Impact of Confining Pressure on Reservoir Permeability

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Abstract

For conventional analysis of plug samples (porosity and permeability), the absolute and relative permeability that are measured on rock samples at ambient conditions (no overburden pressure), can lead to serious errors of estimating reserve, since a11 reservoirs are produced under confining formation pressure. Laboratory measurements were conducted on samples for two fields representing Libyan sandstone reservoirs to investigate absolute and relative permeabilities at ambient and at different confining stresses. In this study the permeability in the lower cretaceous of Nubian sandstone formation is braided fluvial reservoir and the measurement of permeability in this reservoir are variable from high to good and sometimes is very poor during the hole of reservoir based in laboratory routine measurement of permeability.

Experimental data were collected from samples which were selected based on petrotyping technique named (GHE, s) to investigate the effect of confining stress to absolute (Klingenberg) and relative permeabilities. These experiments were conducted on sandstone rock samples (17 plugs) under net overburden pressures reach to (5000 psi).

Our results show a decrease in permeability with increase in overburden pressure. Both correlations for the two fields are found to be polynomial. The relative permeability to water is a little reduced compared with oil relative permeability by applying confining stress. If the measurements are conducted at ambient conditions this may result in over or under estimation of fluid distribution in many situations in reservoir and the error in the estimation can subsequently lead to inaccurate estimates of the hydrocarbon in place.

Key words: Absolute**,** Relative Permeability, Confining, Nubian, Coefficient

تأثير ضغط الحصر على نفاذية المكمن

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الملخص

في التحليل التقليدي لعينات السد (المسامية والنفاذية)، قد تؤدي النفاذية المطلقة والنسبية المقاسة على عينات الصخور في الظروف المحيطة (بدون ضغط علوي) إلى أخطاء جسيمة في تقدير الاحتياطي، نظرًا لأن المكامن تتكون تحت ضغط تكويني محصور. أُجريت قياسات مخبرية على عينات من حقلين يمثلان مكامن الحجر الرملي الليبي لدراسة النفاذية المطلقة والنسبية في الظروف المحيطة وتحت ضغوط محصورة مختلفة. في هذه الدراسة، تُصنف النفاذية في العصر الطباشيري السفلي لتكوين الحجر الرملي النوبي كمكمن نهري متشعب، وتتفاوت قياسات النفاذية في هذا المكمن من عالية إلى جيدة، وأحيانًا تكون ضعيفة جدًا، وذلك بناءً على القياسات المخبرية الروتينية للنفاذية.

جُمعت البيانات التجريبية من عينات مختارة بناءً على تقنية تصنيف الصخور (GHE) لدراسة تأثير الضغط المحصور على النفاذية المطلقة (Klingenberg) والنسبية. أُجريت هذه التجارب على عينات من صخور الحجر الرملي (17 عينة) تحت ضغوط صخور علوية صافية تصل إلى 5000 رطل لكل بوصة مربعة.

تُظهر نتائجنا انخفاضًا في النفاذية مع ازدياد ضغط الصخور العلوية. وقد وُجد أن كلا الارتباطين للحقلين متعدد الحدود. تنخفض النفاذية النسبية للماء قليلًا مقارنةً بالنفاذية النسبية للنفط عند تطبيق ضغط الحصر. إذا أُجريت القياسات في الظروف المحيطة، فقد يؤدي ذلك إلى تقدير مفرط أو ناقص لتوزيع السوائل في العديد من حالات المكمن، وقد يؤدي الخطأ في التقدير لاحقًا إلى تقديرات غير دقيقة للهيدروكربون الموجود.

الكلمات المفتاحية: النفاذية المطلقة، النفاذية النسبية، الحصر، النوبي، المعامل

1. Introduction

For any reservoir rock there are two key petrophysical parameters. The first is the capacity of the rock to store fluid, namely porosity. The second is connectivity of the pore space, which allows fluid to flow through the rock, namely permeability. Routine core analysis defines the porosity and permeability magnitude and distribution. SCAL complements this routine data and furnishes information that allows calculation of static fluid distribution as well as dynamic flow performance of a well or reservoir. Moreover, a special core analysis program can assist in defining the most favorable recovery technique to maximize oil recovery and profitability. Downhole log interpretation is considerably enhanced by a SCAL program through the measurement of electrical and acoustic properties of reservoir rocks and fluid saturations from displacement experiments (capillary pressure and relative permeability data). The objectives of performing a SCAL program are to achieve an accurate representation of the reservoir rock characteristics, information that is necessary for reliable reservoir engineering calculations and modelling. In routine core analysis, porosity, absolute and relative permeabilities are measured on rock samples which are not under net overburden pressure. However, under actual reservoir conditions, the rocks experience a net overburden pressure which is equal to the weight per unit area of the vertical overburden column from the reservoir depth to the surface of the earth less the pressure of the liquid in the pores of the rock. Sometimes only the initial net overburden pressure is considered while subsequent increase in this pressure caused by reduction in pore pressure upon reservoir depletion is ignored.

1.1 Objectives

In this paper, the data obtained from permeability, and relative permeability measurements at ambient and at overburden pressure were analyzed and interpreted. The aim was to develop methodologies for reliable prediction using more representative data. The methodologies were desired to possess the following characteristics:

1. Rapidity
2. Cost–effectiveness
3. Deriving correlations for Predicting permeability at any given pressure.

2.Literature Review

The GHE template can be potentially applied to core data for identification of other significant trends in a wide range of crossplots for different parameters (Corbett and Potter, 2004).

Some researchers studied the effect of confining stress on permeability and are similar in their conclusions such as Dobrynin (1962) and Fatt and Davis (1952); they note that the permeability reduce as the overburden pressure applied on the sample due to compressibility. Gray et al. (1963) found that final reduction in permeability happens when the pressure is stabilized. Wilhelmi et al. (1967) on the other hand, developed a method for simultaneous measurement of pore and elastic properties of rock under non-uniform stress. Marek (1979) observed decrease in absolute permeability accompanied by a little decrease in porosity

under overburden pressure. The decrease in permeability was attributed to pore collapse. Owens (1971), Weinbrandt, R. (1972), Sufi, A.H., Ramey H.J, and Brigham (1982) and Amaefule, et al. (1982), have studied the effect of different parameters on permeability. Although, H.S. Ali; et al. (1987) attempt to investigate the effect of overburden pressure on relative permeability, we tried in our study to explore a relationship between confining stress and some rock properties especially relative permeability for samples related to Libyan sandstone reservoirs.

3. Methods

The permeability was measured by using Nitrogen Gas Permeameter instrument (Corex Services). The clean, dry sample is placed in the Hassler-type core holder, and an overburden pressure of 200 psig is applied to the cell, compressing the rubber sleeve around the sample. Nitrogen gas pressure is applied to one end face of the sample, whilst the other end face is open to atmospheric pressure, causing the gas to flow through the sample. The flow of gas is measured at the low pressure (downstream) end face of the sample. The flow rate is measured by passing the gas through one of three laminar flow orifices and measuring the differential pressure developed across the orifice. The transducers and flow orifices are calibrated using a dead weight tester and soap film meter at least once every three months, or when any component is altered or replaced. The air permeability calculated as follows: -

$$Kg = \frac{2000 \times P_b \times Q_g \times \mu_g \times L}{(P_1^2 - P_2^2) \times A} \qquad (1)$$

where:

Kg	=	Gas permeability, mD
Pb	=	Barometric pressure, atm
P_1	=	Upstream pressure, atm
P_2	=	Downstream pressure, atm
Qg	=	Gas flow rate, cc/sec
μ_g	=	Gas viscosity, cp
L	=	Sample length, cm, A= cross sectional area, cm^2

The clean dry samples were placed in CMS-300 instrument which is fully automated permeameter used to determine permeability at overburden pressure. The permeability was measured at five pressure values of (1000-5000) psig. The base permeability was measured at 200 psig overburden pressure. The measurements and the calculations of these parameters are based on the techniques described by API recommended practice 40. Two samples from two oil fields (H, and M) were selected to perform relative permeability test. After the test of gas-oil relative permeability was completed, samples were placed in an oil-filled desiccator and evacuated until no gas bubbles came out of the samples, and then samples were gravimetrically checked to ensure removal of gas from sample pore spaces. The prepared sample was individually placed in a hydrostatic core holder, and an overburden pressure was applied. Simulated formation brine was injected at the top end face of the sample at constant flow rate using HPLC pump. The produced volumes, differential

pressure, time and confining pressure were all monitored and recorded. The brine flood was only terminated when the water cut reached 99.98%. When oil production was ceased, permeability to water was measured and the test was terminated.

The time, oil volume and the total volume were used to calculate relative permeability excel sheets. In these years, the analysis, interpretation and calculation of relative permeability are used by software named "Sendra".

4. Data Collection

To compare the experimental results, the samples were having been chosen sixteen (16) samples with different porosity and permeability from two oil fields (sandstone). The selection was based on Global Hydraulic Elements (GHE, s) technique. Initially, core samples were selected to study the effect of confining stress on flow behavior in the reservoirs. One and a half inch diameter core plugs were cut from full diameter core in the horizontal direction using a diamond core bit with water as the bit coolant and lubricant. The samples were extracted of hydrocarbons using toluene, leached of salt using methanol, and oven dried at 80 ^{o}C for a period of 48 to 72 hours, and then left to cool to room temperature before conventional core analysis commenced. Routine core analysis porosity and permeability measurements were first conducted on the plugs in core Laboratory at Libyan Petroleum Institute (LPI) and the results will be explained in this study. Ten plug samples were selected based on Global Hydraulic Elements technique (GHE, s), Corbet et al. (2004), from wells H1, and H2, (H-field) and six samples from wells M1, M2 which related to M-field (Figures 1, and 2) to investigate the effect of overburden pressure on absolute permeability. In this study we select two samples from both fields as case study.

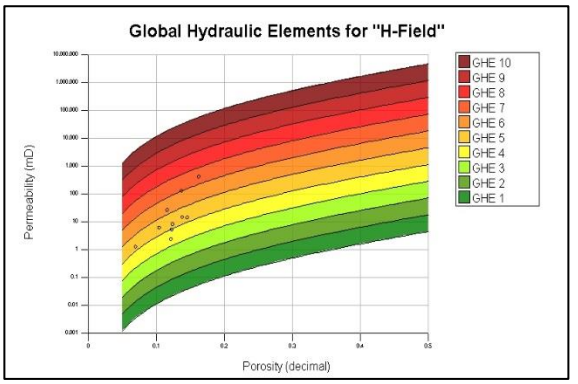


Figure1. Global hydraulic element porosity-permeability crossplot for the ten selected representative samples from "**H**" field.

5. Results and Discussion

5.1 Confining stress on absolute permeability

Core data of porosity and permeability for Nubian Sandstone Formation which belongs to "H" field (two wells, H1, and H2,) are presented in Table 1, while the values of "M" field (two wells M1, and M2) are presented in the same table. The results of averaging horizontal permeability measurements for ten samples selected from sandstone core

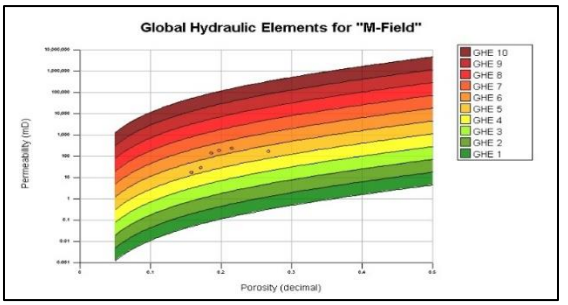


Figure2. Global hydraulic element porosity-permeability crossplot for the six selected representative samples from

samples of "H" field as a function of overburden pressure are presented in Table 2 and in Figures 3. The six core samples from "M" field were selected and the results are presented in the same table and in Figure 4. The data for both cores exhibits a reduction in absolute permeability with increasing overburden pressure. The reduction in permeability values at 5000 psi for samples selected from "H" field, is 7.94%, while in M-field is 15.72% respectively. These reductions in absolute permeabilities with increasing overburden pressure can be attributed to the decrease in pore diameter and rock compaction.

Table 1. Porosity and permeability values of the selected representative samples for studied area.

Sample No.	Depth (ft-in)	Ø (%)	K (mD)	FZI	GHE
H-Field					
7	1385	10.3	6.250	2.1	5
12	1385	14.5	14.34	1.8	5
13	1385	12.2	5.260	1.4	4
18	1386	12.3	8.400	1.8	5
20	1386	12.1	2.430	1.0	4
3	1394	13.7	14.90	2.0	5
5	1394	16.1	424.0	8.3	7
14	1396	6.90	1.280	1.8	5
15	1396	13.6	132.0	6.1	7
21	1397	11.5	26.60	3.6	6
M-Field					
2	7612.	19.7	189.0	3.9	6
4	7614.	15.8	17.80	1.7	5
6	7616.	17.1	29.50	1.9	5
8	7618.	18.6	144.0	3.8	6
9	8608.	26.7	172.0	2.1	5
10	8609.	21.5	237.0	3.8	6

Table 2. Results of averaging absolute permeability at O.B.P for the studied area

Pressure, Psi	Averaging K, mD (H-Field)	Averaging K, mD (M-Field)
200	129.01	95.61
500	127.81	93.69
1000	126.08	90.98
2000	123.38	86.88
3000	121.40	84.05
4000	119.92	81.99
5000	118.77	80.58
Reduction (%)	**7.94**	**15.72**

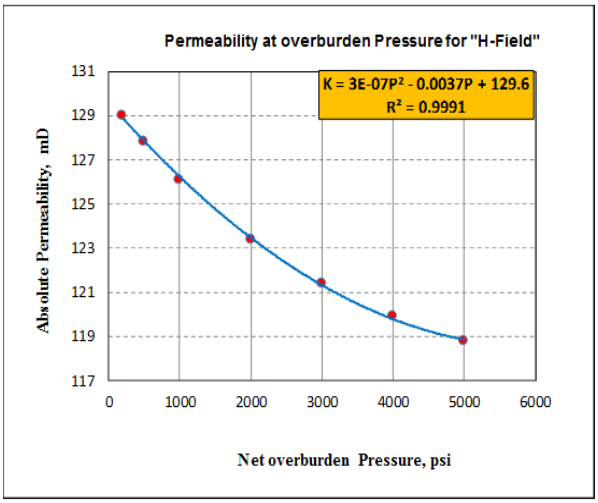


Figure 3. Crossplot of Permeability at O.B.P for H-Field

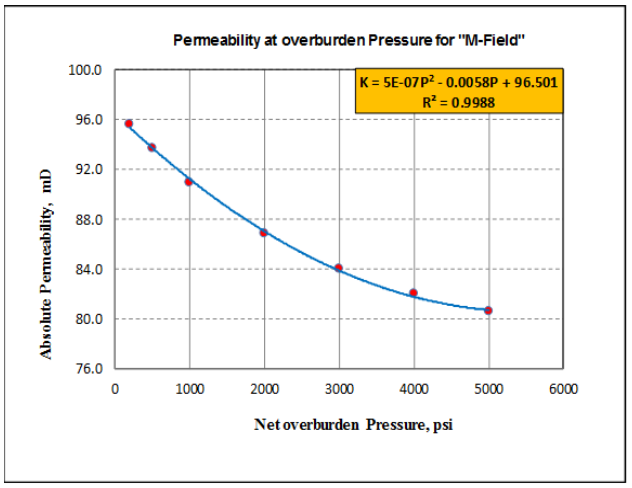


Figure 4. Crossplot of Permeability at O.B.P for M-Field

A polynomial correlation was obtained for study area between permeability and overburden pressure as following:

$$K = a \times P^2 - b \times P + c \qquad (2)$$

Where K and P denote permeability and overburden pressure, respectively. a, b, and c are constants for a given rock sample. These constants are based on individual samples to yield the correlations which represent the samples studied. Statistical error analysis is applied to evaluate the accuracy of the developed relations.

$$K = 3.0E-07 \times P^2 - 0.0037 \times P + 129.6$$
$$K = 5.0E-07 \times P^2 - 0.006 \times P + 96.5$$

According to above correlations, it is easy to find sample's permeability by knowing the pressure.

5.2 Relation Between Confining Stress and Effective Permeability

The recorded data of pressure drop, and flow rate are utilized to calculate the oil effective permeability at irreducible water saturation using Darcy 's law. Table 3 below show the reduction values between 1000 and 5000 psi for two sample for two oil fields, while tables 4, and 5 summarise the calculated results of effective permeabilities at each overburden pressure for two oil fields. Figures 5 and 6 show the effect of overburden pressure on Effective permeabilities for sample # 36 from "H" field, and sample # 18 from "M" field respectively. Our results showed reduction in effective oil permeability and water oil relative permeability, the decrease in effective permeabilities of the fluids may be attributed to the increase in pressure; at early stages (i.e. at low stress) of compression, fissures start to close with small compression in mineral grains (Goodman, 1980). As the stress increases, the rock undergoes bulk compression resulted from pore and grain deformation.

Table 3. Summaries of the reduction in Effective permeability between 1000 and 5000 psig

Pressure (psig)	Ko	Kw
Sample # **36** (H- field)		
1000	69.30	31.60
5000	49.00	24.00
Sample # **18** (M -field)		
1000	203.0	60.0
5000	135.0	45.0

Table 4. Calculated values of effective permeability of oil and water for sample # **36** (**H**-field).

Absolute Permeability(mD) :87 sample #36		
Pressure, Psig	**Ko (mD)**	**Kw (mD)**
1000	69.30	31.60
2000	64.00	29.00
3000	58.30	27.00
4000	54.00	25.50
5000	49.00	24.00

Table 5. Calculated values of effective permeability of oil and water for sample # **18** (**M**-field).

Absolute Permeability(mD) :321 sample #18		
Pressure, Psig	**Ko (mD)**	**Kw (mD)**
1000	203.0	60.0
2000	181.0	57.0
3000	161.0	49.0
4000	149.0	47.0
5000	135.0	45.0

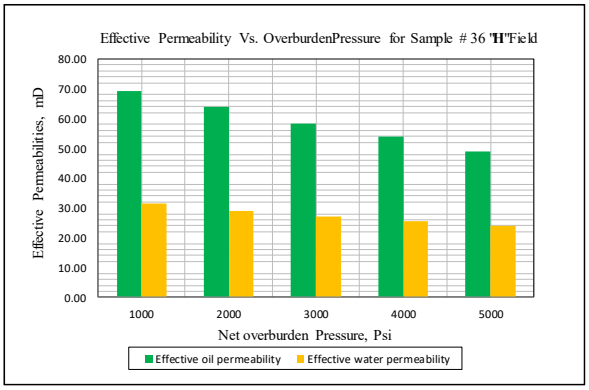


Figure 5. Crossplot of effective permeability for oil and water at different effective stress (Sample # **36**); **H**-Field.

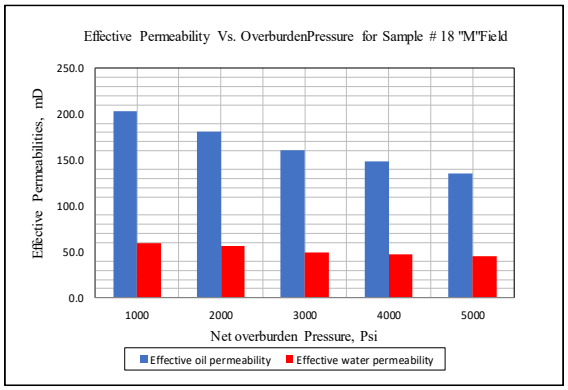


Figure 6. Crossplot of effective permeability for oil and water at different effective stress (Sample # **18**); **M**-Field.

5.3. Effect of Confining Stress on Endpoints

The maximum oil permeability is calculated from the oil effective permeability and absolute permeability measured at the same value of overburden pressure. Maximum oil relative permeability versus overburden pressure plots, are shown in figures (7 and 8). In this study, the reduction is clear in maximum oil relative permeability and maximum water oil relative permeability, the reduction values according to each pressure are represented in table 6.

Table 6. summaries the reduction in Endpoints of relative Permeabilities between 1000 and 5000 Psi.

Pressure (psig)	**Kro (Maximum)**	**Krw (Maximum)**
Sample # **36** (**H**- field)		
1000	0.7965	0.3640
5000	0.5632	0.2908
Sample # **18** (**M** -field)		
1000	0.6321	0.18802
5000	0.4215	0.14000

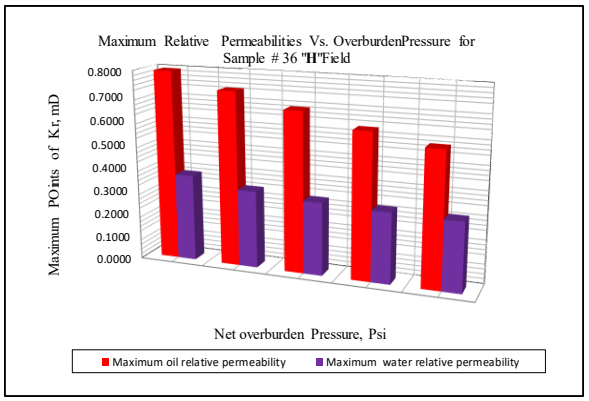


Figure 7. Crossplot of Endpoints for oil and water relative permeabilities at different effective stress (Sample # **36**); **H**-Field.

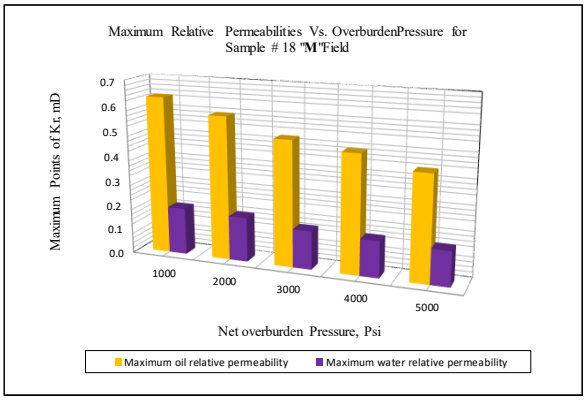


Figure 8. Crossplot of Endpoints for oil and water relative permeabilities at different effective stress (Sample # **18**); **M**-Field.

Using core sample data (sample pore volume, sample length, sample cross-sectional area, effective permeability to oil at irreducible water saturation and irreducible water saturation), fluid data (oil and water/gas viscosities), flood data (time cumulative oil and water volumes, pressure and the flowrate) are used to determine relative permeability to oil and water/gas as a function of water/gas saturation using JBN (Jonson-Bossler-Neuman, 1959), JR (Jones Roszelle, 1978). Figures (9, 10) show the behaviour of relative permeability measurements at ambient and at overburden pressure of two samples selected for studied area (sample # 36 from "H" field, and sample # 18 from "M" field). Our results showed reduction in kr_o with increase in overburden pressure compared to the ignore the effect on kr_w. This may be attributed to; As the overburden pressure start to up, the grain matrix starting to close each other causing a narrow in channels of the pores. For a certain value of S_w, this leads to redistribution of the wetting phase to occupy more pore throat, while this give hint no significant change in kr_w, it leads to more blockage of oil flow and then lead to reduces kr_o.

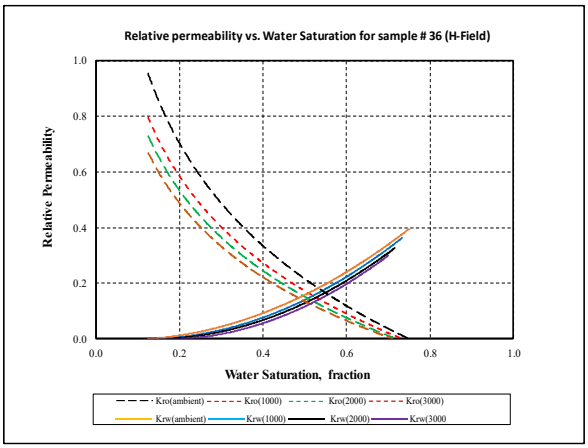


Figure 9. Crossplot of relative permeability test at different effective stresses (Sample # 36); **H**-Field

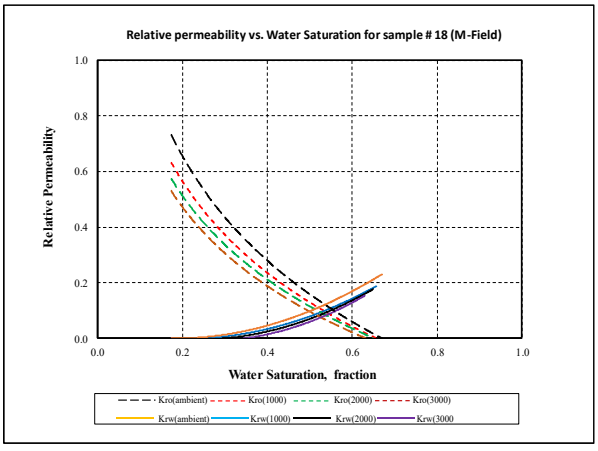


Figure 10. Crossplot of relative permeability test at different effective stresses (Sample # 18); **M**-Field

6. Conclusion

- In this study, the Global Hydraulic Elements (GHE, s) has been used for the first time for Nubian sandstone Libyan reservoirs.
- As the overburden pressure was applied on the samples, the reduction in absolute permeability was observed due to rock compressibility.
- Good relationship between permeability and overburden pressure was obtained using regression analysis.
- A significant Changes have been observed in values of oil relative permeability when the overburden pressure was applied, these values start decreasing while little decrease in values of water relative permeability

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