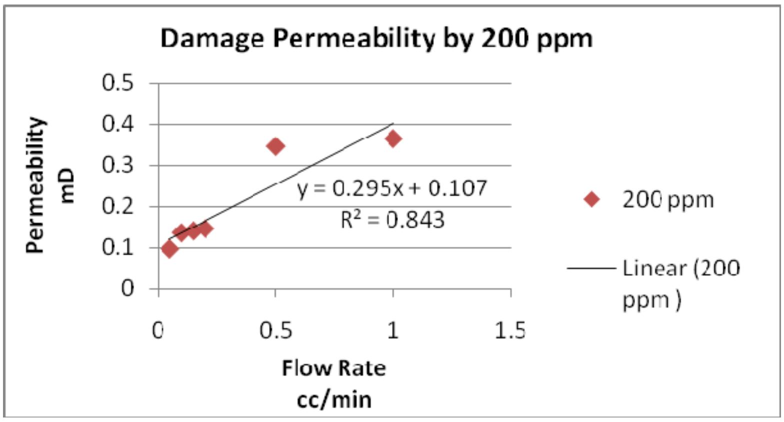

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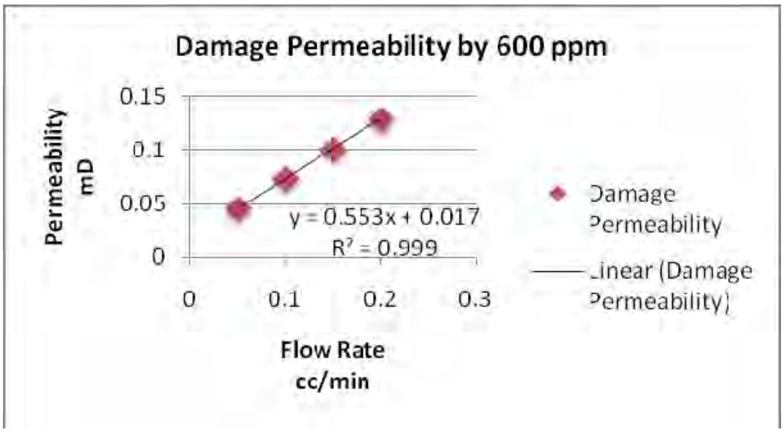

Figure 4

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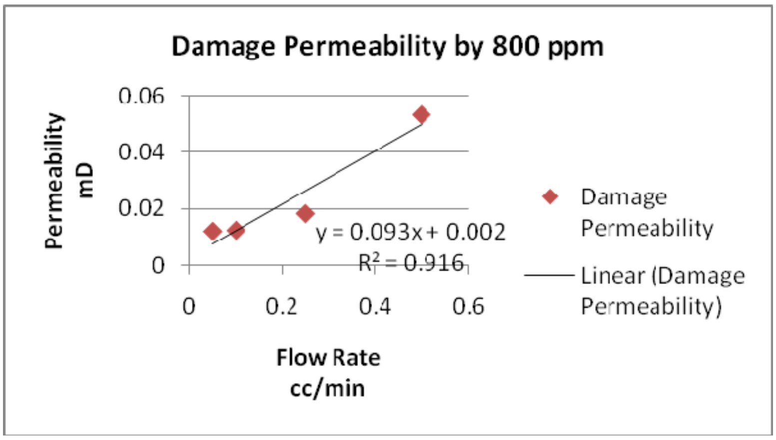
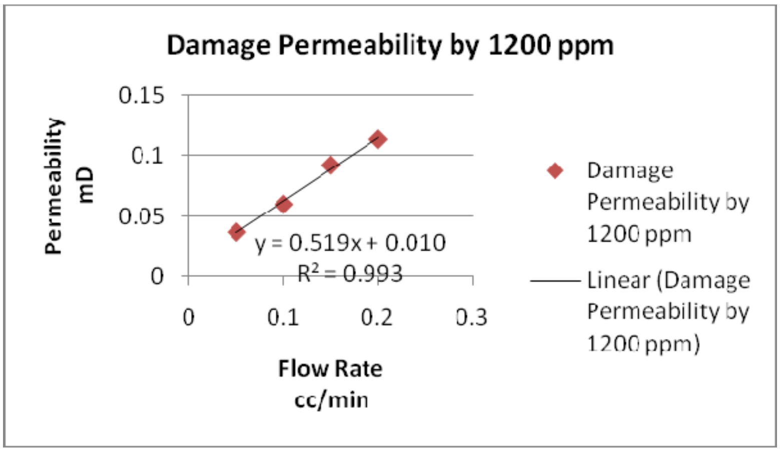


Figure 5



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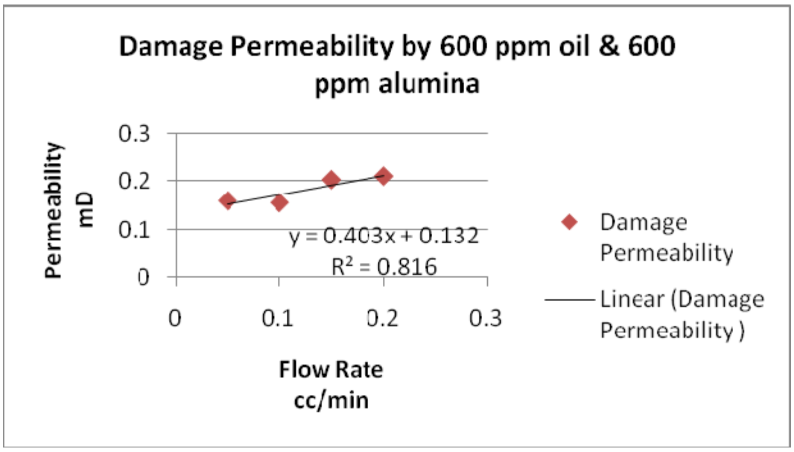

Figure 7

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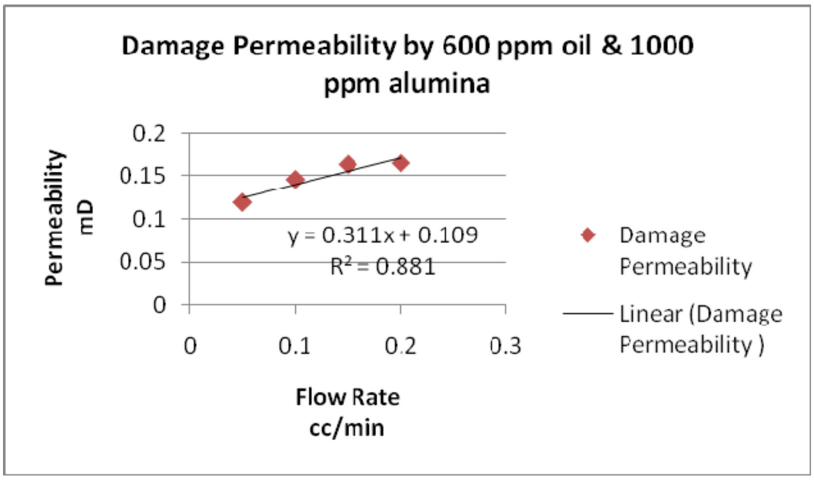

Figure 8

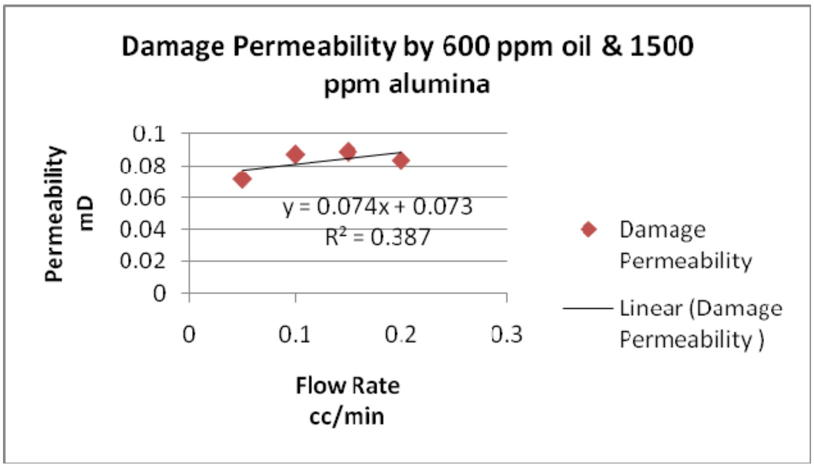

Figure 9

4-Conclusions

The following conclusions are drawn from this study:

1)The extent of the damage depends on the flow rate of emulsion, higher flow rates correspond to relatively low levels of permeability decline than lower flow rates.

2) The extent of the damage depends on oil droplets concentration when injecting oily water, and increase by increasing oil droplet concentration.

3) The permeability decline produced by presence, concentrations of oil and solids increases by increasing solid particle concentration at a constant oil concentration with high slope.

4) By plotting permeability decline versus oil concentration (figure1) it has shown that at the concentration of 600 ppm the slope ofpermeability decline has changed considerably and formation damage increases severely. It is concluded that for any formation there is a critical oil droplet concentration above which permeability decline increases severely.

NOMENCLATURE

PV	Pore volume
K	Permeability
K_j	Initial permeability
cp	Centipoise
RPM	Revolution per minute
Q	Flow rate
A	Cross sectional area
ΔP	Differential pressure across core holder
μ	Liquid viscosity
L	Length of core
mD	MiliDarcy
gr	Gram
Eq	Equation

ACKNOWLEDGMENTS

The authors would like to thank Mr. Amin Kordestani for giving me advice during the design stage of the experimental set up.

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