# ROCK WETTABILITY CHARACTERISTICS OF SOME INDONESIAN LIMESTONES. CASE STUDY: BATURAJA FORMATION

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***ABSTRACT***

*Rock wettability plays a very important role in affecting various rock physical properties such as relative permeability and capillary pressure. Common practice at present is that carbonate rocks are assumed to be preferentially oil wet in nature. This assumption may prove fatal since the need of true knowledge over the real wettability for one's carbonate reservoir is often neglected, and wettability aspect in reservoir modeling is in turn based on assumption. To prove over reliability of the assumption a study is carried out using information from 350 core samples taken from Baturaja Formation. The choice for the Baturaja limestone is basically based on the fact that it is a mature productive rock formation and its extensive spread into three of the most productive sedimentary basin in Indonesia, Northwest Java Basin, South Sumatra Basin, and Sunda Basin. The study proves that the assumption of the generally oil wet limestone does not apply for Baturaja limestone. The Baturaja limestone tend to exhibit, quantitatively, equality in their tendency towards oil wettability and water wettability and leave some proportion to neutral or mix wettability as well. However, when a more detailed comparison is made results show that qualitatively the limestone are indeed more inclined to oil wettability than water wettability even though this finding is insufficient to support a conclusion that the Baturaja limestone are specifically oil wet. Other finding from comparison with past studies also shows that limestone may behave in the way sandstones do. Both limestone and sandstones may vary in the same way and no assumption over their preferential wettability is justified without direct measurements. Wettability alteration as the result of hot core cleaning following the widely accepted standard procedure is also strongly indicated. It is therefore concluded that the practice has to be abandoned for a better and reliable laboratory testing results.*

***Keywords:*** *wettability, limestone, Baturaja Formation, wettability variation, wettability alteration*

## I. INTRODUCTION

As the effort for maximizing oil recovery from existing accumulations is gaining momentum, the challenges faced by geologists, petrophysicists, and engineers to understand more about carbonate reservoirs are mounting. These challenges become specifically significant when high level of heterogeneity commonly shown by carbonate rocks is taken into consideration. From petrophysical point of view this high level of heterogeneity also provides challenges in understanding variations and regularities of properties such as porosity, permeability, and wettability.

Wettability is simply defined as the tendency of a solid surface (i.e. reservoir rock's surface) to be alternately wetted by oil or formation water, but since its effect on oil recovery cannot yet be readily quantified and directly related its presence is often

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regarded as of secondary importance. The still widely practiced standard procedure of core hot cleansing – a practice that can alter rock original wettability – prior to various core measurements provides an example. With the increasingly intensive global effort to maximizing oil production from existing oil pools – e.g. application of waterflood and enhanced oil recovery – information provided by laboratory measured rock wettability cannot be longer neglected.

Wettability of limestone is as varied as in the case of sandstone, and it is often perceived that limestone is in general more inclined towards oil wettability than sandstone. This common perception is certainly not unfounded since some studies regarding the issue have been performed in the past. For instance, Treiber *et al* (1972) conducted a series of wettability tests on 30 sandstone and 25 limestone samples found that 88% of the limestone samples are oil wet by nature, with the remaining comprised 4% neutral and 8% water-wet. In a similar but more recent study, Chilingarian and Yen (1983) found similar finding of 80% oil-wet, 12% neutral, and 8% water-wet. The perception of oil-wet limestone also applies in Indonesia and this is widely practiced when reservoir modeling on limestone reservoirs is of concern. No one actually knows what the reality is and to the author's knowledge there no such study has been performed on Indonesian limestone. Therefore, such study has to be carried out so that its valuable finding will be beneficial to all.

The choice over samples from Baturaja Formation comes from the fact that this geological formation contains many producing reservoirs that contribute significantly to Indonesia's national oil production up to present. A deeper study on the reservoir rocks has become relevant in order to understand further their nature, especially when it is considered that from those reservoirs further oil recovery is expected (e.g. through enhanced oil recovery). As concluded by Donaldson *et al* (1969) after a series of core waterflood tests, a strongly water-wet system the flooding water tend to breakthrough after most of the recoverable oil has been produced. No significant production took place after the water breakthrough. On the contrary, waterflooding in strongly oil-wet rocks always experience early water breakthrough with significant and continuous oil production occurring long after the breakthrough. The need for information regarding reservoir rock wettability is therefore obvious.

The study over limestone reservoir rocks of the Baturaja Formation used data from 350 core samples consisting of both reports from wettability and water-oil relative permeability tests. From the results of wettability tests the original wettability tendency of the Baturaja limestone is studied, whereas the effect of core cleansing during core preparation is also investigated using the relative permeability data. Upon using results from the core analysis tests a more comprehensive understanding of the Formation's limestone wettability characteristics is hoped.

## II. BATURAJA FORMATION: A BRIEF PETROPHYSICAL OVERVIEW

In term of oil and gas production the Baturaja Formation is one of the most active and productive rock formations in Indonesia. Its lateral existence extends in three mature sedimentary basins of South Sumatera Basin, Sunda Basin, and Northwest Java Basin. In South Sumatera Basin the early Miocene Baturaja Formation is widely in the form of platform carbonates, 20 – 75 m thick, with some carbonate buildup and reefs of 60 – 120 m thick (Hutchinson, 1996). With its maximum thickness of 200 m (Darman and Sidi, 2000) the Baturaja limestones are mix of wackestone, grainstone, packstone, and reef buildup (Hadi and Simbolon, 1976). Table 1 provides description over some typical Baturaja limestone samples used in the study. High quality reservoir rocks are mostly located in the southern part of the basin and become rarer in northward direction. Most of the porosity of the productive reservoirs is of secondary porosity as the result of the reefs' aerial or sub-aerial exposure prior to burial. Average porosity in producing fields is 21% (maximum 38%) with permeability that ranges from a few milidarcies up to values of as high as 3.8 Darcies (Ginger and Fielding, 2005).

In Sunda Basin, the Baturaja limestone reservoirs are present in the upper part (Upper Baturaja) and the lower part (Lower Baturaja) of the formation. In the Upper Baturaja the reservoir rocks are typically argillaceous, tight, no significant fracturing, and the limestone is not extensively distributed. On the contrary, the more extensive reservoirs in the Lower Baturaja are generally characterized by presence of

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**Tabel 1**
**Typical limestone of Baturaja Formation (wells: T-07, T-08, and T-10 of Northwest Java Basin)**

| Sample | Porosity (%) | Permeability (mD) | Visual description |
|---|---|---|---|
| 1A | 14.54 | 11.19 | LM: Packstone, ltgy, hd, coral, L. foram, foss, loc x-lin, pp-mott vugs. |
| 3A | 21.44 | 748 | LM: Grainstone, brn-wh, bioturb (mold/cast/brw), vug, skeleton, med-v.coarse, grain sprtd, calc, qz, aragnt |
| 4A | 27.91 | 15.5 | LM: Sucrrosic packstone, ltgy-ltbrn, csl, L foram, coral, micro x-lin |
| 9B | 15.5 | 7.59 | LM: Wackestone, ltbrn, bioturb (mold/cast), oolites, fine grn, mud sprtd, sli x-lin |
| 12A | 22.2 | 19.85 | LM: Packstone-grainstone, ltbrn, hd-vhd, coral, L foram, foss fragm, succrosic, pp-mott vugs |
| 16A | 14.93 | 14.2 | LM: Boundstone, ltgy-ltbrn, csl, foram, algae, micro x-lin |
| 17A | 17.17 | 34.99 | LM: Grainstone, crm, hd, coral, L. foram, loc succrosic, mot-6 mm vugs |
| 23A | 19.49 | 56.87 | LM: Packstone, ltgy-ltbrn/loc hd, L foram, algae, vug < 5 mm, loc intra partcl por. |

secondary and excellent inter-granular porosities within thick zones. The moldic and inter-crystalline pores are formed through dissolution of aragonite skeletal material (Bushnell and Temansja, 1986). Fractures contribute significantly to the reservoir rocks' permeability. Wight and Hardian (1982) recognized ten distinctive facies, both depositional and clastic types, and concluded that biomicrite (sparsely fossiliferous limestone) as the most extensive facies. They put further that this facies was deposited in low to intermediately high energy lagoonal areas and parts of the back-reef. Thickness may exceed 30 meters with average porosity of 25%.

In the Arjuna Basin of the Northwest Java Basin, the reservoirs are mainly reef buildup which developed at various places on and around Basement highs. The porosity, as well as permeability was developed through dissolution during sea level low-stands through which leaching of aragonite grain occurred and moldic porosity was generated (Pertamina, 1996). Thickness of the reef varies within 30 – 45 m with reservoir net-pay thickness within 2 – 8 m. Porosity and permeabiliy vary but may reach as high as 36% and 1 D, respectively (Pertamina, 1996). In the Jatibarang Basin part of the Northwest Java Basin the reef thickness can also reach up to 50 m with comparable quality to the reservoirs in the Arjuna Basin. However, reservoirs in the Jatibarang Basin contribute little to total production of Baturaja reservoirs in the Northwest Java Basin (estimated at 5%, Pertamina, 1996). This contribution is unlikely to change much at present-day production level.

## III. WETTABILITY INDICATOR

Various methods for obtaining indication over rock wettability have been acknowledged. Apart from the direct measurement to obtain contact angle data in water-oil system such as Sessile Drop (e.g Treiber *et al*, 1972) and Wilhelmy Plate (e.g Mennella *et al*, 1995) measurements, some other indirect techniques are also known and intensively used. Widarsono (2010) in his study over wettability characteristics of some western Indonesia's sandstones presented and describe general information about four known indirect wettability indicators: Amott Wettability Index, USBM Wettability Index, Direct Imbibitions, and Water-oil Relative Permeability curves. Briefly, the techniques are described as follows:

**Amott Wettability Index (Amott 1959).** The technique is based on spontaneous imbibition and forced displacement of oil and water out of tested core plugs. Through spontaneous imbibitions two indexes are made, the oil index ($l_o$) and water index ($l_w$). The oil index is a ratio between volumes of water in a water-saturated core sample displaced by oil, if any, in an imbibitions (immersion in oil) process and volumes of all remaining water displaced through forced displacement by oil down to irreducible water saturation ($S_{wirr}$). For producing water index, the already oil-saturated sample (at $S_{wirr}$) is imbibed with water (immersion in water) leading to some volume of displaced oil after which – in the same manner with oil forced displacement – a water forced-displacement is applied to yield total produced oil. In the same manner to the oil index, the water index is a ratio between the two produced oil volumes.

Interpretation using the two indexes is somewhat relative in nature and there is no guideline for definitive judgment. Amott (1959) put 1.0 as strong wettability while a value of zero for neutral wettability. Users may adopt different interpretation for values between zero and unity. Conclusion from interpretation may even become less clear when values for the indexes are somewhat between the two extreme values. In this case, one can only judge the relative strength between the two wettability inclinations. In a similar manner as adopted in Widarsono (2010) this study puts wettability as $I_w$ - $I_o$ for which then the Amott wettability index would vary from +1 for absolute water wet to -1 for absolute oil wet with zero indicating neutral or mixed wettability. A detailed categorization is set through establishing wettability sub-class of 'strong oil wet', 'medium oil wet', 'weak oil wet', 'neutral', 'weak water wet', 'medium water wet', and 'strong water wet'. A set of similar criteria for the classes as in Widarsono (2010) is also adopted and presented in Table 2.

**USBM Wettability Index.** The principle of this technique is obtaining capillary pressure curves through displacing oil and water using centrifuge equipment (Donaldson *et al*, 1969). Forced displacement used in this technique is similar to the one used in the Amott technique. In the conduct of this method a sample is alternately put under forced displacement; firstly, being spun under water-saturated condition with oil as the displacing fluid, and secondly, centrifuging the now oil-saturated sample using brine as the displacing fluid. Capillary pressures are calculated based on the known rotational speeds.

With this alternate displacement a rock sample with inclination towards one wettability type will have two different capillary curves with non-wetting phase displacing wetting phase having higher and steeper curve. Presence of two different capillary pressure curves means that the areas underneath the curves are also different, a logarithmic ratio of which is then taken as indicator of the rock's wettability (Donaldson *et al*, 1969).

The values of the logarithmic ratio (i.e. the USBM Wettability Index) could range from $+\infty$ (complete water wet) to $-\infty$ (complete oil wet) with zero for neutral wettability. No guideline in regard to classification of wettability. Therefore, similar to the criteria used for the Amott wettability index, the USBM index is also divided using the same categorization into the same seven wettability groups. Table 2 presents the value ranges in the categorization.

**Direct Imbibitions.** This technique is basically simpler than the Amott and USBM techniques. The technique assumes that a rock with a preference toward a certain wettability type responds directly when being imbibed using the wetting phase, and its volume and imbibitions rate reflect the wettability strength. Despite the negligence of other factors such as imbibing liquid viscosity, permeability, porosity, and sample's edge condition (Tiab and Donaldson, 2004) this technique used to be widely applied.

**Tabel 2**
**Categorization criteria used in the study**

| Wettability class | Amott | USBM | Imbibition | Relative permeability |
|---|---|---|---|---|
| | $\Delta I = I_W - I_O$ | $I$ | $\Delta V = V_w - V_o$ | $S_w$ at $K_{ro} = K_{rw}$ |
| Strong water-wet | $0.8 < \Delta I \leq 1$ | $1 < I \leq +\infty$ | $50 < \Delta V \leq 100$ | $0.85 < S_w \leq 1$ |
| Medium water-wet | $0.5 < \Delta I \leq 0.8$ | $0.25 < I \leq 1$ | $15 < \Delta V \leq 50$ | $0.65 < S_w \leq 0.85$ |
| Weak water-wet | $0.1 < \Delta I \leq 0.5$ | $0.1 < I \leq 0.25$ | $5 < \Delta V \leq 15$ | $0.55 < S_w \leq 0.65$ |
| Neutral/mix | $-0.1 \leq \Delta I \leq 0.1$ | $-0.1 \leq I \leq 0.1$ | $-5 \leq \Delta V \leq 5$ | $0.45 < S_w \leq 0.55$ |
| Weak oil-wet | $-0.5 \leq \Delta I < -0.1$ | $-0.25 \leq I < -0.1$ | $-15 \leq \Delta V < -5$ | $0.35 < S_w \leq 0.45$ |
| Medium oil-wet | $-0.8 \leq \Delta I < -0.5$ | $-1 \leq I \leq -0.25$ | $-50 \leq \Delta V \leq -15$ | $0.15 < S_w \leq 0.35$ |
| Strong oil wet | $-1 \leq \Delta I < -0.8$ | $-\infty \leq I \leq -1$ | $-100 \leq \Delta V \leq -50$ | $0 \leq S_w \leq 0.15$ |

Tabel 3
Origin of data used in the study

| Sedimentary basin | Number of fields | Wettability indicator | | | |
|---|---|---|---|---|---|
| | | Amott | USBM | Imbibition | Rel perm |
| NW Java | 11 | 72 | - | 15 | 138 |
| South Sumatera | 4 | 23 | - | 7 | 53 |
| Sunda | 5 | 11 | 4 | 2 | 25 |
| **Total** | **20** | **106** | **4** | **24** | **216** |

Tabel 4
Example of Amott wettability test showing a set of Baturaja limestones with mixed wettability. The data set is from PD – 1 well, South Sumatera Basin

| Sample number | Permeability (mD) | Porosity (%) | Wettability Index | | | Interpretation |
|---|---|---|---|---|---|---|
| | | | W-wet | O-wet | $\Delta I$ | |
| 2 | 3.7 | 8.5 | 0.2500 | 0.3750 | -0.1250 | weak oil-wet |
| 5 | 2.8 | 12.8 | 0.1163 | 0.4746 | -0.3583 | medium oil-wet |
| 8 | 1.2 | 14.1 | 0.1579 | 0.4088 | -0.2509 | medium oil-wet |
| 33 | 2.5 | 11.3 | 0.3810 | 0.0000 | 0.3810 | medium water-wet |
| 37 | 264 | 7.5 | 0.2083 | 0.0000 | 0.2083 | medium water-wet |

No specific criteria is given for interpreting the technique's output, but the most common judgment for establishing wettability type is through relative comparison between rates and volumes (percent of pore volume) of the imbibed water and oil. However, in order to clearly quantify the wettability, criteria Index in the form of difference in imbibed volume ($\Delta V$) between volumes of imbibed water ($V_w$) and oil ($V_o$) is established. The value ranges are presented in Table 2.

**Water-oil relative permeability curves.** One of the most crucial influences of wettability upon rock physical properties is its potential to shift the water-oil relative permeability curves. Different type or strength in wettability leads to different fluid saturating path and characteristics within the tested rock hence changing the effective permeability of the fluids present. Shifts in relative permeability curves certainly affect prediction of fluid movements in reservoir with its direct relation to levels of oil recovery. The influence of wettability on relative permeability curves provides an opportunity to use water-oil relative permeability curves for indicating wettability type and strength.

As described in Widarsono (2010) wettability changes the movement tendencies of oil and water. In an oil-wet system early water breakthrough is expected due to easier water movement compared to oil. On the other hand, in a water-wet system oil recovery is likely to be higher due to higher oil mobility compared to water. As put by Archer and Wall (1986), the two wettability systems may become different even though the shape of curves remains the same. Shift in intersect between the two curves can therefore be used as indicator for rock wettability. Water wet rocks tend to have intersects falling at water saturation values lower than 50%, and the reverse is true for oil-wet system. Gradual degrees in wetting tendencies for both wettability systems naturally fall between neutral and the two strong wetting tendencies. For neutral or mix wettability – the term of 'mix wettability' is usually used for rocks that can be wetted by both oil and water but show no strong preference towards either of the two liquids – the curve intersect is likely to be at water saturation values of around 50%. To make analysis easier, the seven categories used in Amott and USBM is also used with water saturation ranges representing the curve intersect as reference. The water saturation ranges used are also presented in Table 2.

## IV. LABORATORY DATA

The wettability data for the study was obtained from Lemigas Core Laboratory database. The data was derived from laboratory testing on 350 samples consisting of 106 Amott wettability test, 4 USBM wettability test, 24 Direct Imbibitions test, and 216 water-oil relative permeability tests. The total Baturaja limestones of 350 samples are made of 225 from Northwest Java Basin, 83 from South Sumatera Basin, and 42 from Sunda Basin. Table 3 presents the summary of the data inventory. All wells' identities presented in the text, tables, and figures are obscured for proprietary reason.

All data was obtained in the form of unpublished reports. Amott and Direct Imbibitions test results are presented in tabular form whereas the USBM and relative permeability data is in both tabular and graphical forms. Table 4 shows an example of Amott wettability test data (PD–1 well, South Sumatera Basin) which consists of rocks with opposite wettability tendencies. Table 5 presents the only data set (SB–5 well, Sunda Basin) for USBM technique, of

**Tabel 5**
**Example of wettability test data obtained through the use of USBM technique.**
**The generally water-wet rocks are from SB –5 well, Sunda Basin**

| Sample No. | Permeability (mD) | Porosity (%) | $I = \log\left(\frac{A1}{A2}\right)$ | Interpretation |
|---|---|---|---|---|
| 30 | 959 | 30.7 | 0.2665 | medium water wet |
| 11 | 20 | 24.5 | 0.1447 | weak water wet |
| 14 | 750 | 27.3 | -0.1183 | weak oil wet |
| 27 | 187 | 23.9 | 0.3921 | medium water wet |

**Tabel 6**
**Example of of wettability test data obtained through the use of Direct Imbibition technique.**
**The The Baturaja limestones derived from RD-1 well, Northwest Java Basin, are generally water-wet**

| Sample number | Permeability (mD) | Porosity (%) | Imbibed fluid (%PV) | | | Interpretation |
|---|---|---|---|---|---|---|
| | | | Water | Oil | $\Delta V$ | |
| 6 | 1.4 | 22 | 40.3 | ND | 40.3 | medium water-wet |
| 11 | 0.6 | 14 | 65.7 | ND | 65.7 | strong water-wet |
| 39 | 3.2 | 16 | 43.4 | ND | 43.4 | medium water-wet |
| 41 | 12 | 21 | 27.6 | ND | 27.6 | medium water-wet |

ND: not detected

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**Tabel 7**
**Example of wettability indication from water-oil relative permeability data.**
**The data set is from T-24 well, Northwest Java Basin**

| Sample No. | Permeability (mD) | Porosity (%) | Sw @ Krw = Kro, (%) | Interpretation |
|---|---|---|---|---|
| 1 | 457 | 23.2 | 38 | weak oil-wet |
| 9A | 47 | 14 | 44 | weak oil-wet |
| 16A | 226 | 24.3 | 40 | weak oil-wet |
| 19 | 6.3 | 12.6 | 50 | neutral/mix |

which the resulting *I* values show inclination towards water-wettability. For Direct Imbibitions test, Table 6 presents an example (RD-1 well, Northwest Java Basin), which shows a preference towards water-wetness. Following the procedure in wettability tests, all wettability tests were performed using un-cleaned native cores, hence yielding unaltered wettability.

Unlike in the case of wettability tests, the samples assigned to water-oil relative permeability test are already cleansed based on consideration that any salts and crude oil within the samples' pore space may disturb flow of liquids during tests. This may alter the rock's original wettability, and therefore, even though water-oil relative permeability data provides indication over the rock's wettability but it does not always reflect the original wettability. Table 7 provides a wettability summary of samples taken from TB-24 well, Northwest Java Basin.

## V. DATA ANALYSIS

For the analysis over the data one has to be aware about some issues. Firstly, the quantity of samples that underwent wettability tests is limited to 156 only, leaving open a question over representative ness to Baturaja Formation. Secondly, although wettability test results are in form of values, interpretation over it is usually made in qualitative manner. Therefore, the criteria set presented in Table 2 should not be taken as a rigid and absolute reference. Thirdly, 'mix-wettability' is taken as equal neutral wettability, in an understanding that if neutral wettability is attributed to rocks that do not absorb neither water nor oil then the mix-wettability represent rocks that tend to attract the two liquids in roughly similar quantity/portion. The commonly used term of 'preferential wettability' for rocks that draw more of one liquid than the other one is not used here. Fourthly, although some rocks may to some extent succeed in preserving their original permeability after core hot cleaning the information regarding wettability given by water-oil relative permeability has to be taken with caution and not to be regarded as representing the rock's original wettability.

**Rock original wettability.** The data provided by the three wettability tests have shown that the Baturaja limestone do not preferentially inclined onto a specific wettability type. Results from the three wettability tests have revealed a composition of 41.8% water-wet, 40.3% oil-wet, and 17.9% neutral/mix wettability. These percentages represent 56 water-wet, 54 oil-wet, and 24 neutral neutral/mix wettability samples of the total 134 samples. Figure 1 presents the wettability composition in general.

Figure 2 depicts a more detailed wettability grouping in accordance with the categorization criteria presented in Table 2. The histogram in Figure 2 promptly shows that the even wettability tendency as exhibited on Figure 1 is not exactly the case. Although it appears that 'weak water-wet' group comes out as the group with the largest number (42 samples) the oil-wet group is more evenly distributed with 'medium oil-wet' and 'strong oil-wet' groups having more significant weight than their counterparts in the water-wet group. This creates 'weak oil-wet' group that sizes only about a half of its water-wet counterpart. This skewed composition towards oil wettability can be interpreted as a proof that the Baturaja limestone is evenly distributed quantitatively but more oil-wet qualitatively.

As described previously, the Baturaja Formation is an extensive rock formation existing in an area

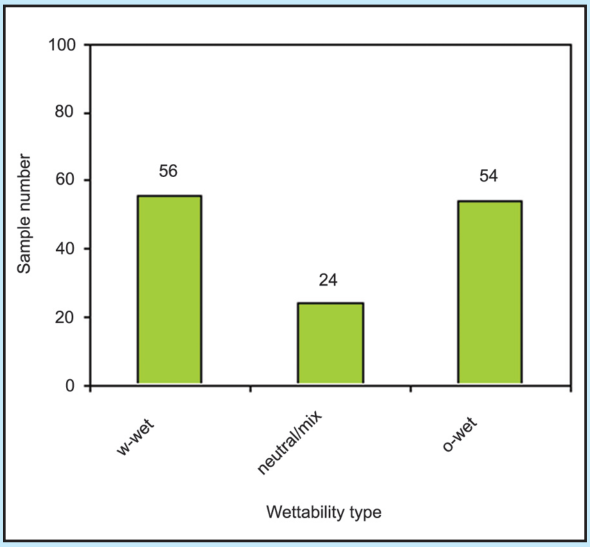


**Figure 1**
**Wettability composition of the Baturaja Formation's limestone samples, which wettability test results are used in this study. Water-, neutral-, and oil-wettability make 41.8%, 17.9%, and 40.3% of the total core samples, respectively**

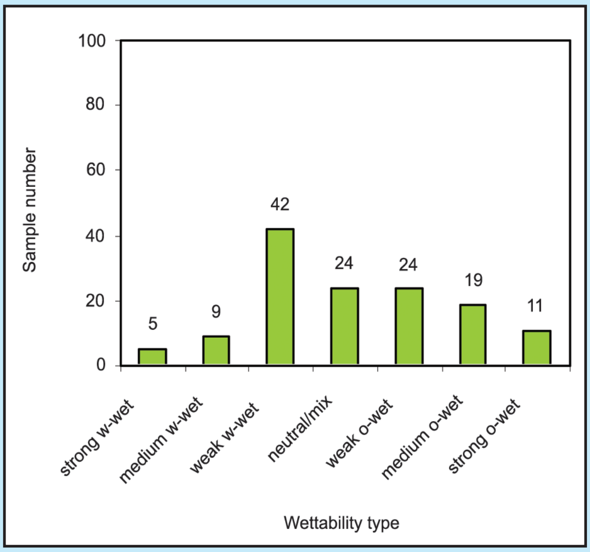


**Figure 2**
**A more detailed wettability composition of the Baturaja Formation's limestone samples. Although weak water-wettability is the largest single group the composition exhibits stronger oil wettability tendency shown by the significant presence of 'medium oil-wet' and 'strong oil-wet' samples**

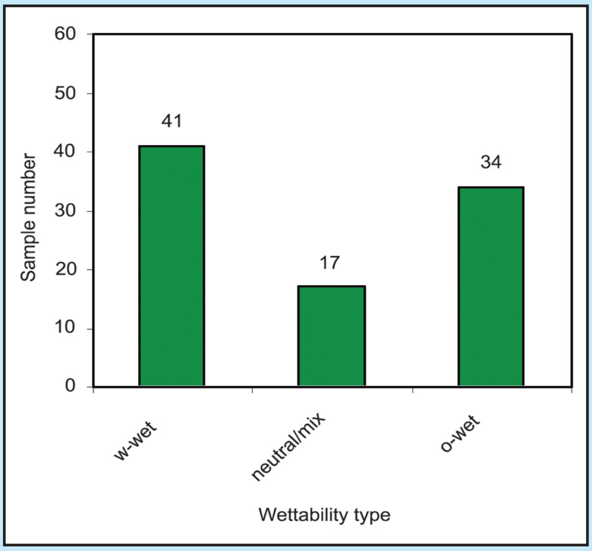


**Figure 3**
**Wettability composition of limestones taken from Northwest Java Basin (92 samples). Water-wet samples appear to be of majority (44.5%) but the oil-wet group trails closely behind (37%). Like the picture in general, the neutral/mix wettability samples are the smallest in proportion (18.5%).**

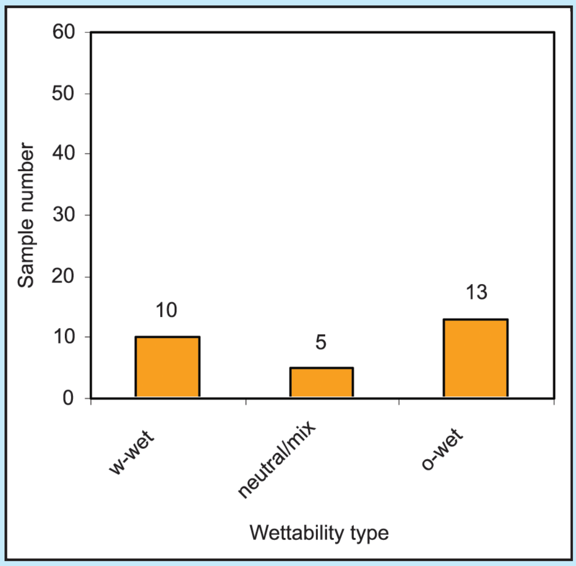


**Figure 4**
**Wettability composition of limestones taken fro South Sumatra Basin (28 samples). Water-wet samples are apparently not as numerous as the oil-wet samples (35.7.5% and 46.5%, respectively), and the neutral/mix wettability samples are typically the smallest in proportion with 17.9%**

that spans from eastern part of West Java to the southern part of Central Sumatra. Although the rocks of concern are mostly reef limestone in nature differences may exist. Figures 3 through 5 show the wettability distribution for the limestone from the three sedimentary basins. Histogram on Figure 3 shows that the Baturaja limestone from the North west Java Basin (92 samples) have 44.5% water-wet, 37% oil-wet, and 18.5% neutral/mix wettability. The corresponding respective figures are 35.7%, 46.4%, 17.9% for Baturaja limestone in South Sumatera Basin (28 samples) and 35.7%, 50%, 14.3% for the Sunda Basin's Baturaja limestone (14 samples).

From the wettability compositions shown on Figures 3 through 5 one may promptly concludes that Baturaja limestone from the Northwest Basin tends to be more water-wet while the reverse is true for limestone from the two other sedimentary basins. This may be true quantitatively but considering the stark similarity shown by the three sample populations – large but more or less even for water-wet and oil-wet and small for neutral/mix wettability – a more general conclusion should prevail. This consideration may channel the analysis into a more general conclusion that, despite differences that may exist due to local factors, the limestone from the three sedimentary basins show similar wettability compositions. Detailed compositions for the three sets of samples are also similar to the general composition shown on Figure 2.

**Wettability alteration,** The influence of hot cleaning of core samples prior to water-oil relative permeability tests are obviously shown by the relative permeability-derived wettability (Figure 6). Out of the total samples of 216, 54.6% (118 samples) are of neutral/mix wettability group. Although the samples used in relative permeability tests are not the same as the ones for wettability tests – samples assigned for wettability tests are usually taken at points a few centimeters away from the samples assigned for relative permeability tests – the data can still speak of wettability alteration. A more detailed view is provided on Figure 7 in which all seven wettability classes are exhibited. Out of the neutral/mix wettability group the rest of the data appears to belong to 'weak' wettability groups both oil (46 samples) and water (33 samples). The two combined with the neutral/mix wettability group make up 91.2% of total

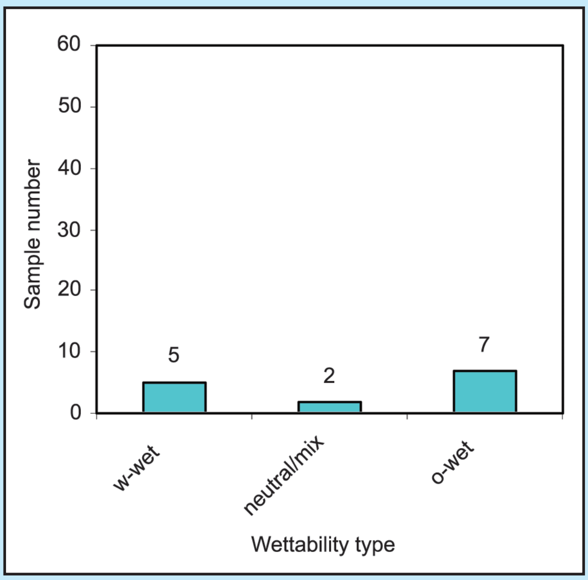


**Figure 5**
**Wettability composition of limestones taken from Sunda Basin (14 samples). Similar to the case of South Sumatera samples the limestones from the Sunda Basin – despite small in number – tend to have more oil-wet samples (50%) than water-wet (35.7%) and neutral/mix wettability (14.3%) samples**

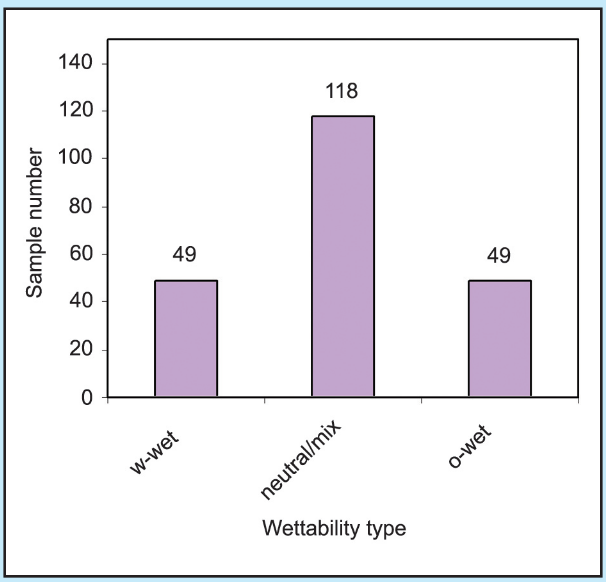


**Figure 6**
**Composition of relative permeability-derived wettability for all limestones used in the study (216 samples). The data shows clear majority for neutral/mix wettability group (54.6%) compared to 22.7% each for the water-wet and oil-wet groups.**

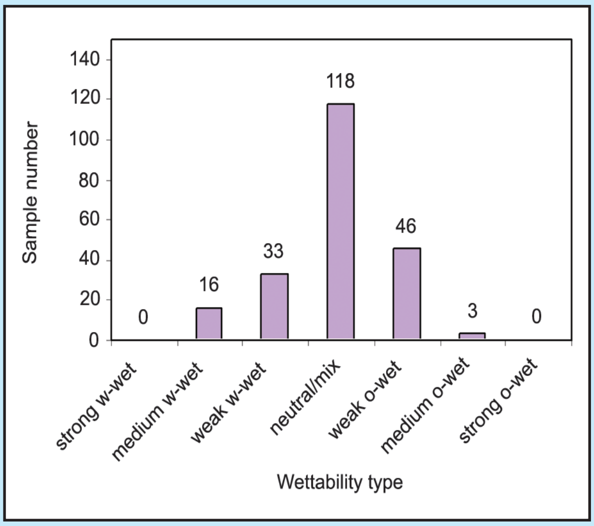


**Figure 7**
**The fully detailed composition of the relative permeability-derived wettability (216 samples). When the two groups of weak water-wet and weak oil-wet are combined with the neutral/mix wettability group they make up 91.2% of total. Notice the absence of strong wettability samples**

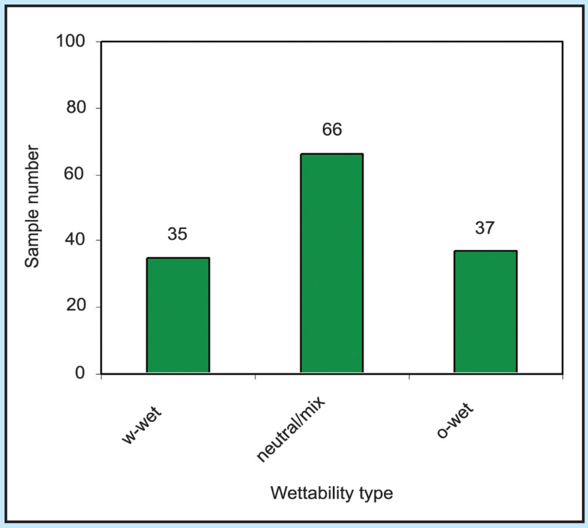


**Figure 8**
**Relative permeability-derived wettability for samples taken from Northwest Java Basin (138 samples). 47.8% of the samples belong to neutral/ mix wettability group while the other two groups have roughly equal portions (25.4% and 26.8% for water-wet and oil-wet groups, respectively)**

samples. When compared to the original wettability depicted on Figure 2 a weakening in wettability strength is apparent.

A further analysis was made to observe this wettability alteration effect on the samples from the three sedimentary basins. Figure 8 through 10 present the information. There are differences in wettability compositions for the three data sets but similar trends are existent, all of which show that neutral/ mix wettability group makes up the bulk of the data. A more detailed analysis involving all wettability classes also exhibit similar compositions to the one shown on Figure 7.

## VI. FURTHER DISCUSSION

From the results of wettability tests, it has been shown that the Baturaja limestones are characterized with equally strong wetting tendencies between water wettability and oil wettability with each having around forty percent in proportion. This fact is certainly different from what is commonly believed that carbonate rocks tend to be strongly inclined to oil wettability. As put previously, Treiber *et al* (1972) and Chillingarian and Yen (1986) found 80% or higher of carbonate samples they studied as being oil-wet. The Baturaja limestones certainly behave differently in a sense that a significant portion of them tend to be water wet, and when combined with some of the neutral or mixed in wettability the oil-wet limestone in the formation are obviously not the majority (40.3%, Figure 1). However, when the water-wet and oil-wet tendencies are of concern detailed classification presented on Figure 2 obviously shows that – qualitatively – the Baturaja limestone is still inclined towards oil wettability rather than water wettability. For the oil wet group 55.6% belongs to medium oil-wet and strong oil-wet groups whereas only 25% belonging to the corresponding groups in the water-wet group. This cannot, nevertheless, be taken as a strong preference towards oil wettability.

Widarsono (2010) reported that from the 139 sandstone samples he obtained from various fields in western Indonesia 48.2% are water-wet, 30.2% oil-wet, and 21.6% neutral. This finding was also reported as in common with results from past reported studies on sandstones from other parts of the world. Nonetheless, when this finding is compared to the results for Baturaja limestone a semblance

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of similarity in composition is observed. It is not yet obvious that other limestone from other rock formation will behave likewise but this evidence has shown that wetting tendencies of both limestone and sandstone may behave similarly. As put by Tiab and Donaldson (2004), all petroleum reservoirs are thought of having water-wet tendency originally, but different processes and interactions along their existence had resulted in the present-day rock wettability.

Different wettability compositions exhibited by results from the three wettability tests and water-oil relative permeability test have prompted the fact that wettability alteration indeed takes place during core preparation. This is particularly critical when hot cleansing is involved in core preparation. It is admitted that hot cleansing is an effective way to remove salts and oil residue in the pore space in order to avoid any potential disturbance to the planned tests. Despite the test practicality validity of test results may be put into question. Therefore, as also stated in Widarsono (2010), methods such as cold cleansing or core ageing for cores that have undergone hot cleansing are advised to be adopted as substitute of the commonly practiced hot cleaning.

## VII. CONCLUSIONS

A set of conclusions have been obtained from the study, which are:

- The Baturaja limestone shows in general no preference to wettability, some exhibit preference to oil wettability but a respectable proportion of roughly similar to them tend to be water wet. This defies the common assumption that carbonate rocks are oil wet in nature.
- No evidence is known whether other carbonate rocks behave in the same way as the Baturaja limestone do but the wide extension of the Baturaja Formation itself, along with their varied genetics circumstances imply that the occurrence shown by the associated limestone may also apply to other limestone.
- In a way similar to the case of sandstones, the Baturaja limestone also shows some tendency towards neutral/mix wettability even though at proportion lesser than the tendencies towards either oil wet oil water wet.
- A more detailed study on the Baturaja limestone exhibits that they are quantitatively more inclined towards oil wettability relative to towards water

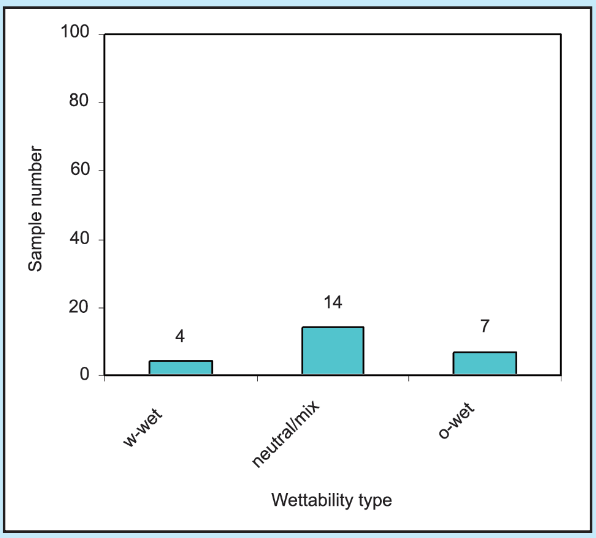


**Figure 9**
**Relative permeability-derived wettability for samples taken from South Sumatra Basin (53 samples). The neutral/mix wettability group makes 71.7% of total leaving the water-wet and oil-wet groups with 18.9% and 9.4%, respectively**

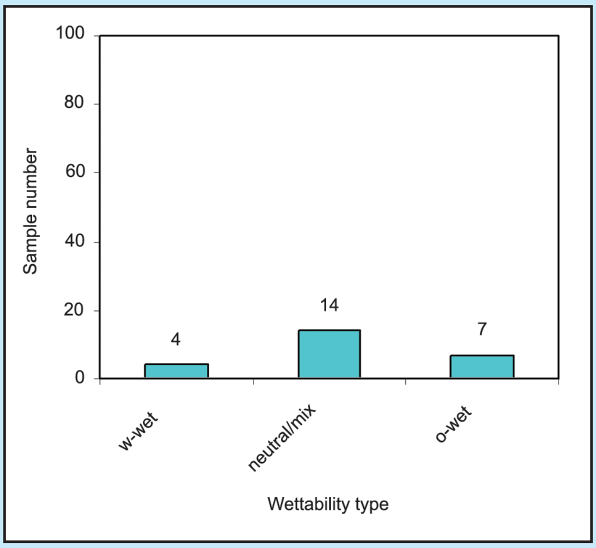


**Figure 10**
**Relative permeability-derived wettability for samples taken from Sunda Basin (25 samples). Despite the limited quantity a similar composition to the general composition prevails in which 56% belongs to neutral/mix wettability group, 16% to water-wet group, and 28% to oil-wet group**

wettability. However, that does not mean that the Baturaja limestone is oil wet in nature.

- The finding of wettability alteration in the Baturaja limestone has led to a suggestion that the commonly practiced hot cleansing practice for core preparation has to be abandoned, even though it is still a part of a 'recommended practice'. Core cold cleansing method and core ageing in native crude for cores that have undergone hot cleansing are strongly advised.

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