# POROUS PLATES INFLUENCE ON EFFECTIVE IMBIBITION RATES IN CAPILLARY PRESSURE EXPERIMENTS

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## ABSTRACT

Capillary displacement using the porous plate technique has been used for decades to determine capillary behavior in a reservoir. The disadvantage is that the technique is quite time consuming.

During the last few years, membrane techniques have been developed to speed up the experiments. However, membranes have problems in enduring mechanical stress and resisting wettability change during an experiment.

The recently published layered porous plate technique,[1] has been shown to yield the same drainage capillary behaviour as the standard porous plate technique but with a significantly reduced turnaround time. In this paper we present the continuation of this research by focusing on porous plates influence on effective imbibition rates. We document the properties of both hydrophilic and hydrophobic high-flux porous plates, and compare the results against standard porous plate types.

Parallel experiments using standard industry porous plates have been performed on reservoir rocks from the North Sea. The results of the study demonstrate how the flux properties of hydrophilic and hydrophobic porous plates affect the effective rates and stabilisation time during spontaneous and forced imbibition.

## INTRODUCTION

The determination of representative capillary pressures is of vital importance for the mapping of the reservoir fluid distribution. However, variations between the data obtained by various standard techniques (mercury injection, porous plate technique and centrifugation) or for different fluid systems have often been observed and reported in the literature.[2]

During the last few years, substantial work has been carried out to improve the laboratory procedures for measurement of relative permeability behaviour. Less effort has been made to improve the techniques for determination of capillary properties.

The traditional porous plate technique is very reliable, but quite time consuming. During recent decades, different techniques like the membrane technique,[3,4] and the continuous injection technique,[5] have been developed to reduce the amount of time required. The membrane technique,[3,4] which is analogous to the standard porous plate technique, has been reported to be 30 times faster than the standard porous plate technique.[3] However, this technique seems to have problems in enduring mechanical stress and resisting wettability change during the experiment. The continuous injection technique,[5] is a fast method to establish I-$S_w$ relationships. However, constant injection of a non-wetting fluid results in fluctuations in capillary pressure. The method is therefore rather uncertain with respect to determine the capillary pressure curve itself.

The recently published layered porous plate technique has been proven to yield the same drainage capillary behaviour as the standard porous plate technique at a significantly reduced turnaround time. We documented the properties of both hydrophilic and hydrophobic high-flux porous plates, and compared the results with standard types of porous plates.[1]

In this paper, we present the outcome of an experimental study on reservoir rocks from the North Sea. The motivation was to verify consistent capillary behaviour at different imbibition pressure steps using both standard homogenous porous plates and layered porous plates.

Capillarity on a microscopic pore level is a complex subject to investigate due to the irregular and complex pore architecture of a natural reservoir rock. Possible hierarchies and mechanisms during imbibition are much more complex, compared with primary drainage. In order to illustrate how porous plates influence time to achieve capillary equilibrium, we have established transient production curves using exponential functions.[6]

## DESCRIPTION OF POROUS PLATES

In this study we have used layered hydrophilic and hydrophobic porous plates with plug set A, while we used hydrophilic and hydrophobic homogeneous porous plates with plug set B. Plug set B is a twin plug set corresponding to plug set A.

A hydrophobic version of the homogeneous plate is not available from the manufacturer. We have therefore treated the plates with to make them hydrophobic using recommended practices.[7] Layered hydrophobic plates are available in both hydrophilic and hydrophobic versions from the manufacturer.

The layered hydrophilic and hydrophobic porous plates used in this study are known by the trade name Keraflux. Layered porous plates have a highly permeable and homogeneous substrate structure with a large pore size. On top of the substrate there is a top layer with smaller pore sizes. This layer is constructed as a graded layer with respect to pore size, porosity and composition.

The Soil Moisture plate is a well-known, homogeneous porous plate. We have used the traditional hydrophilic 15 bar gas-water version together with a chemically treated hydrophobic version, for plug set B.

The properties of layered and homogeneous porous plates, both hydrophilic and hydrophobic versions, are reported in Table 1.

## CAPILLARY PRESSURE MEASUREMENTS

Traditionally, capillary pressure curves have been generated by the porous plate method. It is well known that drainage and imbibition could take over a year to complete. It is not uncommon to use between 20-30 weeks to establish oil-water drainage curves at ambient conditions.

In this study we performed drainage, spontaneous imbibition and forced imbibition on relatively homogeneous reservoir rocks. All experiments were performed at pseudo reservoir conditions (157 bar net confining pressure @ 85° C) using stock tank oil as the invading non-wetting fluid. Porosity varied from 0.268 to 0.272 and permeability varied from 1717 mD to 2421 mD. The core plugs were cleaned and saturated with brine prior to primary drainage.

Four sections of the reservoirs oil zone were investigated using two comparable plugs from each section. Capillary behaviour on plug set A, plug no.1a-4a, was investigated using layered hydrophilic and hydrophobic ceramic plates. Corresponding plug set B, plug no. 1b-4b, was investigated using homogeneous plates.

In order to study how porous plate types influence time to achieve equilibrium during imbibition, we decided to use very strict equilibrium criteria compared to normal practice. Equilibrium criteria required (1) no changes in water saturation and (2) no changes in resistivity index over a period of at least 48 hours. Long experimental turnaround time for the homogeneous porous plate experiments is therefore observed.

Wilson et al.[1] have shown how the properties of different porous plates influence experimental turnaround time without affecting the primary drainage curve itself. However, representative imbibition curves are functions of fluid distribution and wetting condition obtained during primary drainage. Hence, experiments using layered porous plates could yield an unrepresentative imbibition curve. We therefore decided to use stringent equilibrium criteria in order to compare the two techniques.

The core plugs from plug set A, using layered plates, were drained by stock tank oil to irreducible water saturation using eight capillary pressure steps. Final equilibrium, at irreducible water saturation, was reached after 76 days. Then, spontaneous imbibition was initiated using three capillary pressure steps. Final equilibrium was reached 86 days after drainage was completed. The layered hydrophilic plates were then dismounted from the core holders and replaced by hydrophobic versions in the opposite end. Final equilibrium at residual oil saturation was reached 108 days after drainage was completed.

The core plugs from plug set B, using homogeneous plates, were investigated using the same capillary pressure steps. Corresponding comparable equilibrium data was recorded after 247, 238 and 279 days respectively.

It should be noted that applied capillary pressure is increased or decreased after obtaining equilibrium on all core plugs from the same plug set.

Capillary pressure curves using layered porous plates are presented in Figure 1. Corresponding curves using homogeneous porous plates are presented in Figure 2. Figure 3 illustrates transient water saturation versus time for all the eight core plugs. A total experimental time saving factor of 2.86 is observed.

## DESCRIPTION OF THE TRANSIENT PRODUCTION MODEL

A primary drainage sequence is relatively easy to forecast with respect to the hierarchy involved. The hierarchy is, under normal circumstances, known as a percolation process, i.e., the next largest pore channel along the continuous non-wetting interface will be invaded next. Wilson et al. [1] has shown how the properties of different porous plates influence experimental turnaround time without affecting the capillary pressure curve itself.

Capillary imbibition is a much more complex sequence. Hierarchies and mechanisms involved are a function of several parameters such as wettability and pore to throat size ratio. It is therefore difficult, if exciting, to find an analytical solution describing the influence of a ceramic plate for an imbibition process. Lenormand et al. [8] has proven, at certain assumptions, that an analytical solution describing production for small pressure steps is a sum of exponential terms. Fleury et al. [6] introduced a first order approximation of the analytical solution using an optimisation routine, in order to determine $V_{\max}$ and $t_c$. Transient production after changing the capillary pressure step can be described as:

$$V(t) = V_{\max} \cdot (1 - \exp(-\tfrac{t}{t_c})) \tag{1}$$

$V_{\max}$ can be considered as a known constant and the first order approximation can be written as:

$$V_r = \frac{V(t)}{V_{\max}} = 1 - \exp(-\frac{t}{t_c}) \Rightarrow \ln(1 - V_r) = -\frac{t}{t_c} \tag{2}$$

Characteristic time, $t_c$, is determined by plotting $\ln(1 - V_r)$ versus $t$. Characteristic times for the eight core plugs, at each capillary pressure, are presented in Tables 2-5. The characteristic time ratio, $\psi$, illustrates the influence of layered porous plates relative to homogeneous porous plates at each capillary pressure step. An example of establishing characteristic time, for each primary drainage pressure step, is presented in Figure 4, for plug no. 1a.

## RESULTS

Determination of characteristic time, $t_c$, at each capillary pressure step produced a set of linear functions for the primary drainage sequences. However the accuracy of two of these pressure steps, at 800 and 5000 mbar, was reduced by lack of data immediately after increasing the pressure step.

By studying characteristic time ratio, $\psi$, for the primary drainage sequences, there is a clear tendency towards decreasing $\psi$ as a function of increasing drainage pressure. This is also consistent with earlier reported observations.[1] Figure 5 indicates that this tendency is properly described by a power function for each of the four core sections. The reported regression is for the correlation of data from plugs no 3a and 3b.

Characteristic time ratio is established from transient production data, which reflects the changes in water saturation at a capillary pressure step. Since $\psi$ correlates with capillary pressure, we decided to use $dS_w/dP_c$ as a parameter versus $\psi$. Figure 6 verifies that there is a tendency of increasing $\psi$ as a function of increasing $dS_w/dP_c$, described as a power function.

Characteristic time, $t_c$, at each capillary pressure step for the spontaneous imbibition sequences, produced a set of linear functions for the first two capillary pressures. However, imbibition at Pc=0 was a very slow process. The ln (1-Vr) vs. $\Delta t$ relationship at this capillary pressure indicated several exponential steps within the same capillary pressure step. Lenormand at al.[8] assumed that capillary pressure varies linearly with water saturation and that transient production is a sum of several exponential terms. It is possible that observations were limited because of the accuracy of measuring the small volumes of water produced. Further investigation is needed to clarify the shape of the production curve for transient spontaneous imbibition at near-zero levels of capillary pressure.

Characteristic time ratio relationships for spontaneous imbibition are more scattered than the corresponding drainage curves. Characteristic time ratio seems to increase when the capillary pressure is reduced. However, Figures 7 and 8 illustrate that it is reasonable to believe that $\psi$ can be expressed using power functions similar to the drainage sequence. It should be noted that increasing the number of spontaneous imbibition steps would probably make the model more robust.

Forced imbibition data is produced using hydrophobic ceramic plates. Characteristic time, $t_c$, at each capillary pressure step for the forced imbibition sequences produced a set of linear functions for all three capillary pressure steps.

Characteristic time ratio, $\psi$, for the forced imbibition sequences indicates a clear tendency towards decreasing $\psi$ as a function of increasing negative imbibition pressure. Figures 9 and 10 indicate strongly that this tendency is described by an exponential function for each of the four sections. However, it is felt that the number of forced imbibition pressures should have been increased in order to verify the exponential trend properly.

It should be noted that characteristic time ratio, $\psi$, approaches unity both at irreducible water saturation and residual oil saturation. In other words, the relative influence of two porous plate types is negligible at the end points for the primary drainage and the forced imbibition sequence. This can be interpreted as follows: the flux restriction in the porous plate is negligible when the mobile phase, water near irreducible water saturation and oil near residual oil saturation, goes to zero.

## CONCLUSIONS

Effective drainage and imbibition rates depend on the type of porous plate used, but the capillary pressure curve and electrical properties are the same.

The layered plate is faster than the homogeneous plate at all saturation levels. The difference almost disappears at low water saturation for primary drainage and at low oil saturation for forced imbibition, when the drainage and imbibition rates are controlled by the fluid mobilities in the core itself, and not by the plate properties.

Characteristic time, established from a first order exponential approximation, is a useful parameter for evaluating the influence of porous plates at different capillary pressure steps. The method seems to be robust for most of the investigated pressure steps, but becomes uncertain if the amount of transient production data is reduced.

It seems that characteristic time from transient imbibition data, at a very slow velocity, is not properly described with a first order exponential approximation. Further investigation should therefore be carried out.

The characteristic time ratio, or the relative influence of porous plate types, correlates with capillary pressure and $dS_w/dP_c$.

## NOMENCLATURE

$V(t)$ : Production as a function of time

$V_{\max}$ : Asymptotic production at infinite time

$V_r$ : Relative production at the pressure step

$t_c$ : Characteristic time

$t$ : Time relative to the time when changing the pressure step

$\psi$ : Characteristic time ratio. I.e. the relative influence of layered to homogeneous porous plate

$P_c$ : Capillary pressure

$S_W$ : Water saturation

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Table 1: Porous plate parameters

| **Parameter** | **Keraflux-W**<br>Hydrophilic | **Keraflux-O**<br>Hydrophobic | **Soil Moisture-W**<br>Hydrophilic | **Soil Moisture-O**<br>Hydrophobic |
|---|---|---|---|---|
| Diameter | 38.1mm | 38.1mm | 38.1mm | 38.1mm |
| Thickness/length | 5 mm | 5 mm | 9.5 mm | 9.5 mm |
| Average pore size | 100nm/4miron | 100nm/4miron | 160nm | 160nm |
| Pc-max g/w | 12 bar | - | 15 bar | - |
| Pc-max o/w | 26 bar | - | 14 bar | - |
| Pc-max w/o | | 18 bar | - | >5 bar |
| Flux using water | 10ml/h @ 1 bar | - | 0.13ml/h @ 1bar | - |
| Flux using oil | - | 20ml/h @ 1 bar | - | <0.13ml/h @ 1 bar |

Table 2: Characteristic time ratio, plug no. 1a and 1b.

| | **Layered porous plate** | | | **Homogeneous porous plate** | | | |
|---|---|---|---|---|---|---|---|
| | **Plug no. 1a:** | | **n: 2.04** | **Plug no. 1b:** | | **n: 2.03** | |
| **Pc** (bar) | **Sw** (frac.) | **Time** (days) | $t_c$ | **Sw** (frac.) | **Time** (days) | $t_c$ | $\psi$ |
| 0.000 | 1.000 | 0.0 | | 1.000 | 0.0 | | |
| 0.050 | 0.615 | 11.9 | 1.380 | 0.613 | 71.9 | 8.591 | 6.228 |
| 0.100 | 0.344 | 25.9 | 2.484 | 0.340 | 140.4 | 11.962 | 4.815 |
| 0.200 | 0.258 | 40.0 | 3.705 | 0.253 | 188.6 | 14.493 | 3.912 |
| 0.400 | 0.222 | 49.9 | 3.286 | 0.218 | 210.8 | 6.418 | 1.953 |
| 0.800 | 0.199 | 53.9 | 0.834 | 0.194 | 217.0 | 1.358 | 1.628 |
| 1.600 | 0.170 | 62.9 | 1.790 | 0.165 | 229.7 | 2.523 | 1.409 |
| 3.000 | 0.146 | 72.0 | 3.591 | 0.141 | 241.7 | 4.766 | 1.327 |
| 5.000 | 0.128 | 76.0 | 1.157 | 0.124 | 246.9 | 1.481 | 1.280 |
| 1.000 | 0.152 | 86.0 | 3.923 | 0.148 | 261.4 | 4.840 | 1.234 |
| 0.200 | 0.181 | 96.0 | 2.554 | 0.177 | 279.1 | 5.222 | 2.045 |
| 0.000 | 0.246 | 162.1 | 84.75 | 0.242 | 485.2 | 166.667 | 1.967 |
| -0.100 | 0.569 | 169.9 | 1.477 | 0.567 | 503.4 | 3.427 | 2.320 |
| -0.500 | 0.681 | 178.9 | 3.132 | 0.679 | 520.3 | 5.889 | 1.880 |
| -1.000 | 0.692 | 183.9 | 1.009 | 0.691 | 526.2 | 1.180 | 1.169 |

Table 3: Characteristic time ratio, plug no. 2a and 2b.

| | **Layered porous plate** | | | **Homogeneous porous plate** | | | |
|---|---|---|---|---|---|---|---|
| | **Plug no. 2a:** | | **n: 2.08** | **Plug no. 2b:** | | **n: 2.09** | |
| **Pc** (bar) | **Sw** (frac.) | **Time** (days) | $t_c$ | **Sw** (frac.) | **Time** (days) | $t_c$ | $\psi$ |
| 0.000 | 1.000 | 0.0 | | 1.000 | 0.0 | | |
| 0.050 | 0.612 | 11.9 | 1,410 | 0.613 | 71.9 | 11.099 | 7.872 |
| 0.100 | 0.339 | 25.9 | 2,455 | 0.340 | 140.4 | 16.103 | 6.559 |
| 0.200 | 0.252 | 40.0 | 3,828 | 0.253 | 188.6 | 14.793 | 3.864 |
| 0.400 | 0.217 | 49.9 | 3,564 | 0.217 | 210.8 | 7.463 | 2.094 |
| 0.800 | 0.192 | 53.9 | 0,769 | 0.194 | 217.0 | 1.316 | 1.711 |
| 1.600 | 0.163 | 62.9 | 1,824 | 0.165 | 229.7 | 2.691 | 1.475 |
| 3.000 | 0.140 | 72.0 | 3,814 | 0.141 | 241.7 | 5.155 | 1.352 |
| 5.000 | 0.122 | 76.0 | 1,157 | 0.123 | 246.9 | 1.481 | 1.280 |
| 1.000 | 0.146 | 86.0 | 3,923 | 0.148 | 261.4 | 5.627 | 1.434 |
| 0.200 | 0.175 | 96.0 | 2,469 | 0.177 | 279.1 | 5.456 | 2.210 |
| 0.000 | 0.240 | 162.1 | 74,627 | 0.242 | 485.2 | 172.414 | 2.310 |
| -0.100 | 0.566 | 169.9 | 1,640 | 0.567 | 503.4 | 3.298 | 2.011 |
| -0.500 | 0.679 | 178.9 | 3,139 | 0.679 | 520.3 | 5.838 | 1.860 |
| -1.000 | 0.690 | 183.9 | 1,074 | 0.690 | 526.2 | 1.263 | 1.176 |

Table 4: Characteristic time ratio, plug no. 3a and 3b.

| | **Layered porous plate** | | | **Homogeneous porous plate** | | | |
|---|---|---|---|---|---|---|---|
| | **Plug no. 3a:** | | **n: 1.97** | **Plug no. 3b:** | | **n: 1.93** | |
| **Pc** (bar) | **Sw** (frac.) | **Time** (days) | $t_c$ | **Sw** (frac.) | **Time** (days) | $t_c$ | $\psi$ |
| 0.000 | 1.000 | 0.0 | | 1.000 | 0.0 | | |
| 0.050 | 0.603 | 11.9 | 1.424 | 0.602 | 71.9 | 11.223 | 7.881 |
| 0.100 | 0.323 | 25.9 | 2,608 | 0.322 | 140.4 | 12.516 | 4.799 |
| 0.200 | 0.234 | 40.0 | 4.030 | 0.233 | 188.6 | 14.535 | 3.607 |
| 0.400 | 0.199 | 49.9 | 3.029 | 0.197 | 210.8 | 6.831 | 2.255 |
| 0.800 | 0.174 | 53.9 | 0.594 | 0.173 | 217.0 | 1.104 | 1.859 |
| 1.600 | 0.145 | 62.9 | 1.823 | 0.143 | 229.7 | 2.518 | 1.381 |
| 3.000 | 0.120 | 72.0 | 4.621 | 0.117 | 241.7 | 5.102 | 1.104 |
| 5.000 | 0.101 | 76.0 | 1.157 | 0.100 | 246.9 | 1.481 | 1.280 |
| 1.000 | 0.126 | 86.0 | 3.639 | 0.125 | 261.4 | 5.165 | 1.419 |
| 0.200 | 0.156 | 96.0 | 3.937 | 0.154 | 279.1 | 4.344 | 1.103 |
| 0.000 | 0.223 | 162.1 | 85.470 | 0.221 | 485.2 | 166.667 | 1.950 |
| -0.100 | 0.556 | 169.9 | 1.452 | 0.555 | 503.4 | 3.334 | 2.296 |
| -0.500 | 0.672 | 178.9 | 3.264 | 0.671 | 520.3 | 5.744 | 1.760 |
| -1.000 | 0.683 | 183.9 | 1.078 | 0.681 | 526.2 | 1.117 | 1.036 |

Table 5: Characteristic time ratio, plug no. 4a and 4b.

| | **Layered porous plate** | | | **Homogeneous porous plate** | | | |
|---|---|---|---|---|---|---|---|
| | **Plug no. 4a:** | | **n: 2.00** | **Plug no. 4b:** | | **n: 2.06** | |
| **Pc** (bar) | **Sw** (frac.) | **Time** (days) | $t_c$ | **Sw** (frac.) | **Time** (days) | $t_c$ | $\psi$ |
| 0.000 | 1.000 | 0.0 | | 1.000 | 0.0 | | |
| 0.050 | 0.610 | 11.9 | 1.386 | 0.610 | 71.9 | 8.696 | 6.274 |
| 0.100 | 0.336 | 25.9 | 2.505 | 0.336 | 140.4 | 13.072 | 5.218 |
| 0.200 | 0.249 | 40.0 | 3.357 | 0.249 | 188.6 | 14.771 | 4.400 |
| 0.400 | 0.213 | 49.9 | 2.893 | 0.214 | 210.8 | 6.024 | 2.082 |
| 0.800 | 0.189 | 53.9 | 0.834 | 0.189 | 217.0 | 1.520 | 1.823 |
| 1.600 | 0.159 | 62.9 | 1.786 | 0.160 | 229.7 | 2.303 | 1.289 |
| 3.000 | 0.135 | 72.0 | 4.177 | 0.136 | 241.7 | 5.294 | 1.267 |
| 5.000 | 0.117 | 76.0 | 1.157 | 0.118 | 246.9 | 1.268 | 1.096 |
| 1.000 | 0.141 | 86.0 | 4.284 | 0.144 | 261.4 | 5.181 | 1.209 |
| 0.200 | 0.171 | 96.0 | 2.696 | 0.172 | 279.1 | 3.975 | 1.474 |
| 0.000 | 0.236 | 162.1 | 82.645 | 0.236 | 485.2 | 163.934 | 1.984 |
| -0.100 | 0.564 | 169.9 | 1.455 | 0.565 | 503.4 | 3.465 | 2.381 |
| -0.500 | 0.677 | 178.9 | 3.010 | 0.678 | 520.3 | 6.046 | 2.009 |
| -1.000 | 0.688 | 183.9 | 1.078 | 0.689 | 526.2 | 1.119 | 1.038 |

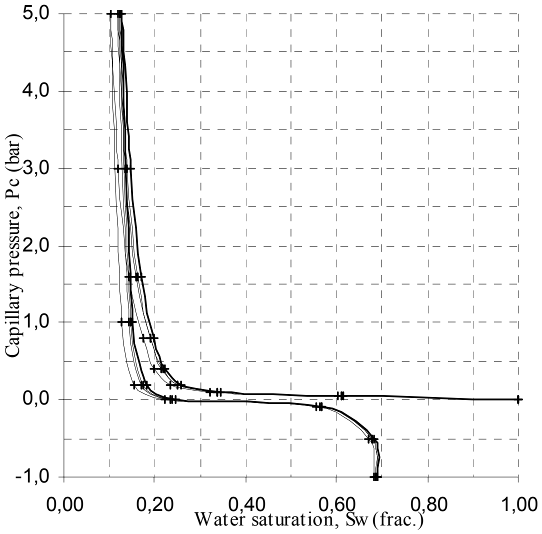

Figure 1: Capillary behaviour, plug set A.

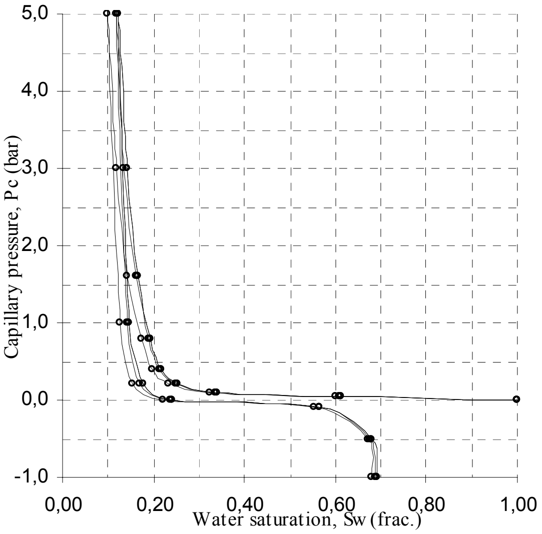

Figure 2: Capillary behaviour, plug set B.

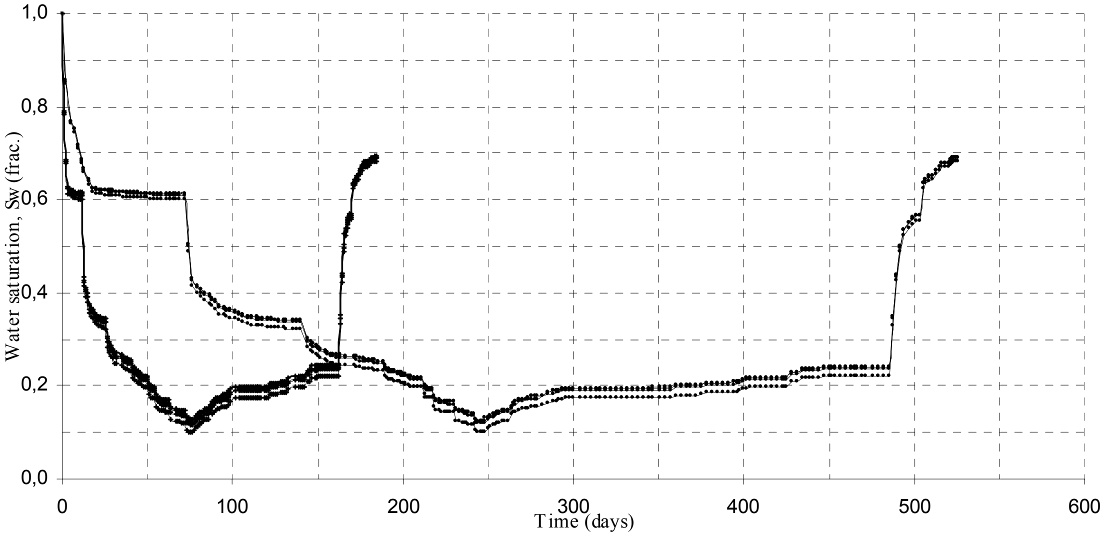

Figure 3: Transient capillary behaviour for layered and homogeneous experiments.

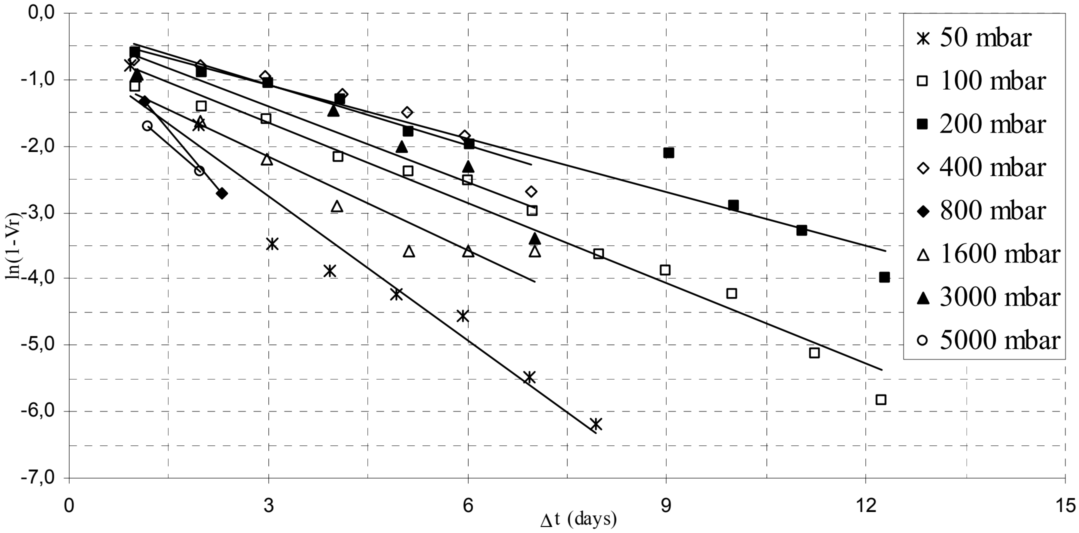

Figure 4: Characteristic time during drainage, plug no. 1.

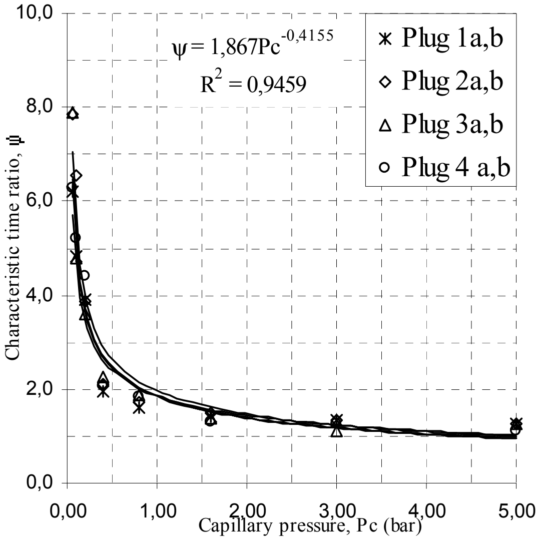

Figure 5: Primary drainage interpretation

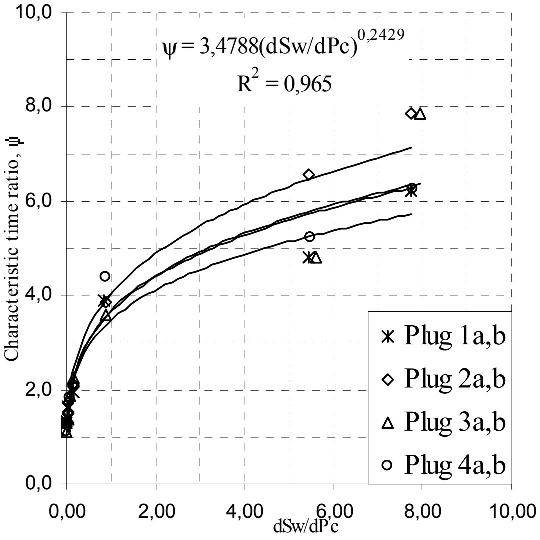

Figure 6: Primary drainage interpretation

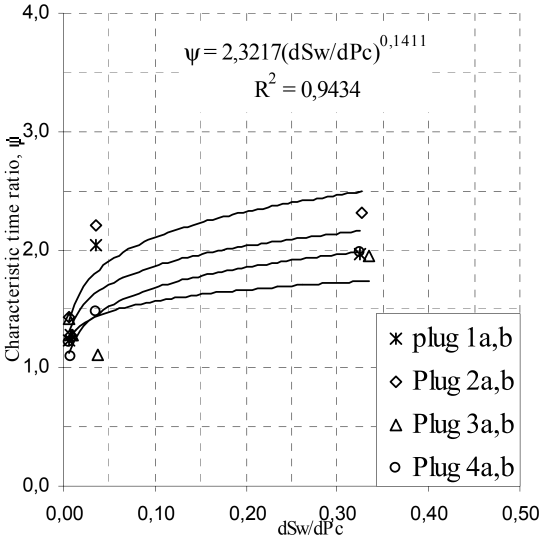

Figure 7: Spontaneous imbibition interpretation interpretation

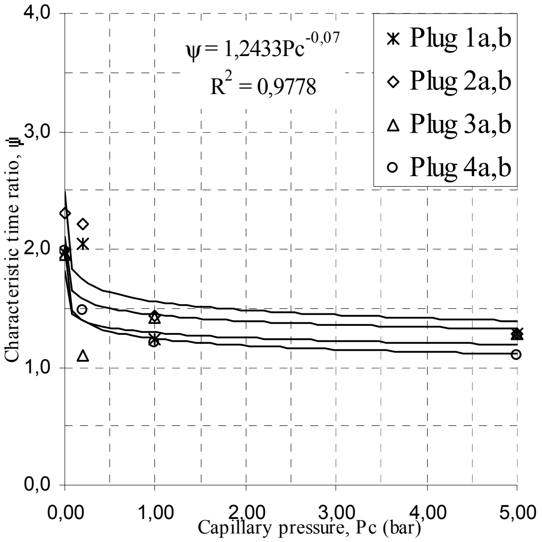

Figure 8: Spontaneous imbibition

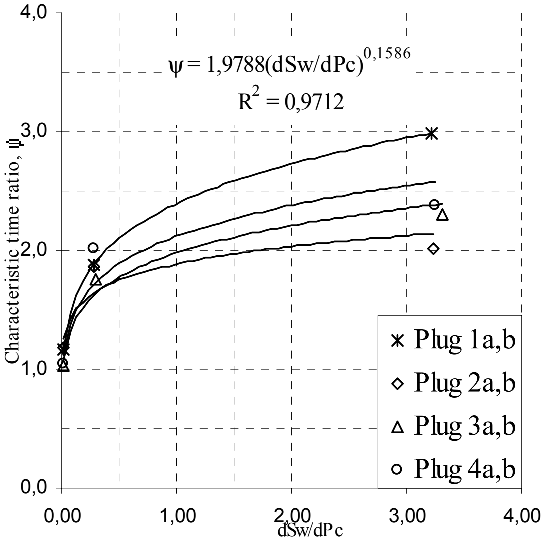

Figure 9: Forced imbibition interpretation

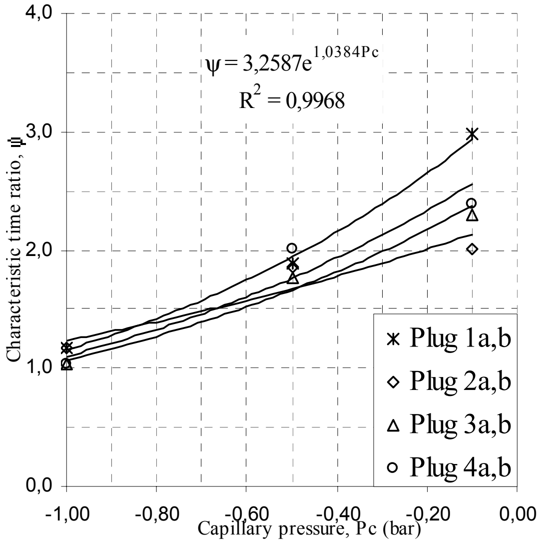

Figure 10: Forced imbibition interpretation