EFFECT OF WETTABILITY ON OIL RECOVERY FROM CARBONATE MATERIAL REPRESENTING DIFFERENT PORE CLASSES

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ABSTRACT

This paper discusses experimental studies of waterflooding native state cores and also waterflooding results for the same cores after aging in crude oil. The topics discussed are related to the effect of wettability change on relative permeability and oil recovery for different carbonate core materials. The unsteady state method was used as experimental procedure for measuring relative permeability and obtaining oil recovery data. The wettability was measured after aging, using the combined Amott / USBM method.

The core material used in this study represents different pore classes within carbonate reservoirs. The cores used represent outcrop and gas well cores and had an initial water-wet state. Different carbonate pore classes showed large variation in properties with regard to two-phase flow properties. The waterflood experiments showed that low permeable carbonate ($K << 1$ mD) may still display a high oil recovery efficiency. The wettability of the cores after aging was intermediate towards oil wet, and nearly all the material displayed a mixed-wet small behaviour.

The initial water saturation (S_{wi}) was very similar for the water-wet cores and the same cores after aging, which is essential for comparing the different wetting states. A strong increase in oil recovery after aging was observed in most cases, except for the cores that showed no spontaneous imbibition after aging. These cores had a lower oil recovery for aged cores compared to waterflood at initial water-wet conditions.

INTRODUCTION

Carbonate reservoir rocks are generally more heterogeneous than siliclastic materials, and contain a wide range of different pore type classes. It is therefore likely that their multiphase flow properties are different. Two widely used classification systems for carbonates are those suggested by Choquette and Pray, and Lucia, respectively. Recently, Lønøy introduced a new pore type classification system based on elements from the Choquette and Pray and the Lucia pore type classification systems. So far, the new classification system includes 20 pore type classes, which show a predictable relation between porosity and permeability.

Lønøy's pore type classification system (Lønøy) is based on three main elements, pore structure, porosity, and permeability. The pore structure can be determined by visual inspection of thin sections of the rock material.

Many carbonate rocks have intermediate wettability (Cuiec) and display heterogeneities significant at the core plug scale (Narayanan and Deans, Hicks et.al., Moctezuma-B and Fleury, Siddiqui, Funk, and Khamees, deZabala and Kamath). A review of studies on carbonate systems by Espie et al., displayed a wide range of waterflood process efficiencies. They found that the residual oil saturation to water flood varied from 28 to 80% OOIP. deZabala and Kamath, used CT scanning on rock that was predominantly intercrystalline In their study the remaining oil saturation varied from 67% to 37% PV, when the waterflood rate was changed from the reservoir rate to conventional laboratory rate. The CT images showed that the reduction in remaining oil saturation was due to unswept areas of the core being invaded as the flow rate was increased.

In order to improve the understanding of multiphase flow properties of carbonates, this study aims at finding characteristic correlations between each basic petrophysical property and oil recovery efficiency for different pore types. In view of the challenges reported in the literature, the core samples selected were as homogeneous as possible, judged from CT images. An additional objective was also to investigate the influence of change in wettability on oil recovery.

EXPERIMENTAL

Waterflooding has been performed on six core plugs at cleaned and aged conditions. The cores were 3.8 cm in diameter and the core length was about 6.5 cm. The origin of the cores was exploration wells from different parts of the world. The main selection criteria were that the cores were homogeneous, contained only one pore class and had no detectable micro-fractures. CT images were used to investigate micro-fractures. Five of the cores are different subclasses of the intercrystalline pore class, while one sample is a mouldic pore type.

The cores were cleaned with toluene/methanol, and dried before saturating with brine. Porosity and permeability were measured both by gas phase and brine. The brine porosities and permeabilities are reported in Table 1. The cores were brought to S_{wi} by primary drainage centrifugation, using decane as the oil phase, before being waterflooded.

Waterflooding. Waterflooding experiments were performed with model fluids. The water phase was synthetic seawater, and the oil phase was decane. The displacement experiments were made on vertical oriented cores with water injection from the bottom of the core. The flow rate used in the core floods was scaled to the permeability of the carbonate core sample, ensuring that the differential pressure was approximately the same for all the experiments.

The flow rate was typically 0,4 cc/min for a 10 mDarcy core. After the first waterflood, the cores were cleaned, saturated with brine and porosity and permeability measurements were repeated. The cores were brought to S_{wi} by primary drainage centrifugation, before aging in crude oil under slow oil flow. The cores were aged for a minimum of 4 weeks at 60°C.

After aging, the wettability indices of the samples were estimated by the combined USBM/Amott test procedure (Donaldson et al.). F-48 shows a neutral wettability, while the other plugs were classified as mixed wet small (Dixit et al., and Skauge et al. 2002). None of the plugs spontaneously imbibed oil. The spontaneous imbibition was observed for a minimum of three weeks if no production was initiated, and the cores were monitored for two weeks further after the last measureable production was observed. F-48 and F-108 did not spontaneously imbibe water, hence the Amott-Harvey-indices for these two samples were zero. The wettability determination test also generated data for drainage- and imbibition capillary pressure curves.

Waterflooding, oil recovery. The six cleaned plugs were waterflooded at constant rate until oil production ceased. Problems due to the low pore volume of plug sample F-108 gave high uncertainty in the saturation measurements. Table 1 shows large oil recovery on all samples, especially considering the low permeability. All the cores, but F-48 (IC-UMa) produced more than 50% of OOIP.

RESULTS AND DISCUSSION

Earlier studies have shown that different carbonate pore classes show large variation in properties with regard to flow (Skauge et al., 2005). Observations from dispersion analysis based on single phase flow have proved to be consistent with two-phase flow results, and low permeable carbonate still gave high oil recovery efficiency. Single phase dispersion of carbonate core material has been extensively studied, and the capacitance model proposed by Coats and Smith, can be used to quantify the fraction of dead-end and inaccessible pores (Skauge et al., 2006). A general result is that waterflood oil recovery was correlated to flowing fraction porosity for almost all studied pore classes. Further, as the fraction of flowing pores increases, higher recovery is expected (Skauge et al., 2006).

***Capillary pressure*.** The capillary pressure for forced water imbibition and secondary oil drainage after aging of the cores are given in Figures 1 and 2. The area under the forced processes reflects the work needed to displace either oil or water. The USBM index reflects the relative area under the curves and the data for wettability indices are reported in Table 1.

Wettability. In general, the combined Amott/USBM wettability tests show weak spontaneous imbibition of water. The two cores belonging to the intercrystalline uniform macroporosity class (F-48 and F-108) showed no spontaneous water imbibition. Oil did not spontaneously imbibe into any of the cores. The USBM indices are negative for all the cores except for the mouldic sample that has a low positive USBM index of 0.08, see

Table 1. The Amott index is generally higher than the USBM index. A more detailed analysis, analogue to earlier studies of sandstone reservoirs (Skauge et al., 2002, 2003, 2004) would indicate a mixed wet small local wettability for all cores. An exception is one of the intercrystalline macroporosity core that would be characterised as fractional wet with a weak tendency towards mixed wet small. Two of the cores, both of the pore type intercrystalline macroporosity, displayed no spontaneous imbibition of either water or oil.

Recovery comparison. The effect of wettability is in this paper studied by comparing recovery from waterflooding core plugs at cleaned state and restored (aged) state. An overview of the oil recovery response after aging is shown in Figure 3. Details on porosity, permeability, initial water saturation and recovery factor for the different plugs can be found in Table 1. The waterflood response is analysed in relation to the measured wettability properties by Amott and USBM wettability tests. In the following, examples of oil recovery from each of the pore classes are discussed separately. In another paper dispersion characteristics of a large number of carbonate cores have been analysed by a capacitance model, Skauge et al., 2006. Dispersion characteristics can give information about the amount of dead-end pores, inaccessible pore volume, and hydraulic mixing due to the pore structure.

Intercrystalline uniform macroporosity. The cores F-48 and F-108 had an unusual high recovery at cleaned state. The F-108 core had a very low permeability of 0.48 mD. These core are the only ones with lower recovery after restoring. The oil recovery for core F-48 is shown in Figure 4. The two cores F-48 and F-108 both with intercrystalline uniform macroporosity pore structure showed no spontaneous imbibition of water. They are also the only cores were oil recovery was not significantly increased upon aging. The reason for this behaviour is not totally understood, but we believe that the results are coupled to the lack of spontaneous water imbibition (Morrow, and Skauge et al., 2002)

Intercrystalline patchy microporosity

The waterflood oil production for cleaned and aged state of the core O-10 is shown in Figure 5. There are similarities in the production curves after water breakthrough for the two different states. A likely reason is that the shape of the production curves also reflects properties of the local pore structure. The oil recovery is highest for aged state indicating that change to less waterwet properties lead to improved oil recovery.

Intercrystalline patchy mesoporosity. The third pore class investigated was a patchy intercrystalline mesopore structure. The tracer production profile was very different from the intercrystalline macropore cores, and indicates little amount of inaccessible and dead-end pores (Skauge et al., 2005). The core (O-30) had a porosity of 14.5 per cent and a permeability of 5.0 mD. Although the oil recovery at cleaned state was high (54 per cent of OOIP, see Figure 6), the recovery after aging was even higher. The recovery from core O-30 after aging was the highest of all the core plugs in terms of OOIP.

Intercrystalline uniform microporosity. The dispersion characteristics for O-35 show a highly connected pore structure (Skauge et al., 2005). This leads us to expect a high, piston-like oil production during water injection. The waterflood at cleaned condition of core O-35 showed an oil recovery that corresponds to more than one third of OOIP, Figure 7. The restored waterflood produced an even higher oil recovery of 62 per cent of OOIP. Hence, the production profile and dispersion characteristics are consistent with respect to expected recovery relative to OOIP.

Mouldic microporosity. Core O-3 has a porosity of 11.9 per cent and a permeability of only 0.19 mD. The origin of this secondary formed porosity was initially expected to give poor connectivity of the porous medium, and correspondingly low waterflood response. An early breakthrough and low total production is expected for this heterogeneous pore structure. However, the dispersion characteristics have earlier shown a good connectivity of this core, (Skauge et al., 2005). The waterflood at cleaned condition shows an oil recovery of 30 per cent of the oil in place, Figure 8. The piston-like oil production curve resembles a typical water-wet sandstone production curve. This mouldic material has an exceptional high oil recovery for such low permeability. The higher flowing fraction of the pores is consistent with such a high oil recovery, (Skauge et al., 2005). The waterflood at aged condition resulted in a significant increase in oil production up to 60% of OOIP, Figure 8.

Wettability and oil recovery. Cuiec showed that many carbonate rocks have an intermediate wettability. This definition of intermediate wettability includes mixed, fractional and neutral wettability. As discussed earlier, several later experimental studies have also confirmed these observations. The carbonate cores used in this study also falls into the group of intermediate wettability, especially after restoration by aging with crude oil. While some of the plugs had low recovery factor at cleaned and more water-wet state, all had quite high recovery after being aged (see Table 1). These results are consistent with change from more water wet to intermediate wettability (Morrow, and Skauge et al., 2002). The plug displaying neutral wettability was the only one that had a reduction in recovery from water wet state to restored state. The recovery, however, was still high. All cores but one are interpreted as having gained a mixed-wet small wettability after aging. The initial water saturation was unchanged from the cleaned to the aged state for all cores, and this enable easier comparison of the waterflood response at the different wetting states.

CONCLUSIONS

Different carbonate pore classes show variation in properties with regard to flow.

Low permeable carbonate may give a high oil recovery efficiency (ex. 45% recovery at K=0.7 mD. The same goes for low porosity carbonates.

The earlier observations from dispersion analysis based on single phase flow are generally consistent with two-phase flow results, also after wettability restoration.

Oil recovery is correlated to dispersion and porosity, but the relationship of oil recovery to different pore classes as defined by the porosity-permeability relationship is unclear. More data is needed to conclude on these issues.

The core samples show intermediate- to weakly oil-wet behaviour after aging, similar to many other studies of carbonate rocks.

The Swi was similar for water-wet and restored state cores for most cases.

There is a strong increase in oil recovery after aging for most of the cores studied.

Neutral wettability and/or zero spontaneous water imbibition have a strong and negative effect on the oil recovery by waterflooding

NOMENCLATURE

Swi: initial water saturation
K: permeability (mD)
USBM: United States Bureau of Mines
OOIP: original oil in place
PV: pore volume
IC-UMa: Intercrystalline uniform macro-porosity
IC-PMi: Intercrystalline patchy micro-porosity
IC-PMe Intercrystalline patchy meso-porosity:
IC-UMi: Intercrystalline uniform micro-porosity
Mouldic micro: Mouldic micro-porosity
RF: recovery factor (fraction of oil in place)
FW: fractional wettability
MWL: mixed wet large
MWS: mixed wet small

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Table 1: Petrophysical data, wettability data, and recovery factors for core plug being waterflooded at cleaned and aged states.

Plug sample	F-48	F-108	O-10	O-30	O-35	O-3
Porosity (fraction)	0.128	0.045	0.115	0.145	0.243	0.119
Permeability (mD)	33	0.48	0.78	5.0	0.18	0.19
Swi	0.17	0.69	0.29	0.10	0.70	0.44
Amott-Harvey index (aged cores)	0	0	0.18	0.18	0.54	0.51
USBM – index (aged cores)	-0.02	-0.37	-0.11	-0.14	-0.08	0.08
FW	X					
MWS		X	X	X	X	X
Pore class	IC-UMa	IC-UMa	IC-PMi	IC-PMe	IC-UMi	Mouldic micro
Recovery factor (RF) cleaned cores	0.65	0.45	0.2	0.54	0.34	0.30
Recovery factor (RF) aged cores	0.46	0.38	0.57	0.73	0.62	0.60
RF aged / RF cleaned	0.71	0.84	2.85	1.35	1.82	2.00

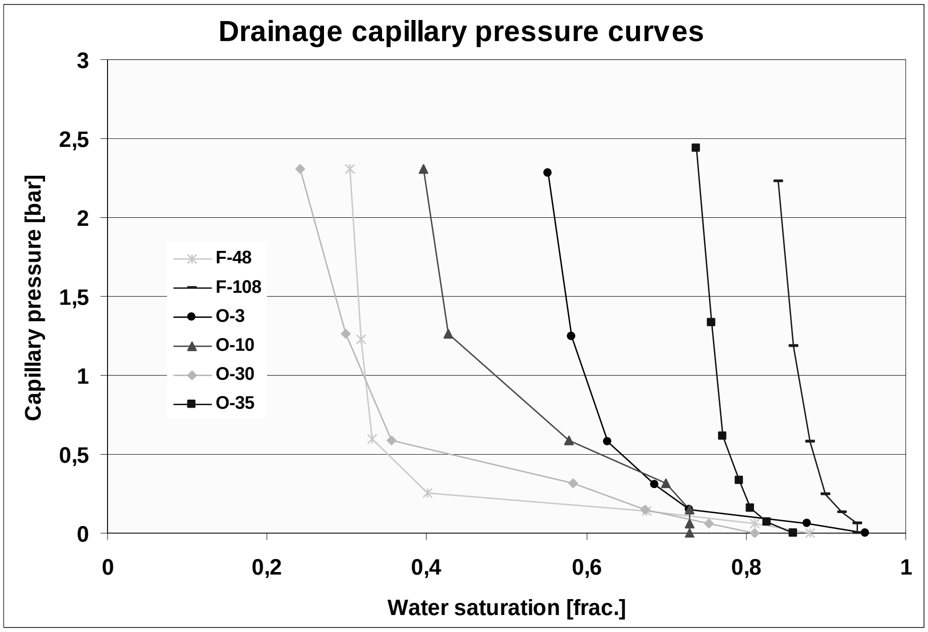

Figure 1: Secondary drainage capillary pressure curves as part of the wettability determination test (following the imbibition below).

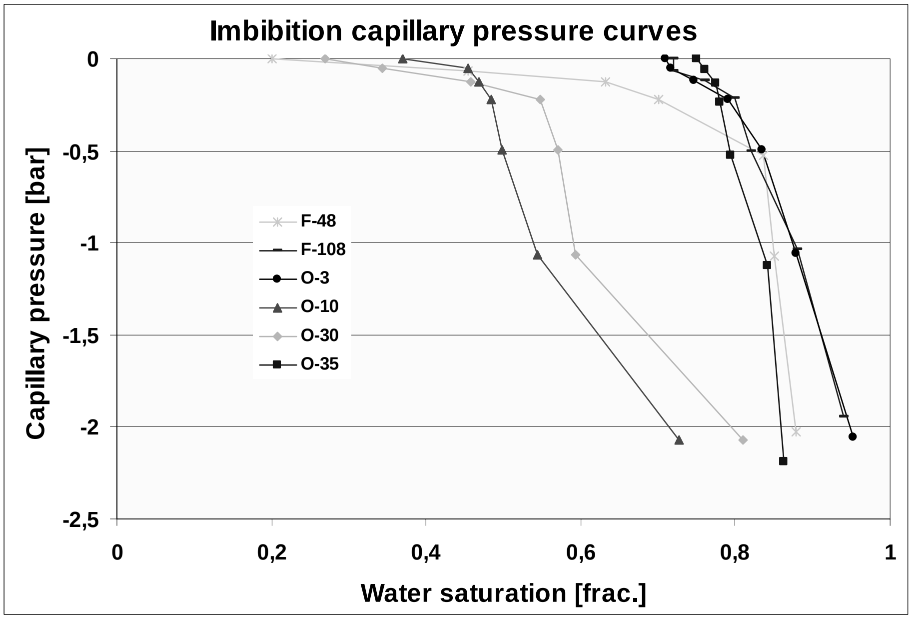

Figure 2: Forced imbibition capillary pressure curves as part of the wettability determination test (after primary drainage)

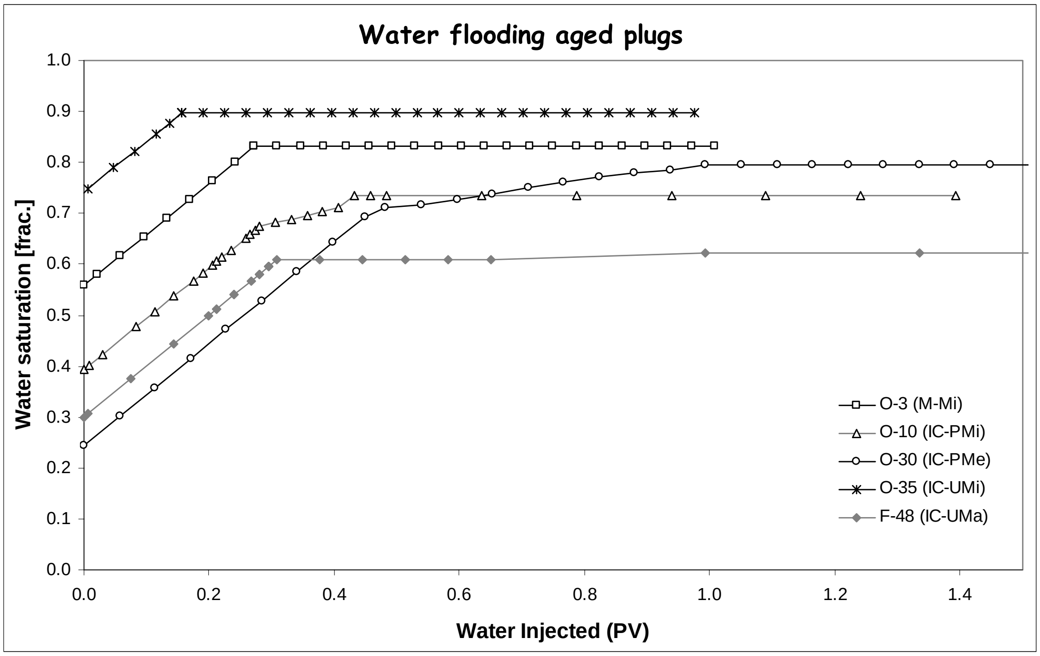

Figure 3: Change in water saturation for five of the aged core plugs when waterflooded.

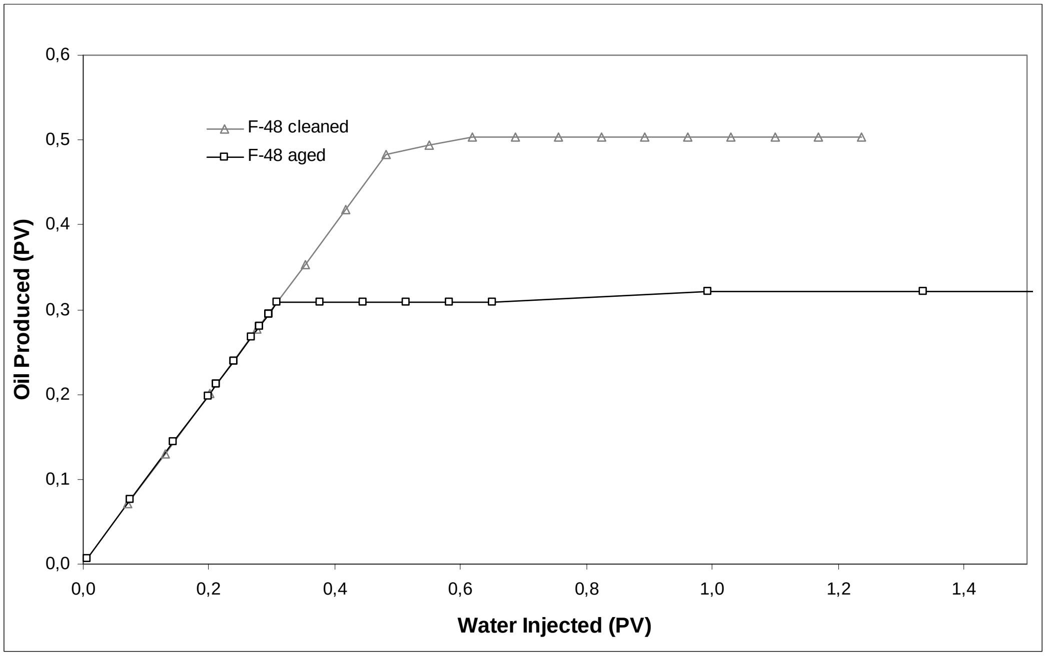

Figure 4: Production profiles of waterfloods on the plug F-48 at water wet state and restored state.

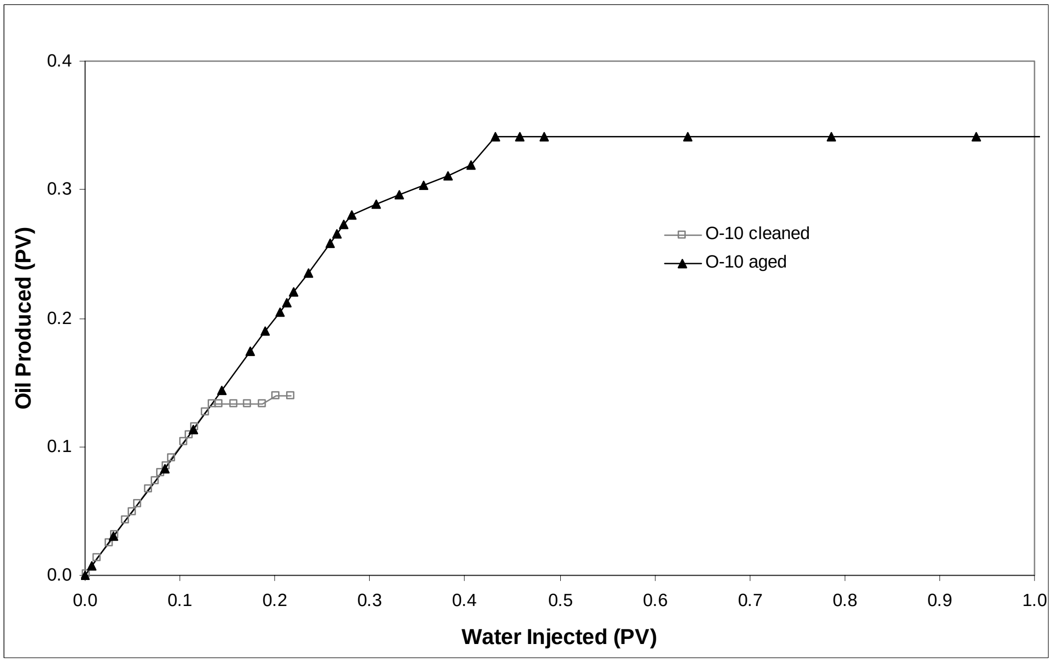

Figure 5: Production profiles of waterfloods on the plug O-10 at water wet state and restored state.

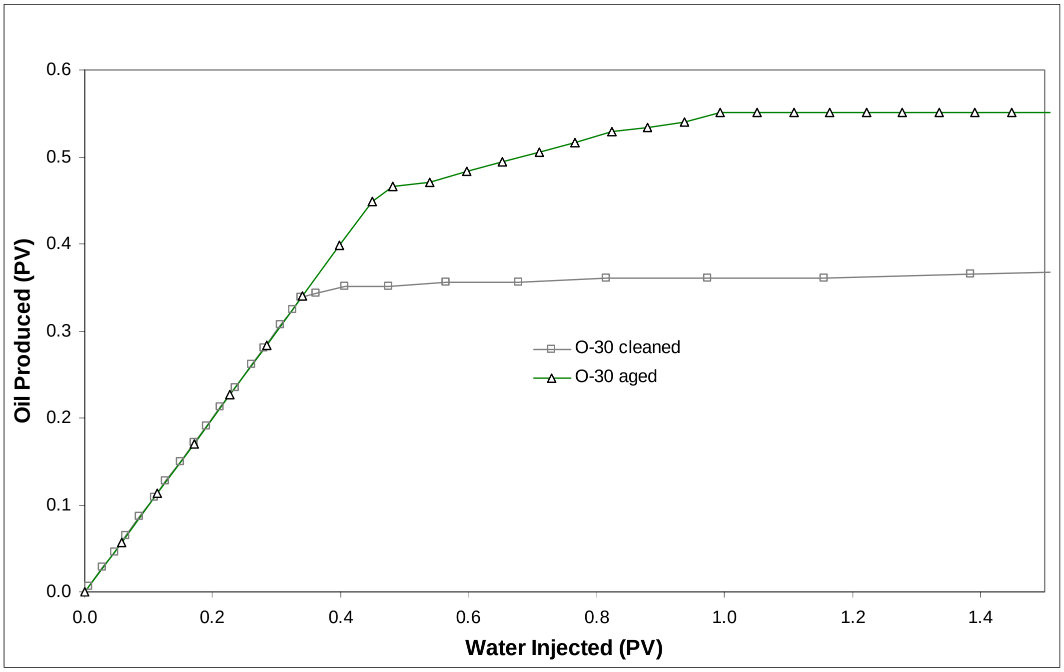

Figure 6: Production profiles of waterfloods on the plug O-30 at water wet state and restored state.

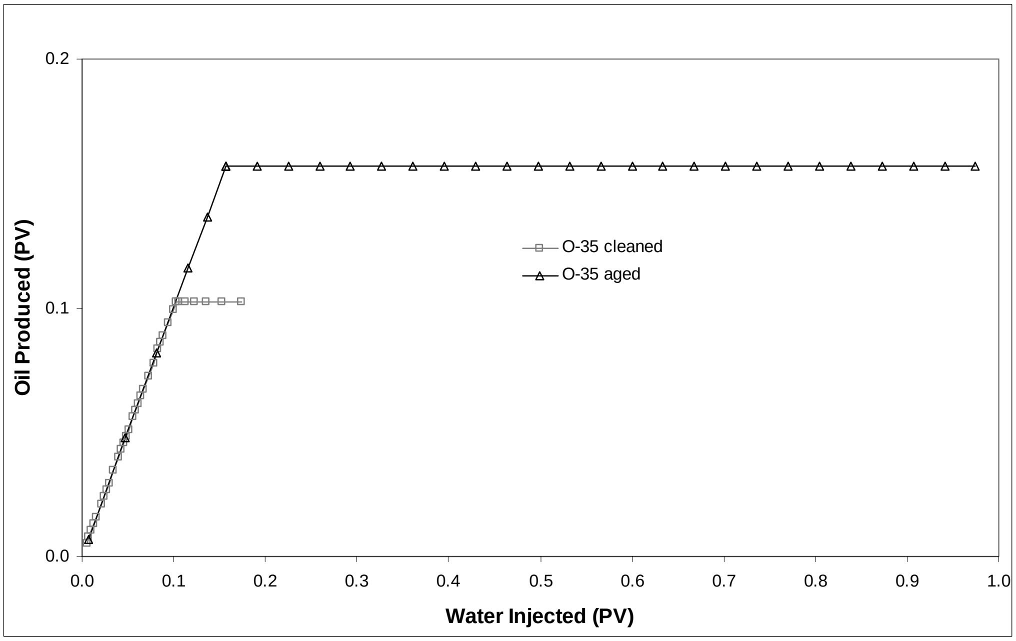

Figure 7: Production profiles of waterfloods on the plug O-35 at water wet state and restored state.

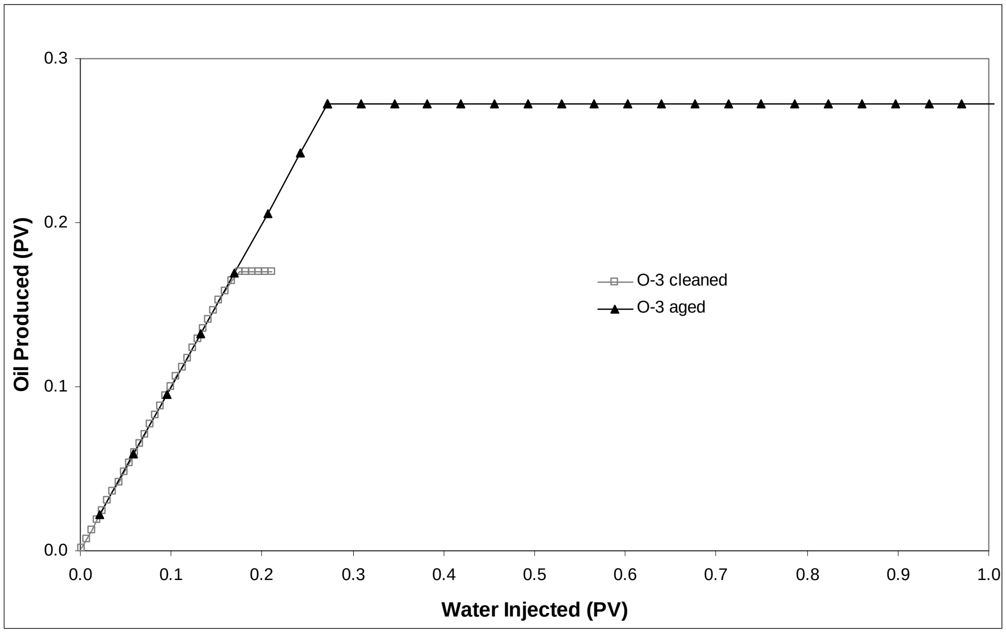

Figure 8: Production profiles of waterfloods on the plug O-3 at water wet state and restored state.