CHAPTER 4
RESULTS AND DISCUSSION

4-1 Data Collection

In this chapter we measurement and comparison have been done for sandstone core sample using SCAL data. We have obtained four results from four samples for this study. All of these samples from the same formation; two of these results we have obtained from the measurement of the relative permeability case and the another from centrifuge case. Table 4-1 shows the petro physical properties of each core sample, in addition to the type of method which used in the experiments.

Table (4-1): Petrophysical properties and type of mehod of each sample

Sample	K,md	Ø ,frac	Type of Method
1	641	0.226	Unsteady state
2	1096	0.218	Centrifuge
3	41.49	0.218	Unsteady state
4	292	0.220	Centrifuge

4-2 Unsteady State Relative permeability:

The data from the laboratory measurements are inaccurate, so it need to perform a normalization procedure. There are six steps to normalize the lab data and remove the error coming from the experiments.

4-2-1The Available Lab Data:

Table 4 -2 show two samples laboratory data from the same formations available for this study.

Table (4-2):Unsteady state Relative Permeability Laboratory Data for sample 1 and 3

SAMPLE : 1		
S_w	K_{ro}	K_{rw}
21.8	1.0000	0.000
34.01	0.6339	0.057
44.56	0.3741	0.147
51.56	0.2388	0.222
55.63	0.1718	0.258
58.1	0.1312	0.275
59.66	0.1130	0.283
61.1	0.0944	0.296
63.8	0.0656	0.306
65.47	0.0419	0.313
67	0.0258	0.318
70.6	0	0.321

SAMPLE : 3		
S_w	K_{ro}	K_{rw}
29.6	1.000	0.000
35.5	0.813	0.005
42.0	0.577	0.021
47.2	0.371	0.038
53.2	0.201	0.063
57.6	0.111	0.083
58.7	0.099	0.091
60.4	0.079	0.100
66.2	0.028	0.124
69.4	0.012	0.135
71.2	0.006	0.144
72.9	0.003	0.149
74.0	0.000	0.151

4-2-2 Unsteady State Relative Permeability Results and Discussion

Using the calculation procedures that described in chapter 3; figure (4-1) and (4-2) shows the relationship between water saturation and relative permeability for tow samples.

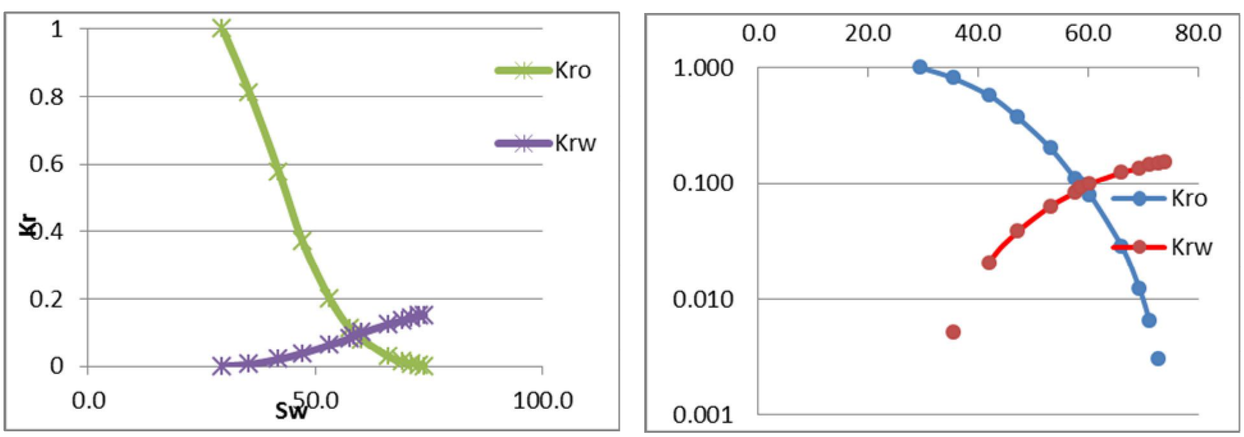


Fig (4-1): S_w vs. K_r Laboratory Data for Sample 1 (Linear and Semi-log Scale)

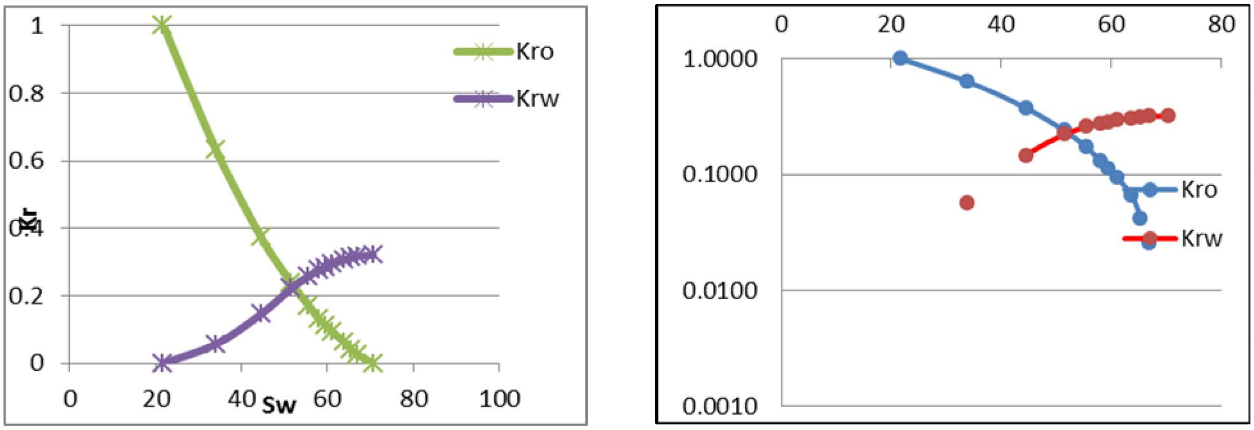


Fig (4-2): S_w vs. K_r Laboratory Data for Sample 3 (Linear and Semi-log Scale)

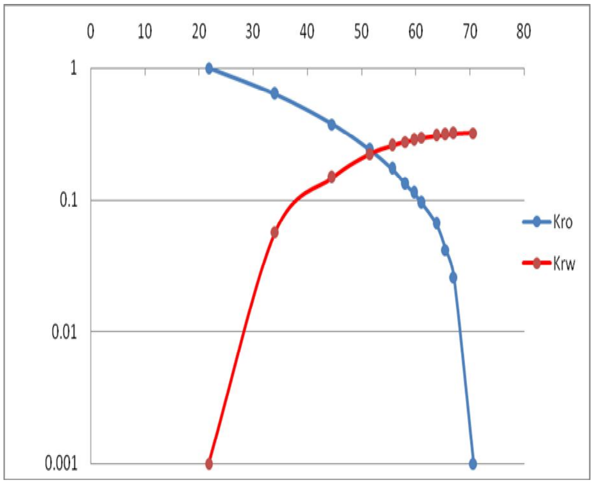
True Residual Oil Saturation (Sor)

To get the correct S_{or} for the two samples the general procedure described in chapter 3 was used. Table 4-3 below shows calculated normalize Oil Saturation (S_{on}) using equation 3-21 for three values of S_{or} (the lab value (0.294), 0.29 and 0.36). Figure (4-3) and (4-4) show the plot of the different S_{or} and relative permeability data plot using the true S_{or} respectively for sample 1. The same tables and figures for sample 3 in the appendix A.

Table (4-3): S_{on} Calculated from S_{or} (Sample 1)

S_{wi}	0.218			
S_{or}	0.294	0.36	0.29	0.2

S_w	S_{on1}	S_{on2}	S_{on3}	S_{on4}	K_{ro}
0.218	1.000	1.000	1.000	1.000	1.00
0.3401	0.750	0.711	0.752	0.790	0.63
0.4456	0.534	0.461	0.537	0.609	0.37
0.5156	0.390	0.295	0.395	0.489	0.24
0.5563	0.307	0.198	0.312	0.419	0.17
0.581	0.256	0.140	0.262	0.376	0.13
0.5966	0.224	0.103	0.230	0.349	0.11
0.611	0.195	0.069	0.201	0.325	0.09
0.638	0.139	0.005	0.146	0.278	0.07
0.6547	0.105	-0.035	0.112	0.250	0.04
0.67	0.074	-0.071	0.081	0.223	0.03
0.706	0.000	-0.156	0.008	0.162	0.00



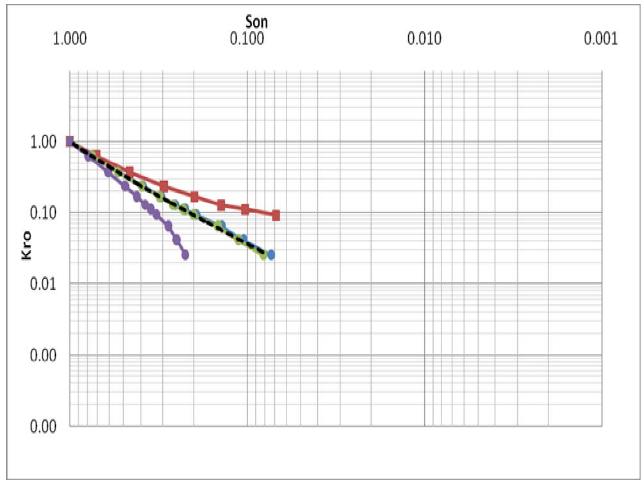


Fig (4-3): K_r vs. S_w (True Sor) -(Sample1)

Fig (4-4): Different S_{or} (Sample1)

Normalized Water Saturation (S_{wn})

As described in chapter 3, Table (4-4) below shows the S_{wn} that equivalent to the true S_{or} and figure 5-5 show the relationship between K_{rw} and S_{wn} for sample 1 as an example, the same tables and plots for sample 3 in appendixe B. From figure (4-5) it is clear that the real water end point (true S_{or}) at S_{wn} =1 is 0.38.

Table (4-4): S_{wn} from True S_{or} (Sample 1)

S_{wi}	0.218	
S_{or}	0.29	
S_w	**S_{wn}**	**K_{rw}**
0.218	0	0
0.3401	0.248171	0.056885
0.4456	0.462602	0.146893
0.5156	0.604878	0.222331
0.5563	0.687602	0.258226
0.581	0.737805	0.275423
0.5966	0.769512	0.283139
0.611	0.79878	0.295801
0.638	0.853659	0.306196
0.6547	0.887602	0.312608
0.67	0.918699	0.317687
0.706	0.99187	0.321324

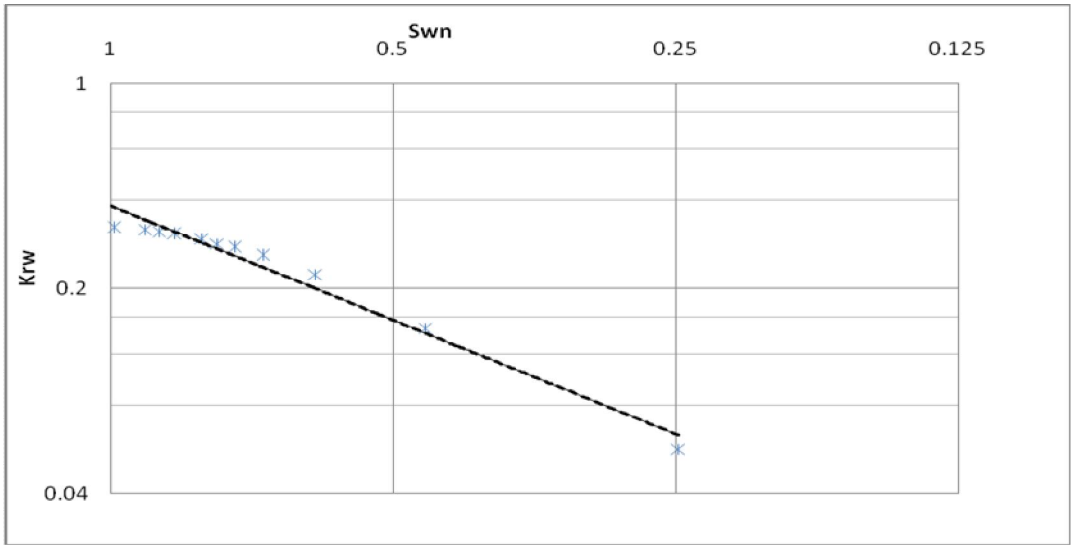


Fig (4-5) : K_{rw} vs S_{wn} (Sample 1)

Corey Exponents

Corey exponents for oil (No) and water (Nw) were calculated Tables (4-5) then No and Nw vs. S_w for sample 1 was plotted in figure (4-6). The tables and figures for the other sample were summarized in appendix C.

Data for sample 1:

Table (4-5): Corey Exponent for Oil and Water (Sample 1)

S_{wi}	0.218	K_{rw}*	0.38
S_{or}	0.29		

S_w	S_{wn}	K_{rw}	N_w
0.218	0	0	
0.34	0.24	0.056	1.36
0.44	0.46	0.146	1.23
0.51	0.60	0.22	1.06
0.55	0.68	0.258	1.03
0.581	0.73	0.275	1.05
0.59	0.769	0.28	1.12
0.611	0.79	0.29	1.1
0.638	0.853	0.306	1.36
0.65	0.887	0.312	1.6
0.67	0.918	0.317	2.11
0.706	0.99	0.321	
			1.31

S_{on3}	K_{ro}	No
1.000	1.00	
0.752	0.63	1.59
0.537	0.37	1.58
0.395	0.24	1.5
0.312	0.17	1.513
0.262	0.13	1.51
0.230	0.11	1.485
0.201	0.09	1.47
0.146	0.07	1.41
0.112	0.04	1.45
0.081	0.03	1.457
	0.00	
		1.50

No line	Nw line
1.44	1.31
1.44	1.31
1.44	1.31
1.44	1.31
1.44	1.31
1.44	1.31
1.44	1.31
1.44	1.31
1.44	1.31
1.44	1.31
1.44	1.31

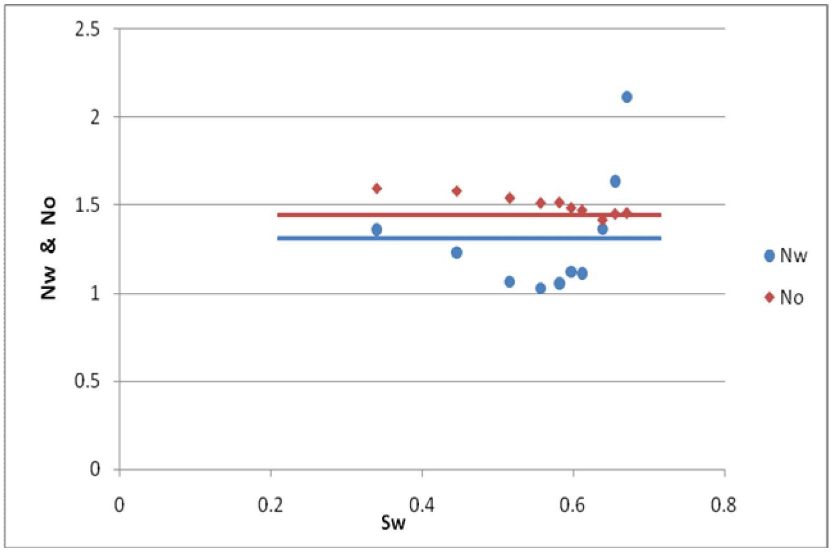


Fig (4-6): Nw , No Vs S_w (Sample 1)

Refining Relative Permeability Data

Refined (corrected) K_r was calculated and compared with the lab data. Table (4-6) shows the calculation of refined relative permeability for sample 1. Figure (4-7) and (4-8) show the refine relative permeability vs. water saturation for sample 1. The calculation tables and figures for the other sample in the appendix D.

Table (4-6): Refining Relative Permeability (Sample 1)

Lab RealPerm							Refined RealPerm	
S_w	K_{ro}	K_{rw}		S_w	S_{wn}	S_{on3}	R-K_{ro}	R-K_{rw}
21.8	1.00	0.000		0.21	0	1.000	1.00	0
34.01	0.63	0.057		0.34	0.24	0.752	0.65	0.061
44.56	0.37	0.147		0.44	0.46	0.537	0.39	0.138
51.56	0.23	0.222		0.51	0.60	0.395	0.24	0.196
55.63	0.17	0.258		0.55	0.68	0.312	0.17	0.232
58.1	0.13	0.275		0.581	0.73	0.262	0.13	0.255
59.66	0.11	0.283		0.59	0.76	0.230	0.11	0.269
61.1	0.09	0.296		0.611	0.79	0.201	0.09	0.28
63.8	0.06	0.306		0.63	0.85	0.146	0.05	0.308
65.47	0.04	0.313		0.65	0.88	0.112	0.037	0.32
67	0.02	0.318		0.67	0.91	0.081	0.02	0.34
70.6	0	0.321		0.71	1	0.000	0.00	0.38

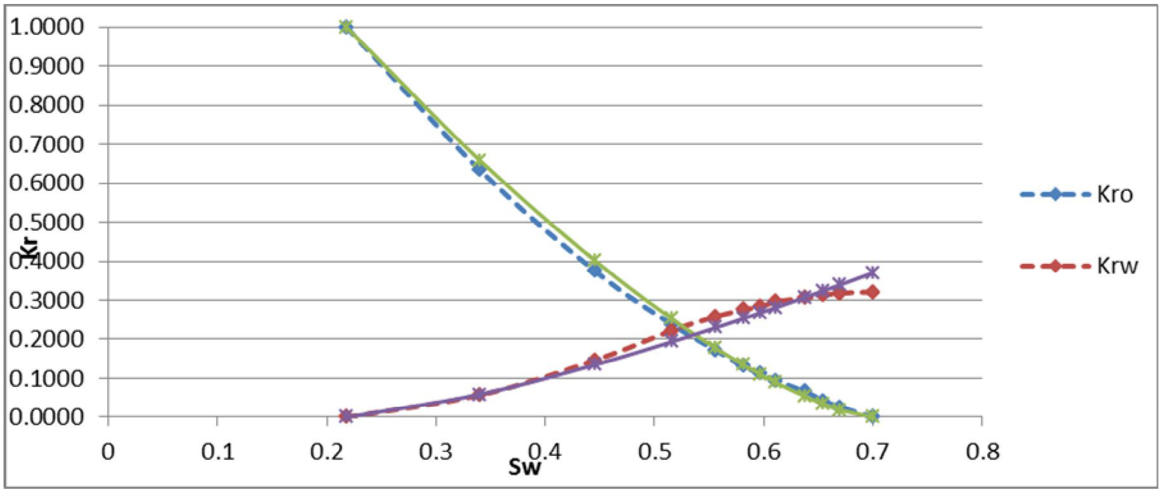


Fig (4-7): Refined K_{ro}, K_{rw} Vs S_w for Sample 1 (normal plot)

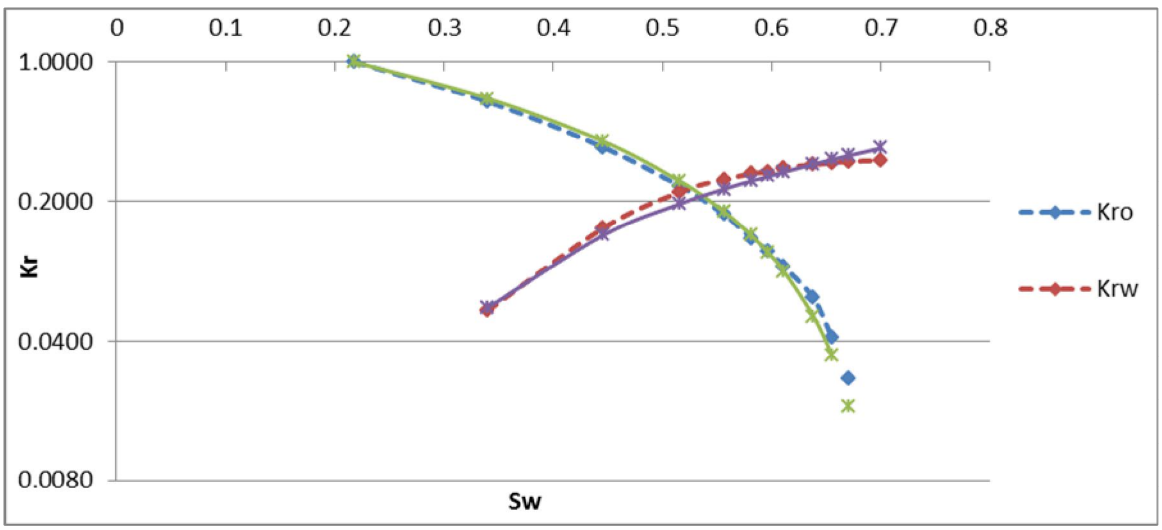


Fig (4-8): Refined K_{ro}, K_{rw} Vs. S_w for Sample 1 (inverse plot)

The Final Refined Chart

Figures (4-9) and (4-10) show the final refined plot for sample 1 and 3 respectively. From the figures it is clear that the initial water saturation for (sample 1) is about 0.218 while the S_{or} is 0.29. Also K_{ro} at S_{wi} is 1 while K_{rw} at S_{or} is 0.38. Table (4-7) summarized the final results from two samples.

Table (4-7): Final Result Data for sample 1 and 3

sample	S_{wi}	S_{or}	$K_{ro}@S_{wi}$	$K_{rw}@S_{or}$
1	0.218	0.29	1	0.38
3	0.296	0.26	1	0.169

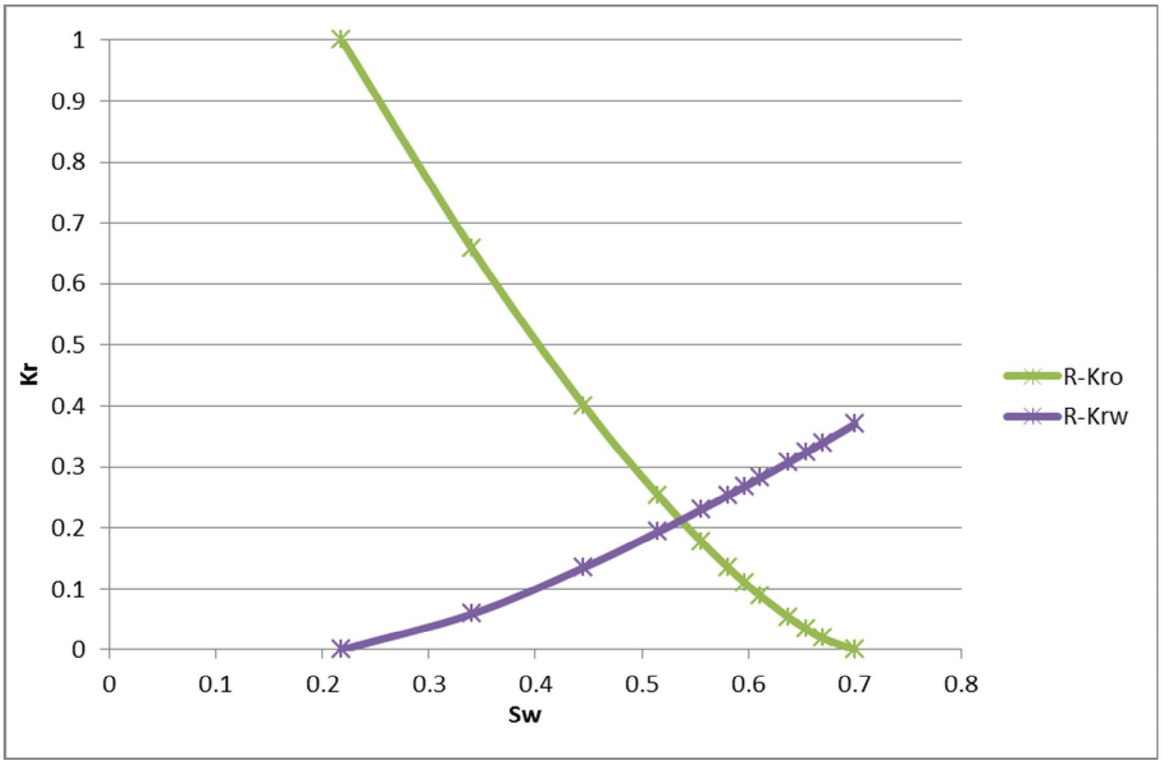


Fig (4-9): the Final Refined K_{ro}, K_{rw} Vs. S_w (Sample 1)

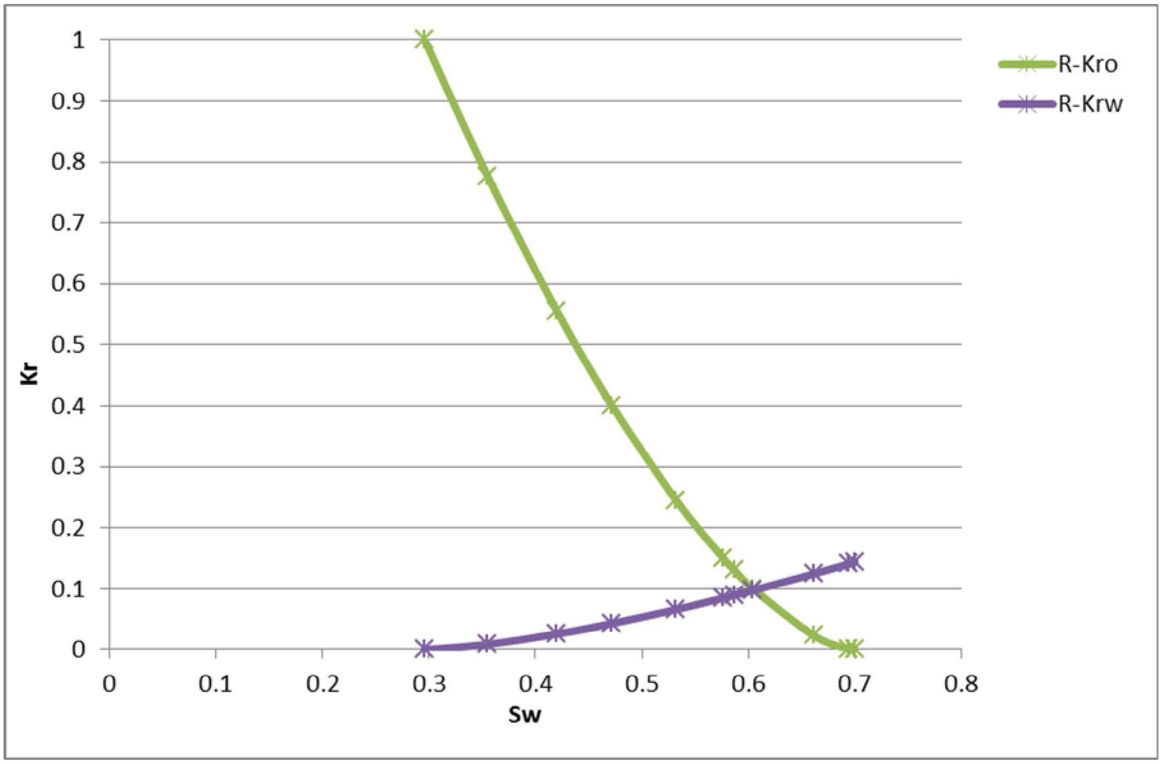


Fig (4-10): the final refined K_{ro}, K_{rw} Vs S_w (Sample 3)

4-2-2-1 Average Relative Permeability for Sample 1 And 3

As mentioned above, sample 1 and 3 representative of unsteady state test and the end points for the curve are not the same therefore normalize and de-normalize for sample 1 and 3 are needed. The procedure and equations that mentioned in chapter 3 and the data in table (4-8) were used.

Table (4-8): Reservoir Data for sample 1 and 3

sample	Depth	Zone name	Porosity	Permeability (md)
1	1471.3	Ben	22.6	641
3	1474.05	Ben	22	41.49

➢ ***Step One :***

Normalized Real Permeability curve S_w* ,K_{ro}* and K_{rw}* was calculated (Table 4-9 and 4-10)

Table (4-9): Calculated S_w*, K_{ro}* & K_{rw}* (sample 1)

		Sample: 1			
S_w	R-K_{ro}	R-K_{rw}	S_w*	K_{ro}*	K_{rw}*
21.800	1.00000	0.000	0.000	1.000	-
34.010	0.6519	0.061	0.253	0.652	0.1655
44.5600	0.3940	0.138	0.472	0.394	0.3742
51.5600	0.24837	0.197	0.617	0.248	0.5317
55.63000	0.17461	0.233	0.702	0.175	0.6289
58.10000	0.13426	0.255	0.753	0.134	0.6897
59.66000	0.111	0.270	0.785	0.111	0.7288
61.10000	0.090	0.283	0.815	0.090	0.7654
63.8000	0.056	0.309	0.871	0.056	0.8350
65.4700	0.038	0.325	0.906	0.038	0.8787
67.0000	0.023	0.340	0.938	0.023	0.9193
71.0000	0.000	0.380	1.000	0.000	1.0000

Table (4-10): Calculated S_w*, K_{ro}* & K_{rw}* (sample 3)

		Sample: 3			
S_w	R-K_{ro}	R-K_{rw}	S_w*	K_{ro}*	K_{rw}*
29.6	1.00000	0.000	0.000	1.000	-
35.5	0.75512	0.003	0.1329	0.7551	0.0177
42.0	0.52457	0.013	0.2793	0.5246	0.0780
47.2	0.36990	0.027	0.3964	0.3699	0.1571
53.2	0.22451	0.048	0.5315	0.2245	0.2825
57.6	0.15032	0.085	0.6315	0.1399	0.3988
58.7	0.13023	0.089	0.6932	0.0975	0.4806
60.4	0.09750	0.081	0.8236	0.0328	0.6784
66.2	0.03276	0.115	0.8964	0.0115	0.8035
69.4	0.01149	0.136	0.9302	0.0700	0.8652
70.9	0.07000	0.146	0.9550	0.0022	0.9119
72.0	0.00223	0.154	1.0000	0.0000	1.0000
74.0	0.00000	0.169	0.6932	0.0975	0.4806

- ***Step two :***

Normalized curves were averaging in figure (4-11):

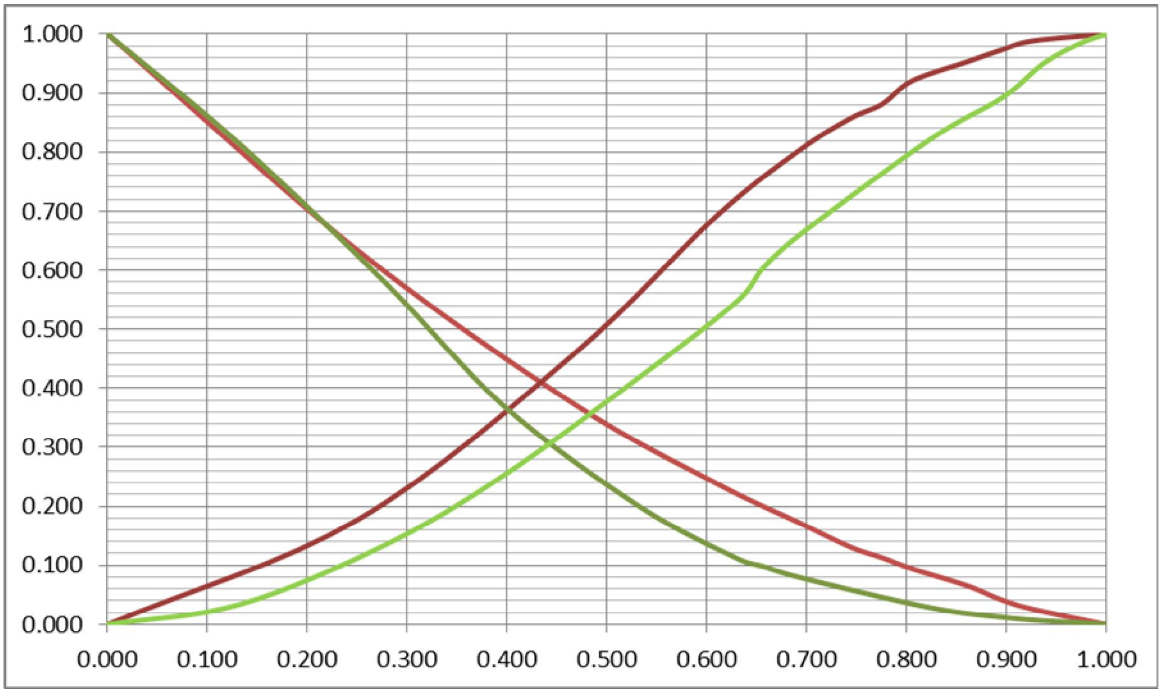


Fig (4-11): Normalized Curve for Samples 1 and 3

- ***Step 3:***

De-normalizing data: Table 4-11 and figure 4-12 show the final de-normalized relative permeability data

Table (4-11): The Final De-Normalized Relative Permeability Data (Sample 1 And 3)

S_w	K_{ro}	K_{rw}
0.304	1.000	0.000
0.351	0.658	0.057
0.397	0.402	0.131
0.444	0.256	0.187
0.491	0.178	0.223
0.538	0.135	0.247
0.585	0.111	0.261
0.631	0.091	0.275
0.678	0.055	0.303
0.725	0	0.367

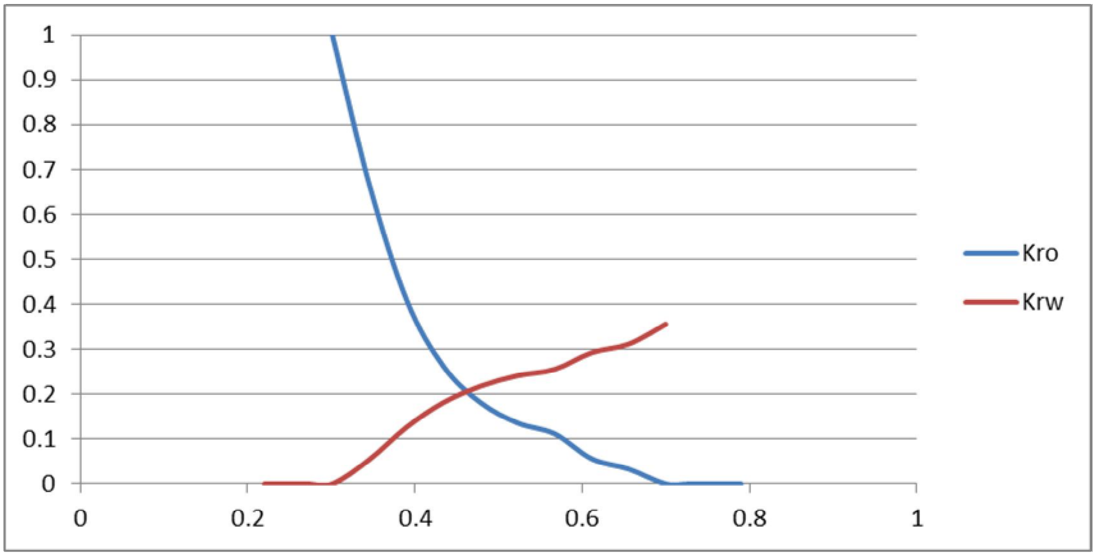


Fig (4-12): De- Normalized K_{ro}, K_{rw} Vs. S_w (Sample 1 and 3)

From the figure above; it is clear that the initial water saturation for unsteady state test is about 0.301 while the residual oil saturation is about 0.275 and the water relative permeability at S_{or} is 0.367. Table 4.12 summarized the data for two unsteady state test.

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Table (4-12): Relative Permeability data final Results

Property /Formation	sample 1	Sample 3	Average
S_{wi}	0.218	0.296	0.301
S_{or}	0.29	0.26	0.275
K_{ro} @ S_{wi}	1	1	1
K_{rw} @ S_{or}	0.38	0.169	0.367

4-3 Centrifuge Relative Permeability:

The data from the laboratory was measurments by capillary pressure and it need to change the data to relative permeability .To do that there are six steps to normalize and remove the error are coming from the experiments.

4-3-1The Available Lab Data:

There are two samples laboratory data from the same formations available for this study. The below tables below show these data.

Table (4-13) : Data of Centrifuge Samples

Sample No.	Depth (metres)	K_g (mD)	Porosity (%)
2	1471.45	1096	21.8
4	1475.47	292	22.0

Table (4 -14) : Drainage of Centrifuge Capillary Pressure

Sample No.	Brine Saturation (% Pore Space) at Capillary Pressure (psi)								
	Drainage								
	0	1	5	10	25	50	100	201	300
2	100	68.8	50.3	39.1	31.1	25.7	21.8	19.2	17.4
4	100	84.5	71.2	54.6	38.6	31.4	27.6	25.3	24.5

Table (4 -15) : Imbibition of Centrifuge Capillary Pressure

Sample No.	Brine Saturation (% Pore Space) at Capillary Pressure (psi)								
	Imbibition								
	-0	-1	-5	-10	-25	-50	-100	-201	-300
2	25	39.5	46.1	52.0	57.8	62.0	64.9	67.6	69.4
4	17	33.2	42.4	51.1	55.4	58.9	61.0	63.1	64.6

To get the relative permeability data from this samples the general procedure described in chapter 3 was used. Table (4-16) below shows centrifuge relative permeability laboratory data for the 2 Samples calculated using equation (3-12) and (3-13) .

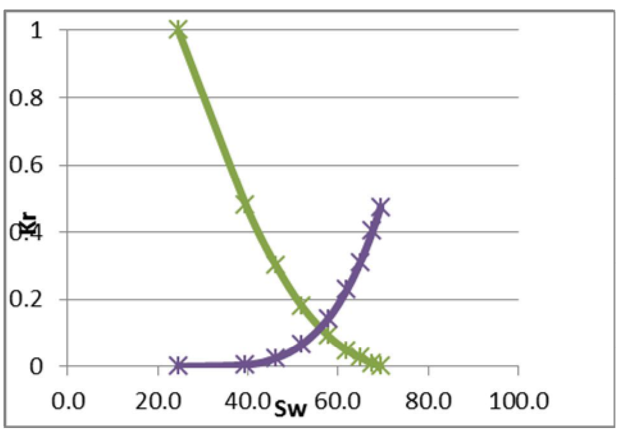
Table (4-16): Centrifuge Relative Permeability Laboratory Data for sample 2 and 4

SAMPLE : 2		
S_w	K_{ro}	K_{rw}
17.4	1.000	0.000
33.2	0.438	0.009
42.4	0.205	0.054
51.1	0.070	0.179
55.4	0.033	0.290
58.9	0.014	0.412
61.0	0.007	0.502
63.1	0.001	0.606
64.6	0.000	0.689

SAMPLE : 4		
S_w	K_{ro}	K_{rw}
24.5	1.000	0.000
39.5	0.482	0.006
46.1	0.303	0.025
52.0	0.179	0.067
57.8	0.092	0.144
62.0	0.049	0.231
64.9	0.028	0.311
67.6	0.009	0.403
69.4	0.000	0.474

4-3-2 Centrifuge Relative Permeability Results and Discussion

Using the calculation procedures that described in chapter 3; figure (4-13) and (4-14) show the relationship between water saturation and relative permeability for the 2 samples.



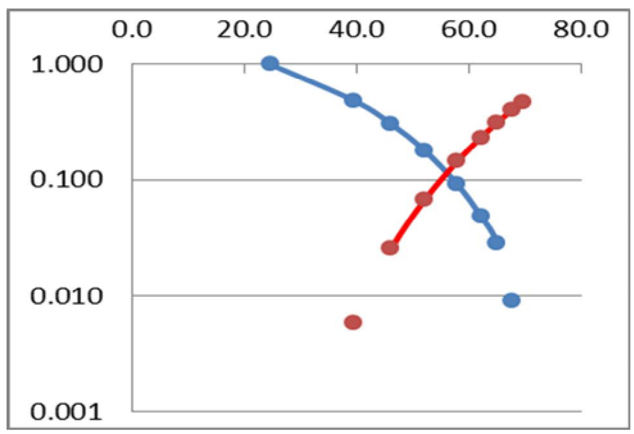
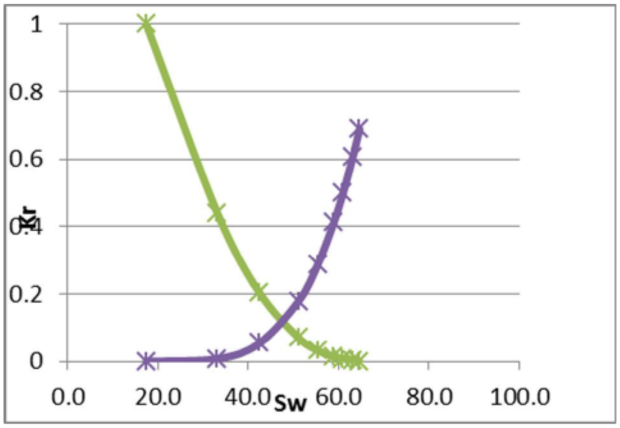


Fig (4-13): S_w vs. K_r Laboratory Data for Sample 2 (Linear and Semi-log Scale)



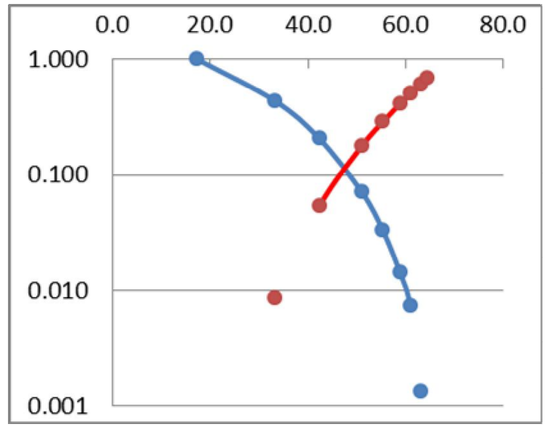


Fig (4-14): S_w vs. K_r Laboratory Data for Sample 4 (Linear and Semi-log Scale)

True Residual Oil Saturation (S_{or})

To get the correct S_{or} for the two samples the general procedure described in chapter 3 was used. Table 4-17 below shows calculated normalize Oil Saturation (S_{on}) using equation 3-9 for three values of S_{or} (the lab value (0.354), 0.3 and 0.36). Figure 4-15 and 4 -16 show the plot of the different S_{or} and relative permeability data plot using the true S_{or} respectively for sample 2. The same tables and figures for sample 4 in the appendix A.

Table (4-17): S_{on} Calculated from S_{or} (Sample 2)

S_{wi}	0.174				
S_{or}	0.354	0.36	0.3	0.2	
S_w	S_{on1}	S_{on2}	S_{on3}	S_{on4}	K_{ro}
0.174	1.000	1.000	1.000	1.000	1.000
0.332	0.665	0.661	0.700	0.748	0.438
0.424	0.470	0.464	0.525	0.601	0.205
0.511	0.286	0.277	0.359	0.462	0.070
0.554	0.195	0.185	0.278	0.393	0.033
0.589	0.121	0.109	0.211	0.337	0.014
0.61	0.076	0.064	0.171	0.304	0.007
0.631	0.032	0.019	0.131	0.270	0.001

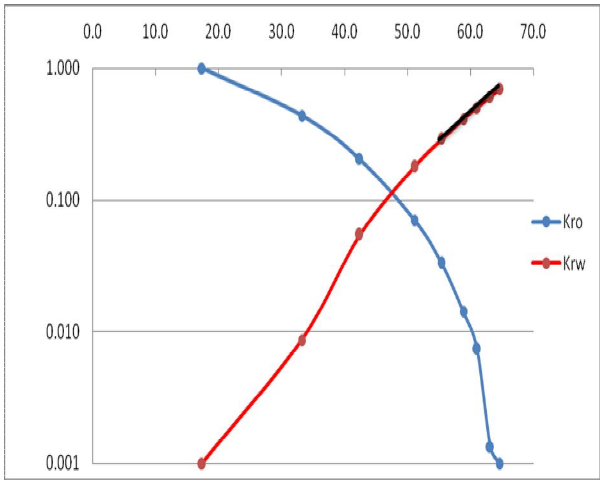


Fig (4-15): K_r vs. S_w (True S_{or})–Sample 2

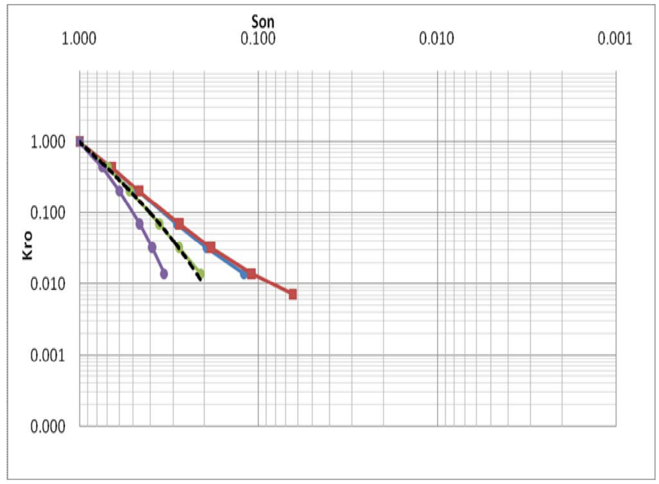


Fig (4-16): Different S_{or} (Sample 2)

Normalized Water Saturation (S_{wn})

As described in chapter 3, Table (4-18) below shows the S_{wn} that equivilant to the true S_{or} and figure 4-17 show the relationship between K_{rw} and S_{wn} for sample 2 as an example, the same tables and plots for sample 4 in appendix B. From figure 4-17 it is clear that the real water end point (true S_{or}) at S_{wn} =1 is 1.0.

Table (4-18): S_{wn} from True S_{or} (Sample 2)

S_{wi}	0.174
S_{or}	0.3

S_w	S_{wn}	K_{rw}
0.174	0	0.000
0.332	0.30038	0.009
0.424	0.475285	0.054
0.511	0.640684	0.179
0.554	0.722433	0.290
0.589	0.788973	0.412
0.61	0.828897	0.502
0.631	0.868821	0.606
0.646	0.897338	0.689

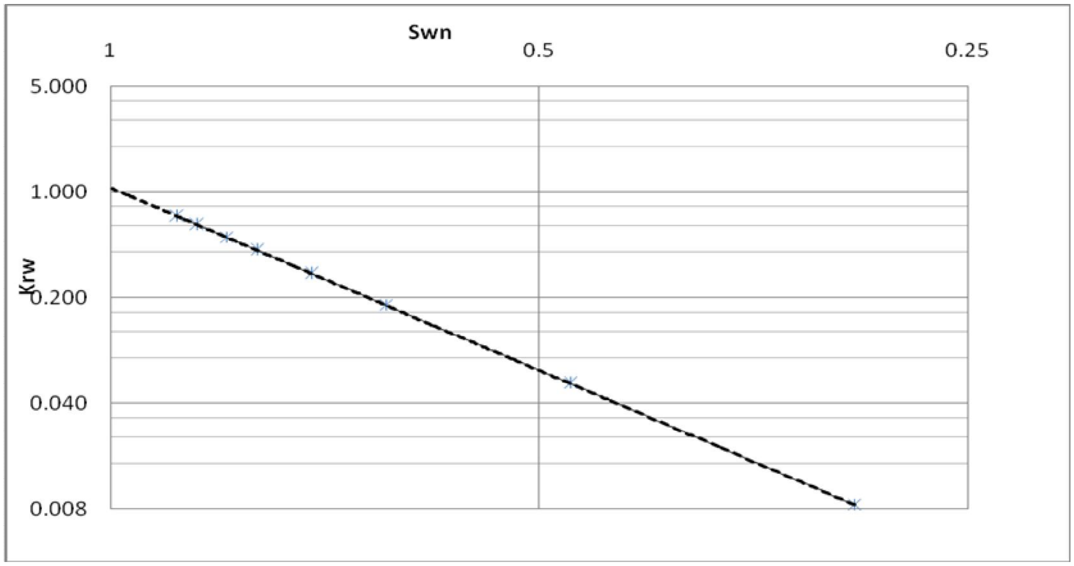


Fig (4-17) : K_{rw} vs S_{wn} (Sample 2)

Corey Exponents

Corey exponents for oil (No) and water (Nw) were calculated Table (4.19) then No and Nw vs. S_w for sample 2 was plotted in figure (4-18). The tables and figures for the other sample were summarized in appendix C.

Data for sample 2:

Table (4- 19) :Corey Exponent for Oil and Water (Sample 2)

S_{wi}	0.174	K_{rw}*	1.0
S_{or}	0.3		

S_w	S_{wn}	K_{rw}	N_w
0.174	0	0.000	
0.332	0.30	0.009	3.99
0.424	0.47	0.054	3.99
0.511	0.64	0.179	3.99
0.554	0.72	0.290	3.99
0.589	0.78	0.412	3.99
0.61	0.82	0.502	3.99
0.631	0.86	0.606	3.99
0.646	0.89	0.689	3.99
			4.0

S_{on3}	K_{ro}	No
1.0	1.0	
0.70	0.44	2.311
0.53	0.21	2.45
0.34	0.07	2.59
0.28	0.03	2.66
0.21	0.01	2.73
0.17	0.01	2.78
0.13	0.0	3.25
		2.69

No line	Nw line
2.6	3.99
2.6	3.99
2.6	3.99
2.6	3.99
2.6	3.99
2.6	3.99
2.6	3.99
2.69	3.99

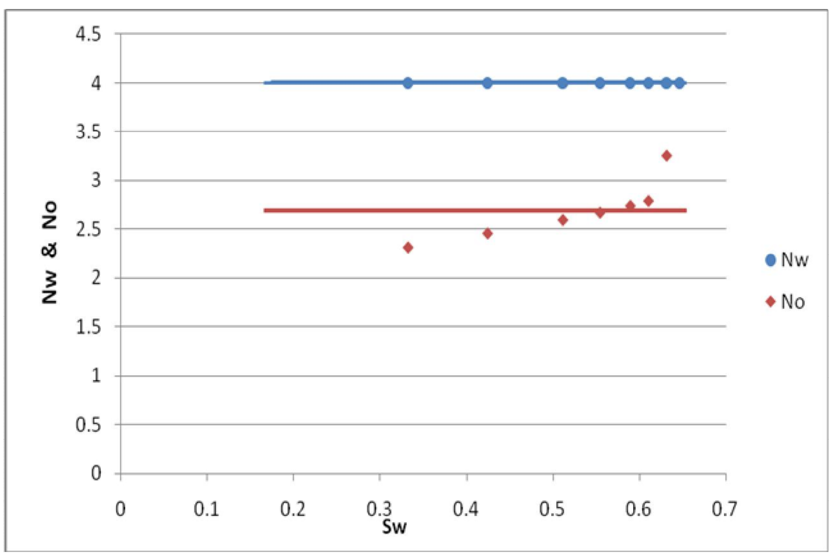


Fig (4-18): Nw , No Vs S_w (Sample 2)

Refining Relative Permeability Data

Refined (corrected) K_r was calculated and compared with the lab data. Table (4-20) shows the calculation of refined relative permeability for sample 2. Figure (4-19) and (4-20) show the refine relative permeability vs. water saturation for sample 2. The calculation tables and figures for the other sample in the appendix D.

Table (4-20): Refining Relative Permeability (Sample 2)

Lab RealPerm							Refined RealPerm	
S_w	K_{ro}	K_{rw}		S_w	S_{wn}	S_{on3}	R-K_{ro}	R-K_{rw}
17.4	1.000	0.000		0.174	0	1.000	1.0000	0
33.2	0.438	0.009		0.332	0.30	0.700	0.3825	0.01
42.4	0.205	0.054		0.424	0.475	0.525	0.1764	0.054
51.1	0.070	0.179		0.511	0.64	0.359	0.0637	0.179
55.4	0.033	0.290		0.554	0.72	0.278	0.0318	0.289
58.9	0.014	0.412		0.589	0.78	0.211	0.0152	0.411
61.0	0.007	0.502		0.61	0.82	0.171	0.0087	0.501
63.1	0.001	0.606		0.631	0.868	0.131	0.0042	0.605
64.6	0.000	0.689		0.646	0.89	0.103	0.0022	0.689
				0.7	1	0.000	0.0000	1.0

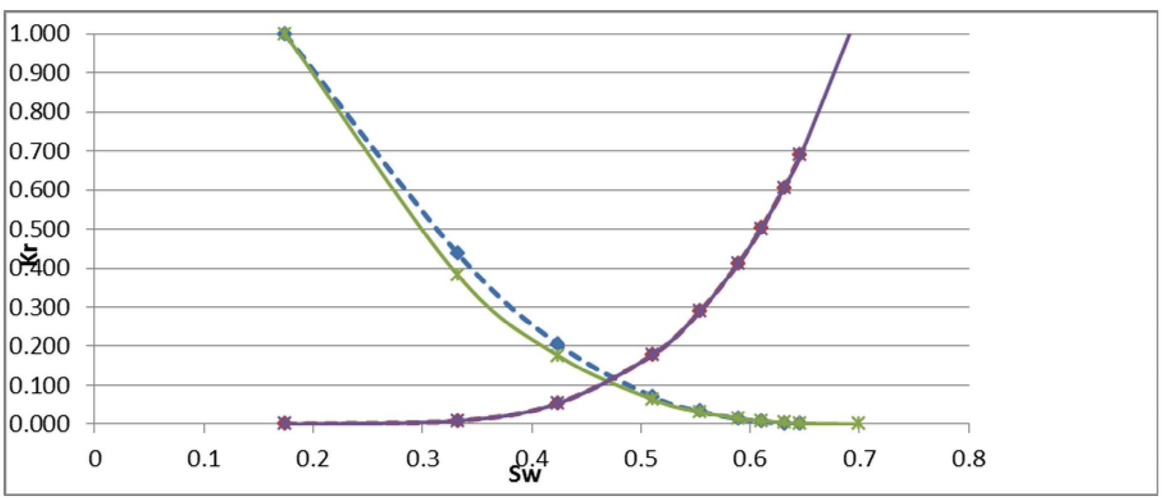


Fig (4-19): Refined K_{ro}, K_{rw} Vs S_w for Sample 2 (normal plot)

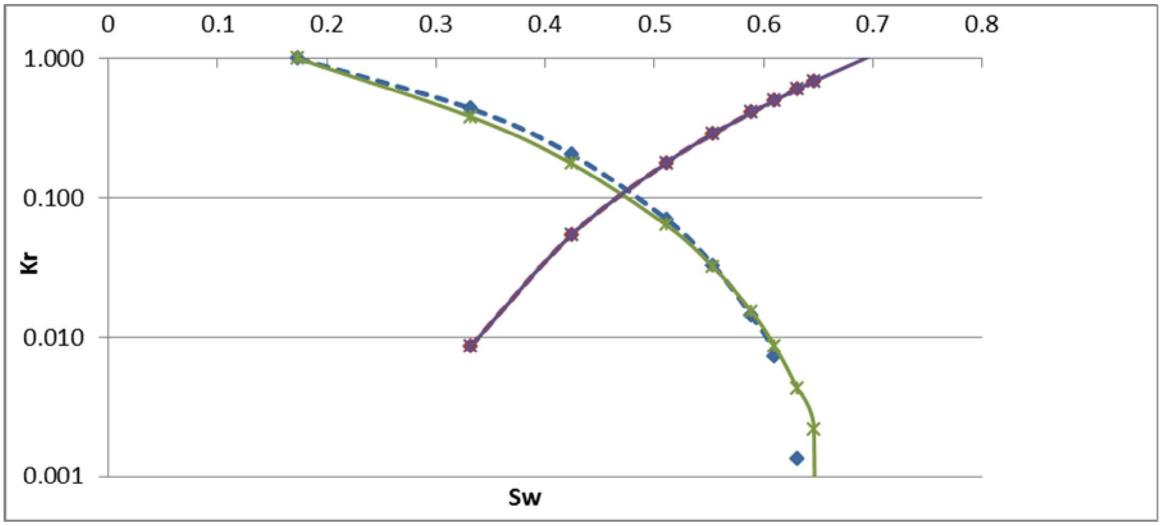


Fig (4-20): Refined K_{ro}, K_{rw} Vs. S_w for Sample 2 (inverse plot)

The Final Refined Chart

Figures (4-21) and (4-22) show the final refined plot for sample 2 and 4 respectively. From the figures it is clear that the initial water saturation for (sample 2) is about 0.174 while the Sor is 0.3%. Also K_{ro} at S_{wi} is 1 while K_{rw} at S_{or} is 1.0. Table (4-21) summarized the final results from two samples.

Table (4-21): Final Result Data for sample 2 and 4

Sample	S_{wi}	S_{or}	K_{ro}@S_{wi}	K_{rw}@s_{or}
2	0.174	0.30	1.0	1.0
4	0.245	0.30	1.0	0.50

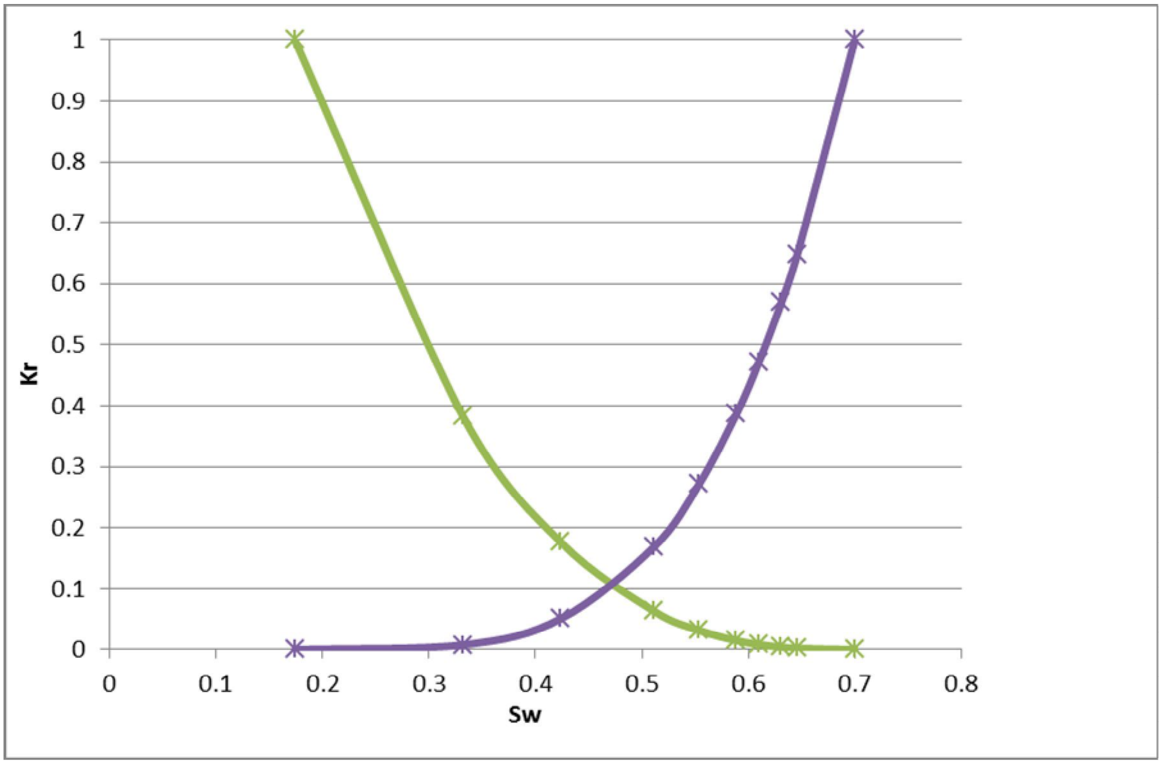


Fig (4-21): The Final Refined K_{ro}, K_{rw} Vs. S_w (Sample 2)

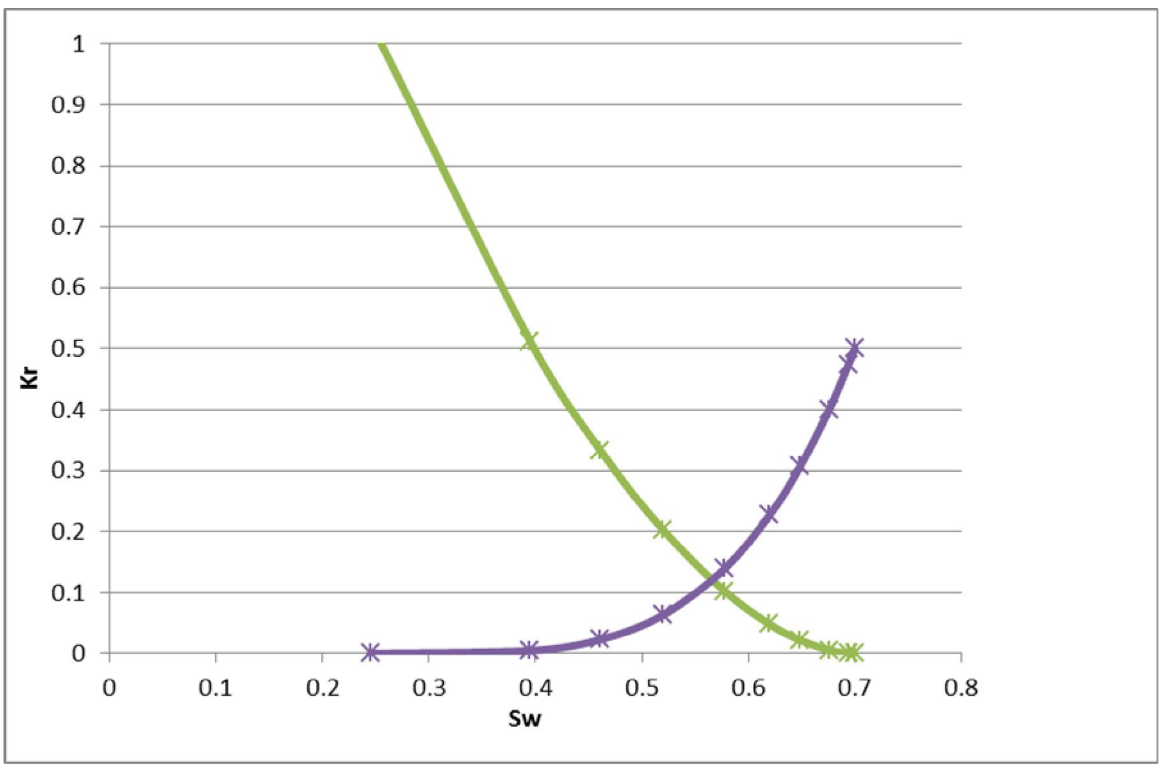


Fig (4-22): The Final Refined K_{ro}, K_{rw} Vs S_w (Sample 4)

4-3-2-1 Average Relative Permeability for Sample 2 And 4

As mentioned above, sample 2 and 4 representative of centrifuge test and the end points for the curve are not the same therefore normalize and de-normalize for sample 2 and 4 are needed. The procedure and equations that mentioned in chapter 3 and the data in Table (4-22) were used.

Table (4-22): Reservoir Data for sample 2 and 4

Sample	Depth	Zone name	Porosity	Permeability (md)
2	1471.45	Ben	22.8	1096
4	1475.47	Ben	22	292

- ***Step One :***

Normalized Real Permeability curve S_w* ,K_{ro}* and K_{rw}* was calculated (Table 4-23 and 4-24).

Table (4-23): Calculated S_w*, K_{ro}* & K_{rw}* (sample 2)

		Sample: 2			
S_w	R-K_{ro}	R-K_{rw}	S_w*	K_{ro}*	K_{rw}*
17.400	1.00000	0.000	0.000	1.000	-
33.200	0.3825	0.009	0.300	0.383	0.0087
42.400	0.1764	0.054	0.475	0.176	0.0542
51.100	0.06371	0.179	0.641	0.064	0.1791
55.400	0.03182	0.290	0.722	0.032	0.2896
58.900	0.01522	0.412	0.789	0.015	0.4119
61.000	0.00866	0.502	0.829	0.009	0.5018
63.100	0.00424	0.606	0.869	0.004	0.6057
64.600	0.00219	0.689	0.897	0.002	0.6892
70.000	0.00000	1.000	1.000	0.000	1.0000

Table (4-24): Calculated S_w , K_{ro}* & K_{rw}* (sample 4)

		Sample: 4			
S_w	R-K_{ro}	R-K_{rw}	S_w*	K_{ro}*	K_{rw}*
24.500	1.00000	0.000	0.000	1.000	-
39.500	0.51232	0.005	0.330	0.512	0.0101
46.100	0.33354	0.023	0.475	0.334	0.0468
52.000	0.20251	0.064	0.604	0.203	0.1272
57.800	0.10213	0.140	0.732	0.102	0.2794
62.000	0.04860	0.227	0.824	0.049	0.4544
64.900	0.02200	0.308	0.888	0.022	0.6160
67.600	0.00584	0.401	0.947	0.006	0.8020
69.400	0.00051	0.474	0.987	0.001	0.9474
70.000	0.00000	0.500	1.000	0.000	1.0000

- ***Step two :***

Normalized curves were averaging in figure (4-23):

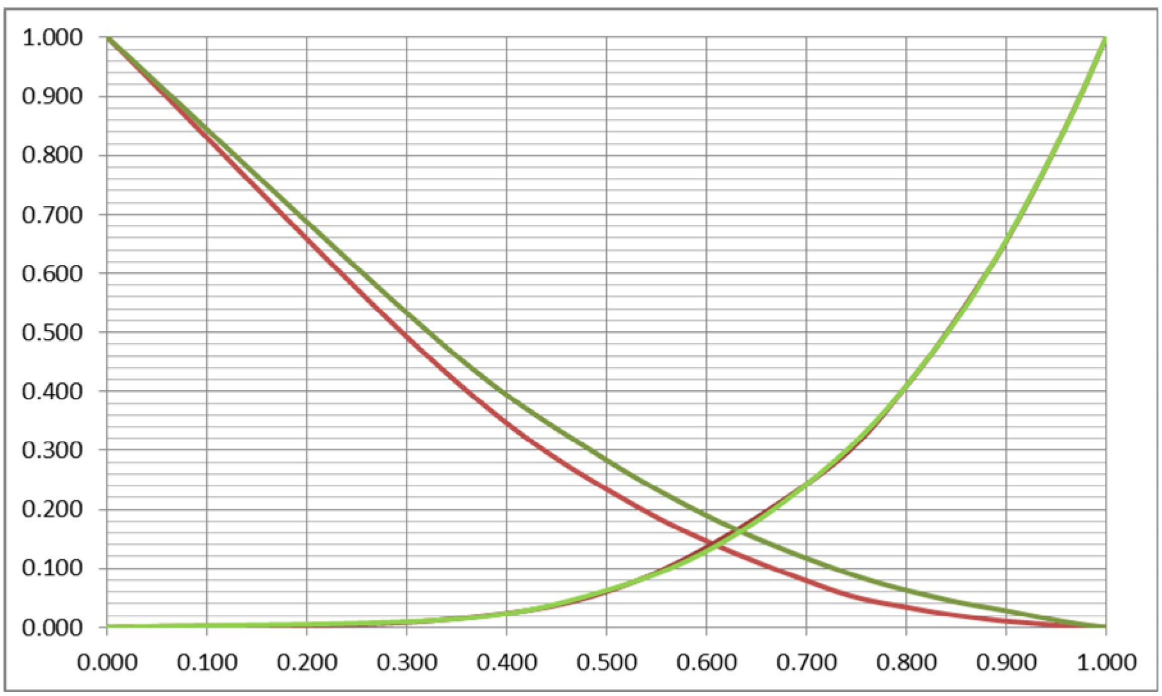


Fig (4-23): Normalized Curve for Samples 2 and 4

➢ ***Step 3:***

De-normalizing data: Table (4-25) and figure (4-24) show the final de-normalized relative permeability data

Table (4-25): The Final De-Normalized Relative Permeability Data (Sample 2 And 4)

S_w	K_{ro}	K_{rw}
0.259	1.000	0.000
0.308	0.410	0.008
0.357	0.209	0.047
0.406	0.093	0.150
0.455	0.047	0.257
0.504	0.022	0.377
0.553	0.011	0.471
0.602	0.005	0.579
0.651	0.002	0.665
0.7	0.0	0.895

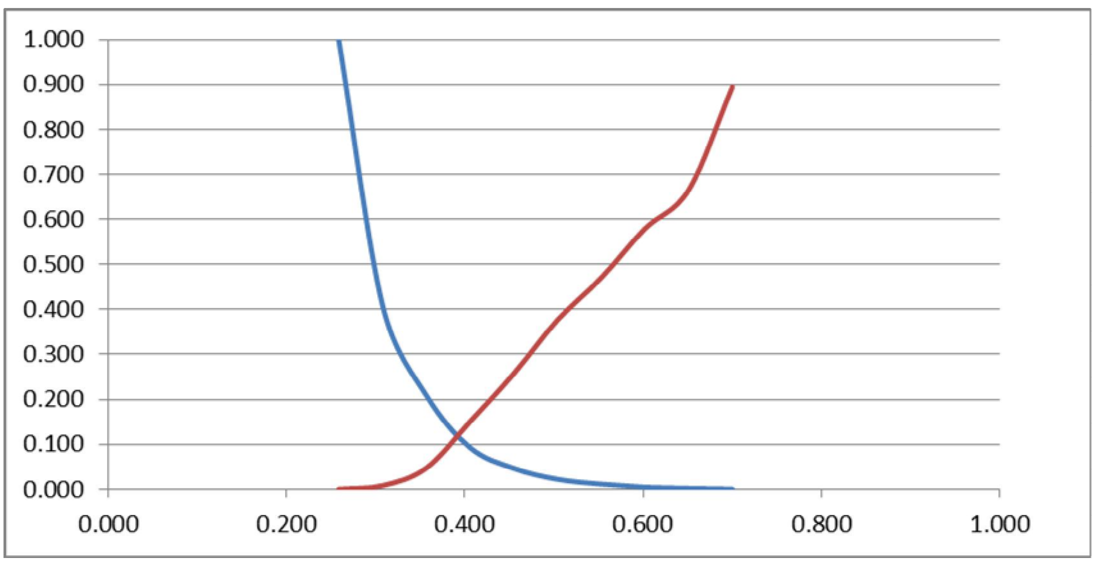


Fig (4-24): De- Normalized K_{ro}, K_{rw} Vs. S_w (Sample 2 and 4)

From the figure above; it is clear that the initial water saturation for centrifuge test is about 0.259 while the residual oil saturation is about 0.30 and the water relative permeability at S_{or} is 0.895. Table (4-26) summarized the data for two centrifuge test .

Table (4-26): Centrifuge Relative Permeability data final Results

Property/Formation	sample 2	Sample 4	Average
S_{wi}	0.174	0.245	0.259
S_{or}	0.30	0.30	0.3
K_{ro} @ S_{wi}	1	1	1
K_{rw} @ S_{or}	1.0	0.50	0.895

4-4 Summary of Result and Discussion

The final comparison between centrifuge relative permeability curves and unsteady state relative permeability curves (figure 4-25) showed a very good correlation for the non wetting phase curves and the parallel of this curve depended to different permeability , but completely different shapes of the wetting phase carve. The graphical technique implied a much higher irreducible water saturation for unsteady state than centrifuging ($S_{wir/unseady\ stat}$= 0.301 versus $S_{wir/centrifuge}$ =0.259). The difference in endpoints has a large effect on the shape of the wetting phase curve. It may be necessary to match the flow rate of centrifuge with flow rate of unsteady state and it depended on the end effect and the capillary pressure would be zero. This could be accomplished by running the centrifuge at a high speed and using the centrifuge history match model to determine an average production rate of the run. This production was used as the injection rate for the unsteady state experiment. From this result the unsteady state has a good representation for relative permeability.

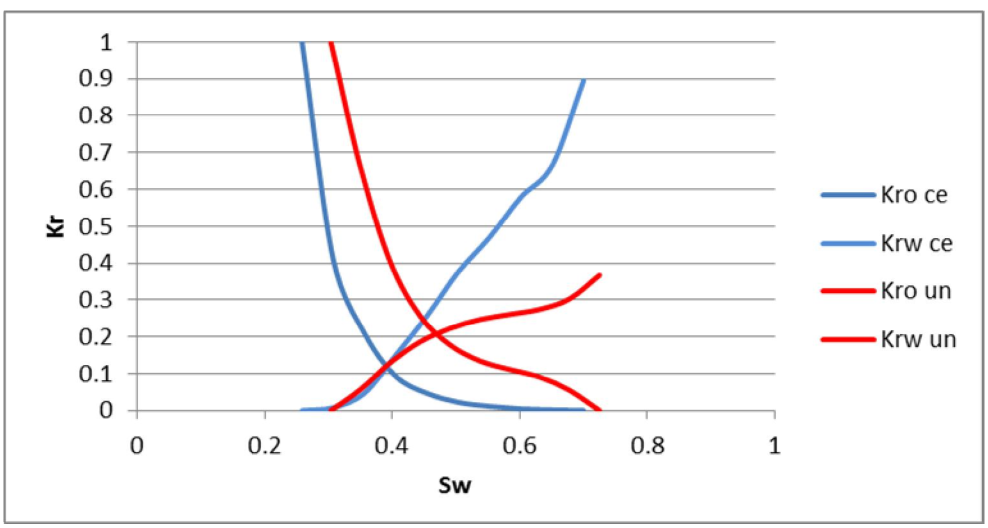


Fig (4-25): Comparison of Centrifuge vs. Unsteady state Relative Permeability

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5-1 Conclusions :

- Unsteady state and centrifuge data was obtained from the same sandstone core plugs .
- The centrifuge relative permeability was derived by Corey –Brook model.
- All relative permeability data for unsteady state and centrifuge were normalized and averaged.
- There is a correlation in the wetting phase curve between centrifuge and unsteady state..
- Comparison between unsteady state and centrifuging the nonwetting phase curves were different in both shape and irreducible wetting phase saturation endpoints (S_{wiun}= 0.301, S_{wic}=0.259) .
- The relative permeability curves effected by different permeability of plugs.
- The end effect is more important and it's influence clearly in relative permeability.
- The unsteady state has a good representation for relative permeability from this result.

5-2 Recommendations:

- The study prefer to make calibration in laboratories to be sure the result is more accurate because there are some limitation in our devices like laminar flow in Darcy's low application.
- Also there is another limitation refer to fine migration which is lead to big validity in relative permeability so it is better to do runs test to get best result.
- The study proposed measure two methods of relative permeability in one sample to determine the effecting factor.
- To overcome the end effect in unsteady state relative permeability it must increase the flow rate.
- Relative permeability system is fully computerize by selection of pumps flow rates.
- The volumes are monitored by interface which separate water from oil in visual cell is detected by camera.
- The study recommend to use X-ray because it is very sensitive to measure saturation and to avoid dead volumes calculations.

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APPENDIX A

The True Residual Oil Saturation (Sor) For Sample 3 and 4

Sample 3 :

Calculate Son from equation (3-21)

Table (A-1): Son Calculated from Sor (Sample 3)

Swi	0.296			
Sor	0.294	0.36	0.26	0.2

Sw	S_{on1}	S_{on2}	S_{on3}	S_{on4}	Kro
0.296	1.000	1.000	1.000	1.000	1.000
0.355	0.867	0.828	0.867	0.883	0.813
0.42	0.721	0.640	0.721	0.754	0.577
0.472	0.604	0.488	0.604	0.651	0.371
0.532	0.468	0.314	0.468	0.532	0.201
0.5764	0.368	0.185	0.368	0.444	0.111
0.587	0.345	0.154	0.345	0.423	0.099
0.6038	0.307	0.105	0.307	0.389	0.079
0.6617	0.176	-0.063	0.176	0.274	0.028
0.694	0.104	-0.157	0.104	0.210	0.012
0.712	0.063	-0.209	0.063	0.175	0.006
0.729	0.025	-0.259	0.025	0.141	0.003
0.74	0.000	-0.291	0.000	0.119	0.000

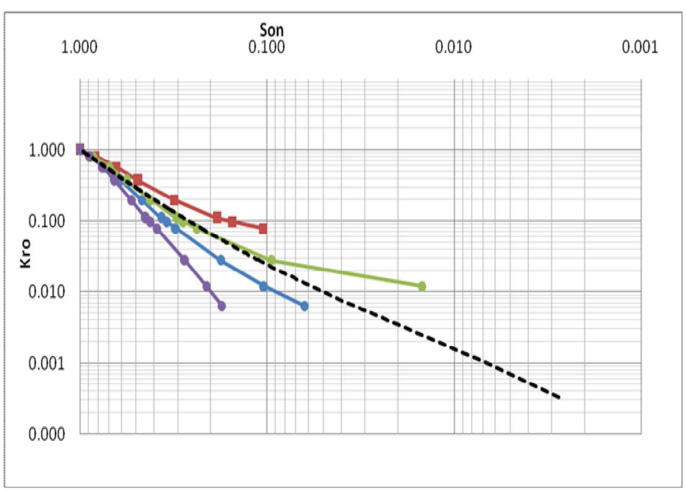

Fig (A-1): Different Sor (Sample 3)

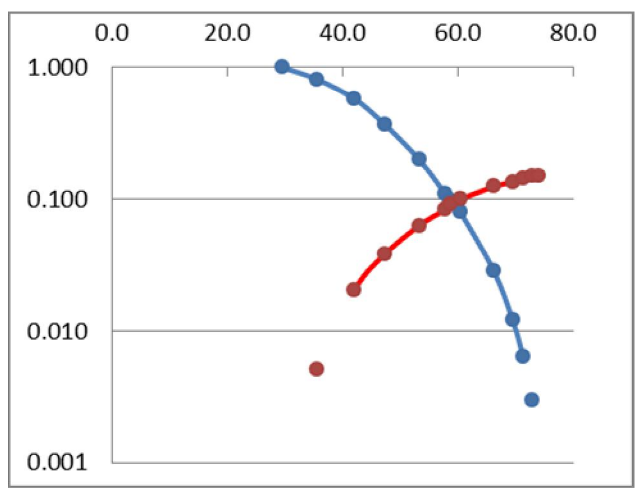

Fig (A-2):Kr vs Sw(True Sor) Sample 3

- **In figure (A.1) the true Sor (0.26) appears almost as straight line.**

Sample 4 :

Calculate Son from equation(3-21)

Table (A.2): Son Calculated from Sor (Sample 4)

Swi	0.245			
Sor	0.306	0.36	0.3	0.2

Sw	S_{on1}	S_{on2}	S_{on3}	S_{on4}	Kro
0.245	1.000	1.000	1.000	1.000	1.000
0.395	0.666	0.620	0.670	0.730	0.482
0.461	0.519	0.453	0.525	0.611	0.303
0.52	0.388	0.304	0.396	0.505	0.179
0.578	0.258	0.157	0.268	0.400	0.092
0.62	0.165	0.051	0.176	0.324	0.049
0.649	0.100	-0.023	0.112	0.272	0.028
0.676	0.040	-0.091	0.053	0.223	0.009
0.694	0.000	-0.137	0.013	0.191	0.000

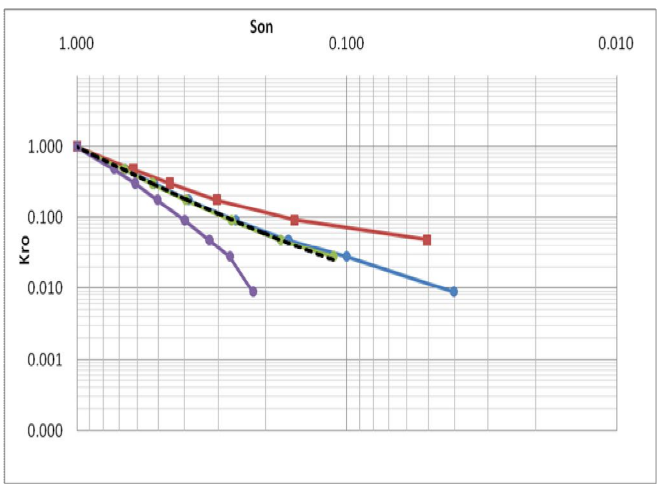

Fig (A-3): Different Sor (Sample 4)

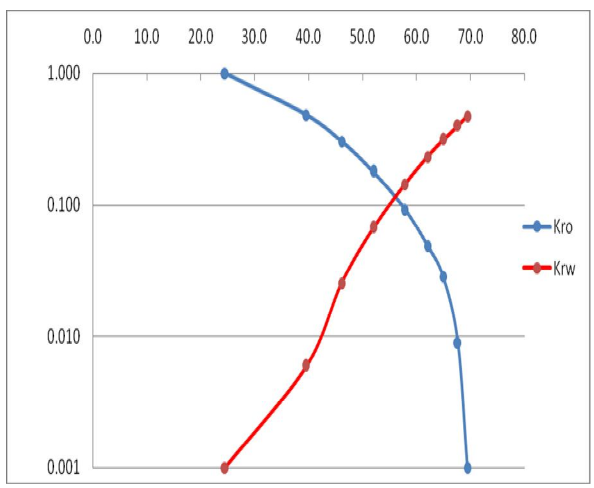

Fig (A-4)Kr vs.Sw(True Sor)–Sample 4

- **In figure (A-3) the true Sor (0.3) appears almost as straight line.**

APPENDIX B

Normalized Water Saturation (Swn) For Sample 3 and 4

<u>Sample 3 :</u>

Table (B-1): Swn from True Sor (Sample 3)

Swi	0.296
Sor	0.26

Sw	Swn	Krw
0.296	1.25E-16	0.000
0.355	0.132883	0.005
0.42	0.279279	0.021
0.472	0.396396	0.038
0.532	0.531532	0.063
0.5764	0.631532	0.083
0.587	0.655405	0.091
0.6038	0.693243	0.100
0.6617	0.823649	0.124
0.694	0.896396	0.135
0.712	0.936937	0.144
0.729	0.975225	0.149
0.74	1	0.151

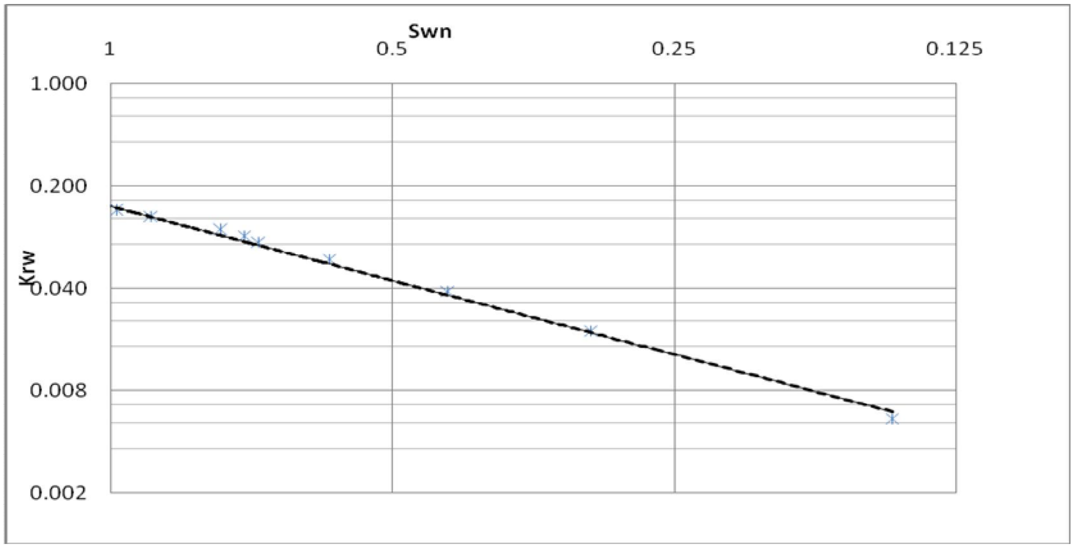

Fig (B-1) : Krw vs Swn (Sample 3)

*The Real water end point (true Sor) @ Swn =1 is 0.169

Sample 4 :

Table (B-2): Swn from True Sor (Sample 4)

Swi	0.296
Sor	0.3

Sw	Swn	Krw
0.245	0	0.000
0.395	0.32967	0.006
0.461	0.474725	0.025
0.52	0.604396	0.067
0.578	0.731868	0.144
0.62	0.824176	0.231
0.649	0.887912	0.311
0.676	0.947253	0.403
0.694	0.986813	0.474

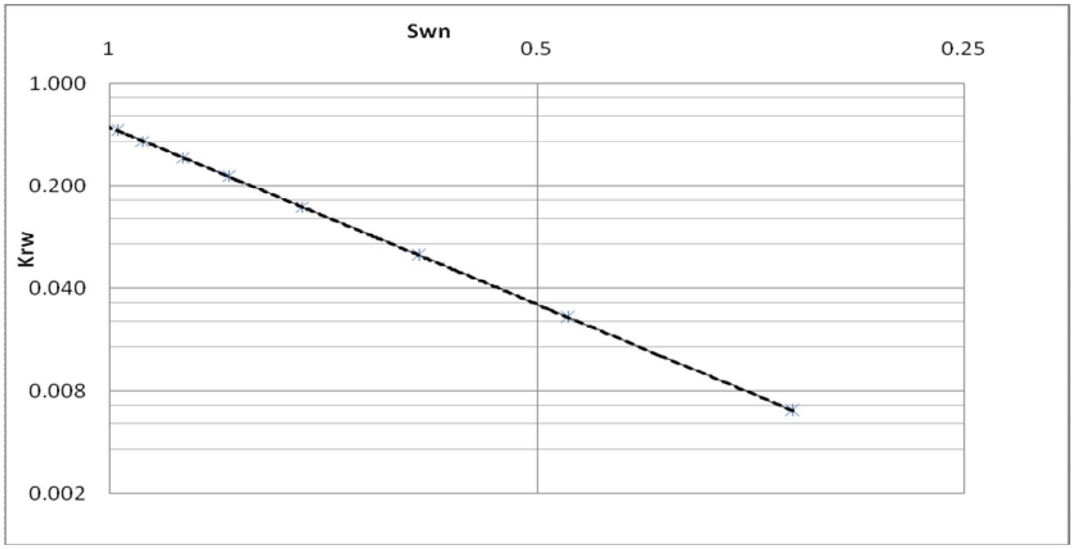

Fig (B-2) : Krw vs Swn (Sample 4)

*The Real water end point (true Sor) @ Swn =1 is 0.5

APPENDIX C

Corey Exponents

Sample 3 :

Table (C-1) :Corey Exponent for Oil and Water (Sample 3)

Swi	0.296	Krw*	0.169
Sor	0.26		

Sw	Swn	Krw	Nw
0.296	1.2E-16	0.000	
0.355	0.132	0.005	1.73
0.42	0.279	0.021	1.65
0.472	0.396	0.038	1.60
0.532	0.53	0.063	1.55
0.5764	0.63	0.083	1.54
0.587	0.655	0.091	1.45
0.6038	0.693	0.100	1.43
0.6617	0.823	0.124	1.57
0.694	0.896	0.135	2.03
0.74	1	0.151	
			2.0

S_{on3}	Kro	No
1.000	1.00	
0.867	0.81	1.453
0.721	0.57	1.680
0.604	0.37	1.965
0.468	0.20	2.116
0.368	0.11	2.202
0.345	0.09	2.172
0.307	0.07	2.143
0.176	0.02	2.05
0.104	0.01	1.94
		1.97

No line	Nw line
1.99	2.0
1.99	2.0
1.99	2.0
1.99	2.0
1.99	2.0
1.99	2.0
1.99	2.0
1.99	2.0
1.99	2.0

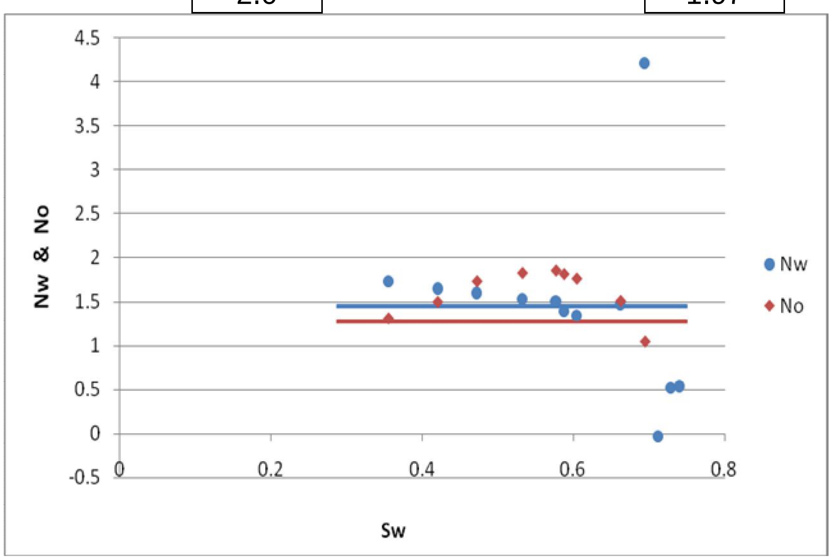

Fig (C-1): Nw , No Vs Sw (Sample 3)

<u>Sample 4 :</u>

Table (C-2) :Corey Exponent for Oil and Water (Sample 4)

Swi	0.245	Krw*	0.5
Sor	0.3		

Sw	Swn	Krw	Nw
0.245	0	0.000	
0.395	0.329	0.006	3.99
0.461	0.474	0.025	3.99
0.52	0.604	0.067	3.99
0.578	0.731	0.144	3.99
0.62	0.824	0.231	3.99
0.649	0.887	0.311	3.99
0.676	0.947	0.403	3.98
0.694	0.986	0.474	3.95
			3.99

S_{on3}	Kro	No
1.000	1.0	
0.670	0.48	1.82
0.525	0.3	1.85
0.396	0.17	1.85
0.268	0.09	1.81
0.176	0.04	1.73
0.112	0.028	1.62
0.053	0.009	1.60
		1.76

No line	Nw line
1.75	3.99
1.75	3.99
1.75	3.99
1.758	3.99
1.75	3.99
1.75	3.99
1.75	3.99
1.75	3.99
1.75	3.99

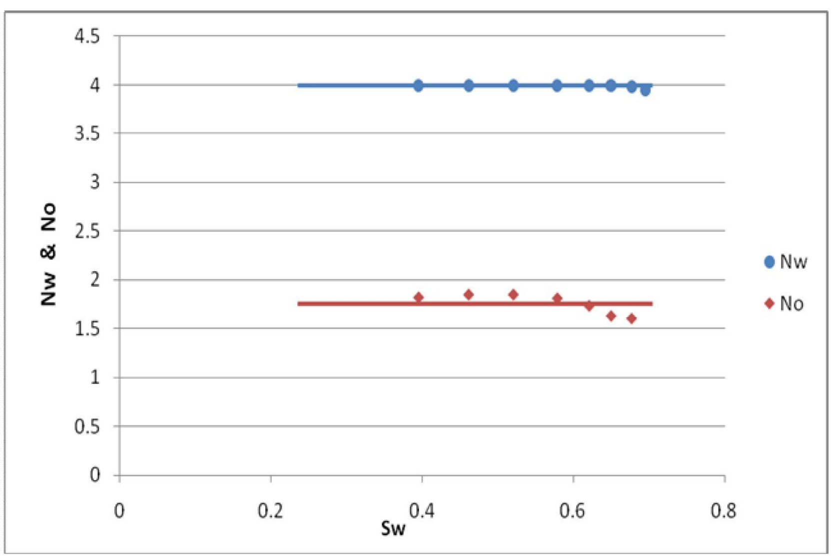

Fig (C-2): Nw , No Vs Sw (Sample 4)

APPENDIX D

Refining Relative Permeability

Sample 3 :

Table (D-1): Refining Relative Permeability (Sample 3)

Swi	0.296	Krw*	0.169	No	1.97
Sor	0.26			Nw	2.0

Lab RealPerm		
Sw	Kro	Krw
29.6	1.000	0.000
35.5	0.813	0.005
42.0	0.577	0.021
47.2	0.371	0.038
53.2	0.201	0.063
57.6	0.111	0.083
58.7	0.099	0.091
60.4	0.079	0.100
66.2	0.028	0.124
69.4	0.012	0.135
71.2	0.006	0.144

			Refined RealPerm	
Sw	Swn	Son3	R-Kro	R-Krw
0.296	1.25E-16	1.000	1.0000	0
0.355	0.132	0.867	0.7551	0.0029
0.42	0.279	0.721	0.5246	0.013
0.472	0.396	0.604	0.3699	0.026
0.532	0.53	0.468	0.2245	0.047
0.5764	0.63	0.368	0.1399	0.067
0.587	0.65	0.345	0.1226	0.072
0.6038	0.693	0.307	0.0975	0.08
0.6617	0.823	0.176	0.0328	0.116
0.72	0.954	0.045	0.0022	0.154
0.74	1	0.000	0.0000	0.169

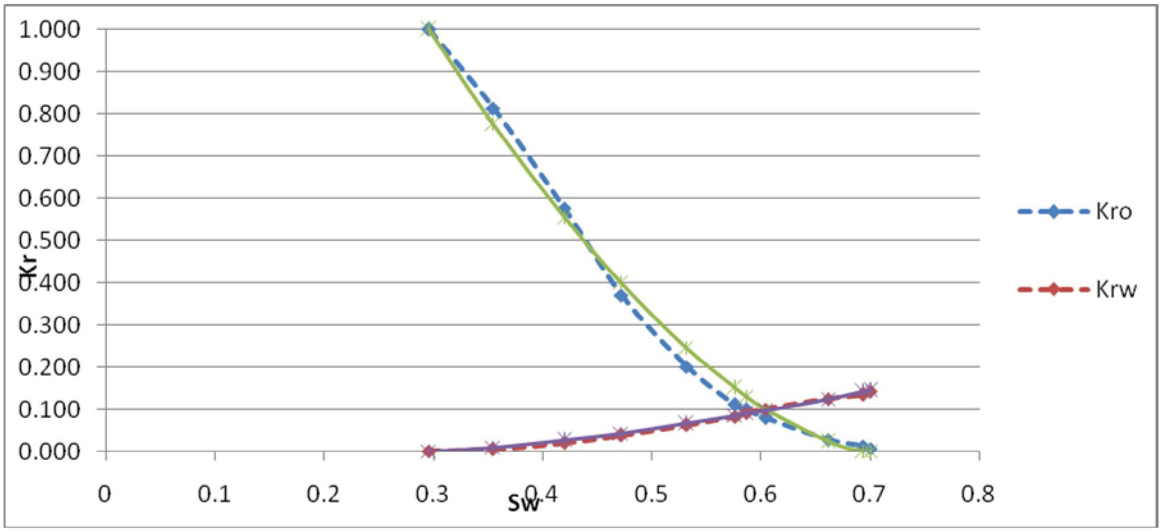

Fig (D-1): Refined Kro, Krw Vs Sw

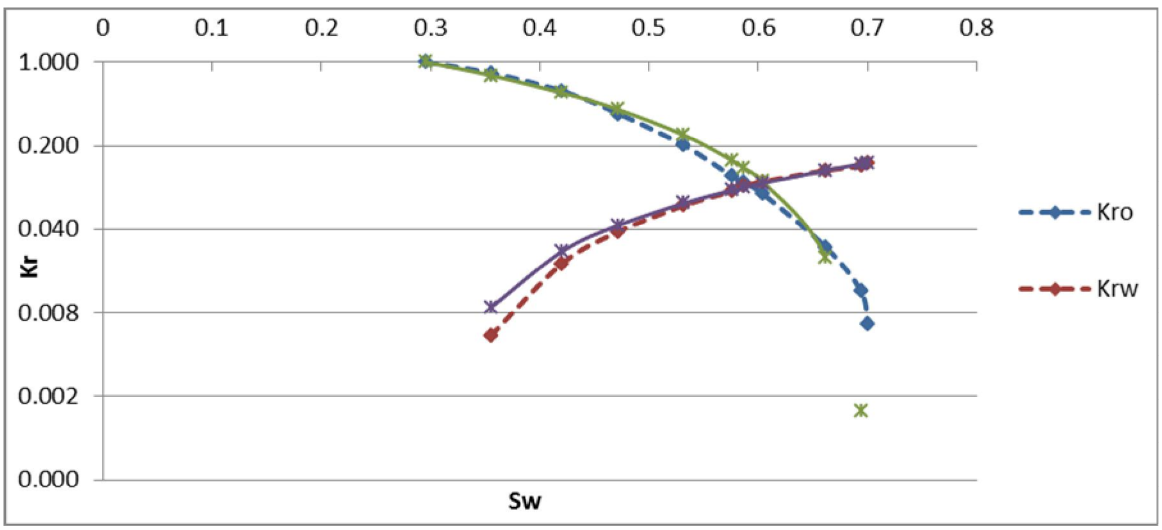

Fig (D-2): Refined Kro, Krw Vs. Sw

Sample 4 :

Table (D-2): Refining Relative Permeability (Sample 4)

Swi	0.254	Krw*	0.5	No	1.76
Sor	0.3			Nw	3.99

Lab RealPerm		
Sw	Kro	Krw
0.245	1.000	0.000
0.395	0.482	0.006
0.461	0.303	0.025
0.52	0.179	0.067
0.578	0.092	0.144
0.62	0.049	0.231
0.649	0.028	0.311
0.676	0.009	0.403
0.694	0.000	0.474

			Refined RealPerm	
Sw	Swn	Son3	R-Kro	R-Krw
0.245	-0.020	1.020	1.0358	0
0.395	0.316	0.684	0.5123	0.005
0.461	0.464	0.536	0.3335	0.023
0.52	0.59	0.404	0.2025	0.063
0.578	0.726	0.274	0.1021	0.139
0.62	0.82	0.179	0.0486	0.227
0.649	0.88	0.114	0.0220	0.307
0.676	0.94	0.054	0.0058	0.400
0.694	0.98	0.013	0.0005	0.473
0.7	1	0.000	0.0000	0.5

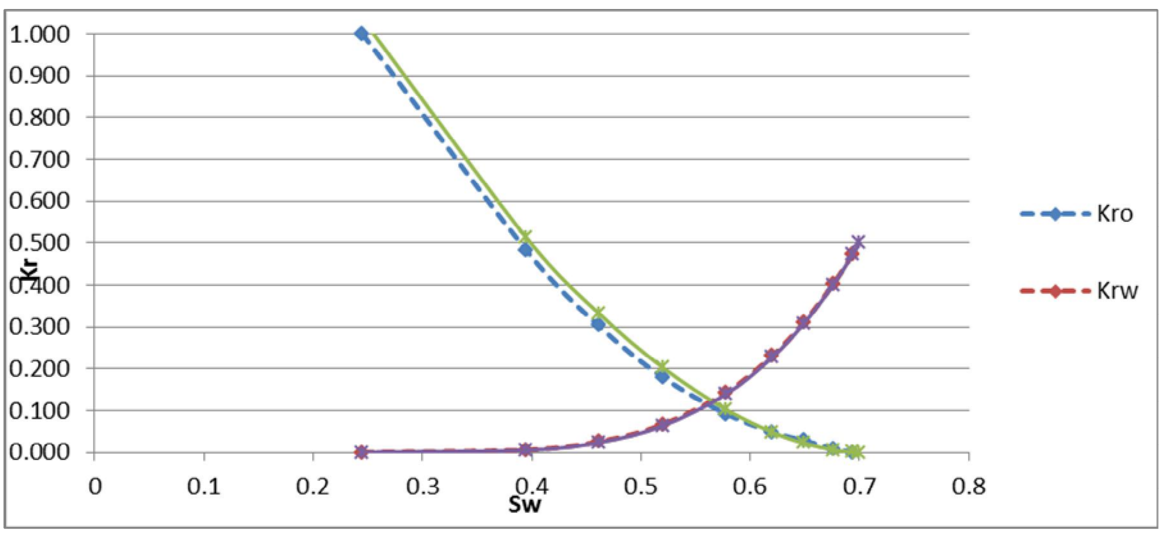

Fig (D-3): Refined Kro, Krw Vs Sw

Fig (D-3): Refined Kro, Krw Vs. Sw

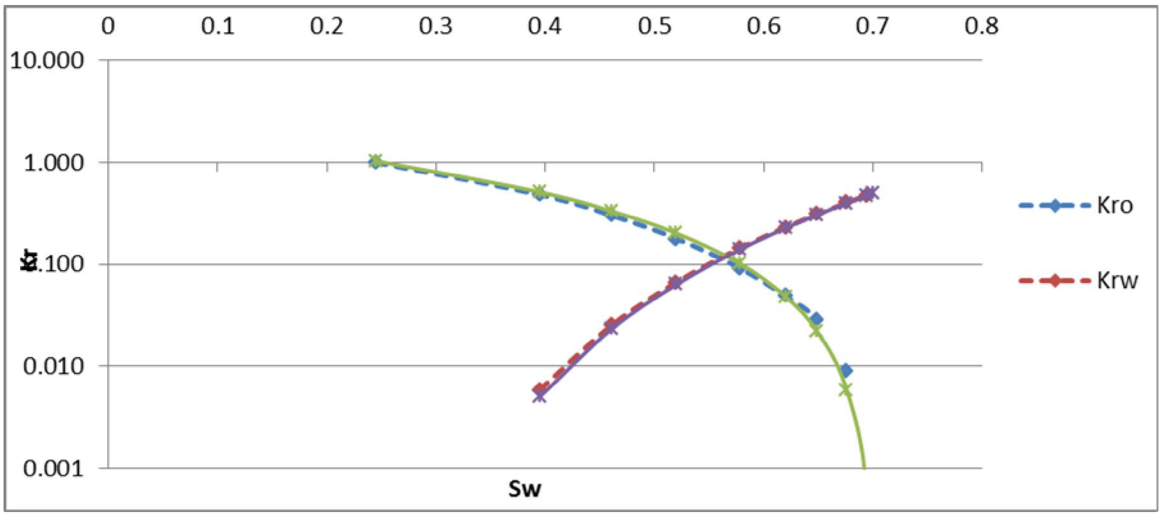

Fig (D-4): Refined Kro, Krw Vs. Sw