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Comparative Study Of Using Sea-Water For Enhanced Oil Recovery In Carbonate And Sandstone Reservoirs: Effects of Temperature and Aging Time on Oil Recovery

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Abstract

Oil recovery process is an essential element in the oil industry, in this study, a laboratory study to investigate the effect of temperature and aging time on oil recovery and understand some of the mechanisms of seawater in the injection process. In order to do that, the sandstone and carbonate cores were placed in the oven in brine to simulate realistic reservoir conditions. Then, they were aged in crude oil in the oven. After that, they were put in the seawater to recover, and this test is called a spontaneous imbibition test. The spontaneous imbibition test in this study was performed at room temperature to oven temperature 80 ^{o}C with different sandstone and carbonate rock with aging time of 1126 hours. The result shows that the impact of seawater on oil recovery in sandstone is higher than carbonate. At higher temperature, the oil recovery is more moderate than low temperature. Likewise, as the aging time increase for both sandstone and carbonate rocks the oil recovery increase.

Keywords: Carbonate, Sandstone, Oil Recovery, Aging Time, Temperature, Spontaneous Imbibition Test.

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INTRODUCTION

Normally, only 5-30% of the original oil in place (OOIP) can be produced by the native pressure energy stored in the reservoir (Castor et al., 1981) and (Farouq-Ali and Stahl, 1970). This phase of the production cycle is called the primary production period. The water-flooding method discovered nearly by accident in 1870, (Schumacher, 1978). This was increased the oil production to a total recovery of 40-60 % of OOIP, which is called the secondary production period. Secondary production mentions to procedures, such as gas or water injection, (Naser et al., 2013). During the water-flooding period, oil is produced at a steady state with increasing water-oil ratio at the production wells. When the water-oil ration has become too high, oil cannot be produced in a cost effective way anymore and the field has reached the economical limit. At this point, about 40-60% of OOIP is left in reservoir, mainly because of unfavourable wettability conditions, heterogeneous rock properties (fractures, layers with large permeability contrasts, impermeable layers) and capillary trapped-and bypassed oil. Wettability is very important parameter in oil recovery processes, because it has strong impacts on distribution, location and flow of oil and water in the reservoir during production, (Anderson, 1987b, 1987c; Anderson, 1986a; Anderson, 1986b, 1987a; Cuiec, 1975). Water will occupy the narrowest pores and oil will reside as small droplets in the middle of the pores in uniform water-wet system. The reserve fluid distribution will be the case in an oil-wet reservoir. The residual oil is left in the reservoir after the secondary oil production stage, which is the target for enhanced oil recovery (EOR) processes. EOR define is the methods aimed at increasing ultimate oil recovery by injecting agents not normally present in the reservoir, such as chemicals, solvents, oxidizers and heat carriers in order to induce new mechanisms for displacing oil, (Bavière, 1991).

A number of research works have been investigated of the effect of brine concentration on oil recovery often showed significant increase in laboratory water-flood recoveries with a decrease in salinity for duplicate outcrop core plugs. However, companion data sets for water-floods and spontaneous imbibition both showed increased recovery with a decrease in salinity, (Tang and Morrow, 1999a; Tang and Morrow, 1999b; Tang and Morrow, 2002; Zhang and Morrow, 2006). The studies shows that, the effect of temperature on oil recovery oil production rate increase or decrease with temperature, which the viscosity of oil, reduce due the increase of temperature. Therefore, the decrease in the viscosity ratio of oil and water due to increasing temperature result in oil being displaced more easily and the ultimate recovery being improved. Aging time is required to incubate the core samples, however, varies from one laboratory to another, ranging from a few days to months, (Mungan, 1972; Wissmann, 1963), (Wendell et al., 1987), (Cuiec, 1975; Culec, 1977). Naser investigated the effects of temperature, hardness, surfactants and alkaline on oil recovery from carbonate reservoirs using spontaneous imbibition tests. The spontaneous imbibition test in this study was performed at 25°C and 80°C with different limestone rocks. The results show that, at high temperature, the oil recovery is higher than at low temperature. The hardness has various impacts on the wetting properties. $SO-_4^2$ and $Ca^{2+}$are important in changing wettability on limestone surface and were proved by increase in oil recovery. Mg^{2+} ion effects were demonstrated by the very small increase in oil recovery, (Naser, 2014).

This paper has two main objectives. The first objective is to investigate the effect of temperature and aging time on oil recovery and understand some of the mechanisms of seawater in the injection process. The second objective is to compare the effects of seawater on carbonate and sandstone reservoirs related to chemical enhanced oil recovery. Three commercial crude oil located in X Oil Field and (18) eighteen sandstone and carbonate cores were used. For this purpose, the parameters that have been considered for this study are carbonate, sandstone, oil recovery, aging time, and temperature. Experiments presented in this study were run at an elevated temperature (27, 30, 40, 50, 60, 70, and 80) °C conditions. Afterwards, a sandstone and carbonate sample is chosen and saturated with oil. The oil-saturated sample is then placed in an imbibition cell surrounded by seawater. The seawater is allowed to imbibe into the core sample displacing oil out of the sample until equilibrium is reached. The volume of oil displaced is measured directly or determined by weight measurements and the oil recovery is determined.

MATERIALS AND METHODS

Spontaneous Imbibition Test

The spontaneous imbibition Amott test consists the placing oil saturated in core plug, which the Amott cell is filled with displaced fluid with sea-water. The oil expelled from the core can be measured accurately by reading the graduation on the top of the cell. Graduated cylinder was used to simulate the operation of imbibition cell (Amott cell).

Oil Samples

Figure 1 shows the three types of oils from Hamada Field-V32 and V2, Jakhira Field-GSOP. The analysis of composition of oil done at petroleum institute in Tripoli, Libya as listed in **Table 1**. Sea-water samples used in this study were collected from Tajora-Tripoli, Libya.

Fig. 1. Oil samples used in this study.

Table 1. Oil composition used in this study.

Component	Hamada field V32	Hamada field V2	Jakhira field-GSOP
	Flashed Liquid Mole%	Flashed Liquid Mole%	Flashed Liquid Mole%
Hexane	3.24	3.99	2.92
Heptane	6.94	8.08	3.45
Octane	13.53	14.71	6.27
Nonane	12.38	12.74	6.54
Decane	11.05	10.69	6.44
n-Undecane	8.78	8.81	6.44
n-Dodecanes	6.83	7.15	5.78
n-Tridecanes	6.87	6.88	6.93
n-Tetradecanes	4.80	4.70	5.89
n-Pentadecanes	4.17	4.05	6.11
n-Hexadecanes	3.05	2.89	4.76
n-Heptadecanes	3.04	2.72	4.69
n-Octadecanes	2.76	2.52	4.90
n-Nonadecanes	2.48	2.30	4.48
n-Eicosane	1.59	1.41	3.39
n-Heneicosane	1.46	1.31	3.34
n-Docosane	1.32	1.19	2.92
n-Tricosane	0.99	0.89	2.66
n-Tetracosane	0.89	0.74	2.18
n-Pentacosane	0.74	0.60	1.90
n-Hexacosane	0.66	0.53	1.58
n-Heptacosane	0.59	0.46	1.55
n-Octacosane	0.50	0.36	1.21
n-Nonacosane	0.31	0.26	1.11
n-Triacontane	0.25	-	0.69
n-Hentriacontane	0.24	-	0.66
n-Dotriacontane	0.22	-	0.45
n-Tritriacontane	0.18	-	0.33
n-Tetratriacontane	0.13	-	0.24
n-Pentatriacontane plus	-	-	0.20

Collection of Core Samples

The core samples were collected from the deep water well in Temnhent, north of Sebha City, Sebha State, Libya. **Figure 2** shows the core cutting processing. The cores were cut with uniform cylindrical shape and the volume of cores were correctly estimated. All cores have height between (4.2 to 4.9 cm) and diameter around (2.45 cm).

Fig. 2. Process of cut core sample & shape of cores after cut process.

The cores were cleaned and washed by using distillate water and were put in the oven with 70°C. The dry core samples weight were measured until the constant weight was obtained. Then, the core samples were put in the vacuum chamber with known density of brine solution (with 3% of ($NaCl_2$)) for at least 24 hrs, and the weight of the core samples were measured. The porosity was also calculated.

Core Aging

The cores were put in different oils inside the oven for eleven days with 70°C and then placed in the vacuum chamber for 4 hrs, to ensure the core samples are saturated with 100 % of oil. The core sample were saturated with different of oils, then their weight were measured.

Original Oil in Place Calculation (OOIP)

The calculation of OOIP is done by using following equation:

$$OOIP = \frac{W_1 - W_2}{D} \quad (1)$$

Where: W_1=weight of core sample saturated, $W_{2=}$weight of core sample dry and D=density of saturated oil.

Spontaneous Imbibition Test

The core samples were placed in the in imbibition cell, which were filled with the sea-water and close it with filler and para film at room temperature. The sea-water was allowed to imbibe into the cores displacing oil out of the cores until equilibrium was reached. The volume of oil displaced by seawater was measured directly for each 2 hrs. The spontaneous imbibition test was repeated at different temperature 30, 40, 50, 60, 70, and 80°C. It was noted that the oil production inside the tube was evaporated at 80°C, which require to lowering the oven temperature to 70°C.

RESULTS AND DISCUSSIONS

Porosity and OOIP Result:

The properties of core samples were listed in **Table 2.**

Table 2. Porosity and OOIP results.

Name of sample	Original oil in place (OOIP)	Bulk volume (ml)	Pore volume (ml)	Porosity (%)
S301 (V2)	8.5871	28.4706	7.7611	27.26
S304 (GSOP)	11.6146	35.3429	10.105	28.591
S305 (GSOP)	11.2908	36.8155	9.8907	26.865
S306 (GSOP)	12.3241	35.3429	10.5881	29.658
S308 (V32)	11.5289	37.7972	10.479	27.724
S312 (V32)	12.2476	39.2669	10.7683	27.423
S313 (V32)	11.4029	37.7972	10.0385	26.558
S314 (V2)	11.0809	32.8885	9.7685	29.701
S315 (V2)	9.1532	28.9615	8.0789	27.895
C401 (V32)	10.6061	33.8702	9.3698	27.663
C402 (V32)	10.3602	35.2938	9.098	25.777
C403 (V32)	13.2458	37.3064	11.6927	31.342
C404 (V2)	8.5521	34.3611	7.539	21.94
C405 (V2)	8.8505	31.9068	7.6759	24.057
C406 (V2)	9.1881	33.3794	8.3008	24.868
C408 (GSOP)	6.9482	23.071	6.0929	26.409
C410 (GSOP)	14.1313	22.0893	6.7586	30.596
C411 (GSOP)	7.4168	24.0528	5.4792	22.779

Spontaneous Imbibition Test Results

Carbonate Rock Samples aged in Jakhira Field- GSOP Oil Results

The carbonate Rock Samples were aged in Jakhira Field- GSOP Oil as shown in the Figure 3. The effect of temperature on recovery was reported.

Room Temperature 27^{o}C: After 22 hrs, the oil recovery rate was about 1.21%, while the cores, C408 and 410, had no recovery rates yet. At 48 hrs, the oil recovery for the core C410 was 1.41%, and for C408 the oil recovery was 0.2% at 115 hrs.

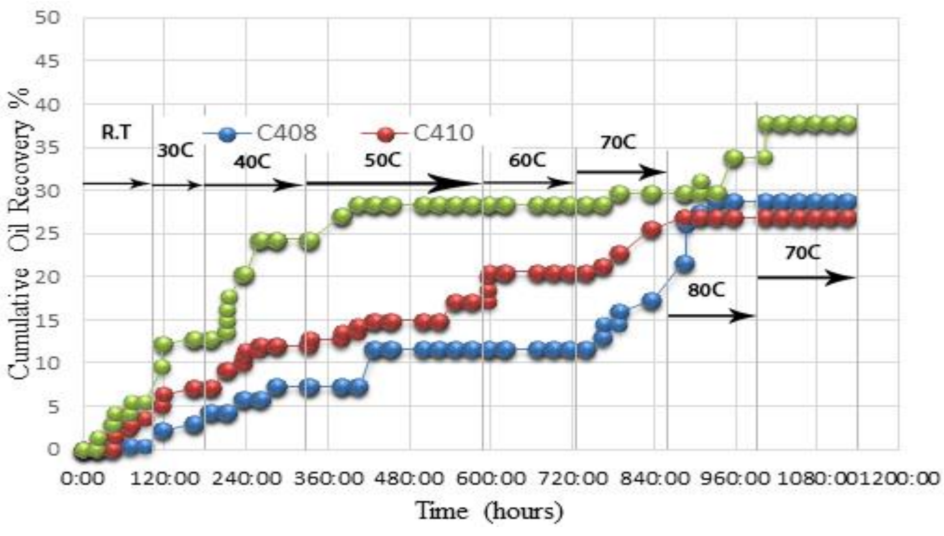

Fig. 3. Cumulative oil recovery in carbonate aged in Jakhira Field- GSOP Oil.

Oven Temperature 30^{o}C: At 162 hrs, the cumulative oil recovery rate increase spontaneously in C408 to reached 2.87% and C411 to reach 12.80% at 30^{o}C. While the oil recovery rate for C410 was still stable with 7.07%. At 188 hrs, the core C408 was produced with mini bubbles of oil till the oil recovery was 4.31%.

Oven Temperature 40°C: At 210 hrs, the C410 was slightly increased to 9.19%, and 13.48% in C411 at 330 hrs,.

Oven Temperature 50°C; At 263 hrs, the oil rate for C410 and C411 have increased to 12.03% and 24.26%, respectively. While the C408 had no change in cumulative oil recovery.

Oven Temperature (60°C): In the first hr, the oil recovery core in C410 was increased to 18.39% with continues increase till 20.52%. In cores C408-C411 oil rate were stable and no significant change was noted.

Oven Temperature (70°C): at 766 hrs, the oil recovery increased to reach 14.39% in C408, and 21.22% in C410, and 28.31% in C411. At 838 hrs, the oil recovery increased till 17.27% in C408, and 25.47% in C410, and 29.66% in C411. At 1005 hrs, the oil recovery increased in C411 to reach 37.75% until 1126 hrs, the oil recovery was stable.

Oven Temperature (80°C): at 955 hrs, the oil recovery increased to reach 28.78% in C408, and 26.89% in C410, and 33.70% in C411. At 80°C, the laboratory problem was required to lowering the temperature of the oven to 70°C.

Sandstone Rock Samples aged in Jakhira Field-GSOP Oil Results

The sandstone rock samples were aged in Jakhira Field-GSOP Oil as shown in the Figure 4. The effect of temperature on the oil recovery was reported.

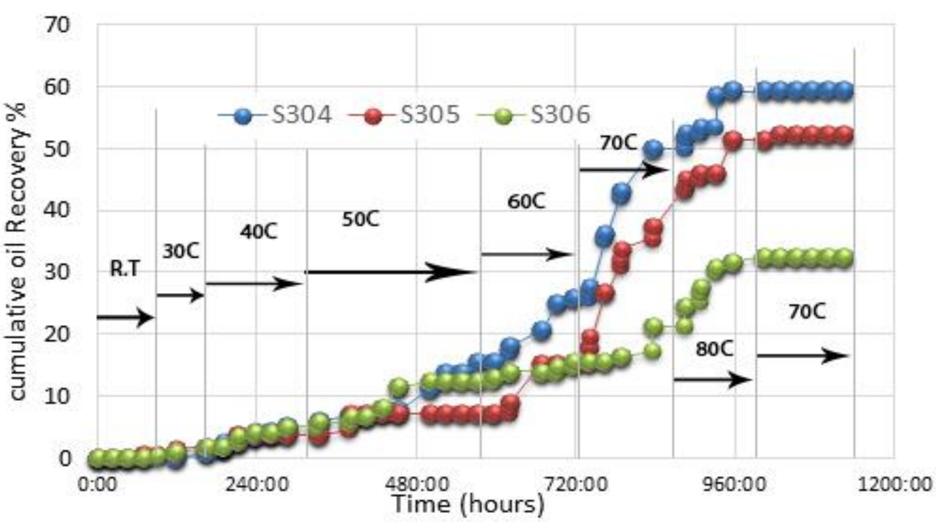

Fig. 4. Cumulative oil recovery in sandstone aged Jakhira Field- GSOP Oil.

Room Temperature (27°C); At 67 hrs, the oil recovery for S305 was slightly increased to 0.44%, where S304 and S306 was still in zero of production. At 115 hrs, the oil recovery for S305 and S306 was increased to 0.44% and 0.81%, respectively. S304 sample was still in zero of production.

Oven Temperature (30°C): At 162 hrs, the oil recovery for S304, S305, and S306 were increased to 0.88%, 1.77%, and 1.62%, respectively.

Oven Temperature (40°C): At 210 hrs, the oil recovery for S304, S305, and S306 were increased to reach 2.58%, 3.54%, 2.43%, respectively. At 330 hrs, the oil recovery for S304 and S306 were stabled at 4.30% and 4.86%, respectively.

Oven Temperature (50°C): At 379 hrs, the oil recovery was increased in S304, S305, and S306 to 6.88%, 4.42%, and 5.67%, respectively. At 571 hrs, the oil recovery for S304 was increased to 15.49% and for S306 to 12.17%, while S305 was still stable.

Oven Temperature (60°C): At 618 hrs, the oil recovery for S304, S305, and S306 were increased to 17.21%, 7.08%, and 13.79%, respectively. At 715 hrs, the oil recovery of S304, S 305, and S306 was significantly increased to 25.82%, 15.05% and 14.60%, respectively.

Oven Temperature (70°C); At 763 hrs, the oil recovery was increased to 35.30% in S304, and 26.57% in S305, and 15.41% in S306. At 838 hrs, the oil recovery was continued increasing to 49.93% in S304, and 37.19% in S305, and 21.09% in S306. At 126 hrs, the oil recovery was stabled.

Oven Temperature (80°C); At 907 hrs, the oil recovery was increased 52.52% in S304, 45.16% in S305, and 25.15% in S306. At 1003 hrs, the oil recovery was increase to 59.40% in S304, 51.36% in S305, and 32.45% in S306.

Carbonate Rock Samples aged in (Hamada Field-V2) Oil Results

The carbonate rock samples were aged in (Hamada Field- V2) Oil Result as shown in **Figure 5.**

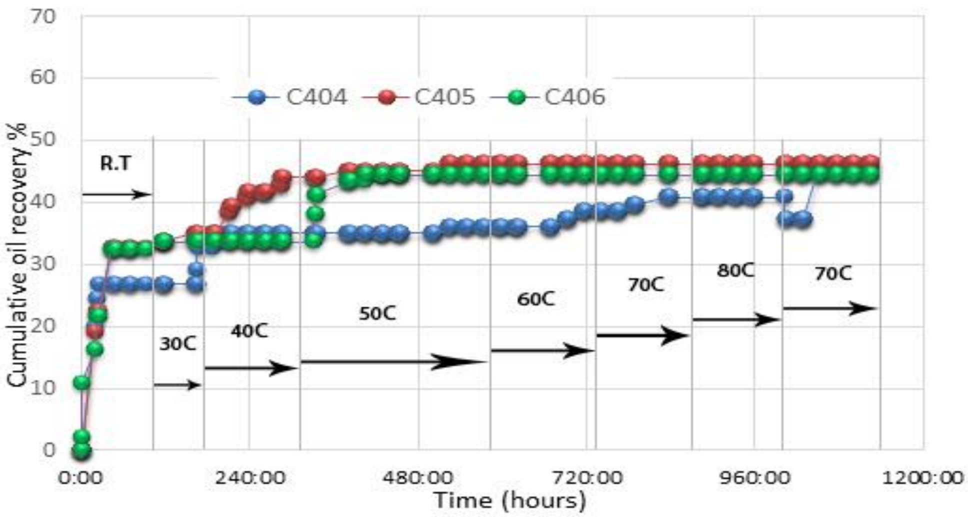

Fig. 5. Cumulative oil recovery in sandstone aged in (Hamada Field-V2) Oil.

Room Temperature (27°C): At 30 min, the oil recovery for C406 was 2.17%. At 19 hrs, the oil recovery was reached to 19.87% in C404, 19.20% in C405, and 16.32% in C406. At 115 hrs, the oil recovery was reached to 26.83% in C404, 33.89% in C405, and 33.73% in C406.

Oven Temperature (30°C): At 166 hrs, the oil recovery was increased to 32.74% in C404, 35.02% in C405. It was stable in C406.

Oven Temperature (40°C); At 210 hrs, the oil recovery was increased to 38.41% in C405, and for C404. It was stable in C405.

Oven Temperature (50°C): At 379 hrs, the oil recovery was reached to 45.19% in C405, and 43.53% in C406, and for C404 was stable. At 595 hrs, it was increased to 36.26% in C404, and 46.23% in C405, and 44.62% in C406.

Oven Temperature (60°C); At 739 hrs, the oil recovery was increased to 38.58% in C404. The cores C405 and C406 were still stable.

Oven Temperature (70°C): At 838 hrs, the oil recovery was increased only in C404 to 40.92% only, while for C405 and C406 were stable. At 1051 hrs, it was increased in C404 to 45.60%, while for C405 and C406 were still stable.

Oven Temperature (80°C): At 956 hrs, the oil recovery was decreased in C404 to 37.41%, while in C405 and C406 were stable.

Sandstone Rock Samples aged in (Hamada Field- V2) Oil Results

The sandstone rock samples were aged in (Hamada Field- V2) Oil as shown in **Figure 6.**

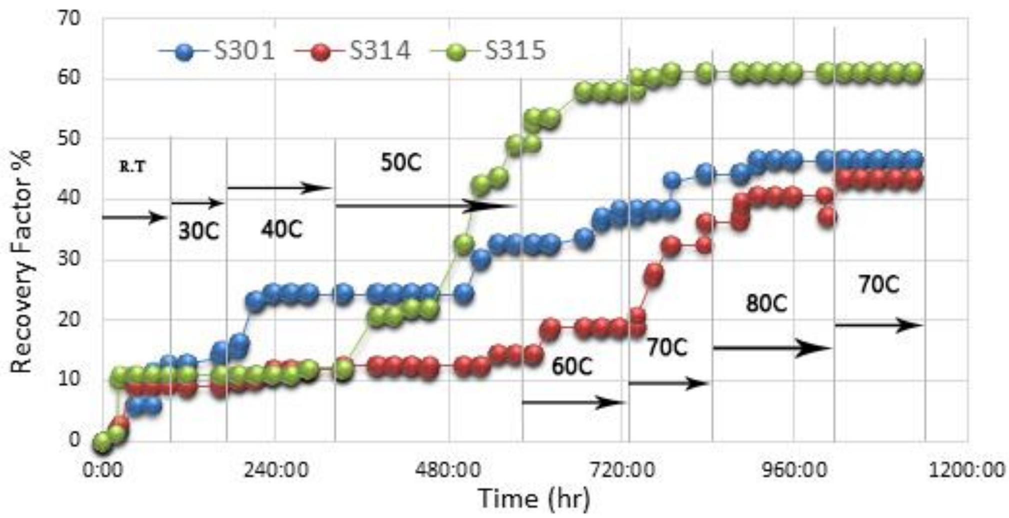

Fig. 6. Cumulative oil recovery in sandstone aged in (Hamada Field- V2) Oil.

Room Temperature (27°C); At 19 hrs, all cores were began to produce oil S301, S314, and S315 to 1.16%, 1.80%, and 1.09%, spontaneously. At 90 hrs, the oil recovery was increased to 12.80% in S301, 9.02% in S314, and 10.92% in S315.

Oven Temperature (30°C): At 166 hrs, the oil recovery in S301 and S314 was increased to 15.13% in S301, and 9.92% in S314, while the S315 was still stable.

Oven Temperature (40°C): At 212 hrs, the oil recovery was increased in S301 and S314 to 23.29% and 10.82%, while S315 was stable. At 330 hrs, it was reached in S301, S314, and S315 to 24.45%, 11.73%, 12.01%, respectively.

Oven Temperature (50°C); At 379 hrs, the oil recovery was increased in S301, S314, and S315 to 24.45%, 12.63%, and 20.75%, respectively. At 523 hrs, it was increased gradually to 30.27% in S301, and 12.63% in S314, and 42.60% in S315. At 595 hrs, it was increased to 60% in S301, and 14.43% in S314, and 49.16% in S315.

Oven Temperature (60°C); At 667 hrs, the oil recovery was increased to 33.77% in S301, and 18.95% in S314, and 57.90% in S315. At 739 hrs, the oil recovery was increased to 37.62% in S301, and 18.95% in S314, and 57.90% in S315.

Oven Temperature (70°C): At 790 hrs, the oil recovery was increased to 43.09% in S301, and 32.48% in S314, and 61.18% in S315. At 838 hrs, it was increased to 44.25% in S301, and 36.04% in S314, and S315 was still stable at 61.18%. At 1028 hrs, the oil recovery was reached in S312 to 43.13%.

Oven Temperature (80°C): At 908 hrs, the oil recovery was increased to 46.58% in S301, to 61.18% in S313, and to 40.61% in S312.

Carbonate Rock Samples aged in (Hamada Field- V32) Oil Results

The carbonate rock samples were aged in (Hamada Field- V32) Oil as shown in **Figure 7.**

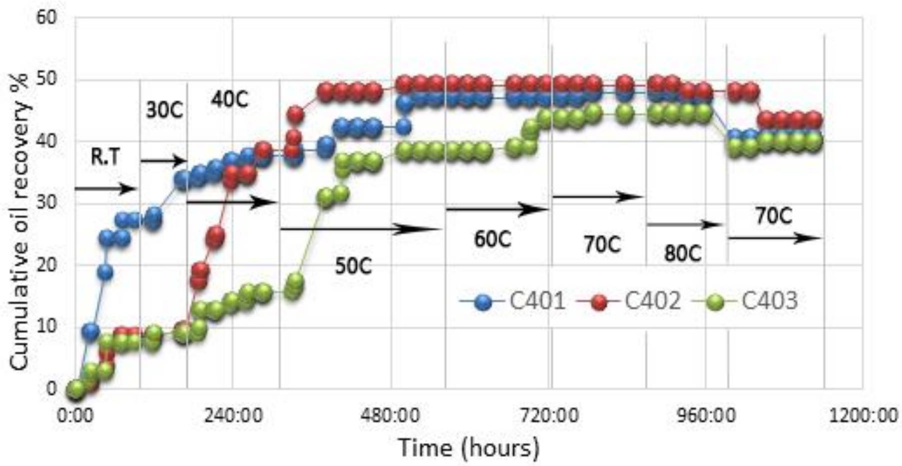

Fig. 7 . Cumulative oil recovery in carbonate aged in (Hamada Field- V32) Oil.

Room Temperature (27°C); When the aging time is 19 hrs, the oil production was began produce and reached to 9.42% in C 401, to 0.96% in C402, and to 1.5% in C403. At 46 hrs, the oil recovery was significantly increased to 24.51% in C401, to 3.86% in C402, and to 7.54% in C403. At 115 hrs, the oil recovery was reached to 27.43% in C401, to 8.68% in C402, and to 7.54% in C403.

Oven Temperature (40°C): At 162 hrs, the oil recovery was increased to 33.94% in C401, to 9.65% in C402, and to 9.05% in C403.

Oven Temperature (50°C); At 188 hrs, the oil recovery was increased to 34.88% in C401, to 19.34% in C402, and to 12.83% in C403. At 212 hrs, the oil recovery was increased regularly to 35.82% in C401, to 25.09% in C402, to 12.83% in C403. At 330 hrs, the oil recovery was increased significantly to 37.71% in C401, to 38.60% in C402, and to 15.82% in C403.

Oven Temperature (60°C); At 335 hrs, the oil recovery was increased to 38.65% in C401, to 44.40% in C402, and to 17.36% in C403. At 405 hrs, the oil recovery was increased to 42.42% in C401, to 48.26% in C402, and to 35.48% in C403. At 595 hrs, the oil recovery was increased to 47.14% in C401, to 49.22% in C402, and to 38.50% in C403.

Oven Temperature (70°C); At 787 hrs, the oil recovery was increased to 48.08% in C401, to 49.22% in C402, and to 44.54% in C403. At 1051 hrs, the oil recovery in C402 was decrease to 43.43% and C403 increased to 40. 01%, while C401 was stable.

Oven Temperature (80°C); At 931 hrs, the oil recovery was decrease to 47.14% in C401, and 48.26% in C402, were in C403 still stable. At 1003 hrs, the oil recovery was still decreased to 40.54% in C401, to 39.25% in C403, while C402 was still stable.

Sandstone Rock Samples aged in (Hamada Field- V32) Oil Results

The sandstone rock samples were aged in (Hamada Field- V32) Oil as shown in **Figure 8.**

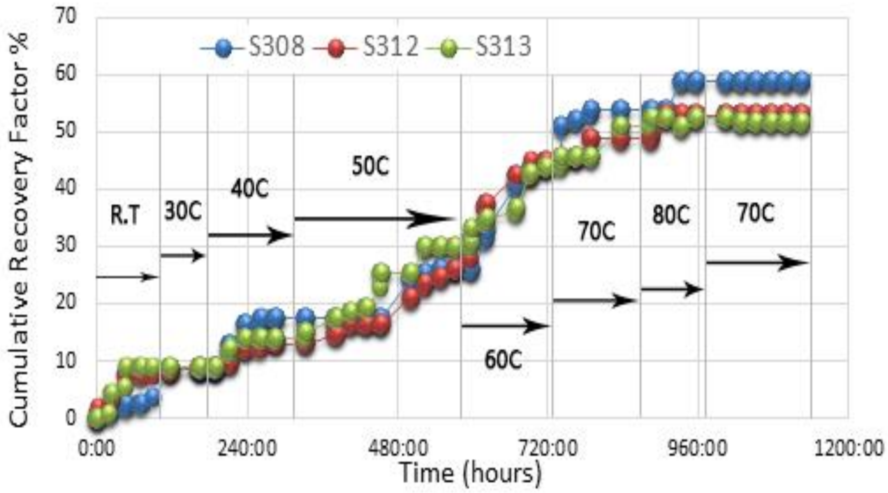

Fig. 8. Cumulative oil recovery in sandstone aged in (Hamada Field- V32) Oil

Room Temperature (27^{o}C): At 19 hrs, the oil recovery was reached to 0.86% in S308, to 1.63% in S312, and to 0.87% in S313. At 115:43 hrs, the oil recovery was increased regularly to 8.67% in S308, to 8.16 % in S312, and to 8.76% in S313.

Oven Temperature (40^{o}C): At 210 hrs, the oil recovery was increased to 13.01% in S308, to 9.79% in S312, and to 11.40% in S313. At 330 hrs, the oil recovery was increased to 17.34% in S308, to 13.06% in S312, and to 14.03% in S313.

Oven Temperature (50^{o}C): At 403 hrs, the oil recovery was increased to 17.34% in S308, to 16.32% in S312, and to 18.41% in S313. At 595 hrs, the oil recovery as increased to 26.02% in S308, to 27.76% in S312, and to 29.81% in S313.

Oven Temperature (60^{o}C); At 618 hrs, the oil recovery was increased to 31.22% in S308, to 36.74% in S312, and to 34.20% in S313. At 739 hrs, the oil recovery was increased regularly to 45.10% in S308, to 44.90% in S312, and to 43.84% in S313.

Oven Temperature (70^{o}C); At 835 hrs, the oil recovery was increased to 53.77% in S308, to 48.98% in S312, and to 50.86% in S313. At 1027 hrs, the oil recovery was increased in S313 to 51.74%, while in S301 and S312 were still stable.

Oven Temperature (80^{o}C); At 931 hrs, the oil recovery was increased in S301 to 58.98%, to 53.07% in S312, and in S313 was decreased to 50.68%.

Compression between Oil Recoveries (Sandstone Rocks)

Figure 9 shows compression between oil recoveries with different sandstone core samples. In sandstone core samples (S308, S312, and S313) were aged in Hamada field-V32 oil and the recovery rate was reasonable and approximate. In sandstone core samples (S315, S314, and S301) were aged in Hamada field-V2 oil and the oil recovery was the highest to reach 61.18%. Therefore, the different in oil recovery rate for S315 comparing to S301 and S314 can be due to the higher porosity for S301 and S314.

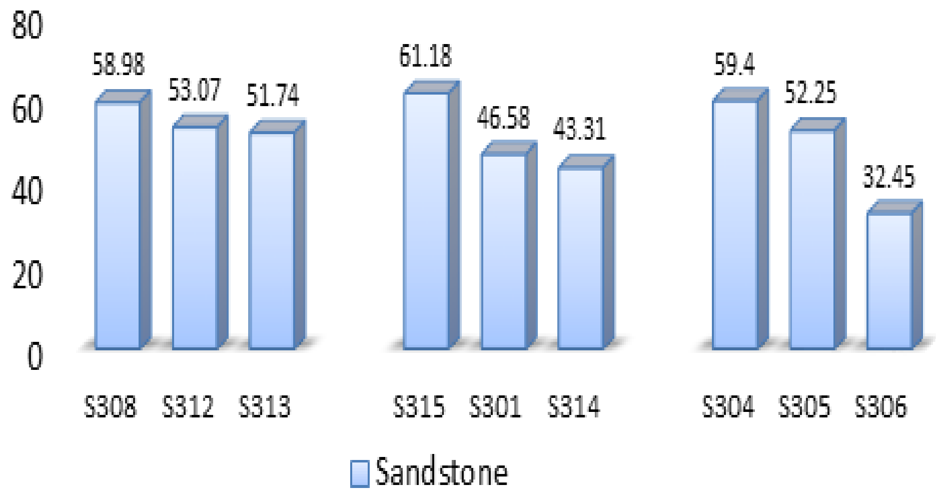

Fig. 9. Compression between oil recoveries with different sandstone core samples.

In sandstone core samples (S304, S305, and S306) were aged in Jakhira field- GSOP oil. The low recovery in S306 could be due to the effect of core plug was caused by permeability reduction. The core plugging and the effect on the permeability of rocks was also reported by Ali and Islam (1998) performed core tests with crude oils from the United Arab Emirates as shown in the figure 10, (Ali and Islam, 1998).

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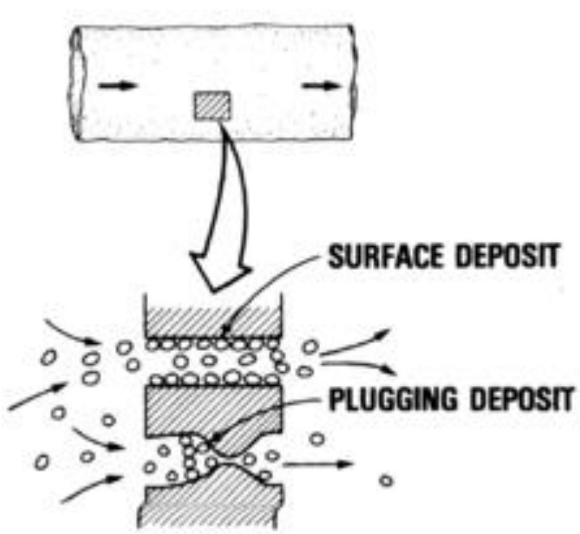

Fig. 10. Core Plugging and Effect on Permeability of Rocks After (Ali and Islam, 1998).

Compression between Oil Recoveries (Carbonate Rocks)

Figure 11 shows the compression between oil recoveries with different carbonate core samples. In carbonate core samples (C401, C402, and C403) that aged by Hamada field-V32 oil, the oil recovery rate was approximate and reasonable. In carbonate core samples (C404, C405, and C406) were in Hamada field-V2 oil and the oil recovery rate was approximate, and which the effect of temperature and aging time. In carbonate core samples (C408, C410, and C411) were aged in Jakhira field- GSOP oil, the oil recovery rate was very high. This could be to the absorption of the lightest oil during aging process.

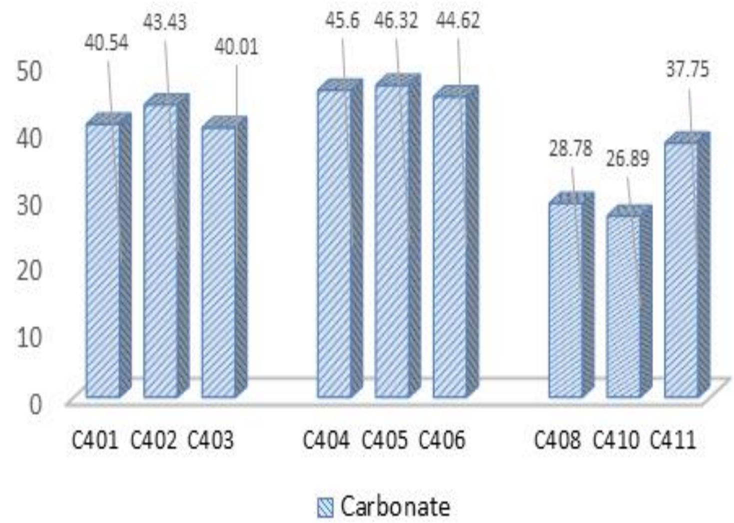

Fig. 11. Compression between oil recoveries with different carbonate core samples.

CONCLUSION

In this study, the experimentally investigated and visualized the comparison of the effects of sea-water with different crude oils, temperature, and aging time on oil recovery in carbonate and sandstone reservoirs were reported. The experimental setup and procedures were specifically designed to simulate the reservoir conditions. It can be concluded that the impact of seawater on oil recovery in sandstone core samples was higher than carbonate core samples. At higher temperature, the oil recovery was more than at lower temperature. Likewise, increasing the aging time for both sandstone and carbonate core samples, cumulative oil recovery was increased drastically

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